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An overview of mercury emissions by global fuel combustion: The impact of international trade

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ABSTRACT

This study provides an overview of mercury emissions by global fuel combustion by compiling the detailed inventory as well as elaborating the impact of international trade. Based on the global fuel-related mercury emissions inventory covering 26 sectors in 186 economies for the year of 2010, systems multi-region input-output analysis is employed for the first time to investigate international trade's impact on mercury emissions induced by each economy. The estimated mercury emissions mainly contributed by coal burning are 859.12 t, approximately 30% of which are embodied in commodities transported to consumers in other economies via international trade. The emerging economies such as mainland China and India are the prominent net exporters of embodied mercury emissions while developed economies like Japan, Germany and the USA are the net importers, indicating that developed economies avoided a large amount of direct mercury emissions by transferring the production of emission-intensive commodities to developing economies. By integrating the direct emissions and the net trade effect, mainland China has the largest embodied mercury emissions, followed by the USA and India. This study verifies the significant role of international trade in drawing a holistic picture of global fuel-related mercury emissions. The findings also suggest that focusing on the atmospheric mercury pollution directly emitted by local producers in isolation may result in an absurd situation of "regional reduction at the cost of global rise". It is anticipated that the current study provides insights for forming a reasonable emission responsibility sharing mechanism and facilitating comprehensive abatement strategies.

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1. Introduction

Since the beginning of the industrial revolution, mercury emissions into the atmosphere have increased threefold [1]. However, its high toxicity to both humankind and ecosystems was not recognized until the breakthrough of the sensational and notorious Minamata Disease. Since then, more and more medical evidence has proved that mercury is one of the most harmful air pollutants [2]. When exposed to atmospheric mercury through inhalation, people's organ systems such as the central nervous system can be adversely affected. Young children, especially fetuses are vulnerable to mercury pollution. Moreover, once mercury element is emitted into atmosphere, it can travel thousands of miles, causing global contamination of plants, animals and human being. In light of the enormous harm of atmospheric mercury to global populations' health and environmental safety, atmospheric mercury is considered as a pollutant of global importance [3].

Additional to the natural sources such as volcano eruption and geothermal activities, a large amount of atmospheric mercury is released by human activities including fuel burning, use of minerals and waste disposal, etc. These anthropogenic activities are blamed as the main reasons for the growth of mercury emissions in the atmosphere [4]. As the quantitative information on global emissions from different anthropogenic sources is essential for the abatement policy design and development of control technology, numerous efforts to investigate global anthropogenic mercury emissions have made by researchers from different organizations and institutions, which are comprehensively reviewed in Section 2.

Although the anthropogenic emissions reported in different studies show variance due to the different methods employed and emissions factors adopted, it is easy to find out one common fact among all the existing studies, which is fuel combustion, especially coal burning has been the leading source of global anthropogenic mercury emissions. In an early inventory, mercury emissions from fuel combustion amounted to about 960 t, accounting for 56% of the global total in the year of 1995 [1]. In recent years, fuel combustion is still considered as one of the main sources of atmospheric emissions, accounting for about 1/3 or even more of global total [3]. The large share of fuel-related mercury emissions in the global picture implies the mitigation of mercury emissions from fuel combustion is vital for reducing human health and environmental risks from airborne mercury pollutants.

Without doubt, the existing global studies on mercury emissions contributed significantly to expanding people's knowledge on mercury emissions, in addition to providing precious information for mercury mitigation. However, the information on mercury emissions from global fuel combustion activities remains to be updated and extended. First of all, the relevant data in previous studies become obsolete as the reference years of inventories were years or even decades ago. Second, since the previous studies only provided emission data for major emitters or major economies, detailed information for a large number of economies is still lacking. Moreover, the concerns about atmospheric mercury emissions of all the basic sectors which constitute our global economy are far from sufficient in this field. Third, most of the global mercury emission inventory suffers incompleteness as those from biomass burning are missing, with regarded to the fact that biomass has become a more important energy source in the global picture of energy [5].

Another major concern of the previous studies is that they were conducted in the framework of direct accounting of local emissions, which is also referred as territory-based method. The essential characteristic of direct accounting method lies in the definition of system boundary of the region concerned. When evaluating the environmental emissions, the scope of territory-based research is limited to calculating the direct emissions that took place within the territory where the local region has jurisdiction. It ignores the trans-boundary embodied emissions fluxes associated with traded commodities originating from places outside of the region concerned [6]. This truncation might result in leakage problem when assessing the national anthropogenic emissions in the times of globalization as international trade displaces fuel consumption and industrial production which are closely related to environmental emissions. Considering the shortcoming of direct emission accounting, embodied emissions, defined as the total amount of emissions directly and indirectly induced by the production of a good or service, is suggested as an indicator to draw the holistic picture of an economy's emissions.

The embodied effect linked to the impact of international trade has been demonstrated well in the cases of greenhouse gas emissions [7–10], water use [11,12], energy use [13,14], materials use [15], land use [16,17] and even biodiversity threats [18]. Even though numerous efforts have been devoted to investigating international trade's role in distributing the ecological elements between different economies, people are still clueless about the facet of international trade's role in shifting atmospheric mercury, an air pollutant with global importance. To solve these problems, this study aims to provides an overview of mercury emissions related to global fuel combustion as well as articulate how international trade influences atmospheric mercury emissions flow by: (1) compiling an up-to-date and comprehensive inventory of fuel-related emissions of 186 individual economies; (2) evaluating the impacts of international trade on mercury emissions caused by global fuel combustion by using input-output analysis; (3) investigating the embodied mercury emissions of each economy by combining the direct emissions with the effect of international trade.

2. Literature review

Since the 1970s, average annual growth rate of global atmospheric mercury concentration has long exceeded 1%, to which anthropogenic activities are considered to contribute the most [19]. An early inventory on global mercury emissions was compiled by Nriagu and Pacyna [20], which reported that mercury released into the air worldwide amounted to 3560 t in the year of 1983. Whereafter, Pirrone et al. launched the similar estimation, indicating that global atmospheric mercury emissions presented an increasing trend from 1983 to 1992 with a variation of 1861–2199 t [21]. Pacyna and his collaborators completed a series of solid work to estimate the global mercury emissions, manifesting that global atmospheric mercury emissions increased from 1900 t in 1995–2190 t in 2000 but slightly declined to 1930 t in 2005 [22–24]. Muntean et al. provided a time-series of man-made emissions of atmospheric mercury from 1970 to 2008. In this study, global mercury emissions from human activities reached 1287 t in 2008, with an average growth rate 1.3% since 1970 [25]. Facing the severe mercury pollution in the atmosphere, mercury emissions estimation has been on the agenda of United Nations Environment Protection Agency (UNEP), which also issued reports on global mercury emissions in some years [1,3,26]. Moreover, Pacyna et al. and Streets et al. projected global atmospheric mercury emissions in 2020 and 2050, respectively, in light of different mercury control policy scenarios [22,27]. Many other efforts have been devoted to accounting mercury emissions from some large emitters or important regions such as China [28,29], North America [30], South America [31] and Mediterranean region [32]. Despite of diverse methods and emission factors adopted by these aforementioned studies, one common fact is that fuel combustion is one of the main contributors to anthropogenic mercury emissions.

