Applied Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Energy implications of China's regional development: New insights from multi-regional input-output analysis

Xudong Sun [a,b], Jiashuo Li [c,d], Han Qiao [e], Bo Zhang [a,b,*]

[a] School of Management, China University of Mining & Technology (Beijing), Beijing 100083, PR China
[b] Research Center for Energy Strategy, State Key Laboratory of Coal Resources and Safe Mining, China University of Mining & Technology (Beijing), Beijing 100083, PR China
[c] State Key Laboratory of Coal Combustion, School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, PR China
[d] Department of New Energy Science and Engineering, School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, PR China
[e] School of Economics and Management, University of Chinese Academy of Sciences, Beijing 100190, PR China

HIGHLIGHTS

- Booming regional economies increase their energy impacts and effects across China.
- China's three major economic circles generated huge demands for embodied energy.
- The three areas used 2/5 of domestic energy supply to provide 2/5 of national GDP.
- These areas were far from self-sufficient and outsourced energy demands via trades.
- Real energy use patterns and interregional energy spillover effects were examined.

ARTICLE INFO

Article history:
Received 20 October 2016
Received in revised form 5 December 2016
Accepted 17 December 2016
Available online xxxx

Keywords:
Embodied energy
Interregional trade
Multi-regional input-output analysis
Three economic circles in China

ABSTRACT

Regional imbalance in development is amongst the most important challenges for China. As the country's leading economic engines, three major economic circles representing 6.5% of the national land territory contributed to more than 2/5 of national gross domestic product (GDP). This paper focuses on the impact of these three growth poles in China's regional development, particularly for their embodied energy uses in light of multi-regional input-output analysis. Significantly, the three developed areas generated huge demands for embodied energy, 1237.52 Mtce and 40.1% of the total domestic supply in 2010, but far from self-sufficient. In *Yangtze-River-Delta*, *Pearl-River-Delta* and *Jing-Jin-Ji*, 93.1%, 85.1% and 63.4% of their embodied energy uses respectively can be traced back to the energy-supply provinces such as Shanxi, Inner Mongolia and Shaanxi and other trade partners. Over a half of the national interregional transfers of embodied energy via domestic trade were induced by the three economic circles' final demand, largely resulted from their large-scale infrastructure construction, upgraded consumption structures, high export dependency and ongoing urbanization process. The results indicate that demand-driven embodied energy is a comprehensive indicator to reflect the real energy use patterns of developed regions or megacities and reveal their industrial positions in domestic and even global supply chains. Understanding the temporal and spatial energy transition along with regional development from consumption-based insights is a vital step toward appropriately targeted policy making for the nation-wide energy saving and emission reduction.

1. Introduction

In the past three decades, China has witnessed rapid economic growth and urbanization, especially in the developed coastal areas [1–3]. Three major economic circles, i.e., *Jing-Jin-Ji* in North China, *Yangtze-River-Delta* in East China and *Pearl-River-Delta* in South China, containing a group of cities with similar development routines, cultures, scales and geographical locations [4], have attracted great concerns for their economic impact on China's regional development. Prominently, the three areas only accounted for 6.5% of the national land territory, but hosted 27.5% of the total population of the whole country (365.15 million, larger than the U.S. population and about 5.2% of the world's population) and contributed to 41.4% of national gross domestic product (GDP) in 2014

* Corresponding author at: School of Management, China University of Mining & Technology (Beijing), Beijing 100083, PR China.
E-mail address: zhangbo@cumtb.edu.cn (B. Zhang).

http://dx.doi.org/10.1016/j.apenergy.2016.12.088
0306-2619/

[3]. The booming economy and fast growing urban population in the three circles are fueled by a continued reliance on energy resources [5,6]. Some studies have focused on the increasing energy demands and related environmental impact of the developed areas or their subsidiary megacities such as *Jing-Jin-Ji*, Shanghai and *Pearl-River-Delta* [7–14], in view of their prominent socio-economic positions.

If only considering the imported energy products, regional real energy demands cannot be fully addressed. The developed regions' specialization in the production of high value-added industries such as service industry and high per capita income levels imply that these regions have shown a tendency to purchase much more final goods from other provinces rather than produce them locally [4,8]. As the production processes of the imported goods also need energy inputs, the consumption of imported goods and services also lead to energy use in related trade partners, implying that the three economic circles have indirect effects on energy demand outside their geographic boundaries [12]. Given the close trade ties with other provinces, the information on direct primary energy input solely is far from enough to depict the true energy picture of China's three growth poles in regional development. Therefore, a more comprehensive indicator rather than direct energy use is necessary to evaluate the real energy status of the three economic circles.

Embodied energy, defined as the direct plus indirect primary energy input to produce the goods used for final demand, is an appropriate indicator used as alternative to direct energy use, which can reflects the total physical energy resources supply for production to satisfy final demand [15,16]. Since an input-output model is a method for quantifying economic interactions including but not limited to final demand, an environmental input-output modeling makes it possible to identify how much ecological element such as energy can be attributed to a specific economic output [17–19]. A large number of studies have employed this method to illustrate the energy used by a specific economy from the perspective of consumption [20–25], i.e., considering both the direct energy due to on-site immediate energy use and the indirect energy related to goods provided by the supply chains.

