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China's energy-related mercury emissions: Characteristics, impact of trade and mitigation policies

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ABSTRACT

As the world's largest energy consumer, China contributes significantly to the global atmospheric mercury emissions, a toxic air pollutant with global importance. This study aims to systematically analyze China's energy-related mercury emissions in light of environmentally extended input-output analysis (EEIOA), considering the impact of China's inter-sector connection and external trade. The results reveal that embodied emission intensities of some manufacturing sectors are magnified about 100 times compared with their corresponding direct mercury emission intensities. Generally, the magnified effect of upstream sectors (e.g., Sector *Coal Mining*) is less remarkable than downstream sectors (e.g., Sector *Electric Equipment and Machinery Manufacturing*), underlying the effect of inter-sector connection. As for external trade, over a quarter of China's direct mercury emissions from fuel combustion (359.7 tonnes) are attributed to foreign consumption of commodities produced in China, manifesting China's role as world factory. Due to the prominent role of China's processing trade, mercury emissions embodied in re-exports takes a considerable amount of total emissions embodied in China's exports. These findings have implications for China's mercury pollution mitigation policies focusing on different stages in domestic supply chains and responsibilities redistribution of international collaborative mitigation.

1. Introduction

Mercury is acknowledged as a highly toxic pollutant with global importance, which can pose adverse effects on both human health and ecosystem (Louis et al., 2011; Mergler et al., 2007; Nd, 2007). As the world's biggest energy consumer, China alone contributes three-quarters of mercury emissions in East and Southeast Asia, or about one third of world's total, making it the largest emitter of atmospheric mercury (UNEP, 2013a). Without exception, fuel energy consumption, especially coal consumption, dominates the atmospheric mercury emissions in China. According to these existing studies, coal combustion generated about 37%–54% of mercury emitted into atmosphere in China (Hu, 2013; Liang et al., 2013; Pacyna et al., 2010; Pirrone et al., 2010; Wu et al., 2006). Therefore, many studies have also been carried out to analyze China's mercury emissions of coal combustion separately (Jiang et al., 2005; Wang et al., 2000, 2009; Zhang et al., 2012). Energy structure will not pursue substantial adjustment for China in the short term, making fuel energy the chief instigator of China's (even the global) atmospheric mercury emissions.

International trade can reallocate natural resources depletion and environmental degradation between different countries. Thus, the neglect of resources and pollution embodied in international

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trade will lead to leakage problems, which has already been well demonstrated in the cases of energy consumption (Chen and Chen, 2015; Su and Ang, 2014; Zhang et al., 2015a), greenhouse gas emissions (Li and Chen, 2013; Li et al., 2013; Peters and Hertwich, 2008), virtual water use (Chen and Chen, 2013; Dalin et al., 2012), land appropriation (Chen and Han, 2015a, b; Weinzettel et al., 2013; Yu et al., 2013) and some air pollutants emissions such as CO_2, $PM_{2.5}$, SO_2, NO_X and NMVOC (Lin et al., 2014; Meng et al., 2015; Zhao et al., 2015). There are also some studies focusing on virtual mercury flows on city level (Jiang et al., 2016; Li et al., 2015), provincial level (Liang et al., 2014), national level (Liang et al., 2013) and global level (Chen et al., 2016; Liang et al., 2015). It's worth noting that Liang et al. conducted the study underlying the Socio-economic driving factors behind the mercury emissions changing in China, based on a macro and general perspective such as population, GDP, technology and so on (Liang et al., 2013). However, the impact of inter-sector connection and external trade, two more specific perspectives, is still unclear.

Given China's significant position in energy-related mercury emissions, comprehensive knowledge about China's energy-related mercury emissions has profound implications for mercury emission reduction (Ancora et al., 2016). However, these previous studies on China's energy-related mercury emissions are still far from enough. Firstly, these studies were mainly conducted under the framework of end-of-pipe concept, i.e., focusing on mercury emissions directly emitted by fossil fuel combustion. This direct accounting method neglects indirect mercury emissions embodied in intermediate inputs from other sectors (Chen and Chen, 2015; Wei et al., 2016; Wu et al., 2016), for economic sectors are not isolated but correlated as an intertwined network. As a result, to obtain a panorama of China's mercury emissions assignable to fossil fuel combustion, the embodied mercury emissions (direct plus indirect) should be investigated. Secondly, processing trade, whose ratio to China's total exports has maintained at a high level of over 50% since 1995, involves domestic sectors obtaining raw materials or intermediate inputs from abroad, processing them domestically and exporting the value-added goods (Xu and Lu, 2009). Processing trade inevitably causes emissions due to the direct energy consumption (Lin and Sun, 2010; Sánchez-Chóliz and Duarte, 2004; Su et al., 2013). This type of mercury emissions, usually referred to re-export emissions induced by commodities imported from abroad and then exported abroad after domestic reprocessing, has never been investigated. These problems mentioned above not only hinder stakeholders from thoroughly understanding China's mercury emissions, but also impede prompting comprehensive and effective emission mitigation policies.