In addition to aforementioned studies based on direct accounting framework, there are a few studies trying to reveal the indirect effect that influences the mercury emissions. Liang et al. used an environmentally extended input-output analysis (IOA) to evaluate the virtual atmospheric mercury emissions of provinces in China and different nations around the world [33,34]. Li et al. and Jiang et al. conducted the studies concentrating on the virtual mercury emissions in Beijing economy based on different emission sources [35,36]. These studies contributed greatly to help us draw a more comprehensive picture of mercury emissions from the global, national, provincial and urban perspectives. However, the impact of international trade on mercury emissions from global fuel combustion has never been addressed. Furthermore, the environmentally extended IOA just attributes the emissions to final demand and incapable to differentiate the local production and imports, while the systems IOA, as a unified network methodology based on the objective principle of biophysical balance to all the economic sectors, can be regarded as a supplement to the environmentally extended IOA [37–39]. Therefore, this study adopts the systems IOA to track the embodiment of fuel-related mercury emitted by global economy. The systems IOA was developed by Chen and his group, in light of Odum's general systems theory [40,41]. This method has been widely used to account for various environmental resources as ecological elements such as energy, greenhouse gas (GHG) emissions, water and even pollutants. For the world economy, Chen and Chen constructed a systems IOA model and drew a holistic picture of embodied GHG emissions and natural resources use in the year of 2000 [39]. Supported by multi-region and multi-scale statistics, Shao employed systems IOA for evaluating embodied water of world, China and Beijing economies as well as depicting the embodied water flows between economies at different scales [42]. To provide comprehensive information for GHG emission mitigation policy design as well as national resources management, the systems IOA was applied to elaborating embodied emissions and resources use induced by Chinese economies in different years [37,38]. Particularly, Chen's group also carried out a series of studies on different types of GHG emissions embodied in Chinese final demand and analyzed the impact of international trade [43,44]. Besides, tentative efforts were also made to investigate international and domestic trade's impacts on urban scale environmental emissions [45,46]. Moreover, the embodied ecological elements founded on systems IOA provided solid basis for assessing the environmental impacts of economic sectors [47,48], commercial buildings [49,50] and renewable energy engineering [51–54].

3. Method and data

3.1. Method

3.1.1. Direct emissions accounting

The estimation of direct emissions from fuel combustion is founded on the direct accounting method. The atmospheric mercury emissions released from fuel combustion activities are estimated using calculation method employed by [33,35,55], with the emissions from each source type obtained by multiplying the emission factor by corresponding activity data.

3.1.2. Embodied emission accounting

For analyzing mercury emissions embodied in international trade and embodied emissions of each economy, a comprehensive and reliable global multi-region input-output (MRIO) table covering high economy and sector details is applied in the present study. Using the inter-economy and intra-economy data provided by Eora database [56] and the estimated corresponding atmospheric mercury emission data from fuel combustion activities, a MRIO model demonstrating both direct mercury emissions and monetary flows is constructed. The simplified format of global MRIO used in the current study is presented in Table 1.

Shown in Table 1, Z_{ij}^{SR} indicates the intermediate use of the global economy, i.e., the products or services imported by Sector *j* in Economy *R* from Sector *i* in Economy *S*; d_{it}^{SR} represents the monetary value of commodity produced by Sector *i* in Economy *S* which is purchased by final demand *t* in Economy *R*; e_i^S denotes the atmospheric mercury directly emitted by fuel combustion activities of Sector *i* in Economy *S*; x_i^S denotes the total economic output of Sector *i* in Economy *S; m* is defined as the number of economies, *n* is the number of basic economic sectors and *l*

Table 1
The format of global multi-region input-output table associated with atmospheric mercury emissions (revised according to [21]).

From/to			Commodity and mercury emissions					Total output
			Intermediate input Economy 1 Sector 1 …	… Sector n	Economy m Sector 1 …	Sector n	Final demand Economy 1…Economy m Category 1 …Category *l* Category 1 … Category *l*	
Commodity output	Economy 1	Sector 1			Z_{ij}^{SR}		d_{it}^{SR}	x_i^S
		…						
	…	Sector n						
	Economy m	Sector 1						
		…						
		Sector n						
Mercury emissions					e_i^S			

represents the number of the categories of final demand.

and

$$\begin{bmatrix} \begin{pmatrix} \sum_{R=1}^{m}\sum_{j=1}^{n} Z_{1j}^{1R}+d_{1t}^{1R} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sum_{R=1}^{m}\sum_{j=1}^{n} Z_{nj}^{1R}+d_{nt}^{1R} \end{pmatrix} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \begin{pmatrix} \sum_{R=1}^{m}\sum_{j=1}^{n} Z_{1j}^{mR}+d_{1t}^{mR} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sum_{R=1}^{m}\sum_{j=1}^{n} Z_{nj}^{mR}+d_{nt}^{mR} \end{pmatrix} \end{bmatrix}$$

For the global MRIO table, the row balance can be formulated as:

$$x_i^S = \sum_{R=1}^{m}\sum_{j=1}^{n} Z_{ij}^{SR} + \sum_{R=1}^{m}\sum_{t=1}^{l} d_{it}^{SR} \tag{1}$$

Economic sector in each economy links the economy with the environment via emitting atmospheric mercury by burning fuels, importing and exporting embodied fuel-related mercury emissions. According to [30–32], the physical balance of embodied mercury emission flow for Sector i in Economy S can be expressed as:

$$e_i^S + \sum_{S=1}^{m}\sum_{j=1}^{n} \varepsilon_j^S \times Z_{ji}^{SR} = \varepsilon_i^S \times \left(\sum_{R=1}^{m}\sum_{j=1}^{n} Z_{ij}^{SR} + \sum_{R=1}^{m}\sum_{t=1}^{l} d_{it}^{SR} \right) \tag{2}$$

where ε_i^S is the embodied emission intensity of output from Sector i in Economy S.

