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Analysis of the energy metabolism of urban socioeconomic sectors and the associated carbon footprints: Model development and a case study for Beijing

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HIGHLIGHTS

- We quantified the embodied energy transfers among Beijing's socioeconomic sectors.
- We calculated the sectors' intensity of energy consumption and carbon footprint.
- The indirect energy consumption was higher than the direct for all sectors.
- The high-indirect-consumption sectors are at the end of industrial supply chains.
- High-indirect-consumption sectors can improve upstream products energy efficiency.

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ABSTRACT

Cities consume 80% of the world's energy; therefore, analyzing urban energy metabolism and the resulting carbon footprint provides basic data for formulating target carbon emission reductions. While energy metabolism includes both direct and indirect consumptions among sectors, few researchers have studied indirect consumption due to a lack of data. In this study, we used input–output analysis to calculate the energy flows among directly linked sectors. Building on this, we used ecological network analysis to develop a model of urban energy flows and also account for energy consumption embodied by the flows among indirectly linked sectors (represented numerically as paths with a length of 2 or more). To illustrate the model, monetary input–output tables for Beijing from 2000 to 2010 were analyzed to determine the embodied energy consumption and associated carbon footprints of these sectors. This analysis reveals the environmental pressure based on the source (energy consumption) and sink (carbon footprint) values. Indirect consumption was Beijing's primary form, and the carbon footprint therefore resulted mainly from indirect consumption (both accounting for ca. 60% of the total, though with considerable variation among sectors). To reduce emissions, the utilization efficiency of indirect consumption must improve.

1. Introduction

Urban metabolism is an important area of study because of energy use efficiency or inefficiency signals the overall carbon metabolism that adversely affects the environment and contributes to climate change. The concept of a low-carbon city is increasingly accepted, and is encouraging governments to study urban energy metabolism, particularly in China due to the nation's rapid pace of development. China's 12th 5-year plan predicts an urbanization rate of 51.5% by 2015, which represents an increase from 47.5% in 2011 (Government of China, 2011). This will have important environmental consequences, since urban areas account for 89.0% of China's total energy consumption (Tong, 2012). Clearly, Chinese cities will play a key role in achieving target carbon emission reductions.

Material-flows analysis is a traditional method for studying metabolic systems (Ayres and Kneese, 1969; Fischer-Kowalski, 1998a,b). This approach calculates the inputs and outputs of materials from a system, including socioeconomic systems, but ignores the energy that accompanies these flows. To account for

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these energy flows, Haberl (1997) pioneered the concept of "energy metabolism", noting that accounting for these flows provides a more detailed understanding of the urban metabolism. To do so, he developed the method of energy-flow analysis (Haberl, 2001a) based on the growing consensus that material and energy flows should have equal status. Many subsequent researchers built on this method. Researchers have used this approach to study the world (Haberl, 2006), Austria (Haberl, 2001b; Krausmann et al., 2003), Southeast Asia (Haberl, 2001b), the European Union (Reinders et al., 2003), the U.S. (Haberl, 2006), and the Czech Republic (Kuskova et al., 2008). An important breakthrough involved replacing the black-box model, in which the flows within the system are not considered, with detailed analyses of the flows within the box (i.e., among the urban ecosystem's sectors). For example, Zhang et al. (2010b, 2011a,b) analyzed the urban energy metabolic system from the perspective of network models, and then used this approach to compare 5–17 sectors of Beijing and other Chinese cities. Unfortunately, this research did not study the energy "embodied" in the exchanges of intermediate non-energy products and materials (IFIAS, 1974). That is, in addition to the direct energy consumption, indirect energy consumption during the utilization and exchange of intermediate products should also be considered. The resulting embodied energy (direct plus indirect) is the sum of all the energy required to produce goods or service (IFIAS, 1974).

