https://doi.org/10.1016/j.jclepro.2020.123403

A bibliometric review of urban energy metabolism: Evolutionary trends and the application of network analytical methods

Miaohan Tang [a], Jingke Hong [a, b, *], Shan Guo [c], Guiwen Liu [a], Geoffrey Qiping Shen [d]

[a] School of Management Science and Real Estate, Chongqing University, Chongqing, 400045, PR China
[b] School of Management Science and Real Estate, Institute of Urban-Rural Construction and Development, Chongqing University, Chongqing, 400045, PR China
[c] Department of Land Management, School of Public Administration and Policy, Renmin University of China, Beijing, 100872, PR China [d] Department of Building and Real Estate, The Hong Kong Polytechnic University, PR China

Abstract

Urban energy metabolism reflects the energy transmission and exchange process to uncover the structure and functionality of urban activities. The literature on urban energy metabolism is overwhelming and still growing. However, few publications have attempted to provide a specific literature review of urban energy metabolism. Therefore, this study conducted a systematic bibliometric analysis on urban energy metabolism publications to explore research status and emerging trends. Results showed that the amount of co-cited literature on urban metabolism displayed an upward trend during the study period. After 2006, the number of urban metabolism publications implied an upsurge. Based on the co-word analysis of keywords, "energy" occupied much of the attention of urban metabolism research. The high citation keywords relating to network analytical methods in urban energy metabolism publications were analyzed via the co-word network, including ecological network analysis, input output analysis, and the complex network. The combination of input-output analysis and ecological network analysis has been widely applied to urban energy metabolism studies worldwide, especially in the context of China. Consequently, future research opportunities were suggested from the following aspects: (1) the inclusion of both spatial and temporal dimensions of energy metabolic systems, and (2) the ability to unravel the interactions of components in a dynamic manner. The findings of this study were not only beneficial for scholars to detail a holistic picture of current research progress, remained questions and emerging research methods, but also valuable to assist practitioners to evaluate and monitor the urban energy metabolic performance with suitable network methods.

1. Introduction

With the high speed of urbanization in recent decades, the population living in urban areas accounts for more than half of the global population and is expected to achieve approximately 90% in 2100 (Fragkias et al., 2013). Due to extensive and intensive human activities, cities have gradually become pivotal communities for energy and material exchange to an extent that has never before been seen. More than 70% of material resources and approximately 80% of global energy have been depleted with nearly half of the world's waste being produced within contemporary cities (Pulido Barrera et al., 2018). These activities inevitably exert interference over the environmental balance and are recognized over the sustained capacity of the earth (Pincetl et al., 2012). It follows that understanding energy and material interactions and causal process induced by the operation of cities is imperative if we are to achieve sustainability.

Urban metabolism (UM) originated from biology, which is widely used to describe the interactions and circulation of material and energy between internal urban bodies and external environments (Díaz-Alvarez et al., 2014). In this regard, it enables us to understand the drivers and mechanisms of urban activities and their functional properties. The first intellectual development of UM was from social metabolism in the economic theory proposed by Karl Marx (in Table 1), which is widely applied to gauge the potential relationships between society and environment. Thereafter, Wolman (1965) put forward the term UM to describe the environmental influence induced by the operation of cities and communities. Later, socioeconomic factors were introduced into the UM concept by Newman (1999). In the definition elaborated by Decker et al. (2000), UM is considered as a novel technology by which to uncover the interactions of energy, material, and carbon flows within the urban system (Li and Kwan, 2018). Kennedy et al. (2007) provided the definition of UM, by clearly covering the components and processes in an urban system, which established a comprehensive framework of UM analysis. From this perspective, urban is an integrated system which comprises the anthropic activities (e.g. political administration and market trading), resource

Table 1
Definitions of urban metabolism.\

Author (Year)	Definition
Marx (1887)	Social metabolism acts as an intermediary between the use and exchange of products.
Wolman (1965)	All the materials and commodities needed to sustain the city's inhabitants at home, at work and at play.
Decker et al. (2000)	Cities transform raw materials, fuel, and water into the built environment, human biomass and waste.
Kennedy et al. (2007)	The sum of total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste.

consumption (e.g. energy and materials), and urban infrastructure (e.g. land use and transportation), thus making it possible to quantitatively assess the metabolic performance of the urban.

Bibliometric analysis is a statistical and mathematical method by mapping the unheeded linkages of topics, publications, authors, and institutes in terms of existing literature (Portner, 2008€). Compared with conventional literature review, bibliometrics can identify the chronological characteristics of publications, intellectual structure, research directions, and leading topics within one research area from a more qualitative perspective (Du et al., 2013). Bibliometric analysis has been successfully applied in the urban area, such as urban resilience (Meerow et al., 2016), urban sustainable development (Fu and Zhang, 2017; Lehmann, 2011), smart city (de Jong et al., 2015), and resources consumption (Geng et al., 2017). Some UM publications conducted by bibliometrics have been gradually developed. Cui (2018) investigated a set of urban metabolic studies to analyze prevailing topics and relationships between sustainability and UM through the application of bibliometric technology. Newell and Cousins (2015) conducted a bibliometric analysis to detail the scholarly networks based on the 47 years of UM publications. Borrett et al. (2018) evaluated the research domains, methods, applications, and cooperators of the ecological network analysis (ENA) via systematically gauging coterm and co-authorship networks based on publications from 2010 to 2016.

Urban energy metabolism (UEM) tracks the process of energy exchanges, consumption and recycle between different components within an urban environment (Zhang et al., 2017). UEM can overcome the shortfall of incomparable metabolic flows by defining energy equivalents in accordance with standard conversion factors for all metabolic processes (Beloin-Saint-Pierre et al., 2017). Academic progresses of UEM have also been made for evaluating metabolic efficiency (Tan et al., 2019), simulating the metabolic process (Lee et al., 2009), comparing metabolic properties (Facchini et al., 2017; Velasco-Fernandez et al., 2015) and assessing environmental sustainability (Mellino and Ulgiati, 2015) in the past few decades. Although UEM publications cover different scopes, it is imperative to build a holistic literature review so that researchers in this field can detail the current research discipline. To date, few review articles related to UEM has been published. Voskamp et al. (2020) conducted a comprehensive overview on urban metabolism, including influence factors and their effects of energy and water consumption. Newell et al. (2019) suggested that urban metabolism provided a suitable boundary for food-energy-water nexus study based on a 40-year literature review. Most of them combined energy with resources to summarize general and overall metabolic properties, but rarely provide a systematic and specific literature review of UEM publications.

Against this background, this study seeks to summarize the chronological evolutionary trends, research hotspots, network analytical methods, current issues, and future research directions of UEM via bibliometric analysis, literature review and visualization method. Quantitative and qualitative analysis can help scholars better detail a network picture for current research progress and emerging topics in UEM field, allow them to understand current research interests, and provide a strategic diagram to urban energy metabolic practitioners.

The research roadmap of this study is presented in Fig. 1. This study firstly presented the process of keyword and document selection. Secondly, the thematic evolution and study hotspots of UM on the basis of co-citation and co-word network analysis were reviewed. Thirdly, special focuses on the accounting methods and network analytical methods applied in the UEM studies were presented based on the content analysis and co-word analysis. Finally, a content analysis to conclude current issues and future directions of UEM.

In light of this, the remainder of this paper is organized as follows. Section 2 introduces a description of bibliometrics followed by data compilation. Results of bibliometric analysis and future directions are presented in Section 3 and Section 4, respectively. Section 5 draws together a series of conclusions.

