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Embodied energy uses by China's four municipalities: A study based on multi-regional input–output model

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ABSTRACT

Consumption demands in China's megacities not only cause energy resource extraction within their own jurisdictional boundaries, but also impose huge energy resource requirements to other regions via interregional supply chains. This paper presents a multi-regional input–output analysis of energy uses embodied in final demand and interregional trade of China's four direct-controlled municipalities, with the recently available Chinese 2007 multi-regional input–output table. The total embodied energy uses (EEUs) of Beijing, Tianjin, Shanghai and Chongqing are 59.1, 60.0, 136.7 and 50.4 Mtce in 2007, respectively. Shanghai has the highest per capita EEUs with an amount of 7.4 tce, followed by Tianjin (5.4 tce), Beijing (3.6 tce) and Chongqing (1.8 tce). Investment is the leading final demand category and accounts for respectively 53.1% and 55.8% of the total EEUs in Beijing and Chongqing. Meanwhile, the shares of energy uses embodied in exports are especially high in Tianjin and Shanghai, due to their location advantages and great economic openness. 98.9%, 92.1%, 51.2% and 35.6% of the EEUs in Shanghai, Beijing, Tianjin and Chongqing are imported from China's other regions, respectively. Shanxi, Inner Mongolia, Hebei, Shaanxi, Heilongjiang and Xinjiang are the important "energy-saving helpers" for these megacities. The largest interregional net embodied energy-import sector is construction for all the four municipalities. Considering the embodied energy uses in urban ecosystems is important for policy makers to recognize visible and hidden energy uses within city boundaries and along the entire supply chains and address cross-boundary potentials for energy saving at the regional, national and global supply chains.

1. Introduction

China's urbanization process can be regard as the great human-resettlement experiment in history (Bai et al., 2014). Mainland China had a total urban population of 712 million or 52.6% of the total population in 2012, rising from 17.9% in 1978 (CSY, 2013). Rapid urbanization provides an enormous opportunity to promote economic growth and regional development, but also poses a huge challenge in harmony with population, resources and environment in urban ecosystems (Liu et al., 2014).

China has become the largest energy consumer and CO_2 emitter in the world (BP, 2013), and urban production and consumption is regard as one of the main drivers (Feng et al., 2014). More than 80% of national total energy consumption is happened in China's cities (Liu et al., 2012c; Liu et al., 2012cc). Studies on city's energy problems of China have increased quickly over the past decade (e.g., Dhakal, 2009; Feng et al., 2013b; Zhang et al., 2010). The challenges of urban energy supply in megacities for the provision of adequate coal, electricity, natural gas and other energy sources for huge population have been emphasized in previous studies (Wang, 2014). However, accounts of territorial energy input/use within their jurisdictional boundaries are insufficient for depicting the true energy picture of the megacities (Feng et al., 2014; Lenzen et al., 2007c). Besides the direct energy inputs within territorial boundary, indirect energy demands or requirements associated with cross-boundary exchange of goods and services in cities are often neglected. It is necessary to undertake quantitative analysis on energy uses in cities and evaluate city's real energy status from different insights.

Since input–output model can capture the exact quantitative economic relationships among industrial sectors (Miller and Blair,

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2009) and make it possible to identify how much energy can be attributed to a specific economic output (Chung et al., 2009; Lenzen, 1998; Liu et al., 2012b; Wiedmann, 2009a), a holistic accounting of city's energy uses based on input–output models can provide energy information related with the consumption of products from upstream production through supply chain to various stakeholders. A large number of studies have employed the input–output models to analyze cities' energy footprints covering both direct and indirect (namely embodied) energy activities throughout the whole supply chains (e.g., Han et al., 2013; Li et al., 2014; Shao et al., 2014; Zhang et al., 2014c; Zhou et al., 2010).

On the basis of the concept of embodied energy originating from the theory of systems ecology (Costanza, 1980; Odum, 1983), the total primary energy input to satisfy final demand, i.e., the direct plus indirect energy resources input through the production processes to produce the goods used for final demand, are termed embodied energy use or demand-derived energy requirement (Bruckner et al., 2012; Chen and Chen, 2010, 2013; Chen et al., 2010; Ukidwe and Bakshi, 2008). When direct energy input indicates the physical energy resources supply for production, embodied energy requirement reflects the virtual energy use by demand (Chen and Chen, 2013; Zhang et al., 2013).

