Journal of Cleaner Production 141 (2017) 1259–1266

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

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

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ARTICLE INFO

Article history:
Received 31 August 2016
Received in revised form
26 September 2016
Accepted 27 September 2016
Available online 28 September 2016

Keywords:
Mercury emissions
Energy
Trade
China

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

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http://dx.doi.org/10.1016/j.jclepro.2016.09.200

and environmental degradation between different countries. Thus, the neglect of resources and pollution embodied in international 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:

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

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. $(\mathbf{I}-\mathbf{A})^{-1}$ 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):

$$\mathbf{A} = \mathbf{A^{im}} + \mathbf{A^d} \quad (2)$$

$$\mathbf{A^{im}} = MA \quad (3)$$

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):

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

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:

$$\mathbf{Im} = \mathbf{A^{im}X} + \mathbf{Y^{im}} \quad (5)$$

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