Introduce the following denotations of

$$\boldsymbol{\varepsilon}^* = \begin{bmatrix} \begin{pmatrix} \varepsilon_1^1 \\ \vdots \\ \varepsilon_n^1 \end{pmatrix} \\ \vdots \\ \begin{pmatrix} \varepsilon_1^m \\ \vdots \\ \varepsilon_n^m \end{pmatrix} \end{bmatrix},$$

$$E^* = \begin{bmatrix} \begin{pmatrix} e_1^1 \\ \vdots \\ e_n^1 \end{pmatrix} \\ \vdots \\ \begin{pmatrix} e_1^m \\ \vdots \\ e_n^m \end{pmatrix} \end{bmatrix},$$

$$Z^* = \begin{bmatrix} \begin{pmatrix} z_{11}^{11} & \cdots & z_{nn1}^{11} \\ \vdots & \ddots & \vdots \\ z_{1n}^{11} & \cdots & z_{nn}^{11} \end{pmatrix} & \cdots & \begin{pmatrix} z_{11}^{m1} & \cdots & z_{n1}^{m1} \\ \vdots & \ddots & \vdots \\ z_{1n}^{m1} & \cdots & z_{nn}^{m1} \end{pmatrix} \\ \vdots & \ddots & \vdots \\ \begin{pmatrix} z_{11}^{m1} & \cdots & z_{n1}^{m1} \\ \vdots & \ddots & \vdots \\ z_{1n}^{m1} & \cdots & z_{nn}^{m1} \end{pmatrix} & \cdots & \begin{pmatrix} z_{11}^{mm} & \cdots & z_{n1}^{mm} \\ \vdots & \ddots & \vdots \\ z_{1n}^{mm} & \cdots & z_{nn}^{mm} \end{pmatrix} \end{bmatrix},$$

then the above simultaneous equations can be shown in a compressed matrix form of

$$E^* + Z^* \times \boldsymbol{\varepsilon}^* = Y \times \boldsymbol{\varepsilon}^* \tag{3}$$

Introduce E, $\boldsymbol{\varepsilon}$ and Z as the transposes of E^*, $\boldsymbol{\varepsilon}^*$ and Z^*, then we have:

$$E + \varepsilon \times Z = \varepsilon \times Y \tag{4}$$

Therefore, with the condition that $(Y - Z)^{-1}$ is reversible, the vector of embodied mercury emission intensities can be calculated as

$$\varepsilon = E \times (Y - Z)^{-1} \tag{5}$$

Based on the set of $\boldsymbol{\varepsilon}$ calculated by Eq. (5), the embodied mercury emissions of output from Sector i in Economy S can be obtained by

$$EME_i^S = \varepsilon_i^S \times x_i^S \tag{6}$$

where EME_i^S represents the embodied mercury emissions of output of Sector i in Economy S.

For Economy R, its fuel-related mercury emissions embodied in imports (EEI^R) can be obtained by summing all the fuel-related mercury emissions embodied in imports from other economies to Economy R. Likewise, mercury emissions embodied in exports from Economy R (EEE^R) can be calculated by summing all the emissions embodied in exports to other economies.

With the obtained values of (EEI^R) and (EEE^R), trade balance of fuel-related embodied mercury emissions, namely, the net embodied mercury emissions of Economy R (EEB^R) can be formulated as

$$EEB^R = EEI^R - EEE^R \tag{7}$$

If the value of EEB^R is negative, Economy R is a deficit receiver of fuel-related embodied mercury emissions, i.e., a net exporter of embodied mercury emissions; if the value of EEB^R turns out to be positive, then Economy R is identified as surplus receiver or net importer of fuel-related embodied mercury emissions. Finally, the each economy's embodied atmospheric mercury emissions related to fuel combustion can be calculated based on DE and EEB of the local economy, referring to [57–62].

3.2. Data sources

The economic MRIO table including the intermediate and final demand matrixes is constructed by Eora database [56]. The economic table includes 186 individual economies, identifies 26 basic economic sectors (seen in Table S1) and includes 6 categories of final demand. Three energy types, coal, oil products and biomass, are considered in this study. It should be noted that natural gas may contain a small amount of mercury. Therefore, natural gas burning is also a source of atmospheric mercury emissions. But the element of mercury is almost entirely removed from the raw gas during the production process so that natural gas can be treated as mercury-free energy source, compared to other energy types [21,63]. The data on fuel combustion activities in each economy are provided by Eora satellite account. Emission factors for all the emission sources are derived from existing studies [3,64] (Seen in Table S2).

4. Results and discussion

4.1. Direct emissions by economy

859.12 t of mercury emissions into the air is estimated due to global fuel combustion, to which coal, oil products and biomass combustion contribute 85.77%, 9.06% and 5.17%, respectively. It is evident that coal burning dominates the atmospheric mercury emission from fuel combustion. The emission intensities of world economy and world's per capita emission are 12.68 g/million USD and 0.13 g/person, respectively. Direct mercury emissions from 6 selected economies' fuel combustion are presented in Fig. 1. The 186 economies concerned in this study contributed 868.60 t while the rest of world is responsible for 0.56 t. Among the 186 economies, mainland China is the largest individual emitter with an amount of 373.72 t, which is 3.7 times as large as that of the USA (Rank 2ed), 4.5 times that of India (Rank 3rd) and 16.5 times that of Japan (Rank 4th). Mainland China's large quantity of atmospheric mercury emissions are attributed to its energy structure which is characterized as coal-dominated and high emissions factor of coal burning which is several times that of developed economies [64]. For each energy type, mainland China has the largest emissions from both coal and biomass combustion while the USA has the largest emissions from oil products burning. The largest 6 emitters are responsible for three fourths of world's total caused by fuel combustion. Unlike the ranking of total emissions, Moldova, North Korea and Belarus have the largest direct emission intensities while Antigua, Seychelles and Bahamas have the three largest per capita emissions.

In previous global research, the amounts of atmospheric mercury emissions from fuel combustion activities are in the range of 416–1422 t in the period of 2000–2010 [22,63–66]. The amounts of mercury emissions in the same year reported in different studies also vary considerably from each other. For instance, fuel-related mercury emission were estimated as 1422, 586 and 416 t for the year of 2000 in [25,66], respectively. Fuel-related mercury emissions documented in the current study are 859.12 t, which is comparable to the results of previous studies. The remarkable difference originates from many factors, e.g., different data sources, methods and emission factors. It is argued that the global fuel-related mercury emissions tend to be stable due to a combination of reasons. On one hand, fast energy consumption growth in emerging economies such as mainland China and India whose energy structure dominated by coal has driven the mercury emissions. On the other hand, the mercury removal and abatement technologies applied in power plants and factories have been improved in many countries, especially in developed countries that contribute to the global mercury mitigation.