Environmentally extended input-output analysis (EEIOA) is adopted to elucidate how international trade re-shapes China's energy-related mercury emission profile. Originally proposed by Leontief in the 1930s, IOA was used as a tool to explore the interdependencies between industries in modern economics in early stage (Leontief, 1936). Later in the 1970s, with the rising concerns about environmental issues, Leontief incorporated contaminants into the conventional economic input-output table, marking the exordium that IOA was applied to assess the economic activities' impact on environment (Leontief, 1970). Moreover, the estimation of pollutant embodied in trade by using IOA can be dated back to the work of Walter (Walter, 1973). Since then, IOA has been excessively used to evaluate the ecological elements embodied in international trade.

This study aims to: (1) revisit China's energy-related mercury emissions by evaluating the impact of inter-sector connection and external trade, in light of EEIOA; (2) quantify the re-export energy-related mercury emissions; (3) provide insights for energy-related mercury pollution mitigation policies focusing on stage of the sector in domestic supply chains and responsibilities redistribution of international collaborative mitigation. The remainder of this paper is structured as follows: methodology and data adopted in this paper are elaborated in Section 2, while detailed results are articulated in Section 3; some discussions and relevant policy implications are presented in Section 4; conclusions are drawn in the final section.

2. Methodology and data sources

2.1. Direct energy-related atmospheric mercury emissions

The direct mercury emissions can be calculated by multiplying fossil fuel consumption with their corresponding emission factors, according to previous studies (Li et al., 2015; Pacyna et al., 2006; Streets et al., 2005). Mercury emissions from natural gas burning can be neglected compared to those from coal and oil, due to its extremely small emission factor (Pirrone et al., 2010).

2.2. Input-output analysis method

Based on the conventional IOA, embodied emission intensities can be calculated as:

$$\mathbf{E^d} = d\mathbf{e^d}(\mathbf{I} - \mathbf{A})^{-1} \tag{1}$$

where $\mathbf{E^d}$ denotes row vector of sectoral embodied mercury emission intensities, defined as the sum of direct and indirect emissions generated to produce per unit monetary value of a particular sector. $\mathbf{de^d}$ is the matrix of sectoral direct mercury emission factor, $\mathbf{I}$ denotes the identify matrix, while $\mathbf{A}$ represents a direct requirement coefficient matrix. $\mathbf{(I{-}A)^{-1}}$ is the kernel of the IOA, which is termed as the Leontief inverse matrix.

As the conventional IOA doesn't distinguish the direct input coefficient matrix $\mathbf{A}$ between domestic products and foreign imports, it is not adequate to quantify the mercury emissions embodied in trade (Lin and Sun, 2010). Thus, this study decomposes the matrix $\mathbf{A}$ into $\mathbf{A^{im}}$ and $\mathbf{A^d}$ (Lin and Sun, 2010; Sánchez-Chóliz and Duarte, 2004; Weber et al., 2008):

$$\mathbf{A} = \mathbf{A^{im}} + \mathbf{A^d} \tag{2}$$

$$\mathbf{A^{im}} = MA \tag{3}$$

where $\mathbf{A^{im}}$ and $\mathbf{A^d}$ are the direct input coefficient matrixes of intermediate inputs from foreign and domestic sources, respectively. $\mathbf{M}$ is a diagonal matrix, representing the proportion of imports in intermediate inputs, which can be obtained by (Miller and Blair, 2009):

$$m_{ij} = \frac{\mathrm{Im}_i}{x_i + \mathrm{Im}_i - Ex_i}(i = j); \text{when} i \neq j, m_{ij} = 0 \tag{4}$$

where x_i, Im_i and Ex_i stand for total output, imports and exports, respectively.

Based on the EEIOA, the mercury emissions avoided by imports (**MEEI**) can be computed as:

$$\mathbf{Im} = \mathbf{A^{im}X} + \mathbf{Y^{im}} \tag{5}$$

$$\mathbf{E^dA^{im}X} = \mathbf{E^dA^{im}}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y} = \mathbf{E^{re}Y} \tag{6}$$

$$\mathbf{MEEI} = \mathbf{E^d} * Diag(\mathbf{Im}) \tag{7}$$

where **Im** represents the import column matrix which can be divided into imported intermediate inputs ($\mathbf{A^{im}X}$) and imported domestic final consumption ($\mathbf{Y^{im}}$), $\mathbf{E^{re}}$ is a row matrix with each element denoting the mercury emissions of imported intermediate inputs caused by per unit final demand **Y** in each sector after domestic reprocessing. As a result, the mercury emissions embodied in re-export (**MEERE**) can be obtained by:

$$\mathbf{MEERE} = \mathbf{E^{re}} * Diag(\mathbf{Ex}) \tag{8}$$

where **Ex** is the column matrix of exports. The mercury emissions embodied in exports (**MEEE**) can be calculated as:

$$\mathbf{MEEE} = \mathbf{E^d} * Diag(\mathbf{Ex}) + \mathbf{E^{re}} * Diag(\mathbf{Ex}) \tag{9}$$

