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Original Article

Air pollutant emissions from economic sectors in China: A linkage analysis

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ABSTRACT

We employ the Hypothetical Extraction Method (HEM) using the Input-Output (IO) table and emissions data for China in 2010 to map flows of embodied air pollutant emissions. The results showed that the Construction sector (28.21% of SO_2, 29.84% of NO_x, 34.74% of Soot, 39.62% of Dust) dominates other sectors in terms of demand embodied emissions, followed by the Machinery Manufacturing (20.63% of SO_2, 19.20% of NO_x, 18.03% of Soot, 24.05% of Dust) and Service sectors (13.86% of SO_2, 13.18% of NO_x, 12.67% of Soot, 10.09% of Dust). The Power & Gas (48.98%, 60.45% and 30.66% of SO_2, NO_x, Soot emissions, respectively), Nonmetal Products (26.87% of Dust) and Metal Mining, Smelting & Pressing (29.51% of Dust) sectors, which provide electricity, steel, and cement and so on, were significant contributors to direct air pollutant emissions. The largest inter-sector flow of SO_2 emissions was from the Power & Gas sector to Construction sector (2301.3 kt). Meanwhile, the largest inter-sector flow of industrial dust emissions was from Nonmetal Products to Construction sector (1560.0 kt). From the regional perspective, Hebei and Shanxi provinces were the main sources of output emissions in China, with their industrial output dominated by energy (mainly coal) and heavy industry. Based on our findings, we suggest a few strategies to control air-pollution in China: (1) designing differentiated sectoral control strategies by considering supply chain; (2) establishing a regional responsibility sharing mechanism for air pollutants emissions; and (3) using pricing mechanisms to implement internalize the emissions along the supply chain.

1. Introduction

Rapid urbanization has demanded a large quantity of energy and materials (Yuan et al., 2013). Severe air pollution associated with the rapid urbanization is a pressing issue in rapidly developing countries or regions (Zhao et al., 2013). These countries and regions rely heavily on energy-intensive industries and consequently experience air quality issues due to the large consumption of fossil fuels (Wei et al., 2014). Two-thirds of the most-polluted cities in the world are located in China (Fujii et al., 2013). According to official statistics in 2015, the annual average $PM_{2.5}$ concentration in 338 core cities was 43% higher than the national standard (Chen, 2016).

The main sources of atmospheric PM are direct energy combustion, industrial process emissions and atmospheric pollutant reactions. Industrial emissions of Dust and Soot constitute direct sources of PM. Local SO_2 emissions are the main sources of SO_4^{2-} in $PM_{2.5}$ (Yao et al., 2002). The formation of sulfate from SO_2 is due to the coexistence of NO_x (Ma et al., 2008; He et al., 2014). Currently, official statistics are only available for SO_2, NO_x, Soot and Dust[1] emissions in China. The Chinese government has regularly published data on these four air pollutant emissions (The first national pollution census data Compilation Committee, 2011).

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[1] The main difference between soot and dust is the size of the particle: if the diameter is less than 0.1 micrometers, then the particle is soot; if it is greater than 0.1 micrometer, then it is dust.

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Nomenclature

Acronyms

HEM	Hypothetical extraction method
MEIC	Multi-resolution emission inventory for china
MRIO	Multi-regional input-output model
DE	Demand emission
NBLE	Net backward linkage emission
OE	Output emission
NFLE	Net forward linkage emission
IE	Internal emission
NTE	Net transferred emissions
ME	Mixed emission
DEI	Direct emissions intensity
TEI	Total emissions intensity
RLI	Regional linkage index

Symbols

A	Technical coefficient matrix
L	Leontief inverse matrix
X	Total output vector
Y	Final demand vector
A^d	Matrices of the direct requirement coefficient that measure domestic products
A^m	Matrices of the direct requirement coefficient that measure imported products
W	Total pollutant emission
M	Vector of imports
E	Vector of exports
S	Target sector
C	The total pollutant emissions related to the hypothetical productive relationships
$\triangle$	The elements of the Leontief inverse matrix

Unfortunately, there is no official emission data on $PM_{2.5}$ emissions. It is well recognized that SO_2, NO_x, Soot and Dust emissions are main sources of $PM_{2.5}$. Therefore, this research aims to study the SO_2, NO_x, Soot and Dust emission flows among economic sectors and regions, as precursors of $PM_{2.5}$. The results could be useful for policy-making processes to control the haze pollution.