As multi-regional input-output (MRIO) model provides a powerful tool to look into the intraregional and interregional economic characteristics [26], it has been widely used to analyze the consumption-based accounting of China's region-specific resource uses [12,16,27], water footprints [28–30], greenhouse gas emissions [31–42], and other environmental emissions such as $PM_{2.5}$, mercury and SO_2 [43–47]. Especially, MRIO analysis can be applied to identify the resource requirements and energy spillover of certain regions through the interregional economic flows. Embodied energy use associated with cross-boundary exchange of goods and services measures a region's direct primary energy inputs caused by other regions' total final demand or one region's energy spillover to other regions through domestic supply chains [12,16]. Some scholars have combined energy statistic data with China's multi-regional input-output tables to elucidate the regional energy uses [4,16,48–52]. Zhang et al. [16,52] reported the impacts and effects of China's interregional trade on the energy requirement of regional economies over 2002–2007. By using a MRIO model, Zhang et al. [12] focused on the embodied energy uses by China's four municipalities: Beijing, Tianjin, Shanghai and Chongqing. A recent study by Zhang et al. [49] also revealed that developed regions' final demand led to spatial distribution of production activities across China by tracking interregional embodied energy flows. These studies have contributed to people's understanding on regional and urban economies' energy profiles. Moreover, they have provided strong evidence that MRIO model is also a valuable practical technology to quantify a region's embodied energy use. Nevertheless, the literature list of using MRIO embodiment analysis on regional demand-derived energy requirements is still very short.

The purpose of this paper is to examine the energy use patterns of China's three major economic circles and capture their interregional energy spillover effects in domestic trade networks, based on the latest statistical data and recently available MRIO table for China 2010. The compiling of both direct production-based and embodied consumption-based energy use inventories by considering frequent trade exchanges help to understand and identify regional real energy uses under the influence of industrial positions, consumption demands and trade (interregional trade and international exports) linkages along the production chain to final consumption. Furthermore, a case study of three major economic circles will contribute to illustrating energy implications of China's regional development and offering fundamental information for exploring energy-saving and emission-reduction potentials across China.

The remainder of this paper is organized as follows. In Section 2, the algorithms for MRIO analysis, data sources and background information for the three economic circles are introduced. In Section 3, the results of embodied energy uses in final demand and interregional trade of the three areas are presented. Regional energy use inventories between 2007 and 2010 are compared, and we also track the embodied energy flows via interregional and intraregional trades in Section 4. Energy implications of regional urbanization and economic development are further discussed in this section. Concluding remarks will be made in the ending section.

2. Material and methods

2.1. Multi-regional input-output model

The MRIO table for Chinese economy 2010 adopted in this study is compiled by scholars from Chinese Academy of Science [53], which provides economic flows of China's 30 regions (excluding the Hong Kong Special Administrative Region, the Macau Special Administrative Region, Taiwan province and the Tibet autonomous region) with 30 economic sectors in each region (see Table S1 in Supplementary materials). This MRIO table is the latest version with the highest regional and sectoral data resolution currently, which is compiled based on the 2007 MRIO table and 30 provincial extended input-output tables for the year of 2010. Since only 17 provincial regions have their provincial extended input-output tables in 2010, the main data sources for compiling the extended IO tables of the rest 13 regions are their 2007 benchmark input-output tables and economic statistics in 2010. Industrial and trade statistics concerning the target province are rectified in a consistent basis, and then interprovincial trade matrixes are corrected by cross-regional and cross-sectoral balancing, referring to the direct consumption coefficients of the 2007 MRIO table and the RAS method (for more information, see Liu et al. [53] and SI in Feng et al. [31]). As the study focuses on the primary energy input within China, international imports are not considered based on the non-competitive import assumption in the initial MRIO table.

For the MRIO model, the basic row balance can be expressed as

$$x_i^f = \sum_{s=1}^{30}\sum_{j=1}^{30} z_{i,j}^{f,s} + \sum_{s=1}^{30}\sum_{t=1}^{5} d_{i,t}^{f,s} + e_i^f + o_i^f = \sum_{s=1}^{30}\sum_{j=1}^{30} z_{i,j}^{f,s} + p_i^f \quad (1)$$

where x_i^f represents the total output of Sector i in Region f; $z_{i,j}^{f,s}$ is the intermediate use of Sector j in Region s supplied by Sector i in Region f. $d_{i,t}^{f,s}$ stands for the domestic final consumption of Region s supplied by Sector i in Region f, covering rural household consumption ($t = 1$), urban household consumption ($t = 2$), government

Please cite this article in press as: Sun X et al. Energy implications of China's regional development: New insights from multi-regional input-output analysis. Appl Energy (2016), http://dx.doi.org/10.1016/j.apenergy.2016.12.088