Therefore, the mercury emissions embodied in trade balance (**MEEB**) can be expressed as:

$$\mathbf{MEEB} = \mathbf{MEEE} - \mathbf{MEEI} \tag{10}$$

And the energy-related mercury emissions embodied in domestic final consumption (**MEEC**) can be obtained by:

$$\mathbf{MEEC} = \mathbf{E^d} * Diag(\mathbf{Y} - \mathbf{Ex}) + \mathbf{E^{re}} * Diag(\mathbf{Y} - \mathbf{Ex}) + \mathbf{E^d} * Diag\left(\mathbf{Y^{im}}\right) \tag{11}$$

where **MEEC** consists of three components. $\mathbf{E^d} * Diag(\mathbf{Y} - \mathbf{Ex})$, $\mathbf{E^{re}} * Diag(\mathbf{Y} - \mathbf{Ex})$ and $\mathbf{E^d} * Diag(\mathbf{Y^{im}})$ denote mercury emissions embodied in domestic final consumption from domestic goods, imported intermediate inputs after domestic reprocessing and imported goods, respectively.

2.3. Data sources

The economic input-output table of Chinese economy in 2010 is derived from *China Statistical Yearbook 2011*, covering 42 sectors (NBSC, 2011). For the best match of sectors from input-output table and energy statistics, the 42 sectors are aggregated into 28 sectors, as listed in SI Table S3. Imported intermediate inputs and imported final consumption can be calculated in terms of Equation (4). Monetary value of each sector's trade is presented in SI Table S4.

Data on direct fossil fuel consumption of each sector are collected from *China Statistical Yearbook 2012* (NBSC, 2012). As for coal, different sectors may use different kinds of coal and apply different air pollution control devices, the emission factor of coal combustion may not be the same for every sector (UNEP, 2013a). This study, therefore, distinguishes mercury emission factors of coal combustion in different sectors, for its dominant position in China's fossil fuel consumption and relatively high mercury emission factor. In this study we divide all the sectors into 3 categories according to the characteristics of each sector's utilization pattern of coal, i.e. Coal-fired power plants, industrial coal combustion and other coal combustion. The emission factors and corresponding sources are expatiated in Table 1.

3. Results

3.1. Direct mercury emissions

Direct mercury emissions caused by fossil fuel combustion in China are calculated as 359.7 tonnes in 2010. According to Liang et al. (Liang et al., 2013), China's energy-related mercury emissions rose from 240.5 tonnes in 2002 to 376.4 tonnes in 2007. Therefore, it can be inferred that China has witnessed a small descending trend in energy-related mercury emissions. Without exception, coal burning is the predominant emitter with the quantity of 316.4 tonnes, accounting for 88% of the total direct mercury emissions.

As shown in Fig. 1, direct mercury emissions vary considerably from sector to sector. The largest mercury emitter is Sector EPSHW (*Electric Power, Steam and Hot Water Production and Supply*), taking up the lion's share of the total direct emissions with a share of about 1/3. The reasonable explanation is that approximately half of coal consumed in China in 2010 is assignable to Sector EPSHW. With relatively large coal or coke consumption, Sector PPCPN (Processing of Petroleum, Coking, Processing of Nucleus Fuel) and Sector SPFNM (Smelting and Pressing of Ferrous and Nonferrous Metals) occupy the second and the third position, respectively. The substantial number of emissions in these two sectors stems from the massive production of cement and steel for infrastructure construction in China. The direct mercury emissions of some industries and service sectors tend to be negligible in comparison with the top three sectors.

As for the emission intensities, the trajectory is not in unison with that of direct emissions. Sector EPSHW is still on the top of the list, as its mercury emission intensity reaches 26.0 kg/billion RMB. The second is Sector PPCPN (16.8 kg/billion RMB), followed by Sector CMD (*Coal Mining and Dressing*) with an amount of 11.8 kg/billion RMB.

