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Dominants in evolution of urban energy metabolism: A case study of Beijing

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A B S T R A C T

Ecological network analysis is an important tool for urban energy metabolism research, but it does not consider the dynamic and synergy features of the system, which constraints its application in urban transition studies. In this paper, we modified the ecological network analysis method to identify the key factors that dominate the evolution of the urban energy metabolism. Focusing on the dynamic and synergy characteristics of the system, we observed the changes of direct and indirect energy consumption flows and combined with Haken model to determine the dominant factors of the metabolic processes. A case study on Beijing was conducted to diagnose the key flows that impact the evolution of Beijing's energy metabolic system during 2010–2015. Results suggest that despite the decline in Beijing's coal consumptions, the direct and indirect parts have different tendency among sectors. During the research period, the pathway "*coal to industry*" displays dominant effects on the evolution of Beijing's energy metabolic system.

1. Introduction

Nowadays, most of the world's energy production and consumption are not performed in a sustainable way. To minimize the environmental impacts while seeking economic development and relieve the contradictions between energy supply and demand, countries have been focusing on plans seeking a high efficient and environmentally friendly energy system. As the world's largest development country, China has experienced rapid industrialization and urbanization. Accompany with the fast development, China's total energy consumption has ranked 1st among the world, reaching 3123 Mtoe in 2016. A high portion of energy is consumed in urban area, resulted in excessive energy consumption and severe air pollutions in major Chinese cities. China is in urgent need to optimize the urban energy system (He et al., 2017; He and Qiu, 2016). In China's 13th Five-year plan, upgrading the urban energy structure and building a modern energy storage & transportation network are proposed to construct an efficient urban energy system (Liu et al., 2018; Wu and He, 2018).

As one of the essential elements for urban development, energy has attracted great research interests on its supply & demand, efficiency, environment impacts and the balance between environment and development. These researches provide valuable solutions on solving the problems about urban energy utilization, including energy shortage, energy waste or energy pollution. But some scholars point that traditional analysis confine the research view on the external characteristics of the urban energy system, making the system become a black box (Zhang et al., 2014). This will lead to the ignorance of the microscopic fluctuations and structural dynamics within the system, resulting in unexplainable phenomenon. Therefore, more and more researchers advocate that urban energy system analysis should cover more than just the total energy consumption or economic output, it also needs to identify the energy metabolic pattern and diagnose the health condition (Pulido Barrera et al., 2018; Hao et al., 2018; Davoudi and Sturzaker, 2017).

Urban energy metabolism, first proposed by Wolman in 1965, consists of the exchange, conversion, use and disposal process of energy in urban areas. It reflects the structure and the functionality of an urban energy system through describing the status of the energy metabolic processes based on the similarities between an urban system and a natural system. Inspired by this analogy, scholars have developed a range of interpretations and extensions of urban metabolic terms and adopted numerous applications of urban metabolism. A series of implementations in the U.S. (Wolman, 1965), Canada (Codoban and Kennedy, 2008), China (Huang et al., 2015; Lei et al., 2018), and have proved the effectiveness of urban energy metabolism. However, as current researches mainly focused on the characteristics of overall urban metabolism, the inherent structures and functions of the system still needs further development.

In the past decades, as urbanization accelerating, population increasing and industrialization expanding, significant growth took place in energy consumption and waste emissions in urban areas, which resulted high metabolic throughputs and severe energy wastes and

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pollutions. As such, researchers conducted various methods in modeling the urban energy metabolism system including life cycle analysis (Norman et al., 2006), material flow analysis (Rosado et al., 2014), emergy analysis (Liang and Zhang, 2012) and ecological network analysis (Zhang et al., 2017, 2011) to assess the sustainability of urban energy system (Alberti, 1999; Su et al., 2010). These studies focused on the flows among the components that formulated the structure of the system, and combined with input-output approach, as a very powerful tool, to calculate the embodied flow through the system.

With the rapid development of complex system science in the past decades, researchers realized that cities cannot be regarded simple accumulation of sectors. The complicated interactions mechanism among sectors make the city into a super organism. This means that any change in population, industries and other facilities within cities can trigger a series of complicated reactions in system. Moreover, the mechanism of these reactions are usually nonlinear due to the cross impacts through the complex structure of the metabolic network in urban areas, resulting the emerge of new operating pattern (Dong et al., 2018). Some scholars (Dijst et al., 2018) noticed this phenomena, and introduced complex theory to explain it. The synergy effects and other complex system features of the metabolic system were analyzed (Zheng et al., 2018) to reflect the dynamic evolution and intrinsic stochastic behavior of the complicated urban energy system (Zheng et al., 2018).