Depicted in Fig. 1 are the compositions of direct mercury emissions from different energy sources in economies with the top 10 emission amounts and the detailed information of all economies is summarized in Table S3. In the figure, the top 3 emitters, mainland China, the USA and India's atmospheric mercury emissions from fuel combustion are dominated by coal. According to Table S3, economies like Pakistan and Kenya have 100% of their direct emissions contributed by coal burning. In some Middle-eastern economies such as Saudi Arabia and UAE, almost all the energy related emissions are attributed to oil products, due to their oil dominated energy structure as these countries are rich in oil resources. In some South American and European economies like Cuba and Finland, biomass becomes the major contributor of fuel-related mercury emissions. A remarkable phenomenon can also be found, which is that coal-related mercury emissions have higher percentage in developing economies than that in developed economies in general. This can be explained by two reasons: one is that oil and biomass take larger share in their energy structure; the other is that the atmospheric mercury emission factors of coal combustion in developed countries are usually smaller than that of developing countries, as developed countries have higher quality reduction technology and stricter emission control policy.

The proportion of coal in global energy consumption structure is just 30% while the coal combustion contributes over 85% of global fuel-related mercury emissions. So the large potential for abating fuel-related mercury emissions lies in the reduction of coal burning. Stringent regulations can be introduced to limit mercury

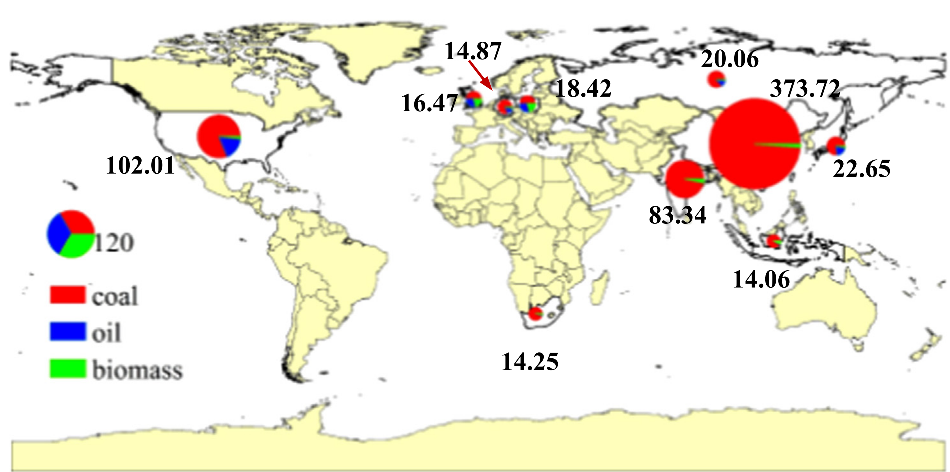

Fig. 1. Direct emission compositions of top 10 emitters (Unit: tonnes).

emissions from prominent coal consumers such as coal-fired power plants. Government should mandate the main mercury emitters to install emission control devices with high mercury removal efficiency. Additionally, promoting cleaner energy such as natural gas or solar power as an alternative for coal would also benefit the global mercury emission reduction. However, reducing mercury from coal still faces great challenge. For economies like mainland China whose energy endowment is characterized as rich in coal but poor in oil, for a long time, coal will be the first-choice. According to the statistics, even though the proportion of coal in Chinese structure has decreased in recent years, the absolute amount of coal burned keeps increasing [67]. Consequently, it is unrealistic to essentially change the status quo of coal dominated energy structure in economies like mainland China [68].

4.2. *Direct and embodied sectoral mercury emissions by sector and industry*

Direct and embodied fuel-related atmospheric mercury emissions of the 26 basic sectors of global economy are calculated and shown in Fig. 2. For direct emissions, Sector 13 (Electricity, Gas and Water) has the highest intensity among all the sectors, with a number of more than 176.61 g/million USD. Followed is Sector 7 (Petroleum, Chemical and Non-Metallic Mineral Products)'s 17.10 g/million USD and Sector 8 (Metal Products)'s 6.29 g/million USD. The Sectors with the lowest direct emission intensities are Sector 26 (Re-export and Re-import), 22 (Public Administration) and 21 (Financial Intermediation and Business Activities), with a number of 0.004 g/million, 0.12 g/million USD and 0.13 g/million USD, respectively. For embodied emissions, sector 13 (Electricity, Gas and Water) has the highest intensity among all the sectors, with a value of 225.51 g/million USD, which is 62.5 times as large as that of Sector 22 (Public Administration) with the lowest value of 3.61 g/million USD. Generally, for both direct and embodied emissions, the secondary industry (Sector 3–14) has the highest average intensities, followed by agricultural industry (Sector 1–2) and tertiary industry (Sector 15 ~ 26).

Secondary industrial sectors' high intensities also means there is potential for emission reduction in these sectors. From the perspective of direct emissions, tertiary industries are usually considered to be low emission-intensive as they consume much less fossil energy than other two industries. However, tertiary industries also need to purchase products, materials and electricity from other two industries to sustain its production. As a result, tertiary industry is more energy-intensive and emission-intensive than it seems to be. The fact implies that green consumption in tertiary industries can reduce the mercury emissions embodied in its supply chain, which is also beneficial for overall reduction.

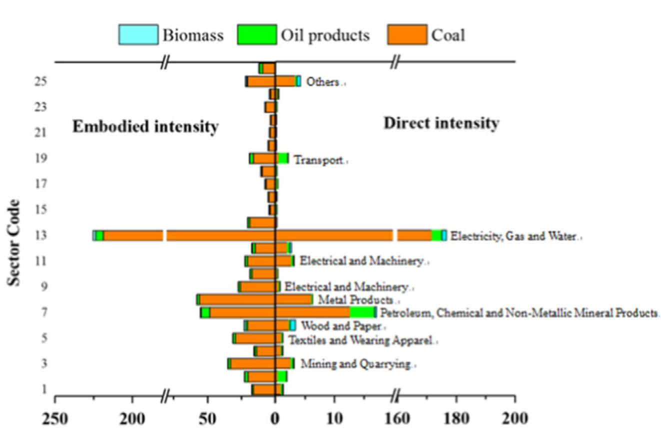

Fig. 2. Sectoral direct and embodied fuel-related mercury emission intensities of global economy (Unit: g/million USD).