2. Methods and data compilation

2.1. Methods

Bibliometric analysis provides an overall structure of a specific research discipline by quantitively uncovering the distributed architecture of publications and research status (Persson et al., 2004). Citespace is regarded as an effective bibliometric analysis tool for statistical and visualizing relationships among publications, institutions, and authors on the basis of taking snapshots in terms of a certain study area (Chen, 2004). This tool thus supports researchers to build and analyze a vast body of networks, for instance, cocitation networks (reflecting the clustering features of publications via citation links and semantic similarities), co-word networks (detecting research domains in accordance with relationships between documents), and collaboration networks (capturing cooperation among authors or organizations) from scientific publications. Meanwhile, Citespace is also superior in the bibliographic data sources. This technique makes it possible to directly derive primary data from the Web of Science Core Collection which comprises full records and references, and is regarded as one of the most representative sources for the bibliometric analysis (Kamalski and Kirby, 2012). Therefore, this study applied the available open-source software program Citespace 5.3.R4 to portray the knowledge map of UEM studies. The software Gephi and CitNetExplorer were used to further visualization of bibliometric results.

2.2. Data sources

The input dataset of this study was retrieved from the Web of Science Core Collection (including the Science Citations Index and the Social Science Citation Index). It is comprised of a widely accepted corpus and the largest repositories of scientific publications. This study initially analyzed the general trends and research topics in the field of UM by reviewing relevant academic literature. This review was undertaken in accordance with search equation (TS¼ (“metabolism” OR “social metabolism” OR “metabolism flow” OR “social metabolism flow”)) AND (TS¼ (“urban” OR “city”)) from titles, abstracts and keywords, and yielded 596 results published from 1900 to 2018. After artificial filtering and excluding duplications, a total of 583 journal papers were extracted to bibliometrics for UM. Based on the former search items of UM, the search equation (TS¼ (“energy” OR “emergy” OR “exergy”)) AND (TS¼ (“metabolism” OR “flow”)) was further utilized to search the academic literature for UEM between 1900 and 2018. As a consequence, 465 publications related to UEM were identified from the Web of Science Core Collection. After excluding ineligible papers, 428 publications related to UEM were finally identified.

3. Results

3.1. General trends of urban metabolism studies

3.1.1. Co-citation analysis

To analyze the research progress and emerging topics of UEM profoundly, this study traced the evolution properties of UM studies on the basis of bibliometric analysis. Fig. 2 shows the cocitation network of UM from the studies undertaken between 1900 and 2018. The results showed that the number of co-cited literature displayed an increasing trend. More specifically, the density and size of nodes have enlarged markedly since 2006. In order to further uncover the temporal variations of UM studies, this study presents a knowledge evolution map with the help of CitNetExplorer (Fig. 3). By combining Figs. 2 and 3, it can be observed that only a few frequently cited papers existed before the node of Odum in 1996. After that, the number of nodes has increased significantly. Consequently, based on the findings of Figs. 2 and 3, three main stages can be identified; the nascent period (before 1995), the growth period (from 1995 to 2005), and the prosperous period (from 2006 to 2018). Table 2 summarizes the basic profile of urban metabolism studies from the aspects of study area, measurement method, indicator, and research topic in these three periods.

Applications of metabolism to urban studies can be traced back to the 1960s. In the nascent period, Wolman (1965) initiated the study of UM in a hypothetical America city to calculate the rate of input and output flows, and emphasized the possibility of calculating interactions between an urban system and its surrounding environment. This initial impulse led to an increase in the number of UM studies. During this phase, two accounting methods for UM, material analysis and emerge analysis, were proposed. Having first originated from the quantitative analysis of UM, material analysis has been widely applied within a broad range of cities worldwide, including Tokyo (Hanya and Ambe, 1977), Hong Kong (Newcombe et al., 1978), and Vienna (Baccini and Brunner, 1991). The emergy analysis proposed by Odum during the 1970s made it possible to quantify different types of flows by a unified type, thus it has been gradually applied in the field of UM studies. For instance, Zucchetto (1975) assessed the relationship between economic and natural systems in Miami by calculating 42 storage and emergy flows from an emergy perspective, whilst Duvigneaud and Smet (1977) examined the energy balance in the urban system of Brussels via quantitative analysis of environmental factors and human activities. Meanwhile, some papers that sought to elaborate upon the urban food metabolism were also published. Bohle (1994) initiated a metabolic analysis to assess food metabolism in developing countries. Above all, the focus of UM studies during this nascent period was not only on human activities but also on biological activities by evaluating the strength of metabolic flows; thereby revealing the relative integrated behavioral patterns of metabolic process in the urban system.

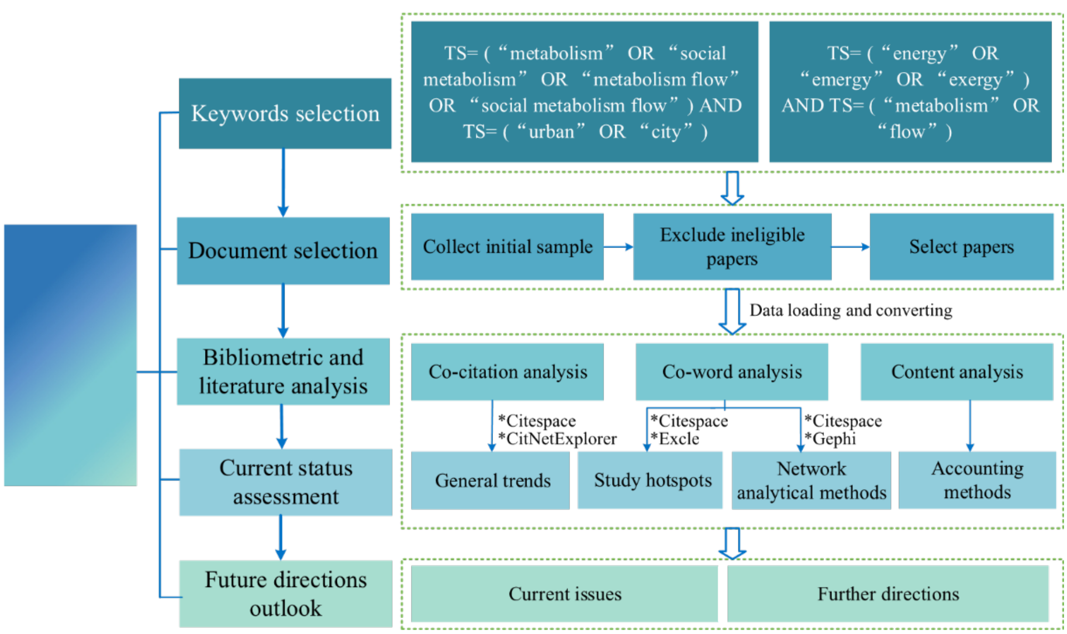

Fig. 1. Research roadmap of this study.