3.2. Embodied mercury emission intensities

Embodied mercury emission intensities of each sector in 2010 are depicted in Fig. 2. Sector EPSHW holds its top position with an intensity of 46.4 kg/billion RMB, followed by Sector PPCPN (22.8 kg/billion RMB) and Sector CMD (19.1 kg/billion RMB). It should be noted that, except for Sector CMD, Sector PPCPN, Sector EPSHW and Sector GPSI (*Gas Production and Supply Industry*), indirect mercury emission intensity contributes the majority of embodied emission intensity in most sectors. The fact indicates that these sectors have a large quantity of embodied mercury emissions in their intermediate inputs from their upstream sectors, such as electricity power, coal mining and metals smelting and pressing sectors, which have high direct emission intensities. For instance, the embodied emission intensities of Sector EEMM (*Electric Equipment and Machinery Manufacturing*), Sector MCE (*Manufacture of Communication Equipment*) and Sector IMCCM (*Instruments, Meters, Cultural and Clerical Machinery Manufacturing*), whose direct emission intensities are among the smallest, are magnified 111, 114 and 98 times compared with their corresponding direct mercury emission intensities, respectively. Generally, the magnified effect of upstream sectors (such as Sector CMD and Sector EPSHW) is less remarkable than downstream sectors (such as Sector EEMM and Sector MCE), for final products in downstream sectors have more complex production processes which will accumulate massive mercury emissions from their upstream sectors. Therefore, different mercury abatement policy should be adopted for different stages of the supply chains.

3.3. Virtual mercury emissions embodied in trade

3.3.1. Virtual mercury emissions avoided by imports/embodied in exports

MEEI and **MEEE** are demonstrated in Fig. 3 (a). China avoids 77.2 tonnes mercury emissions in 2010 by importing commodities from abroad, 17% of which are attributed to Sector CPRI (*Chemical Products Related Industry*). Sector SPFNM (*Smelting and Pressing of Ferrous and Nonferrous Metals*) sits in the second place with the

Table 1
Mercury emission factors of fossil fuel in China.

Fuel type	Subcategory	Emission factors Unit: g/t	Sources
Coal	Coal-fired power plants	0.078	(Hu, 2013; Wang et al., 2009)
	Industrial coal combustion	0.114	(Zhang et al., 2015b; Zhao et al., 2014)[a]
	Other coal combustion	0.130	(Hu, 2013)
Coke	–	0.013	(Hu, 2013)
Crude oil	–	0.058	(Streets et al., 2009)
Gasoline	–	0.058	(Streets et al., 2009)
Kerosene	–	0.058	(Streets et al., 2009)
Diesel oil	–	0.058	(Streets et al., 2009)
Fuel oil	–	0.014	(Streets et al., 2005)

[a] Calculated by this study.

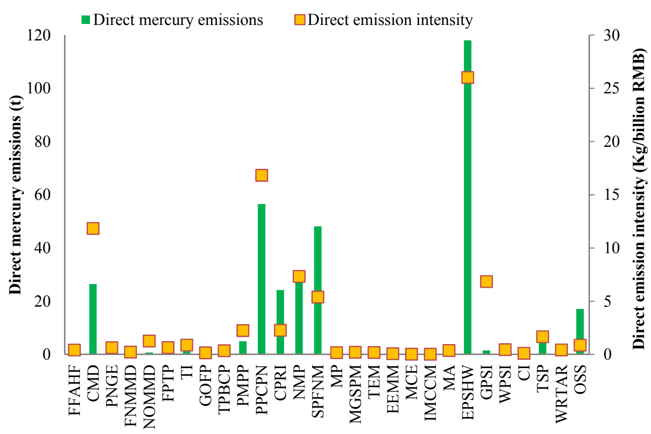

Fig. 1. Direct energy-related mercury emissions and intensities.

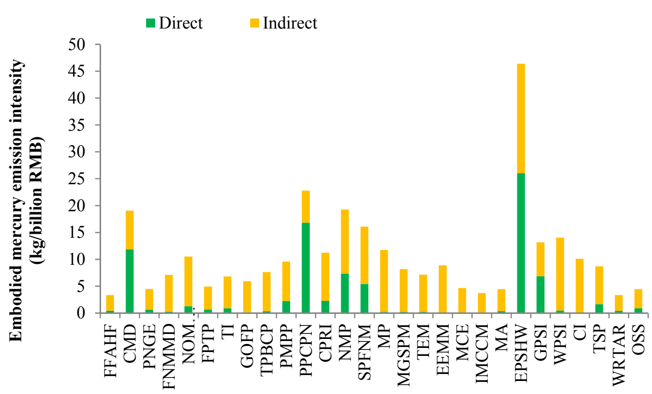

Fig. 2. Embodied mercury emissions intensities.

quantity of 8.3 tonnes, followed by Sector MCE of 8.2 tonnes. Meanwhile, mercury emissions embodied in exports amount to 97.3 tonnes, equivalent to 27% of energy-related direct mercury emissions in China. It suggests that substantial mercury emissions emitted in the production process are induced by the demand from abroad. The largest three mercury exporters are Sector MCE, Sector CPRI and Sector EEMM, with **MEEE** of 15.1, 12.0 and 9.9 tonnes, respectively.

The average mercury emission intensity of imports is 7.6 kg/billion RMB, indicating that China could avoid emitting 7.6 kg mercury by importing one billion RMB of products or services abroad. Meanwhile, the average mercury emission intensity of exports is 8.7 kg/billion RMB which outnumbers that of imports. Namely, though China exports a small amount of fuel energy products, it consumes considerable fuel energy (thus generating massive mercury emissions) during the production of the exports. As a result, these embodied fuel energy and related mercury emissions are exported abroad through international trade.