Fig. 2 also illustrates the compositions of emission intensities of each energy type. It is obvious that coal combustion contributed the largest share to both direct and embodied intensities in most economic sectors, followed by oil products and biomass. However, there are two exceptions. Sector 2 (Fishing) and Sector 22 (Public Administration)'s oil products related emission intensities take the majority parts of their total emission intensities. That is because the amount of oil products directly input into these two sectors is much more than that of coal.

This study also compares the direct emissions and emissions embodied in final demand at global scale in Fig. 3 by dividing all the sectors into 8 categories. For direct emissions, 2/3 of the emissions are emitted by the sector of electricity, gas and water. However, for emissions embodied in final demand, this sector has a much smaller percentage (only slightly higher than 15%). The huge difference implies that a large proportion of electricity, the mercury-intensive products of this sector, flows to other sectors as energy input and ultimately consumed by other sectors for the production of commodities which satisfy different types of final demands. Heavy industry including metal production and mining and quarrying plays an important role in both direct and embodied emission patterns. It has the largest percentage of final demand's embodied emissions and second largest proportion of direct emissions, indicating that it is both an important energy producer and energy consumer. Basically, public services and other service which belong to the tertiary industries have higher percentages in the embodied emissions pattern than that in direct pattern, due to their role as consumers of mercury-intensive products from other sectors.

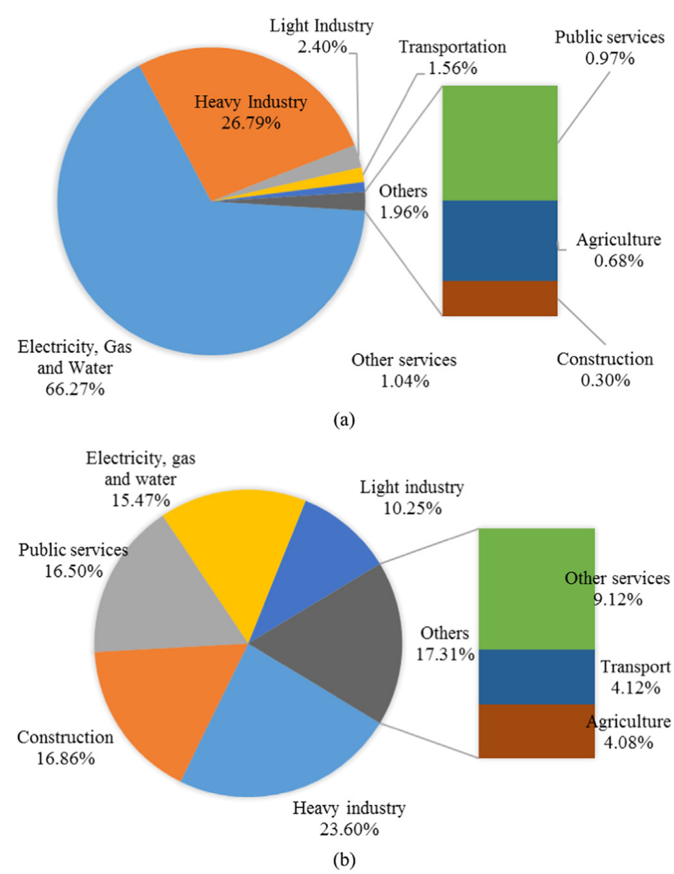

Fig. 3. Compositions of global mercury emissions related to fuel combustion: (a) direct emissions; (b) emissions embodied in final demand.

4.3. Emissions embodied in trade

The calculated fuel-related mercury emissions embodied in trade amount to 253.15 t. That is to say, approximately 30% of mercury emissions from global fuel combustion are released during the production processes of commodities that are transported to consumers in a different economy via international trade. The substantial amount of traded emissions confirms the significant role of international trade in redistributing energy consumption as well as its environmental impacts like airborne mercury pollution between different economies. The major internationally traded mercury emission fluxes are portrayed in Fig. 4. It is clear that mainland China, India, the USA and European Union (EU) are world's trade centers of embodied fuel-related mercury emissions. Notably, mainland China is the source of the embodied mercury emission fluxes. The largest three receivers of the mercury fluxes are EU (13.6 t), Japan (12.9 t) and the USA (10.5 t). As Hongkong heavily depends on imports from mainland China, a considerable amount of embodied mercury emissions also flowing from mainland to Hongkong, as stated in Fig. 4. On the contrary, developed economies such as EU and the USA are the destinations of the embodied mercury emission flows from emerging economies like mainland China and India. Mainland China alone contributes about 30% of global EEE. That is to say, 73.09 t atmospheric mercury emitted by fuel combustion in mainland China are driven by the consumption of commodities in other economies. By contrast, the USA has the largest EEI, with an amount of 38.09 t. Apparently, the emerging economies such as mainland China and India are the prominent exporters of embodied mercury emissions while developed economies like Japan, EU and the USA are the receivers of imported embodied mercury emissions. The large embodied emissions flowing out of emerging economies are mainly due to the high emissions intensity of commodities exported from these emerging economies, reflecting the prevalence of mercury-intensive energy and low value exports. On the contrary, exports from Japan and Western economies have high value and cause much less mercury emissions. It should be noted that the embodied emission intensities of exports from the USA are lower than those of mainland China and India, but apparently higher than those of Japan and some Western European economies.

The striking contrast between developed and developing economies can be explained by two main factors. One is that less mercury-intensive and non-mercury energy types take larger proportions in developed economies. Take France as an example: natural gas and nuclear power together account for about 60% of its energy consumption while coal just takes a fraction of less than 5% [69]. The other factor is the low-emission technology adopted in developed economies. Germany and Japan are also important coal consumers; however their emission factors of coal is much lower than that of coal burned in China and India. That means that for each unit of coal burned, mercury emissions emitted by mainland China and India are several times greater than those by Germany and Japan. The redistribution of fuel-related mercury emissions via international trade implies there is possibility of an absurd situation of "local reduction at the cost of global rise". For instance, Japanese steel factories' mercury emission intensity is much lower than that of mainland China's steel factories in general, as Japan has higher energy efficiency and more advanced emission control technology. That means mainland China will emit more mercury emissions from fuel combustion, compared with Japan to produce the same amount of steel. To achieve the direct emission reduction goal in steel industry, Japan may reduce its own steel production and import steel from mainland China to meet its demand. Then the subsequent consequence would appear like this: from the local perspective, Japan reduces its direct emissions; however, the global fuel-related emissions will witness growth. As a result, unilateral measures guided by direct accounting would mislead the policies designed to reduce the mercury emissions.

