ARTICLE IN PRESS

Applied Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Ecological network analysis of embodied particulate matter 2.5 – A case study of Beijing

Siyuan Yang [a], Brian Fath [b,c], Bin Chen [a,*]

[a] School of Environment, Beijing Normal University, Beijing 100875, China
[b] Department of Biological Sciences, Towson University, Towson, MD 21252, USA
[c] Dynamic Systems, International Institute for Applied Systems Analysis, Laxenburg, Austria

HIGHLIGHTS

- A $PM_{2.5}$ emission inventory framework on sectoral scale is constructed.
- The proportion of direct and indirect $PM_{2.5}$ emissions is 2:1.
- Sectors related to industry are the dominant controller of embodied emission network.

ARTICLE INFO

Article history:
Received 18 February 2016
Received in revised form 4 April 2016
Accepted 16 April 2016
Available online xxxx

Keywords:
Air pollution
Ecological network analysis
Input–output analysis
Embodied emissions
Energy structure

ABSTRACT

Over the past decades, China has been facing severe airborne pollution associated with atmospheric fine particulate matter ($PM_{2.5}$). Much attention has been paid to the physical transport of $PM_{2.5}$ emissions. However, the embodied emissions, namely the emissions transferred through economic activities, have seldom been investigated. In this paper, embodied emission of $PM_{2.5}$ from each sector of Beijing is quantified based on input–output analysis (IOA). Forty-two economic sectors from the input–output table are aggregated into fifteen components. Furthermore, the mutual interactions and control relationship within those sectors have been revealed by using ecological network analysis (ENA) to identify the dominant sectors. The results show that, in 2010, 34% of the total $PM_{2.5}$ emissions, or 59.4 kt $PM_{2.5}$, were indirect emissions traded through economic sectors within Beijing. According to the results of ENA, we found that "Smelting & Pressing of Metals", "Metal Products" and "Nonmetal Mineral Products" are the top three sectors with the highest control levels while "Agriculture", "Catering Services" and "Residential Services" are the lowest-ranking sectors among the system. The network confirms that sectors related to heavy industry are the dominant sectors driving the embodied $PM_{2.5}$ emissions in the whole system. Compared to the conventional approaches for tracking $PM_{2.5}$ emissions, ENA may provide a practical way to reveal the mechanisms of embodied $PM_{2.5}$ emission flows via socioeconomic activities from a holistic perspective.

1. Introduction

Socioeconomic activities heavily dependent on fossil fuel energy sources are coupled with an adverse effect on air quality conditions in China [1,2]. In 2012, nearly 90% of China's total primary energy came from coal and petroleum, which are considered as major air pollution sources [3,4]. In addition, various socioeconomic activities can exert negative impact on air quality [5]. It is necessary to reveal the mechanisms of how socioeconomic activities affect $PM_{2.5}$ emissions and to explore efficient and stable management of mitigating emissions.

The reduction of $PM_{2.5}$ emissions relies on the identification of the pollution source. Previous studies on source apportionment of airborne particulate matter are largely related to chemical pathways and technology-based approach, which refer to the term "production-based emission accounting". Experiments were conducted by taking $PM_{2.5}$ samples from multiple sites and quantitatively apportion the sources that contribute to fine particle mass concentrations [6,7]; The technology-based inventories were established based on calculating the particulate emissions from the combination of energy statistics, technology distributions and emissions factors [8,9]. These researches effectively trace the

* Corresponding author at: No. 19, Xinjiekouwai St., Beijing 100875, China.
E-mail address: chenb@bnu.edu.cn (B. Chen).

http://dx.doi.org/10.1016/j.apenergy.2016.04.087
0306-2619/© 2016 Published by Elsevier Ltd.

Please cite this article in press as: Yang S et al. Ecological network analysis of embodied particulate matter 2.5 – A case study of Beijing. Appl Energy (2016), http://dx.doi.org/10.1016/j.apenergy.2016.04.087

$PM_{2.5}$ emissions back to the sources where particles were physically generated and provide practical suggestions to direct the implementation of emission abatement. For example, the results of Beijing from production-based perspective show that the major direct contributors to $PM_{2.5}$ pollution are industrial process, vehicle exhaust, soil dust, and fuel combustion [6,10].