In the growth period, UM studies showed a relatively modest growth trend along with concern about urban sustainability. Huang et al. (1995) proposed ecological energetic analysis to evaluate both ecological economic status and the contribution of solid waste and water resources of the Taipei metropolitan region via a series of waste water indicators. Newman (1999) noted the importance of taking habitable indicators into account in UM and established a metabolism model containing livability indicators such as income, health, education, housing, and employment. This work facilitated the customization of the State of Environment Report in Australia and gave rise to the combination of UM with sustainability in the following studies. For example, Hendriks et al. (2000) detailed the differences of material metabolic processes between Vienna and Switzerland by comparing resources input and waste output. Warren-Rhodes and Koenig (2001) evaluated the ecosystem appropriation and environmental influence induced by resource use and waste discharges in Hong Kong with the help of an ecological footprint model. Sahely et al. (2003) analyzed the urban

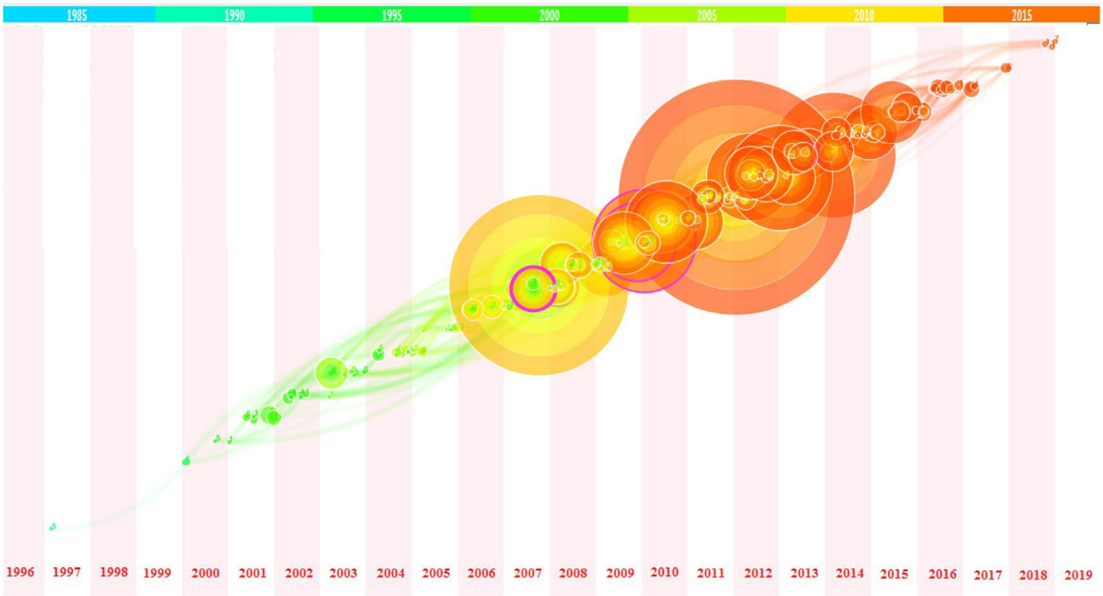

Fig. 2. Co-citation network of urban metabolism. Note: the size of a node displays the number of times a study has been cited; the position of a node indicates its publication year; the color represents the referred time of a specific publication by different studies. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

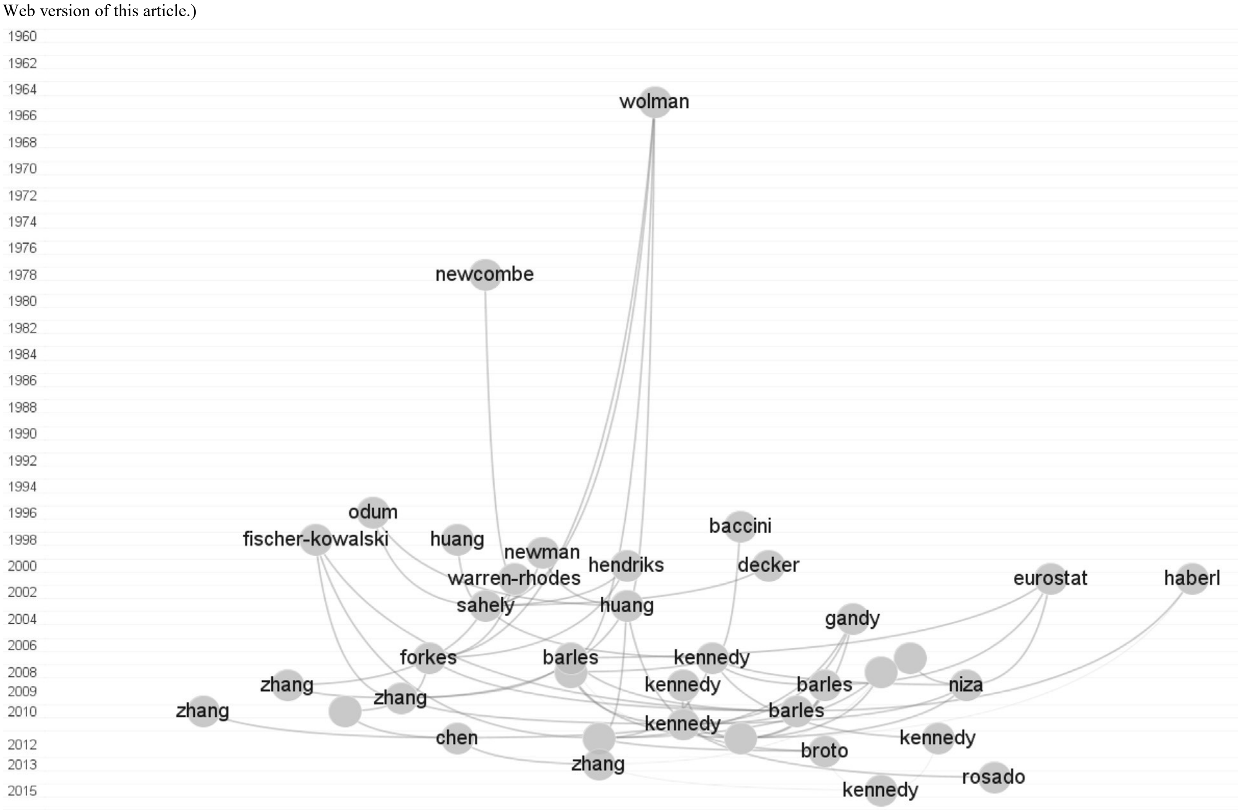

Fig. 3. Results of urban metabolism of time-span analysis.

material metabolism of a region in Canada and compared the material flows of a number of worldwide cities from a sustainable development perspective. A vast body of metabolism publications in the growth period concentrated on the urban ecological or environmental sustainability from a macro perspective, while failing to reveal how the mechanism of metabolic processes within cities.

Compared to the growth period, the co-cite literature in the prosperous period presented a higher concentration. There were several clear clusters; thus, it can be seen that there was an upsurge in research in the field of UM during this period. Moreover, the UM studies undertaken in this period were characterized by the fact that they opened the "black box" of the urban system (Cespedes Restrepo and Morales-Pinzon, 2018 ; Kennedy et al., 2011). To achieve this goal, complex mathematical algorithms, advanced simulation models, and large volumes of data have been gradually conducted to evaluate the performance of metabolic flow, and uncover inner structure properties and operation mechanism of an urban system. At the start of this phase, Kennedy et al. (2007) conducted a literature review to uncover the evolution of UM studies and then compared water, materials, energy, and nutrients flows of several cities to illustrate which key metabolic processes occupied important positions in urban sustainability. Pincetl et al. (2012) expanded the framework of UM by integrating policy and socioeconomic analysis in a quantitative manner. Venkatesh et al. (2014) evaluated the sustainability of urban water services and the influence of metabolic flow in the water system via the environmental, physical, functional, and economic indicators. Kennedy then went even further and accounted for energy and material flows through 27 megacities worldwide to evaluate energy consumption patterns and provided the strategy to achieve energy efficiency improvement (Facchini et al., 2017; Kennedy et al., 2015).

In this period, UM studies were also claimed to elaborate evolution patterns and regional properties of urban systems from systematic and dynamic perspectives (Han, W. et al., 2018; Velasco-Fernandez et al., 2015). For instance, Zhang conducted a series of urban metabolic studies upon carbon (Zhang et al., 2016a), water (Zhang et al., 2010), and energy (Zhang et al., 2016b) flows via network analytical methods (e.g. ecological network analysis, input-output analysis) to uncover the structural characters of UM. Pulido Barrera et al. (2018) developed a multi-level conceptual framework to analyze the roles of UM in the context of energy dynamics and validity from an ecological perspective. Li and Kwan (2018) summarized the common shortcomings of conventional urban metabolic methods and proposed a three-dimensional (3D) geovisualization to analyze spatial and temporal characters of UM. In summary, UM studies in the prosperous period put an emphasis on reflecting upon the mechanisms and the interconnections of UM in a dynamic and systematic way.