Additionally, embodied mercury emissions in secondary industry hold the largest share both in imports and exports, accounting for more than 90% of total **MEEI** and **MEEE**. Despite significant similarities, embodied mercury emissions do differ in terms of tertiary industry, whose proportion of mercury emissions in exports (10%) is almost double the level of that in imports (5%).

3.3.2. Virtual mercury emissions embodied in re-exports

As shown in SI Table S4, more than half of the total imports in each sector are used as intermediate inputs, part of which are later exported abroad after domestic reprocessing. The same trend can also be seen in terms of mercury emissions avoided by imported intermediate inputs, as shown in Table 2.

The total **MEERE** amount to 14.6 tonnes, accounting for 15% of total **MEEE**. Sector MCE yields the largest volume of **MEERE**, as much as 3.8 tonnes. Another 1.6 tonnes embodied mercury emissions are attributable to Sector EEMM. Sector CPRI ranks the third with the quantity of 1.4 tonnes. The three sectors take 47% in weightage in total **MEERE**, implying that re-export mercury emissions are primarily assignable to electronic equipment industry and chemical products related industry with low value-added products but high energy consumption and considerable embodied mercury emissions.

3.3.3. Virtual mercury emissions embodied in trade balance

With the combination of **MEEI** and **MEEE**, **MEEB** are depicted in Fig. 3 (b). Being a net exporter of mercury emissions in 2010, China generates 20.1 tonnes mercury emissions embodied in international trade balance. Furthermore, sectoral distribution of net mercury importers/exporters is broadly in accord with that of net trade importers/exporters (see SI Table S4).

For the mercury net-importers, Sector FNMMD (*Ferrous and Nonferrous Metals Mining and Dressing*) with 5.2 tonnes net imported emissions ranks the first, followed by Sector PNGE (*Petroleum and Natural Gas Extraction*) and Sector PPCPN. It's interesting to observe that these mercury net-importers are mainly the sectors which produce materials and energy products as intermediate inputs for other sectors. Meanwhile, this mirrors from a flank that China is in desperate need of imported natural resources to meet its own requirements. For the mercury net-exporters, the largest net-export sector is Sector MCE (6.8 tonnes), with Sector TI (*Textile Industry*) (6.4 tonnes) and Sector EEMM (6.1 tonnes) going after. Essentially, these sectors are manufacturing sectors which need a significant number of direct and indirect intermediate inputs for processing, thus resulting in massive domestic mercury emissions.

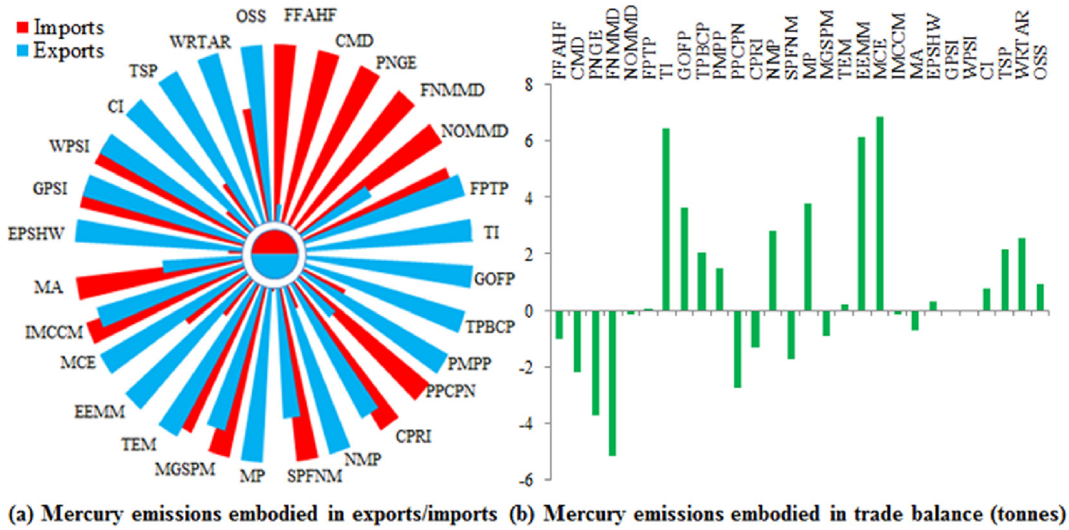

Fig. 3. Mercury emissions avoided by imports/embodied in exports.

Table 2
Components of mercury emissions avoided by imports/embodied in exports (Unit: t).