However, production-based emission accounting lacks an understanding of the socioeconomic drivers of $PM_{2.5}$ emissions when exploring emission mitigation strategies [11]. A consumption-based accounting, which can assign emissions to final consumers of commodities by examining the supply chain, provides fundamentally different information [12]. Several studies have already been demonstrated for smog-forming airborne pollutants from a consumption-based perspective. Streets et al. [13] estimated the trade-related air pollutant emissions and found that 10–40% of emissions in China's Pearl River Delta were caused by export-related activities. Yang et al. focused on trans-boundary air pollution emissions through transactions between Jing-Jin-Ji district and the rest of China and traced the transfer route of embodied particles within the district [14]. Zhao et al. [15] quantified virtual air pollutants through interprovincial trade in China based on a consumption-based emission framework. Guan et al. [11] analyzed production-related $PM_{2.5}$ emission changes in China between 1997 and 2010 to identify the socioeconomic drivers of primary $PM_{2.5}$ emissions from a consumption perspective. The disparity between production- and consumption-based emissions inventories in China were also explored in the context of international trade [16,17]. Others borrowed the concept of "embodied emission" from energy analysis to calculate the emissions embodied in products or services which are traded nationally or globally [18,19]. In general, there are two types of approaches adopted to quantify the embodied emissions: the bottom-up and top-down accounting approaches. The former method is based on the process analysis which collects detailed process data to calculate embodied emissions generated in economic activities. It can be used to assess the impact of the entire life cycle of each individual product on the environment [20]. For instance, emissions embodied in the electricity supply includes those airborne pollutants directly discharged in the power plant plus all the emissions discharged indirectly due to producing other inputs to the power plant, like vehicles, metal processing, building construction, and coal mining [21]. However, the bottom-up approach cannot distribute the responsibility to the intermediate and final consumers, let alone identify driving forces [22,23]. The top-down approach is based on input–output analysis (IOA) which describes the material flow through economic sectors in order to identify how much PM emissions are embodied in producing a specific product [24–27]. The basic foundation of this method based on an input–output table of the economic structure which shows the complex inter-regional or inter-sectoral relationships based on monetary flow [28,29]. Some studies have explored the embodied $PM_{2.5}$ emissions flows via domestic or foreign supply chains on regional or national scale [30,31]. By using this approach, all PM intensive transactions within economic sectors can be identified and captured [32–34].

Nevertheless, few have paid attentions to the systematic configuration of virtual material flows [35], which should be further explored to illustrate the inner interactions and linkages of $PM_{2.5}$ emissions within the socioeconomic system. For this reason, ecological network analysis (ENA), which was first developed by Hannon [36] to analyze the interdependence of each member of an ecosystem upon the others and trace the distribution of both direct and indirect element flows in an ecosystem [37,38], is adopted in this study to investigate the network structure of the embodied $PM_{2.5}$ emission flows. The network control analysis (NCA) derived from ENA is used to investigate the control relationship and interdependence between sectors by quantifying the contribution of each sector to the others' inputs and outputs [39–42]. The cumulative pathways of emission flows can also be highlighted based on the allocation of integral control [43,44]. Considering the specific local conditions (e.g., energy structure, industry specification, and economic activities), the internal structure analysis of embodied $PM_{2.5}$ emissions via the economic sectors may therefore provide a different perspective to understand the fundamental factors that drive the emission flows within concerned areas [45].

In this study, a $PM_{2.5}$ emission inventory framework on the sectoral scale is constructed based on an economic input–output model, which is used to parcel out major exchange pathways into small pieces between sectors and distribute $PM_{2.5}$ emissions to sectors according to where products or services are finally consumed. The $PM_{2.5}$ emissions embodied in economic activities between fifteen sectors in Beijing are quantified accordingly. Then, the embodied $PM_{2.5}$ emission network is configured by ENA to examine the structure and function of each sector and quantify the distribution of control level through the interactions among sectors. Thus, IOA and ENA can be combined to investigate the direct and indirect $PM_{2.5}$ emissions and identify the dominant sectors as well as their linkages.

This paper is organized as follows. In Section 2, the methodologies of IOA and ENA are briefly described. Section 3 quantifies direct and indirect $PM_{2.5}$ emissions and presents the control analysis based on ENA. Finally, a range of results and policy implications are addressed.

2. Materials and methods

2.1. Study site and data

Beijing lies in the north-east of China, which is surrounded on three sides by mountains. The mountainous area has an average elevation of over 1000 m and the urban area of Beijing comprises lowlands of 30–50 m above sea level. Within the administrative boundary of Beijing, 63% of the area is hilly or mountainous region. Its special terrain makes it difficult to disperse the air pollution. Although coal combustion has been prohibited in urban areas except for permitted high capacity boilers with effective emission control system, residential cooking and space heating in both the rural area and suburban area (92% of total area) of Beijing still relied largely on coal combustion (especially coal briquettes) [46]. In 2010, the average concentration level of daily $PM_{2.5}$ is 101.15 $\mu g/m^3$ [47], which is nearly three times higher than the standard concentration of $PM_{2.5}$ (35 $\mu g/m^3$). In response to the severe air pollution, authorities in Beijing released detailed and strict criteria for $PM_{2.5}$ mitigation: a Five-year Clean Air Action Plan in Beijing (2013–2017) has been issued to reduce the concentration of $PM_{2.5}$ by 25% or more by 2017 relative to 2012 [48].

The data for $PM_{2.5}$ emissions in 2010 from 110 sectors are derived from the greenhouse gas–air pollution interactions and synergies (GAINS) model that is developed by the International Institute for Applied Systems Analysis (IIASA). The input–output table for 42 economic sectors in Beijing is provided by Beijing Municipal Bureau of Statistics. To be consistent with the urban I–O table and $PM_{2.5}$ emission sectors, the urban economy was separated into forty-two economic sectors. To better understand the embodied $PM_{2.5}$ emission flow within the system and highlight the key sectors with high intensive of $PM_{2.5}$ emissions, those forty-two economic sectors were then further aggregated into fifteen larger sectors or components. The basic information (area and energy consumption etc.) of the study area is abstracted from China Statistical Yearbook [3]. The other pertinent data can be found in scientific reports or relevant official website [47–49].

Please cite this article in press as: Yang S et al. Ecological network analysis of embodied particulate matter 2.5 – A case study of Beijing. Appl Energy (2016), http://dx.doi.org/10.1016/j.apenergy.2016.04.087