3.1.2. Co-word analysis of keyword

Keywords allow the tracing of research themes from academic articles. Fig. 4 presents the visualized co-word of UM. According to the top keywords, the three main scopes of UM publications can be summarized, namely study scale, environmental impact and management, and research methods. The frontier topics in the study scale include "urban", "city", "industrial", and "China". It is worth noticing that "China" holds a high position in the UM studies. One explanation is that China has caused high pressure on the surrounding environment due to the high-speed economic development in recent years. "Energy", "material", "nitrogen", "flow", "ecological network analysis", "input-output analysis", and "carbon" are main research methods for UM studies. More specifically, "Energy" holds the top position after "urban metabolism," "city"

Table 2
Chronological review of studies on urban metabolism.\

Period	Reference	Study area	Measurement method	Indicator	Research topic
Nascent period	Wolman (1965)	A hypothetical America city	The balance between matter and energy	Water and air pollution	The first originated study of urban metabolism; evaluate the rate of input and output flows in a hypothetical city
	Zucchetto (1975)	Miami	Emergy analysis	Select 42 storage and emergy flows; fossil fuel energy density, energy to money ratios, and ratio of natural to fossil fuel energies	Analyze the relationship between economic and natural systems by considering metabolic activities
	Hanya and Ambe (1977)	Tokyo	Material analysis	Construction materials, entrance and exit of goods, raw water, oxygen, and wastes	Account urban material flow and propose the reverse production system to solve environmental problems
	Newcombe et al. (1978)	Hong Kong	The balance between matter and energy	The inflow and its metabolic network within an urban system, capacity of natural and social circulatory systems	Measure the sustainability of a modern city via urban metabolism
	Bohle (1994)	Developing countries	The balance between food supply and consumption	Review the current state of urban food supply, food security, and social vulnerability	Conduct urban metabolism to detail the functioning and determinants of key food metabolic process
Growth period	Huang et al. (1995)	Taipei	Emergy analysis	Ratio of waste water to renewable emergy flow, ratio of waste water to total emergy used, and ratio of investment on solid waste treatment to total emergy used	Apply emergy theory to urban environmental management
	Newman (1999)	Sydney	Material analysis	Energy, food, water, solid waste, air waste, and human livability	Provide extended metabolism model by considering livability to evaluate the urban sustainability
	Hendriks et al. (2000)	Vienna, Swiss lowlands	Material analysis	Water, fossil fuels, and construction materials, consumer products, air, off-gas, sewage, consumer products, and solid wastes	Elaborate the urban material metabolism of Vienna; develop material management models for urban sustainable management
	WarrenRhodes and Koenig (2001)	Hong Kong	Ecological footprint	Food supply, food consumption, renewable resources consumption, nitrogen discharges, fossil fuel use, and water use	Assess the direct and indirect environmental impacts of Hong Kong from resource consumption and waste discharges
	Sahely et al. (2003)	Toronto	Material analysis	Food, water, energy, material, solid wastes, air emissions, and wastewater discharges	Unveil the overall fluxes of greater Toronto area based on the urban metabolism analysis
Prosperous period	Kennedy et al. (2007)	World metropolitan cities	Material analysis	Water, material, energy, and nutrients	Review urban metabolism studies and identify critical urban metabolic processes
	Venkatesh et al. (2014)	Oslo	Dynamic functional Metabolism Model	Environmental indicators, physical indicators, indicators, and economic indicators	Conduct a sustainability assessment of urban water services
	Zhang et al. (2016a)	Beijing	ENA	Carbon metabolic rates, carbon metabolic density, ecological relationships, and key flows	Illustrate spatial distribution, metabolic structure, and ecological relationships of urban carbon metabolism
	Zhang et al. (2016b)	Jing-Jin-Ji	MRIOA, ENA	Ecological relationships and ecological hierarchy	Detail energy utilization characteristics and

				ecological relationships among regions
Han et al., (2018b)	Shanghai, London, Tokyo, Paris	MuSIASEM	Exosomatic metabolic rate, economic labor productivity, social overhead of human activities, and energy efficiency	Compare the metabolic patterns of four global megacities
Liu et al., (2018)a	Saskatchewan	IOA, FEEIO model, and ENA	System efficiency, ecological hierarchy, redundancy, and robustness	Analyze potential benefits of urban GHG emissions metabolism system and uncover reduction pathways
Maranghi et al. (2020)	Beijing	Life cycle assessment, complex network	In degree, out degree, eigenvector, PageRank, and betweenness centrality	Evaluate the interconnections among urban sub-dimensions to reflect urban sustainability

Note: MuSIASEM ¼ Multi-scale integrated analysis of societal and ecosystem metabolism; IOA ¼ Input-output analysis; ENA ¼ Ecological network analysis; FEEIO model ¼ Factorial-based ecologically-extended input-output model; MRIOA ¼ Multi-regional input-output analysis.

and “sustainability”, indicating energy issues have occupied much of the attention of researchers. Turning to environmental impact and management, “sustainability”, “ecosystem”, “greenhouse gas emission”, and “management” are the frontier keywords.

3.2. Accounting methods of urban energy metabolism

3.2.1. Emergy analysis

Energy measurement types in the context of UEM can be further divided into emergy and exergy analysis (Beloin-Saint-Pierre et al., 2017). Emergy takes account of the physical flows and transformations induced by producing resources, economic goods, and services in a life cycle (Blondel et al., 2008). Emergy is defined as the invested energy utilized from primary solar radiation to the final produce activities. Solar emjoules (sej) is a unified unit of emergy for quantifying solar equivalent energy (Odum, 1995). According to the emergy theory, energy cannot be created or destroyed, but the quality of energy declines in the energy flow process through transformity. Emergy indexes, including renewable emergy, nonrenewable emergy, input emergy, and total emergy, are normally conducted to measure the performance of a specific urban metabolic process. Emergy flows are regarded as bridges that connect renewable and nonrenewable sources, as well as the natural system and the socioeconomic system during the urban metabolic process.

Emergy accounting has been widely utilized to analyze urban metabolic processes at the global (Brown and Ulgiati, 2016), national (Ghisellini et al., 2014), urban (Fan et al., 2018; Qi et al., 2017), and neighborhood (Zhang and Chen, 2017) levels. In practice, however, this accounting method faces lacks transformity data. This deficit gradually impedes the application of emergy analysis in UM studies (Brown and Ulgiati, 2010). To address this issue, emergy accounting can be improved by thermodynamic input-output analysis (IOA) to obtain emergy-to-money ratios from a sectoral perspective (Ukidwe and Bakshi, 2007). Chen et al. (2010) proposed a biophysical balance modeling with the help of an input-output table (IOT) to measure embodied resources and emissions in the context of the Chinese economy. This provided a methodological foundation for obtaining transformation data. However, a significant challenge for emergy accounting method still exists; namely, that it needs to converse multiple energy sources into a unified unit by considering their spatiotemporal properties (An et al., 2015).