Input–output analysis has been widely used to account for embodied resources (Costanza, 1980; Hannon, 1973), such as water (Hite and Laurent, 1971), energy (Casler and Wilbur, 1984; Herendeen, 1978; Limmeechokchai and Suksuntornsiri, 2007; Wright, 1974), and natural resources (Wright, 1975). Researchers have analyzed the structure of energy distribution among sectors and energy utilization for the creation of single products (Berry and Fels, 1973a,b; Chapman, 1974; Cleveland et al., 1984; Jain, 2012; Liu et al., 2012; Wright, 1974). Subsequently, some researchers have combined the tools of systems ecology with economic input–output models to develop equilibrium equations that account for the flows of embodied energy from a macro-scale perspective (Chen and Chen, 2012; Chen et al., 2010; Xu, 2010). This approach also better supports research on the sectoral energy distribution and its impacts for climate change (Proops et al., 1993; Wier et al., 2001), for example, 50 sectors for Vietnam from 1996 to 2000 (Tuyet and Ishihara, 2006), the embodied energy utilization of 130 sectors in India from 1967 to 2012 (Jain, 2012), and the embodied energy of 29 sectors in China in 2007 (Liu et al., 2012). Meanwhile, this method has been widely used in many fields to simulate the energy utilization within and among large economic systems (Bullard and Herendeen, 1975; Herendeen, 1978; Wright, 1974), such as the world (Chen, 2011), and for nations such as China (Chen and Chen, 2010; Liang et al., 2007), Canada (Bush, 1981), Vietnam (Tuyet and Ishihara, 2006), Australia (Lenzen, 1998), and Thailand (Limmeechokchai and Suksuntornsiri, 2007). It has also been used for specific industries, such as automobile production (Berry and Fels, 1973a,b) and the construction sector (Chang et al., 2010). Because fuel combustion results in the emission of greenhouse gases, input–output analysis has also been extended to analyze these emissions for areas such as the United Kingdom (Gay and Proops, 1993). Because this method can cope with both material and non-material inputs and outputs (Lenzen and Trelor, 2002; Voorspools et al., 2000), it has been used to study the embodied energy of various resources (Chen and Chen, 2010).

Although input–output analysis can effectively assess the embodied energy of a product through an integral consumption coefficient, this process cannot specify the energy consumption implied in the production and exchange of intermediate products. Combining input–output analysis with ecological network analysis can solve this problem. This is because ecological network analysis can trace the energy consumption processes backward to account for the total energy consumption involved in producing intermediate products. Therefore, we introduced ecological network analysis in our study. First, using input–output analysis we converted a traditional monetary input–output table into a physical one, and used the table to obtain the energy transferred via the exchanges of intermediate products. These flows comprised the direct paths in the ecological network. Second, using ecological network analysis, we accounted for the indirect paths implied in the direct paths, and traced the energy consumption during the production of intermediate products.

Ecological network analysis can effectively account for the flows of embodied energy from a holistic perspective. The sum of the direct and indirect flows represents the integrated flows within the ecological network, and this sum can help to reveal the system's structure and function (Fath and Killian, 2007; Levine, 1980; Patten, 1982; Szyrmer and Ulanowicz, 1987). This approach originated in the economic analysis of monetary flows. Hannon (1973) first applied economic input–output analysis (the Leontief model; Leontief, 1966) to investigate the distribution of ecological flows in an ecosystem. Hannon (1973) pioneered the use of ecological network analysis based on input–output techniques to simulate the structural distribution of ecosystem components and the interrelationships among trophic levels. Finn (1976) improved on Hannon's method to quantify the ecosystem structure and account specifically for the fraction of flow that is cycled, introducing an important index of ecological networks. Patten (1982) examined the interdependence among an ecosystem's components by describing the flows of materials and energy, thereby refining the traditional ecological network analysis method. He proposed the concept of an "environ", which was his terminology for the within-system environment. The basis of this method is to establish a network flow diagram that captures both the direct and the indirect material and energy flows among the system's components (Levine, 1980; Patten, 1982). This approach has been widely used to study natural ecosystems (Baird et al., 2009; Borrett et al., 2007; Dame and Christian, 2008; Gattie et al., 2006; Heymans et al., 2002; Jordán et al., 2009), but has less often been used to study the flows within socioeconomic systems, such as industrial systems (Bailey et al., 2004a,b; Chen, 2003), water systems (Bodini and Bondavalli, 2002; Li et al., 2009; Zhang et al., 2010a), and energy systems (Zhang et al., 2010b, 2011a, 2011b; Zhao, 2006).

Tracking a system's energy metabolism provides insights into both energy conservation and opportunities for "carbon footprint" reduction. Carbon footprints evaluate the pressure imposed by human activities on the environment by measuring the direct and indirect carbon dioxide emission from or carbon accumulation in products (Wiedmann and Minx, 2011). Researchers have used this approach to study cities around the world (Sovacool and Brown, 2009), Ireland (Kenny and Gray, 2009), Shanghai (Guo, 2009), and Finland (Virtanen et al., 2011). For example, Lenzen (1998) used input–output tables for Australia in 1992/1993 to account for carbon dioxide emissions, and Limmeechokchai and Suksuntornsiri (2007) analyzed the full energy chain to estimate greenhouse gas emissions from energy-related activities in all production chains for the final consumption of 130 economic sectors in Thailand. However, few researchers have studied the sectoral distribution of carbon footprints by accounting for both direct and indirect flows (Chen et al., 2013; Sun et al., 2010).

In this study, we used input–output analysis and ecological network analysis to quantify the direct, indirect, and embodied flows of energy through an overall metabolic system. We used Beijing as an example to calculate the embodied energy flows within and among the city's sectors and the corresponding carbon