Energy consumption and pollutant emissions during the manufacturing process are known as embodied energy and embodied emissions (Peters and Hertwich, 2006). There are several studies on embodied emissions derived from economic activities. Studies on the Chinese context have mainly focused on the embodied CO_2 emissions within the supply chain (Chang, 2015; Chen et al., 2007; Mi et al., 2015; Skelton et al., 2011; Wang et al., 2013; Feng et al., 2014; Singh and Bakshi, 2015; Muangthai et al., 2016). Recently, embodied air pollutant emissions flows between producers and consumers were also evaluated. From embodied emissions perspective, Huo et al. (2014) found the equipment, machinery, and devices manufacturing and construction sectors contributed to more than 50% of SO_2, NO_x, $PM_{2.5}$, and VOC emissions in 2010 respectively according to multi-resolution emission inventory for China (MEIC).

Input-Output models have been widely employed in embodied emissions research field. Single-regional input–output model (SRIO) is a common tool to study inter-sectoral embodied emissions, while Multiregional Input-Output model (MRIO) is widely adopted to examine inter-regional embodied emissions. Based on an MRIO model, Skelton et al. (2011) revealed that the Construction and Service sectors were the major contributors of CO_2 emissions in the global production system. Multi-region analysis has also been employed to investigate the ecological and water footprint of economic activity (Ewing et al., 2012; Zhou et al., 2016).

We used the Hypothetical Extraction Method (HEM), a well-recognized method to measure the importance of economic linkages, to identify flows of the embodied air pollutant emissions. In essence, HEM determines the importance of one sector and its impact on the entire industrial system by comparing the outputs of other sectors before and after the hypothetical extraction of the sector from the production chain (Schultz, 1977). HEM provides a useful method to reveal the importance of a sector for other sectors that require its output as an input (forward linkages); and for sectors that supply inputs into its production process (backwards linkages).

HEM was initially proposed by Strassert (1968) and later reformulated by Cella (1984) and Clements (1990). It can be used to estimate the possible effects of shutting down a particular establishment or other identifiable segment of an economy (Dietzenbacher and Lahr, 2013). These include individual sectors such as agriculture sector (Cai and Leung, 2004) and construction sector (Song et al., 2006). The first application of HEM-based resources accounting intended to attribute the responsibility of water transfer to intermediate consumers (Duarte et al., 2002). HEM has been adopted in previous studies in the fields of environment and resources. The main focuses of these studies include: measuring CO_2 emissions of inter-sectoral or inter-regional linkages (Wang et al., 2013; Zhao et al., 2015, 2016; Ali 2015), measuring energy linkages (Guerra and Sancho, 2010), and estimating inter-temporal direct and indirect water productivity (Pérez-Blanco and Thaler, 2014). However, there is no study to examine atmospheric pollutant emissions via the HEM method.

There are two shortcomings associated with existing studies that employ HEM. First, it cannot distinguish emissions from importers and those from exporters. Second, vast majorities of HEM studies in environmental research focus on describing linkages among sectors, but very few studies have attempted to examine linkages among regions. We modify HEM to address these shortcomings. Our previous study employed a modified HEM to examine the inter-industrial linkages of CO_2 emissions in China (Wang et al., 2013). Here, we extend the HEM methodology to examine sectoral and regional air pollutant emissions. The modified HEM was firstly presented by Duarte et al. (2002). We added the concepts of "demand emission" and "output emission" to describe emissions from consumers and producers respectively. In this paper, we also integrated the HEM model with a Multiregional Input-Output model (MRIO) to study inter-regional embodied air pollution. Zhao et al. (2015) employed a similar method to study the inter-regional linkage of CO_2 emissions in 2007. Air pollutants emissions are different with CO_2 emissions because of the mix of fuels used to power the economy. We also expanded the previous studies by extending the data until 2010.

Using the modified HEM model, this study aims to explore the inter-sector and inter-region air pollutants linkage in China. The major purposes of this paper are: (a) to identify the key atmospheric pollutant sectors and regions in China from the perspective of demand emissions and output emissions, respectively; and (b) to examine if those main air pollution emissions move across sectors in the same manner. The results will help to better understand the relationship between economic structure and air quality. Consequently, corresponding sector and region specific policy interventions could be designed to effectively improve the air quality.

The rest of the paper is organized as follows. Section 2 introduces the input-output method and the HEM method. The sources and processing of data are also reported in Section 2, including the sector classification and aggregation. Section 3 presents the decomposition of SO_2, NO_x, Soot and Dust emissions for 23 sectors and