3.2.2. Exergy analysis

The concept of exergy derived from thermodynamics has been utilized to assess the maximum amount of available energy consumed during a productive process (Rosales Carreon and Worrell, 2018). This form of energy exhibits the amount of real used up part that cannot be conserved. As a result, it follows, that the volume of exergy is always lower than it entering the urban system (Eisenmenger et al., 2017). According to the concept of the second law of thermodynamics, the wasted fraction always occurs in the process of transformation or, to put it another way, improving the performance of exergy is actually a process of decreasing wasted fraction. Exergy has been conducted to evaluate the efficiency of natural resource within the urban metabolic system, and this has also enabled us to gained insights into resource supply and reclamation (Bühler et al., 2016; Stylos et al., 2018), and the efficiency of resource management (Ravalde and Keirstead, 2017). More recently, exergy analysis has been applied to uncover the dynamic properties of the exchange of resources flows in economic activities from a historical perspective (Brockway et al., 2015; Chen et al., 2014). In these studies, exergy puts forward appropriate metrics to establish a common measurement of metabolic flows, which thence provides more information as to the amount of available energy. In summary, this technology can be applied to diagnose the dysfunction of energy metabolic processes and uncover the mechanisms of the urban system.

3.3. Co-word network of urban energy metabolism

In order to identify the hotspots in the UEM corpus, this study built the keywords co-occurrence network on the basis of Gephi software (Fig. 5). Meanwhile, this study presents the highfrequency keywords after combining and deleting similar and insignificant items. Table 3 shows the top 30 keywords by use frequency in the period 1900 to 2018 within the 428 publications. The keywords fall into 3 main groups; research objectives, study area, and research methods. The research objectives of UEM include societal sustainability assessments, energy efficiency evaluations, environmental impact assessments, metabolic flow accounting, and measurements of resource use. Energy metabolism studies were conducted on multiple scales, including global, national (especially China), urban, and communal levels. Turning to the research methods, several high citation keywords relating to network analytical methods are identified, including ENA, IOA, the social-economic-nature complex ecosystem (SENCE), and the complex network. Network analysis is a widely accepted research method in UEM studies by providing systematic and dynamic perspectives (Dai et al., 2012). Network structure has the merits of elaborating the complex structure of UM systems by projecting its structural patterns and inner connections through links (Gao et al., 2018; Zhang et al., 2011). Therefore, reviewing network analytical methods is necessary for UEM studies.

In the SENCE theory, the metabolic process can be described as a complex network that consists of a series of multiple factors derived from social, economic, and natural systems (Wang et al., 2011a; Yao et al., 2015). This study thus treated SENCE as a part of complex network analysis. The following section introduces key network analysis in UEM studies from three aspects; IOA, ENA and complex network analysis.

3.4. Network analytical methods for urban energy metabolism

3.4.1. Input-output analysis

As shown in Table 3, IOA takes the second position in terms of

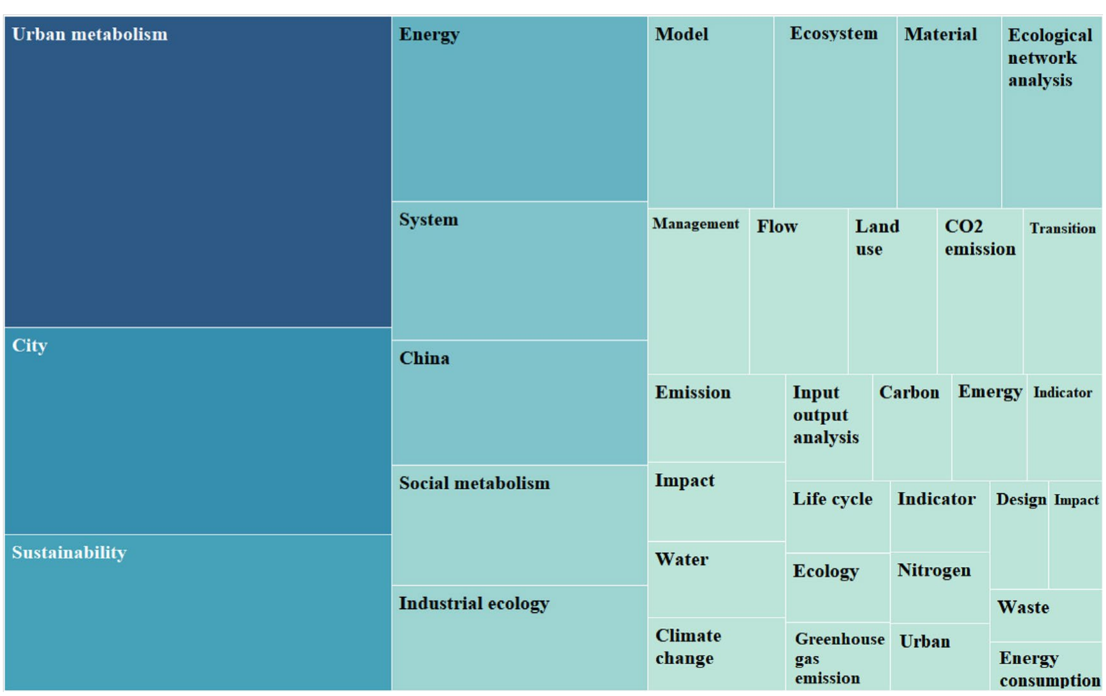

Fig. 4. Co-word analysis of keywords in UM research.

