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Dynamic input-output analysis for energy metabolism system in the Province of Guangdong, China

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ABSTRACT

The development of human society is inseparable from energy. The exploration of urban energy metabolism plays an essential role in improving sustainable development. Combing input-output analysis with ecological network analysis help academics to shed light into the complicated system interactions and interior energy flows. In this study, using Guangdong as a case study, the Energy Ecological Network model is developed to account for the intensity of the embodied energy consumption using monetary input-output tables from 2000, 2002, 2005, 2007, 2010, and 2012. Sectors and energy flows are treated as nodes and paths to compile the corresponding physical input-output tables, which can facilitate a more comprehensive and balanced understanding of urban energy consumption by integrating various accounting perspectives. In detail, network control analysis is extended to reveal inter relationships and relative contribution rate of each sector. Network utility analysis gives an overall consideration of the dynamic changes in energy metabolism relations from multiple perspective. Furthermore, the modified robustness method penetrates into how each sector affects the stability of the system. The results show that the energy metabolic level in Guangdong is relatively low and indirect flows are the key to improving the system efficiency. The advanced manufacturing (AM) sector relied on other sectors in energy trade and have limited reciprocal relationships in the study period. Therefore, it is urgent to adjust the external structure and internal circulation of AM sector. The comprehensive dynamic analysis will give a scientific support to guide the development of energy reform in an attempt to promoting healthier development of energy metabolism system.

1. Introduction

There has been an increasing energy demand in the world due to the development of urbanization, rapid economic growth and population growth (Wang and Chen, 2016). Approximately 70 percent of the energy consumption and carbon emission are caused by activities in urban areas (Hoornweg et al., 2012). Cities are considered as a source of environmental problems and the key to the global sustainable development. China's 13th 5-year plan predicts an urbanization rate of 60 percent by 2020 (SCC, 2014), which may further increase the eco-environmental pressure and break the current of energy supply and demand equilibrium. Urban energy metabolism is the process of energy flowing into and out of the urban ecosystem, with complicated inter-departmental utility relations. By accounting for energy consumption in energy metabolism, it helps us understand how much energy we are consuming in different urban activities and what the performance may be in the future according to our requirement and technology (Mi et al., 2017). Thus, it is vital to study the urban energy metabolism and provide scientific basis for energy conservation policy-making.

The concept of urban metabolism has been introduced to provide an effective way to trace the social, economic and natural processes in cities and to link the emissions with consumption and transformation of raw materials (Zhang et al., 2015). It was initially proposed by Wolman in 1965 (Wolman, 1965) to establish the foundations of understanding urban metabolism development's effect on the external environment and vice versa. In detail, the metabolic flows such as nutrients, energy, water, and materials are considered in the metabolic processes. In the context of climate change, the importance of urban energy metabolism is increasingly

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Nomenclature

Notations

E	Embodied ecological energy element intensity
H	Value flow matrix
X_i	Economic output of sector i
f_{ij}	Energy flow from i to j
T_j	Total amount of flow through sub-sector i
z_j	Boundary flows of sub-sector j
$T_j^{(in)}$	Summation of energy flows in sub-sector j
$T_j^{(out)}$	Summation of energy flows out of sub-sector j
y_j	Outputs from the system into the environment
g'_{ij}	Nondimensional, input-oriented inter-compartmental flow
$\mathbf{G}'$	Matrix of input-oriented inter-compartmental flow
n'_{ij}	Dimensionless integral input flow
$\mathbf{N}'$	Matrix of dimensionless integral input flow
N	Matrix of dimensionless integral output flow
cn_{ij}	Ratio of integral energy flows from matrix N and N′
CN	Matrix of the ratio of integral energy flows from matrix N and N′
Y	Contribution weight of each component
F	Physical energy flow matrix
d_{ij}	Inter-compartmental flow utility
D	Matrix of dimensionless direct utility
U	Matrix of dimensionless integral utility intensity
a	Relative efficiency
R_{EEN}	Robustness of EEN model
$r_{i.}$	Ratio of flows originating from component i to total throughput
$r_{.j}$	Ratio of flows streaming into component j to total throughput