The EEB of 186 countries in terms of mercury emissions is investigated (seen in Table S4). Economies with negative EEB value (traded emission surplus) are net mercury exporter and net importer vice versa. Among the 186 economies, 38 economies have embodied emission surplus while 148 have embodied emission deficit. However, the emission balance of 157 economies is less than 1 t. Moreover, the absolute values of EEB of ten economies are close to zero. That means fuel-related mercury emissions embodied in trade mainly flow between major trade centers which are also economic centers such as mainland China, EU, Japan and the USA. Ten individual economies highlighted in Fig. 5 are the top five net exporters and top five net importers. It is evident that all the top five net importers are developed economies while most of the major developing economies tend to be net exporters. The structure of trade is considered to be the important factors that lead to this result. From the statistics provided by Eora, a large proportion or even a dominant share of these top five net exporters are manufactured goods like steel, cement or even energy products, which are characterized as emission intensive. In contrast, the top

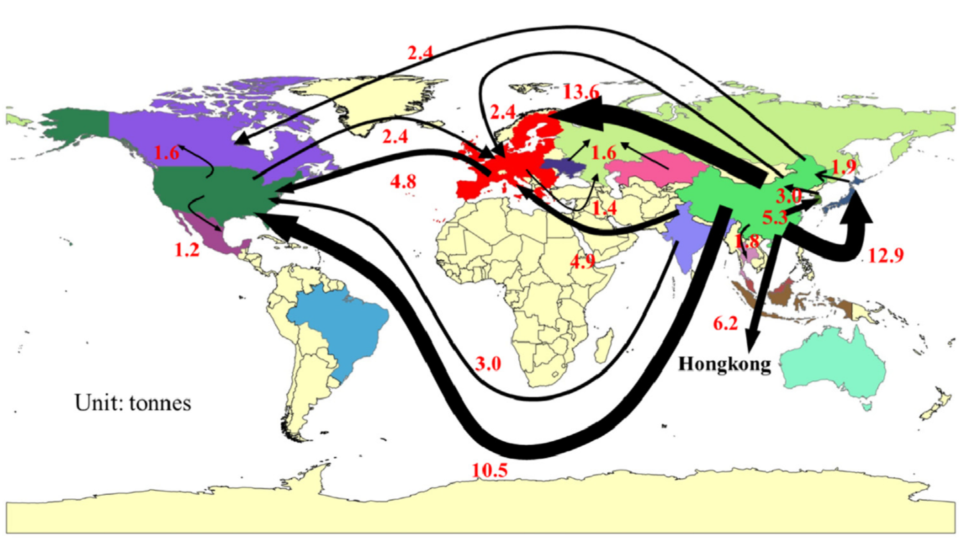

Fig. 4. Main interregional fluxes of mercury emissions embodied in trade.

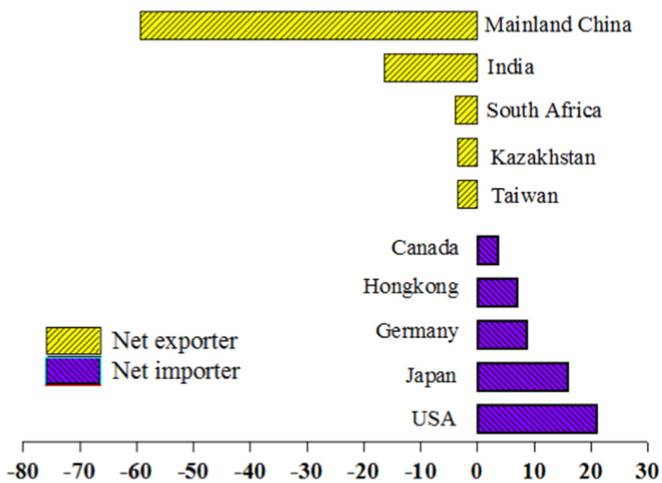

Fig. 5. Top five net importers and exporters (Unit: tonnes).

five net importers import these high emission intensive products while sell low emission intensive products/services with high value-added, making their imports much less than exports. The total amount of mercury emissions embodied in exported goods and services by top five net exporters account for nearly 25% of their total direct emissions. That means 1/4 of atmospheric mercury emitted by fuel combustion within these economies' territory is induced to satisfy the demand in other economies. For the top five net importers, about half of their embodied fuel-related mercury emissions are linked to the emissions embodied in imports. In some developed economies like Spain, the amount of its imported embodied emissions is equivalent to an overwhelming 80% of its total embodied emissions.

4.4. Embodied emissions by economy

By combing the direct emissions with trade balance, EME (embodied mercury emisisons) of each economy are obtained and listed in Table S4. Like direct emissions, mainland China by far has the largest fuel-related embodied atmospheric emissions with an amount of 314.30 t, followed by USA's 122.98 t, India's 66.96 t, Japan's 38.63 t, Germany's 23.57 t and Russia's 21.18 t (Seen in Fig. 6). Energy related embodied mercury emission intensities of each economy are listed in Table S4. Moldova, Belarus and North Korea have the three largest embodied emission intensities while Netherlands Antilles, Nigeria and Myanmar have the three lowest embodied emission intensities. Due to the large amount of embodied emissions, mainland China's intensity ranks the 12th and India ranks 27th among all the economies. In striking contrast, developed economies like the USA, Germany and Japan, they rank after 140th. Mainland China's embodied emission intensity is about ten times as large as that of the USA. However, the ranking of Per capita embodied emissions, which are also listed in Table S4, vary considerably from that of embodied emissions intensities. Antigua, Bermuda and Seychelles have the top three per capita embodied emissions. The rankings of Japan and the USA are higher than that of mainland China and India, due to the much larger population in the two latter economies.

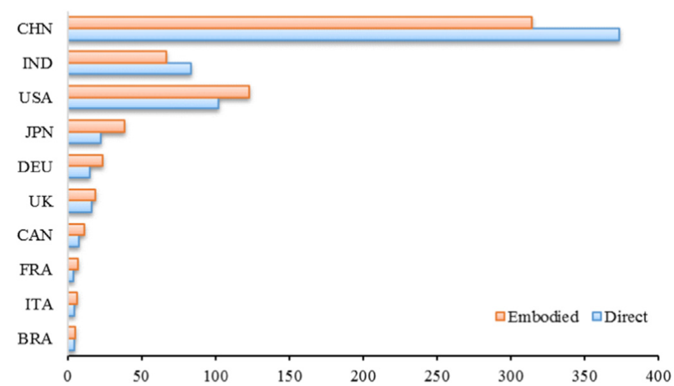

Fig. 7. Direct and embodied fuel-related mercury emissions of the ten largest economies (Unit: tonnes).