Compared with the regional (single-region) input–output model, multi-regional input–output model not only presents the interactions among industrial sectors within an economy, but also provides the spatial linkages of industries between any two regions in the system and distinguishes the production technologies between domestic and other regions, based on a more comprehensive data foundation of the intraregional and interregional economic flows (Hertwich and Peters, 2009; Peters et al., 2011; Su and Ang, 2011; Wiedmann, 2009b; Wiedmann et al., 2012; Zhang et al., 2011). Especially, an multi-regional input–output analysis of the embodied energy use can be applied to identify the energy requirements of certain industrial sectors or regions linked to their direct as well as indirect primary energy inputs by considering the inter-industry linkages between energy producers and energy users (Chen and Chen, 2011a,b,b). By employing the multi-regional input–output models, previous studies have been undertaken to analyze the GHG emissions and resource uses in China (e.g., Guo et al., 2012; Feng et al., 2013a, 2014; Liang et al., 2007; Meng et al., 2013; Su and Ang, 2014; Tian et al., 2014; Zhang and Anadon, 2014; Zhang et al., 2011, 2014a,b; Zhou and Imura, 2011). Zhang et al. (2013) reported the impact of China's interregional trade on the energy requirement of regional economies in 2007 considering the intermediate uses and final uses in a simplified multi-regional input–output model. However, few studies focus on the embodied energy uses in China's megacities based on multi-regional input–output models.

Beijing, Tianjin, Shanghai and Chongqing are the four municipalities directly under the central government in China, which gain equal political stature with provincial governments (Kanada et al., 2013). The total population of the four municipalities is larger than 88 million, about 1/80 of the world's population and 6.5% of the national total population, and their total GDP counts for 10.8% of the whole country as of 2012 (CSY, 2013). In China, these four megacities are key targets for implementing the national policy on "energy saving and emission reduction" (Liu et al., 2012c). Therefore, this paper will present a multi-regional input–output analysis of energy uses embodied in final demand and interregional trade of China's four municipalities, due to their prominent positions and data availability. Particularly, the impacts and effects of interregional trade on city's energy uses will be systematically measured by addressing the demand-derived energy requirements.

The remainder of this paper is organized as follows. In Section 2, the algorithms for multi-regional input–output analysis, data sources and background information for the four municipalities are introduced. In Section 3, the results of embodied energy uses in final demand and interregional trade by China's four direct-controlled municipalities are presented. The impacts of interregional trade on megacities energy use inventories and corresponding policy implications are discussed in Section 4. Concluding remarks will be made in Section 5.

2. Methodology and data sources

2.1. Mathematic form of MRIO model

In this study, the multi-regional input–output (MRIO) table for China 2007 compiled by scholars from Chinese Academy of Science and National Bureau of Statistics of China (Liu et al., 2012a) is adopted, which is the most recently available MRIO table in China. The Chinese MRIO table 2007 is developed based on the single provincial IO tables for 30 regions and interregional trade matrices (Zhang et al., 2013). It is worth noting that noncompetitive import assumption is adopted in the 2007 Chinese MRIO table. The format of revised MRIO table is shown in Table 1 and the item for international imports is excluded to focus on domestic interregional connection. There are 30 regions (Tibet is not included for lack of data), with 30 sectors in each region in the MRIO table (see

Table 1
The format of revised multi-regional input–output table in 2007.

Input		Output														
		Intermediate use							Final use							Total output
		Beijing (R1)				Xinjiang (R30)			Beijing (R1)		⋯	Xinjiang (R30)		Export	Others	
		Sector1	⋯	Sector30	⋯	Sector1	⋯	Sector30	Consumption	Investment	⋯	Consumption	Investment			
Beijing (R1)	Sector 1															
	⋮															
	Sector 30				$z_{i,j}^{f,s}$						$d_{i,t}^{f,s}$			e_i^f	o_i^f	x_i^f
⋮	⋮															
Xinjiang (R30)	Sector 1															
	⋮															
	Sector 30															
Direct primary energy input					c_i^f											

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