Sector	MEEI (Intermediate inputs)	MEEI (Final use)	MEEE (Domestic)	MEERE
FFAHF	0.994	0.379	0.283	0.043
CMD	2.327	0.177	0.269	0.013
PNGE	2.689	1.143	0.071	0.007
FNMMD	3.648	1.594	0.054	0.006
NOMMD	0.308	0.020	0.166	0.018
FPTP	0.637	0.559	1.089	0.161
TI	0.614	0.042	6.127	0.949
GOFP	0.224	0.227	3.440	0.635
TPBCP	0.285	0.068	2.058	0.319
PMPP	0.892	0.098	2.173	0.299
PPCPN	4.286	0.466	1.864	0.106
CPRI	11.334	2.009	10.603	1.438
NMP	1.072	0.036	3.664	0.248
SPFNM	7.691	0.559	5.884	0.631
MP	0.775	0.067	4.053	0.571
MGSPM	4.253	3.662	5.862	1.120
TEM	2.022	2.233	3.640	0.830
EEMM	2.261	1.521	8.250	1.645
MCE	4.792	3.453	11.263	3.832
IMCCM	0.912	0.943	1.344	0.377
MA	0.930	0.651	0.765	0.124
EPSHW	0.081	0.005	0.367	0.009
GPSI	0.000	0.000	0.000	0.000
WPSI	0.000	0.000	0.000	0.000
CI	0.012	0.335	0.991	0.130
TSP	1.317	0.193	3.264	0.380
WRTAR	0.165	0.089	2.502	0.315
OSS	0.850	1.307	2.681	0.381
Total	55.369	21.836	82.727	14.585

3.4. Virtual mercury emissions embodied in domestic consumption

China engenders 339.6 tonnes energy-related mercury emissions by its domestic consumption in 2010, 20.1 tonnes less than domestic direct emissions. It bears mentioning that the difference between **MEEC** and domestic direct emissions is exactly the value of **MEEB** demonstrated in Sector 3.3.2. The domestic final consumption is constituted by five categories: rural household consumption, urban household consumption, government consumption, fixed capital formation and changes in inventory. Fixed capital formation contributes the largest proportion of MEEC with a percentage of 56.3%, followed by urban household consumption's 24.7% and government consumption's 8.1%. The dominant role of fixed capital formation is due to China's investment-led economic growth model.

Shown in Fig. 4 (a) is the sectoral **MEEC**. Sector CI (*Construction Industry*) holds the largest share, contributing over a quarter to total **MEEC**. It can be explained by the fact that infrastructure construction has stepped into a frenzied period of expansion at that time. Notably, about 99% of Sector CI's **MEEC** is attributed to fixed capital formation. Similarly, Sector MGSPM (*Manufacture of General and Special Purpose Machinery*), TEM, EEMM and MCE are among those sectors whose **MEEC** are dominated by mercury emissions embodied in fixed capital formation. With China's burgeoning urbanization, urban household consumption is responsible for over three quarters of **MEEC** in Sector GOFP (*Garments and Other Fiber*

Products, Leather, Furs, Down and Related Products), PPCPN, CI, TSP (*Transport, Storage and Post*) and WRTAR (*Wholesale and Retail Trade, Accommodation and Restaurants*).

3.5. Uncertainties

Activity data and emission factors are the two main uncertainty sources for mercury emission estimation (Pacyna et al., 2010; Pirrone et al., 2010). A method introduced by AMAP/UNEP is adopted to obtain the uncertainties (AMAP and UNEP, 2013; EMEP and EEA, 2009). Major sectoral uncertainties of embodied emissions intensities and direct emissions are presented in Fig. 5 (a) and (b). The direct mercury emissions range from 218.8 to 523.9 tonnes (−39%~+46%). As illustrated by UNEP, the uncertainties associated with emission factor-based estimates can reach the order of ±50% to ± an order of magnitude (AMAP and UNEP, 2013). The uncertainties in MEEI and MEEE are respectively 46.2–113.4 tonnes and 58.6–142.5 tonnes. More details about methodology and results of uncertainty calculation are presented in SI.

4. Policy implications

China has launched a series of laws and regulations to cut the emission of pollutants such as SO_2 and NOx from coal burning. Mercury, however, has never been included in mandatory targets until China adopted the air pollutant emission standards for coal-fired power plants in 2011 (MEP, 2011). In 2012, China published the first comprehensive plan for the prevention of atmospheric pollution, i.e., *Twelfth Five-Year Plan: On Air Pollution Prevention and Control in Key Regions*, which reiterates the urgency to strengthen atmospheric mercury emissions control and compile emission inventories in mercury-intensive sectors. The results obtained in this study could well supplement the current mercury abatement policies.

For the upstream sectors (e.g., Sector CMD and Sector EPSHW), which have large direct mercury emissions, mercury removal devices should be enforced by government. The results show that coal combustion, mainly used in Sector EPSHW, is the culprit of China's massive direct energy-related mercury emissions, indicating enormous pressure but also huge potential for mercury emission reduction. Coal-fired power plants, responsible for 37% of mercury emissions by coal consumption in 2010, have large-scale installation of air pollution control devices (APCDs) to improve mercury removal efficiency (Ancora et al., 2016). PC + CS-ESP and PC + CS-ESP + WFGD (PC: pulverized coal boiler; CS-ESP: cold-side electrostatic precipitator; WFGD: wet flue gas desulfurization) with mercury removal efficiency of 65% and 26% are the two mostly employed APCDs (Wu et al., 2010; Zhang et al., 2012). Additionally, adjusting energy structure, e.g., gradually increasing the share of renewable and sustainable energy is another vital measure for China to mitigate the massive emissions from the dominant coal.