The direct and embodied fuel-related mercury emissions of the ten largest economies are compared in Fig. 7. In fact, the difference between these two types of emissions represents the amount of emissions embodied in trade balance. Apparently, the gap between mainland China's direct and embodied emissions is the biggest while that of Brazil is the smallest. Mainland China and India, the only two emerging economies among the top ten economies, have the same feature, i.e., the amount of direct emissions is more than that of embodied emissions. For mainland China and India, about 20% of the direct emissions can be attributed to the exports to other economies. By contrast, the two types of emission of developed economies show an opposite trend. Particularly, economies like France and Japan, indirect emissions embodied in imports contributed to almost half of their fuel-related embodied mercury emissions, indicating their heavy reliance on fuel-related intensive products from other economies.

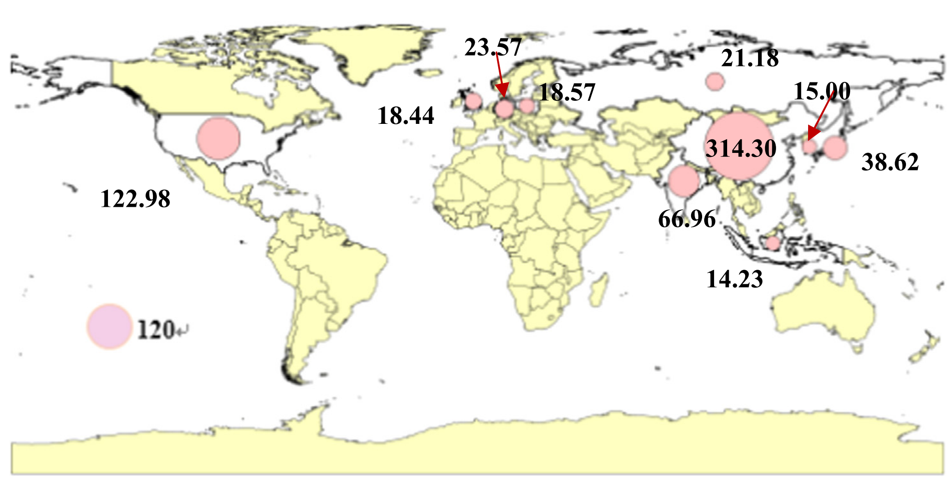

Fig. 6. Embodied emissions of top 10 emitters (Unit: tonnes).

4.5. Embodied emissions of intermediate use and final demand

Based on the sectoral embodied mercury emission intensities and the data in global economic MRIO table, the distribution of sectoral fuel-related mercury emissions in both production and final demand can be simulated.

To analyze the intermediate inputs, we divide all the sectors into three types, i.e., agriculture, the secondary industry and tertiary industry and distribution of their embodied mercury emissions is presented in Fig. 8. For agriculture, the inputs from Sector 7 (Petroleum, Chemical and Non-Metallic Mineral Products) cause the largest amount of embodied fuel-related mercury emissions (18.85 t), followed by Sector 13 (Electricity, Gas and Water)'s 12.42 t and Sector 1 (Agriculture)'s 6.52 t. Fuel-related mercury emissions embodied in the inputs from Sector 13 (Electricity, Gas and Water), Sector 7 (Petroleum, Chemical and Non-Metallic Mineral Products) and Sector 8 (Metal Products) contribute the largest proportions to that of secondary industry. For tertiary industry, the largest amounts of embodied mercury emissions of input come from Sector 13 (Electricity, Gas and Water), Sector 7 (Petroleum, Chemical and Non-Metallic Mineral Products) and Sector 21 (Financial Intermediation and Business Activities). From the perspective of individual sectors, it is obvious, the inputs from Sector 13 and 7 to global economy's intermediate inputs have much larger embodied mercury emissions, compared to that of other sectors. The inputs from Sector 13 (Electricity, Gas and Water) cause 447.33 t embodied mercury emissions and that of Sector 7 (Petroleum, Chemical and Non-Metallic Mineral Products) induced 381.64 t. That is because these two sectors are the major fossil energy suppliers to other sectors and the most of fuel combustion activities are concentrated in these two sectors.

The distribution of sectoral mercury emissions embodied in input to final demand is also presented in Fig. 8. The final demand of global economy is classified into 6 different groups, namely, household final consumption, non-profit institutions serving households, government final consumption, gross fixed capital formation, changes in inventories and acquisitions less disposals of valuables. The total amount of global final demand driven fuel-related mercury emissions is 858.60 t. From the sector point of view, the amount of mercury emissions embodied in inputs from Sector 14 (Construction) into final demand leads among that of all the 26 sectors. Over 90% of emissions embodied in input into final from Sector Construction are attributed to gross fixed capital formation. The large amount of indirect emission induced by this sector are mainly due to the investment in construction of roads, buildings and other infrastructures, especially in emerging economies like mainland China. As construction needs large quantities of energy-intensive materials and products such as cement, steel and electricity, consumption in construction is an important factor which drives global fuel combustion as well as mercury emissions.

There are remarkable differences between the embodied fuel-related mercury emissions of each final demand category (Fig. 9). Household final consumption has a significantly larger amount of embodied mercury emissions, compared with other final demand types. With a dominant proportion of 57.35%, household final consumption caused the majority of emissions in most of the sectors except Sector 8, 9, 10 and 14. Following are gross fixed capital formation's 27.64% and government final consumption's 9.17%. The rest of final demand types together contribute to less than 6% of the total amount of mercury emission embodied in the inputs consumed by final demand.

5. Concluding remarks

This study provides an overview of atmospheric mercury by updating the global fuel-related mercury emissions inventory as well as evaluating the impact of international trade on each economy's embodied mercury emissions.