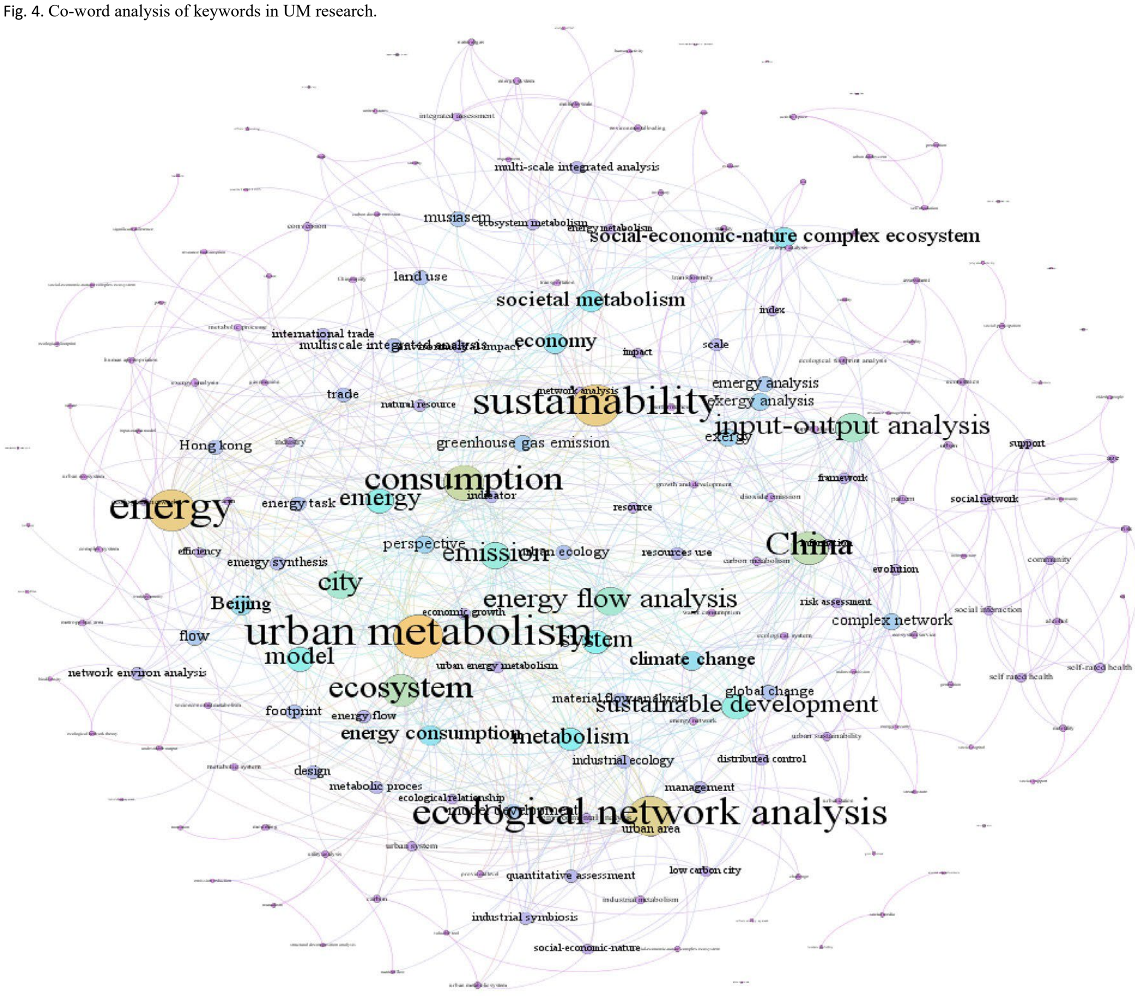

Fig. 5. Combined frequency and centrality of keywords during the entire investigation periodNote: The size of the node represents the frequency and centrality. The color represents a group of nodes based on their frequencies and centralities. . (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Top 30 keywords with co-occurrence analysis.\

Rank	Keywords	Frequency	Rank	Keywords	Frequency
1	Urban metabolism	222	16	Climate change	193
2	Energy	221	17	Beijing	191
3	Sustainability	220	18	Exergy analysis	190
4	Ecological network analysis	219	19	Complex network	189
5	Consumption	214	20	Urban ecology	188
6	China	213	21	Multi-scale integrated analysis	184
7	Ecosystem	211	22	Land use	183
8	Input-output analysis	207	23	Metropolitan area	182
9	Energy flow analysis	206	24	Global	181
10	City	205	25	Efficiency	180
11	Emergy	198	26	Growth and development	179
12	Societal metabolism	197	27	Model	178
13	Social-economic-nature complex ecosystem	196	28	Impact	177
14	Economy	195	29	Environmental analysis	176
15	Energy consumption	194	30	Community	175

network analytical methods. IOA examines the cumulative resource requirements and environmental impacts according to the input and output relationships that exist between various industrial components at the macro level (Hong et al., 2016). IOA, with consideration of region-specific characteristics, can be split into single-region input-output and multi-regional input-output (MRIO) analysis. The former is restricted by ignoring spatial disparities, while the latter allows for investigating regional characteristics in energy interactions (Tang et al., 2019). As a consequence, MRIO has been widely applied in energy metabolism research. Meanwhile, the IOT is regarded as the foundation of IOA, which could present all infinite interdependencies among sectors in the forms of monetary flows. In order to further reflect physical reality, the physical IOT is developed with the physical flows as a basic measurement unit; this is dominant in the existent literature which focuses on energy metabolism (Alcantara and Padilla, 2003). Consequently, by providing a highly integrated data on the basis of IOT, this method makes it possible to quantify energy metabolic flows at the sectoral and regional levels. IOA has been extensively used to analyze energy metabolic processes around the world (Bagheri et al., 2018; Kennedy and Bachmann, 2017). Most of these studies have focused on the practical application of IOA in energy accounting (Pan et al., 2018), energy distribution (Kucukvar et al., 2018; Wu and Chen, 2017), and energy utilization (Guevara and Domingos, 2017; Liu et al., 2018). There are only a few research for theoretical developments. For instance, Liang et al. (2010) performed a regional energy metabolism accounting by proposing a Hybrid Physical input-output model in hybrid units. Rocco and Colombo (2016) proposed a bioeconomic input-output model with the consideration of human labor in energy analysis. With the extension of investigated resources, the IOA method has also been applied to illustrate the coordinated relationships that exist between energy and other flows, including food-energy (Xiao et al., 2019), and energy-water (Wang et al., 2017; Yang et al., 2018); within such studies attention has been drawn to the co-benefits that may accrue from resource conservation and security (Fang and Chen, 2018). IOA provides insights on discovering the mechanisms of UEM, while failing to elaborate upon the characteristics of the internal network (such as network structures, the roles of components, and the exchange processes of energy flows within the urban system).

3.4.2. Ecological network analysis

ENA is the most frequently used method in network analysis for UEM studies according to the result obtained in this study. This technology, which is induced by graph and probability theory, can imitate the complex interactions of energy metabolism to uncover the robustness of an ecosystem with the help of substantial ecological parameters (Dai et al., 2012; Fath, 2007). The purpose of ENA techniques is to build an ecological network flow diagram consisting of network nodes and directed energy flows (the transfer of energy between nodes). Structure, nodes, and control analysis have been widely applied in ENA to evaluate ecological trophic levels, the property of components, and integral mutual relationships (Borrett et al., 2018). ENA provides an effective systemoriented means by which to analyze the ecological relationship between nodes in a quantitative manner on the basis of numerous data information (Zhai et al., 2018). The data sources in ENA studies can be divided into two major forms. The first originates from national or regional statistical books. Su et al. (2017) compared the national energy supply security from the database of the national statistical yearbook. Hu and Mu (2019) constructed an UEM system to depict the metabolic evolution properties based on time-serious inventory data collected from regional energy statistics. Zhang et al. (2010) analyzed the energy metabolic network structure and ecological relationships with statistical data of four Chinese cities. However, there exist difficulties in trying to build an energy matrix that allows the depicting properties of inflows and outflows among sectors based on statistical data. Furthermore, the database also fails to reflect indirect energy interactions. Given this background, the second form of data source for UEM studies is the IOT. Special concern has been paid to the conjunction of ENA and IOA, which has been widely applied to multiple scales, including countries (Sun and An, 2018), urban agglomerations (Zheng et al., 2018), and regions (Chen and Chen, 2015; Tan et al., 2018). In these studies, IOT is regarded as a major data foundation to elaborate upon direct and indirect energy information between nodes in the form of a matrix.

It is worth noting that IOA-based ENA has been widely used especially in the context of China. The empirical areas include Beijing (Chen and Chen, 2015), Guangdong (Zhai et al., 2018), BeijingTianjin-Hebei (Zheng et al., 2018) and so on. This may be due to the fact that the volume of energy consumption in China has sprung up in the last few decades whilst energy efficiency remains at a lower level (Xiong et al., 2019). ENA models can reflect the energy metabolic properties at the annual scale based on these macro statistical data, whilst they are restricted to uncover the network dynamic changes.

3.5. Complex network analysis

Human activities inevitably have repercussions on the UM due to a vast body of social and economic interactions (Grosskurth and Rotmans, 2005). It follows, that considering the human activities into the urban metabolic framework is critical. SENCE theory allows portraying the mechanism of metabolic interactions with considering multiple levels of the system from a holistic perspective. In this theory, the urban system is separated into multiple determinants, including natural, social, and economic subsystems. Against this configuration, a natural subsystem plays the role of a supplier providing natural resources and ecological services to support economic and social subsystems. Accordingly, natural, social, and economic subsystems include excessive exchange activities with the form of energy, material, and information (Wang et al., 2011b). In the context of the SENCE technique, an ecocomplexity network within urban metabolic activities can be built which includes two major analytical tendencies. One is the standardized quantitative analysis that prefers to describe the network in a unified form. For instance, Yao et al. (2015) proposed a standardized analytical network framework containing dominance, consistency, and sustainability levels to elaborate the regional biofuel metabolism. Wang et al. (2016) evaluated the regional sustainability of the Chinese Yellow River Delta using SENCE theory and emergy analysis as underlying methods. Along with the quantitative analysis, obtaining accurate and adequate data, and unifying standards among multiple subsystems are difficult for metabolic studies (Gentleman, 2009). The other analytical perspective, qualitative analysis, was proposed to address this problem by providing system-level information. SENCE theory also offers a qualitative insight into the Chinese traditional human philosophy that draws attention to the self-reliance and symbiosis that exists within a system.