Greek letters

ε	Embodied energy element intensity
ε'	Embodied energy element intensity

Subscripts

i	Sectors of I-O table
j	Sectors of I-O table
$n \times n$	Matrix with n rows and n columns
$(m+s) \times n$	Matrix with $(m+s)$ rows and n columns

Acronyms

IOA	Input-Output Analysis
ENA	Ecological Network Analysis
I-O	Input-Output
EEN	Energy Ecological Network
GDP	Gross Domestic Product
diag	Diagonal Matrix
NCA	Network Control Analysis
NUA	Network Utility Analysis
IEI	Indirect effect indicator
IFCI	Integral flow control intensity
$\mathbf{IFCI^{in}}$	Input-oriented integral flow control intensity
$\mathbf{IFCI^{out}}$	Output-oriented integral flow control intensity
DIFCI	Direct integral flow control intensity
$\mathbf{DIFCI^{in}}$	Input-oriented direct integral flow control intensity
$\mathbf{DIFCI^{out}}$	Output-oriented direct integral flow control intensity
AMI	Average mutual information
H_C	Residual uncertainty
LPG	Liquefied Petroleum Gas
PRD	Pearl River Delta

recognized (Zhang et al., 2015). The energy metabolisms in Beijing (Zhang et al., 2010), Pairs (Kim and Barles, 2012), and Toronto (Bristow and Kennedy, 2013) have been investigated. Unfortunately, pre-studies began with black box model and subsystem models to focus on the risks of human health. Black box models described the overall inputs and outputs of a city and its activity intensity and scale to provide a macro-scale indicator (Zhang et al., 2015), while it neglected the flows within the system. In contrast, subsystems models reflected details of the flows among subsystems and the factors that affected these flows, while it meant the black box was "opened" to reveal its components (Zhang et al., 2015). Later an essential breakthrough was put forward to replace the black-box model. It involved the detailed models covering a network process for examining the inner workings of the urban systems (Zhang et al., 2009a). Examples of network models included an allometric scaling traffic network model (Samaniego and Moses M, 2008), an energy metabolic model (Zhang et al., 2009a) and a materials metabolic model (Z. Yang et al., 2014b).

Table 1 summarizes the methods used in the study of urban metabolism. Different accounting methods for energy consumption in cities have experienced the process of continuous evolution and improvement to better clarify the urban energy profile. Among all the approaches, input-output analysis (IOA) is an acknowledged method to distinguish the direct and indirect energy consumption for cities (Zhang et al., 2014c). It accounted for the embodied energy consumption required to produce goods in the city through an embodied ecological element intensity deriving from the sectoral interactions and exchanges with other economies (Liang and Zhang, 2012). Zhang et al. used this method to determine the embodied energy consumption and associated carbon footprints of sectors in Beijing (Zhang et al., 2014b). Rosado et al. used Lisbon as a case study to show that the relevance of the embodied energy in the household consumption and allow the identification of groups of products that were responsible for the most embodied energy consumed (Haberl, 2006). This method is also suitable for the study of energy metabolism in urban agglomerations. For example, Zhang et al. calculated the energy flow processes in Beijing-Tianjin-Hebei urban agglomeration and the results showed that Hebei had the largest embodied energy consumption, with Beijing coming second (Zhang et al., 2016). However, this approach cannot specify the energy consumption and complicated ecological relationships implied in the production and exchange of intermediate products (Chen et al., 2013).

In addition to IOA, the ecological network analysis (ENA) has also been applied to urban energy analysis. It can holistically assess the structure and function of an urban system (Wu et al., 2016). Thus, ENA was applied in material-flow analysis to simulate the structural distribution of ecosystem components and the interrelationships among trophic levels (Hannon, 1973). Shaikh et al. evaluated the stability of natural gas supply in China and found that increasing the investment in the upstream natural gas production sector can reduce the import requirements (Shaikh et al., 2016). Small et al. constructed and analyzed a nitrogen model for Lakes Superior, Huron and Erie to examine the ultimate source of the N removed via denitrification within each lake (Small et al., 2014). In the flow-based ENA, network control analysis (NCA) and network