For downstream sectors (e.g., Sector EEMM and Sector MCE), which have small direct mercury emissions but large indirect accumulated emissions, attentions have seldom been paid in terms of conventional end-of-pipe concept. As a result, the primary focus should be put on production efficiency improvement of these sectors instead of mercury control technologies. By improving production efficiency, these sectors could cut the mercury-intensive inputs provided by upstream sectors to reduce the indirect emissions.

For final consumption, fixed capital formation contributes more than half of total **MEEC**. Investment is not only one of the main driving forces of China's economic growth, but also a key contributor to mercury emissions. Large amount of money flows into construction and manufacture industries promoting the massive expansion of energy-intensive industries such as the power, steel and cement industries, thus resulting in large indirect mercury emissions. Given this, the blind expansion of infrastructure construction must be reasonably controlled.

The results, that more than a quarter of China's energy-related mercury emissions were attributed to foreign consumption of commodities produced in China, highlight the fact that international trade provides a channel for consumers to shift resource depletion and environmental degradation to producers by creating a geographic separation between production and consumption. Thus, the direct accounting method, which only considers direct mercury emissions within the geographical boundary, can lead to mercury emission leakage. The leakage effect will be amplified

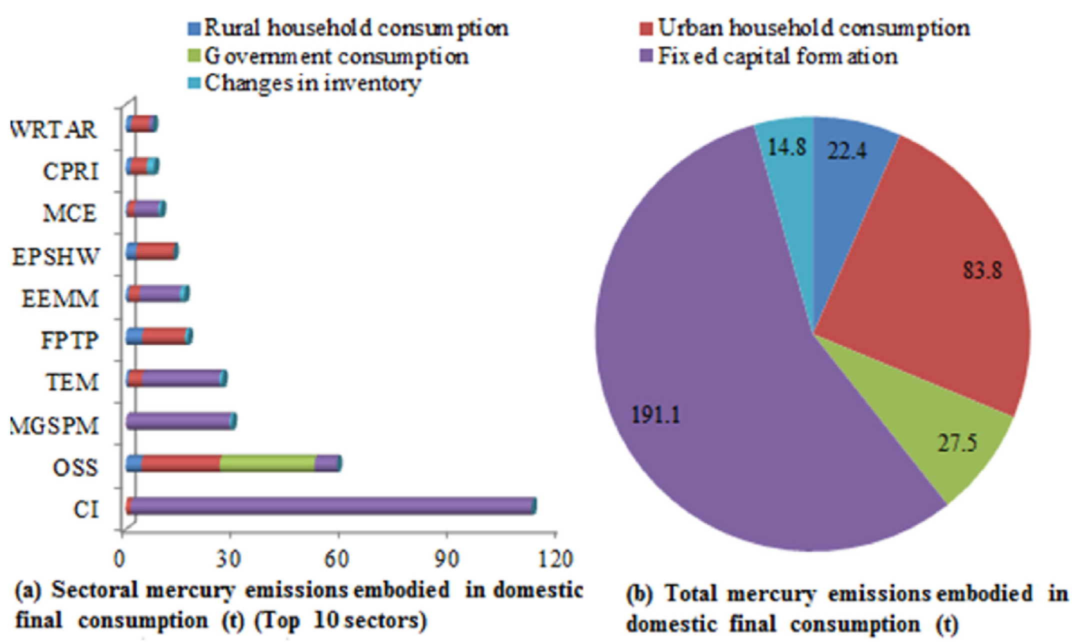

Fig. 4. Mercury emissions embodied in domestic final consumption.