With the emission factors and latest energy data available, the current study presents up-to-date results of global atmospheric mercury emissions from fuel combustion. The total fuel-related atmospheric mercury emissions amount to 859.12 t, to which coal, oil products and biomass contribute 85.77%, 9.06% and 5.17%, respectively. The detailed information of 186 economies, whose total emissions amounted to 858.60, is also elaborated. Mainland China, the world's largest coal consumer, has the largest direct atmospheric mercury emissions, followed by the USA and India. For the global economy, Sector 13 (Electricity, Gas and Water) has the

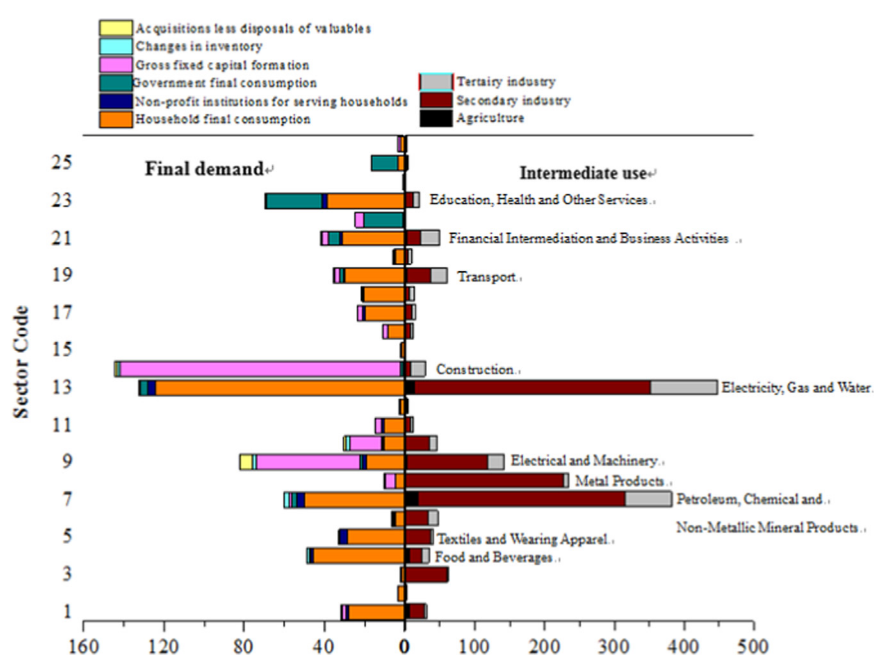

Fig. 8. The distribution of mercury emissions embodied in intermediate use and final demand of global economy (Unit: tonnes).

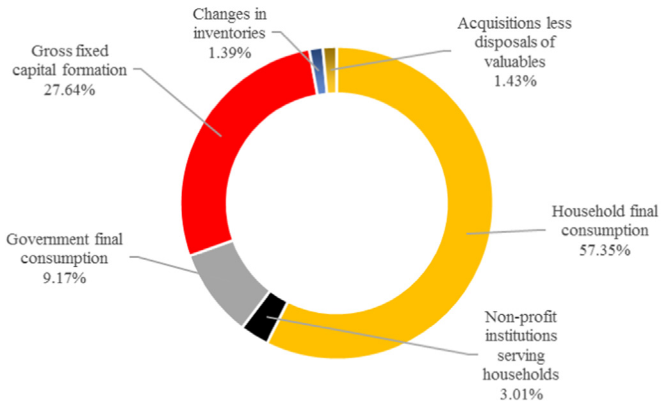

Fig. 9. The compositions of mercury emission embodied in final demand.

highest emission intensity, followed by Sector 7 (Petroleum, Chemical and Non-Metallic Mineral Products) and 8 (Metal Products), from the sector point of view. The global mercury emission inventory provides insights for global mercury reduction from a territory-based perspective. The dominant portion of coal related mercury emissions indicates that reducing mercury emission from coal combustion, especially in emerging economies like mainland China and India, is key to global mercury emission abatement. Actions can be taken in the following aspects: (1) implementing strategies such as stringent regulations about emissions level in key areas; (2) encouraging the efficient mercury control devices in major coal consuming spots like coal-fired power plants; (3) optimizing the energy structure and increasing the proportion of cleaner energy.

To supplement the territory-based analysis, this study also constructs the global MRIO model to investigate the impact of international trade on each economy's fuel-related mercury emissions. The results reveal that about 30% of global fuel-related mercury emissions (253.15 t) are traded internationally. Fuel-related mercury emissions embodied in trade mainly flow from mainland China and other emerging economies like India to developed economies such as the USA, Japan and Western European economies, making the former group of economies net embodied emissions exporters and the latter net importers. Exports from mainland China alone contribute to about 30% of the embodied emission flows and the mercury emission embodied in exports are equivalent to about 1/5 of atmospheric mercury produced in mainland China. On the contrary, in large developed economies, imports of embodied mercury emissions account for a large proportion of their embodied emissions. For instance, mercury emissions embodied in Germany's imports are nearly 1.5 times that of its direct emissions and the net imports of embodied emissions contribute to almost 2/5 of its embodied emissions. Similar phenomenon can also be found in the case of Japan. The large embodied emission flows imply that the reduction of fuel-related atmospheric mercury emissions in economies is founded on not just their stringent emission standards and low-emission technologies, but also on the allocation of emissions in emerging economies. Embodied fuel-related mercury emissions induced by the consumption of each economy are also revealed by integrating the direct emissions and net effects of trade. Mainland China, the USA and India have the three largest quantities of embodied emissions. Apparently, emissions transfer driven by international trade between different economies plays an important role in shaping the emissions induced by an economy. These results indicate that input-output analysis is complementary to direct accounting approach, as it shows the interconnections between economies and provides a holistic picture of global mercury emissions related to fuel combustion.

The present study on embodied mercury emissions also has significant implications for global mercury mitigation. The knowledge about mercury emissions embodied in trade flows extends the current concepts on mercury abatement which focus on reducing direct emissions only and therefore, increases mitigation options. Recognizing the "mercury emission leakage" from developed economies to the developing economies, all the economies should enhance cooperation to avert the absurd "local reduction, global rise" situation. Moreover, the elaboration on the role of international trade in shifting mercury emissions can cast light on a more reasonable emission responsibility sharing mechanism. It is suggested that the reduction commitment should be differentiated according to each economy's role in global trade [70]. As a result, the emerging economies with large amount of direct emissions should make greater efforts to reduce emissions released by fuel consumption activities happening within their territories. Measures such as increasing the share of renewable energies, phasing out the outdated factories, and update its fuel utilization technologies are crucial to be implemented. For developed economies with net imports but relatively smaller direct emissions, more efforts can be contributed to reduce the embodied emissions induced by their consumption, besides continuously to abate the direct emissions. [71]. Economies with a large net export of embodied mercury emissions may face a smaller reduction commitment. Moreover, the striking differences between each sector's direct embodied emissions also provide insight for mercury reduction from fuel combustion. As a producer, Sector 13 (Electricity, gas and water) is responsible for 2/3 of total direct emissions while its proportion in total embodied emissions is less than 1/5 as a producer. However, some other sectors like construction and services show the opposition situation. This is mainly due to the large fraction of mercury intensive electricity that is generated to satisfy the need of tertiary industries and final consumers such as household final consumption. As a result, policies aiming at the sectoral mercury emissions reduction should focus on not only cleaner production in large direct emitters, but also green consumption in sectors and final demand which induced large embodied emissions.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2016.06.049.

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