To fully understand the principles behind, scholars have developed many interdisciplinary and innovative researches on urban system analysis, and highlighted that complex system theory may provide the solution on describing and revealing the nonlinear mechanism of urban energy system. The combination of thermodynamic system theory with socioeconomic system theory was first raised in a meeting organized by Santa Fe Institute (1987) to seek deep insights and new ways of economic problems. Since then, complex system analysis has been focusing on the synergy, self-organization and 3E (Energy-Economy-Environment) effects of urban energy system.

In the research of urban metabolic system, a very important task is to determine the key factors that dominate the energy metabolic pathways and processes. To identify these key factors, researchers have conducted a variety of analysis from different perspectives (Céspedes Restrepo and Morales-Pinzón, 2018; Rosales Carreón and Worrell, 2018). Using the network analysis, different levels from sectors to cities of urban metabolism (Fath and Killian, 2007; Zhang et al., 2010, 2011) were analyzed to figure out the structure and function of urban energy system, which assist the optimization of urban energy system. But there do exist improvements in this method because most of the current associated ecological network analysis were carried in a static perspective. Thus, to reach more accurate and detailed insights on the interactions within the system, a more systematic and dynamic approach is required.

This paper tries to identify the factors that dominate the urban energy metabolic processes, especially from the time scale. Based on the explanation of system theory, the urban metabolic system is more that the agglomeration of energy metabolic processes, the interactions and the effects between these processes should also be considered, which is known as the synergy effects. Thus, the key problem lies in the synergistic effect among the urban energy metabolic processes. According to Haken's synergy theory (Wang and Zhang, 2014), the synergistic effects are the results of nonlinear interaction mechanism within the system. Researchers have conducted a series applications of Haken model in investigating the socioeconomic system (Ye et al., 2016; Yan et al., 2014). Based on Haken's explanation, by identifying the dominant element, or order parameter, this mechanism can be described. Based on Haken's theory, researchers have conducted a range of complex system analysis using Haken model (Guo et al., 2005; Wu et al., 2009).

In this paper, we developed a model that integrate Haken model in the urban energy metabolism analysis and analyzed Beijing's energy statistics in 2010–2015. To accomplish this integration, key energy producers and consumers of Beijing's energy system are identified. By defining the pathway and structure of Beijing's energy system, the metabolic processes within the system are described and various energy flows to different sectors are illustrated. Then, these flows are converted into unified basis using emergy analysis method. Based on Leontief method, we accounted for the backflows and hidden flows within the system to calculate their cumulative effects of urban metabolic process. At last, the discretized Haken model is embodied into the Beijing's metabolic system to find out the order parameter that dominates the evolutionary process of Beijing's energy system.

2. Defining the framework of urban energy metabolic system

2.1. Components of urban energy metabolic system

Metabolic components are basic independent units of the urban energy system. In the course of urban energy metabolism, these components are divided into four sectors according to their features: 1) the exploit sector; 2) the conversion sector; 3) the enterprise sector; 4) the household sector. Every of these sectors consists of many subsectors that share the same function location on the metabolic process. Subsectors are independent with each other under the same sector but can be connected with those under different sector. Similarly, each subsector can be divided into sub-subsectors.

Using this method, the urban energy system can be decomposed into elements that have the basic input and output of energy flow. The advantages of hierarchical structure are, because there is no intersector between flows under an identical sector, the total inflow and outflow of energy of a certain sector can be represented as below:

$$i_s = \sum_{i=1}^{n} f_i$$

$$j_s = \sum_{i=1}^{n} f_i$$

where i_s is the input of sector s, and j_s is the output of sector s, f_i is the energy inflow or outflow of subsector i under sector s, n is the number of subsectors under sector s.

2.2. Structure of urban energy metabolism

The structure of urban energy metabolism can be described with network graph in Fig. 1. In this graph, a node represents a sector and an arrow denotes a directed energy flow. A sequence of nodes and arrows constitutes an energy metabolic pathway. A pathway emerges where two nodes share an relationship of supply & demand or other transaction of energy. Because the network is a directed graph, there may exist many pathways or no pathway between two nodes, which means nodes among the network may have 0, 1 or many connections with each other.

The ef_{ij} denotes the direction of energy flow between two sectors, that is from sector i to sector j. Based on Fig. 2, the energy flow within the system can be calculated as below:

$$Ti_s = i_s + \sum_{m=1}^{n} ef_{ms}$$

$$To_s = j_s + \sum_{n=1}^{n} ef_{sn}$$

where Ti_s is the total inflow of sector s, and To_s is the total outflow of sector s, ef_{ms} is the energy inflow from sector m to sector s, and ef_{sn} is the energy outflow from sector s to sector n.

The Ti_s and To_s can be taken as equal when the energy system is steady. Thus, $To_s = Ti_s = T_s$. Thus, we can build the energy flow matrix of the system (ef_{mn}) and the total inflow/outflow matrix