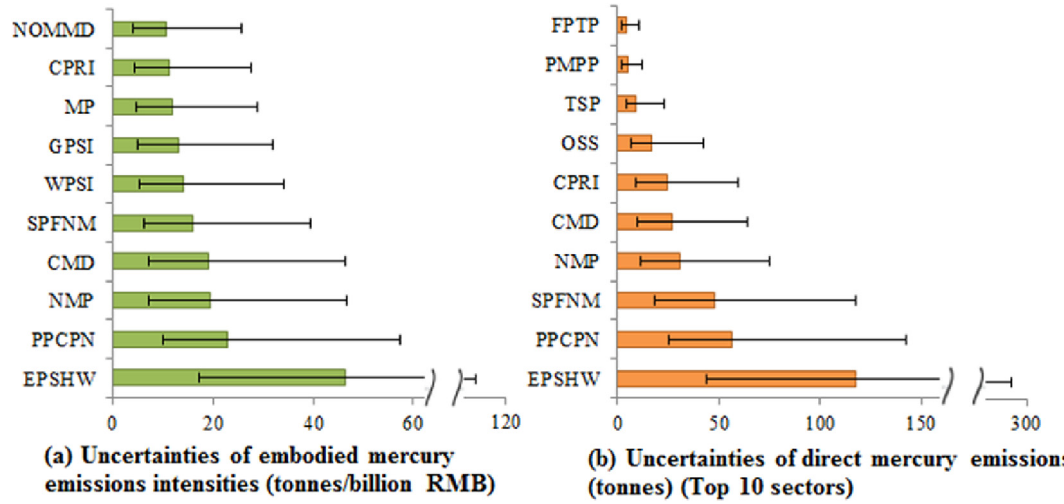

Fig. 5. Uncertainties of mercury emissions.

when it comes to a country like China, which is regarded as world factory that supplies foreign countries with its cheap and energy-intensive products.

China signed *The Minamata Convention on Mercury* in 2013, a global treaty to protect human health and ecosystem from the adverse effects of mercury. The major highlights of this treaty include measures to control supply and trade of mercury and mercury-added products (UNEP, 2013b). But this treaty also neglects the impact of international trade on embodied mercury emissions. Furthermore, the main exported goods with larger embodied mercury emissions were electronic equipment, chemical-related products and textile products, in the relatively low-end position in international industrial specialization. Seemingly, the pace of China's export structure has adjusted from labor-intensive industry to technology-intensive industry, i.e., shifting from textile-dominant to electronic-equipment-dominant. In a more detailed analysis of re-export trade, however, we discovered that electronic equipment industry (Sector EEMM and Sector MCE) holds the largest share of **MEERE**, tantamount to 38% of the total. It implies that, in the global electronic equipment industrial chain, China is only in charge of processing and assembling, from which China obtains extremely low profit margins at a high cost of excessive energy consumption and environmental pollution. This kind of processing trade, which puts both ends of production process (the supply of raw materials and the marketing of products) on world market, will inevitably shift energy-intensive, emission-intensive and low-value-added industries to China. In this regard, China should adjust its export structure. For the exports with high mercury emission intensity, China could impose more tariffs and cancel export tax rebates, or reduce their export quotas. Meanwhile, mandatory measures could be implemented by the government to limit the mercury emission of these industries. More need to be done, however, is that China should strengthen the ability of core technology innovation to produce the highest value-added products with the lowest environmental cost.

For global pollutants like atmospheric mercury, consumers will suffer the consequences regardless of where they are charged. Due to the booming international trade, the current mercury emission allocation mechanism based on producer responsibility is inefficient. Thus, the consumer responsibility should be adopted to tackle with the impact of international trade on energy consumption and its resultant pollution, under the principle of which one country is responsible for pollution associated with its own consumption independently of whether goods/services are produced domestically or imported. Our results highlight that China was a net exporter of energy-related mercury emissions in 2010, which gives China in a more favorable position in international mercury reduction negotiation.

5. Concluding remarks

This study employs EEIOA to assess how inter-sector connections and external trade influence China's energy-related atmospheric mercury emissions in 2010. China directly emitted 359.7 tonnes energy-related mercury in 2010, with an overwhelming percentage of 88% contributed by coal combustion. The results show that embodied emission intensities of Sector EEMM, Sector MCE and Sector IMCCM are magnified 111, 114 and 98 times compared with their corresponding direct mercury emission intensities, respectively. Generally, the magnified effect of upstream sectors (e.g., Sector CMD and Sector EPSHW) is less remarkable than downstream sectors (e.g., EEMM and Sector MCE), for downstream sectors will accumulate massive mercury emissions from their upstream sectors. Our results reveal that China is a net exporter of atmospheric mercury emissions in 2010. China avoids emitting 77.2 tonnes mercury by importing commodities from other countries/regions. Meanwhile, 97.3 tonnes mercury emissions are induced by foreign consumption of commodities produced in China, 15% of which are attributed to re-export trade. What China exports is not the technical superiority but the domestic fuel energy and environmental resource incorporated into the processing operations. Consequently, international trade would impose a huge impact on China's mercury emissions via international division of labor.

Given these, mercury removal devices for upstream sectors, production efficiency improvement for downstream sectors and controlling irrational large investment in construction sectors can be applied for China to mitigate mercury emissions based on the stages of sectors in domestic supply chains. The impacts of external trade on China's mercury emissions indicate the importance of responsibilities redistribution of international collaborative mitigation of mercury emissions. Notably, individual country should adjust their mercury emission policies from a global perspective to avoid the phenomenon that mercury emissions are reduced in its territory at the cost of emissions increasing on a global scale.

For those countries with similar economic characteristic to

China, this study is also applicable to their analysis about the impacts of inter-sector connection and external trade on environmental pollutants.

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Appendix A. Supplementary data

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