In addition to SENCE theory, complex network has also been adopted in urban energy studies. Complex network technique disaggregates metabolic flows coming in and going out between different nodes within a specific system. This technique has the merits of describing the intricate processes, robustness, and resilience of a network through the application of a holistic and systematic angle (Chen et al., 2018). In addition, it allows for the examination and adjustment of different systematic structures and links by analyzing specific components and their interactions in the entire network (Hong et al., 2019). Different from ENA, the complex network technique draws attention to uncovering properties of the metabolic system from a social perspective. A wide range of studies focusing on the complex network technique have been conducted from multiple levels. At the global scale, previous studies drew attention to capturing primary international energy interactions during multilateral trading processes (Chen et al., 2018; Shi et al., 2017). The national studies mainly focused on exploring the roles of regions or sectors in energy transfer systems (Sun et al., 2016; Tang et al., 2019). Regional level studies were conducted to compare properties of energy consumption among different urban scales (Chen and Chen, 2015; Gao et al., 2018). Furthermore, previous

Table 4
Overview of urban energy metabolism studies.\

References	Research topic	Measurement method	Indicator	Scale	Study period	Data sources	Question remained
Zhang et al. (2009)	Compare the urban metabolic properties of four Chinese cities	ENA, emergy analysis	Metabolic length, metabolic pathways, utility intensity matrix, mutualism index	City	2004	BSY, Shanghai Statistical Yearbook, TSY, Chongqing Statistical Yearbook	Improve the accuracy of ENA results in the process of simulation
Lee et al. (2009)	Simulate the spatial dynamics of socio-economic metabolism	Emergy analysis, GIS	Land use change, socioeconomic metabolic flows	City	1971e2005	GIS maps, research and survey, statistic data	Consider more multi-scales factors for developing spatial system models
Dai et al. (2012)	Detail the interrelationship among industrial sectors of the social-economic system	Extended exergy analysis	Resource exergy efficiency metrics, exergy output/input efficiency, social economic exergy proportion metrics	National	2007	SRIO table	Evaluate the long term ecological impacts on the social-economic system
An et al. (2015)	Evaluate the embodied exergy properties of Chinese industries	Exergy analysis, IOA, complex network	Network density, network connectedness, degree, betweenness centrality	National	2007	CESY, CSY, China Industry Economy Statistical Yearbook	Track the dynamic evolution properties of the exergy network
Zhang et al. (2015)	Analysis direct and indirect energy flows among regions	IOA, ENA	Utility intensity matrix, centers of gravity	National	2002, 2007	MRIO table, CESY	Collect energy consumption data in a longer period; reflect recent energy consumption status
Chen and Chen (2015)	Compare three methods for urban energy consumption accounting	IOA, ENA, Energy flow analysis	Control allocation, dependence allocation	City	2007	IOT of Beijing, BSY	Combine land use and infrastructure planning with energy metabolic accounting
Velasco-Fernandez et al. (2015)	Compare the energy metabolism of China and India	MuSIASEM approach	Energy consumption per capita, economic energy intensity, energetic metabolic rate, economic labor productivity	World	1971e2010	IEA, CSY, OECD	Broaden the study scale of energy metabolism
Mellino and Ulgiati (2015)	Analyze the environmental worth and quality of lands	Emergy analysis, GIS	Impervious surfaces, the percentage of imperviousness	Regional	1990e2006	CORINE Land Cover database, NASA	Combine landscape metabolism with environmental planning and management

Bristow and Kennedy (2015)	Analyze city growth from the thermodynamic perspective	Exergy analysis, thermodynamics	Energy intensity, urban and rural population	City	1965e2010	United Nations Statistics, IEA	Develop nonequilibrium thermodynamic models to analyze city growth; examine interactions of exergy flows among cities
Wang et al. (2016)	Measure regional sustainability	Emergy analysis, GIS, a socialeconomic-natural approach	Net primary productivity, emergy indicators of social, economic, and natural subsystems	City	2009	Dongying Statistical Yearbook, China's River Sediment Communique, U.S. National Aeronautics and Space Administration	Analyze the changes of regional sustainability
Zheng et al. (2017)	Evaluate direct and indirect energy flows among sectors in three regions	IOA, ENA	Utility intensity matrix, embodied energy efficiency	City	2002, 2007	MRIO tables, CESY	Collect small-scale data
Su et al. (2017)	Evaluate security levels of energy supply	ENA	Indirect effects, coefficient of variation, synergism index, mutualism index	National	2000e2012	CESY, Statistical Yearbook of Chinese Customs, BP world energy statistics	Integrate other influencing factors; conduct the multi-scale study; data availability
Wang et al. (2017)	Balance urban energy consumption and water use	IOA, emergy analysis	Emergy to money ratio, emergy intensities	City	2012	BSY, CESY	Detail historical changes and drivers of energy consumption
Facchini et al. (2017)	Compare the energy metabolism properties of the world's megacities	Energy flow, a multi-layered indicator framework	Urban population density, energy consumption	City	2010	Local statistical resources, the World Bank, Hoornweg and Freire (2013)	Explore inner relationships between energy flows and the urban metabolism system; combine study results with urban sustainability
Rocco et al. (2018)	Analyze the energy metabolism of World economies	IOA	Energy efficiency hotspots	National	2013	Eora26 Database, IEA	Assess economic and environmental effects by more sophisticated models
Hu and Mu (2018)	Investigate key factors that dominate the evolution of urban energy metabolism	ENA	Metabolic inflows and outflows	City	2010e2015	Beijing Energy Statistical Yearbook	Expand time span and study scale; collect temporal energy flow for continuous data

Hao et al. (2018)	Evaluate regional energy metabolism and ecological relationships among sectors	ENA	Utility intensity matrix	City	2002, 2007, 2010	CESY, CEAD, MRIO table	Extend study scale to the sectoral level
Sun and An (2018)	Evaluate Chinese sectoral ecological sustainability	IOA, emergy analysis, complex network analysis	Sectoral centrality, EYR, ESI, ELR	National	2012	SRIO table, CSY, CES, China Industry Statistical Yearbook, Chinese Rural Statistical Yearbook, BSY, TSY, Hebei Economic Yearbook	Obtain sector-specific resource data
Huang et al. (2018)	Evaluate stocks, flows and drivers of an urban metabolic system	Emergy analysis, system dynamics	Total emergy input, emergy intensity, emergy density	City	2015 e		Get micro data, such as household demand; evaluate interrelationships among metabolic elements
Tan et al. (2019)	Assess resource utilization in the urban metabolic system	Exergy analysis, ENA	Effectiveness of utilization, effectiveness of conversion, exergetic efficiency, exergy intensity	National	2005, 2007, 2010, 2012, 2013, 2014, 2030	Singapore Department of Statistics, Energy Market Authority, Agri-Food and Veterinary Authority	Apply dynamical systems modeling to evaluate temporal evolution of the system behaviors
Fan and Fang (2020)	Evaluate the urban metabolic patterns and sustainability	Emergy analysis	EYR, ELR, ESI, EIR	City	2005 e 2017	Qinghai Statistical Yearbook, Xining Statistical Yearbook, China Urban Construction Statistical Yearbook, government report, interviews	Consider geographical factors and human activities

Note: CSY ¼ China Statistical Yearbook; IOA ¼ Input-output analysis; SRIO ¼ Single-region input-output; MRIO ¼ Multi-regional input-output; CESY ¼ China's Energy Statistical Yearbook; MuSIASEM ¼ Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism; GIS ¼ Geographic Information System; IEA ¼ International Energy Agency; OECD ¼ Organization for Economic Cooperation and Development; BST ¼ Beijing Statistical Yearbook; TSY ¼ Tianjin Statistical Yearbook; CEAD ¼ China Emission Accounts & Datasets; EYR ¼ emergy yield ratio; ESI ¼ emergy sustainability index; ELR ¼ Emergy load rate; EIR ¼ emergy import rate.

energy transfer publications also unraveled the energy trade relationship by considering the process on the whole energy supply chain, from inflow and outflow perspectives, which is similar with the metabolic process. Based on the bibliometric results in Table 3, the complex network technique is in the lowest position compared to IOA, ENA, and SENCE. Thus, this technique could potentially be applied to the urban energy metabolic system to assess key nodes and flows, and uncover the inner mechanisms of the energy transfer system.

4. Discussions

4.1. Issues on urban energy metabolism studies

Following the bibliometrics and content analysis of UEM studies, this study made an in-depth investigation of several representative research to analyze the current knowledge gaps. Table 4 and Fig. 6 summarize the properties, gaps, and future directions of UEM. Current research objectives of network analytical methods in UEM publications can be summarized from four parts, including descriptive analysis, comparative analysis, exploratory analysis, and optimization analysis. Descriptive analysis focuses on unraveling inherent properties of the metabolic network; comparative analysis devotes to detail metabolic differences among urban energy systems; exploratory analysis draws attention to how metabolic system operation; optimization analysis enhances the performance of UEM system. However, most of these publications have provided a snapshot of UEM from the temporal scope, while ignoring the inherent spatial properties. Some studies expanded time span by combined spatial phenomena, such as land use, with energy metabolic process. They rarely reflected comprehensive spatial and temporal factors into urban energy metabolic frameworks. From a temporal perspective, energy metabolism has been investigated based on annual performance with the macro statistical data. These data sources can portray static energy metabolic flows but fail to evaluate dynamic changes. Several studies pointed out that dynamic evolution properties of UEM needed to be considered in further study (Hu and Mu, 2018; Li and Kwan, 2018). Energy interactions gradually become more interconnected and highly dynamic due to the frequent exchanges of commodities and services that takes place among regions. Ignorance of these characteristics may cause an accounting blindness which, in turn, misinterprets the results of energy metabolism studies. Therefore, integrating geographical and dynamic characteristics into urban energy metabolic framework is imperative if one wishes to obtain a clearer metabolic map that supports urban management by the government. Network analysis of UEM in the future need to contain the following two aspects: (1) the inclusion of both spatial and temporal dimensions of energy metabolic systems, and (2) the ability to unravel the interactions of components in a dynamic manner. Based on this, the following part proposes analytical methods that could be used in future metabolic studies.

4.2. Further directions

4.2.1. Spatiotemporal network analysis

Conducting a spatiotemporal investigation is important in UME studies and, therefore, a network framework should be developed in a more integrated manner. GIS can be applied to integrate metabolic processes with spatiotemporal information. Based on the technique of GIS, the energy metabolic flows can be detailed in a map with transparent geographical information. This technique can be combined with metabolic flows to reflect spatial properties in urban infrastructure construction studies. However, GIS is only capable of providing land information but fails to reflect the

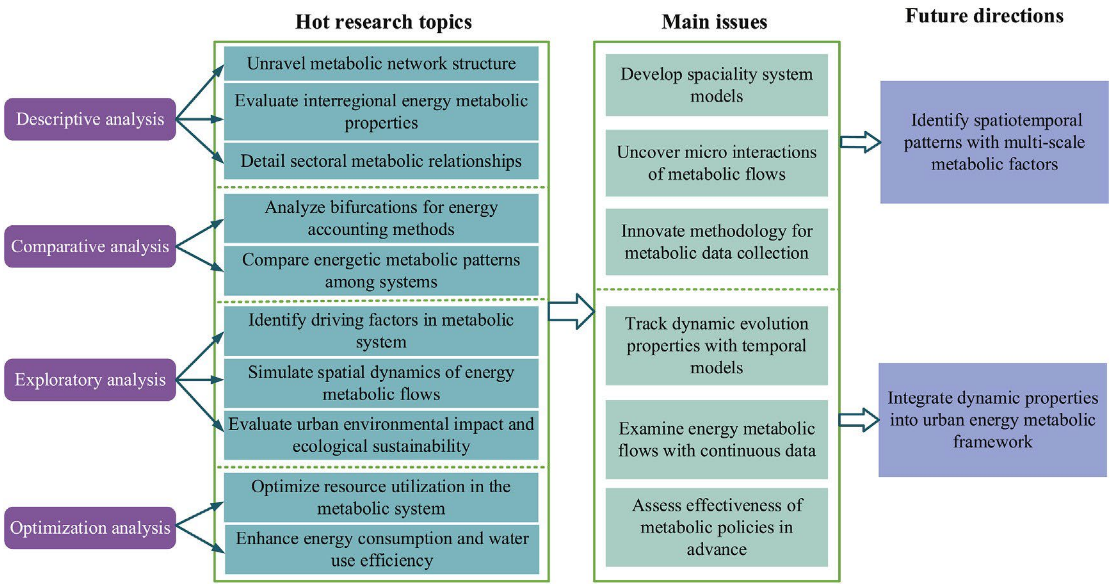

Fig. 6. Future research directions for urban energy metabolism.

temporal trajectory of a specific metabolic process (Han et al., 2018; Zhao et al., 2018). To conduct an in-depth analysis of urban metabolic mechanisms from temporal and spatial perspectives, MeiPoKwan (2012) developed a 3D space-time conceptual framework based on GIS, which consists of a series of thematic layers that include geographical maps and time slices. In the UEM context, a 3D geovisualization framework can facilitate energy metabolic networks to reveal dynamic spatial trajectories along with the axes of time and landscape. Particularly, spatiotemporal metabolic networks can be visualized to clearly reflect the density of metabolic flows on a geographic map (Li and Kwan, 2018). GIS can provide insights with regard to the geovisualization of UEM and, from that, it is possible to clarify the relationships that exist between economic activities and geographic characteristics. In addition to reflect spatial information, a spatiotemporal framework also enables the tracing of energy flows transmissions through the upstream supply chain at the industrial level. However, integrating GIS with network analytical methods faces a number of issues with regard to the availability, accessibility, and compatibility of data. Energy metabolic processes are directly and indirectly correlative with human activities, weather conditions, and economic levels; these comprise a large volume of complex data sets. According to Table 4, data sources of current UEM publications mainly obtained from aggregated national accounts. Lack of data on metabolic flows is one of the difficulties in current UEM studies (Su et al., 2017; Velasco-Fernandez et al., 2015). Big data provides an effective platform to obtain massive data for analyzing such a corpus and has been applied in the urban metabolism area. Shahrokni et al. (2015b) noted that smart-city technologies have the potential to be applied in urban metabolism to provide real-time and high resolution data. Later, Shahrokni et al. (2015a) conducted an empirical analysis based on the smart urban metabolic framework and information and communication technology. Yeow and Cheah (2019) used big data technology to obtain freight transport data for understanding material flows. In the future study, how to mine, integrate and use the dataset through big data analytics to support further UEM studies remains challenging.

4.2.2. Dynamic network analysis

Metabolic interactions within the urban system have dynamic characters that are constantly changing natural, social, and economic factors between city actors along with time. Dynamic network analysis makes it possible to unravel metabolic interactions among components. Computable general equilibrium (CGE) models arising from IOA allows the tracing of dynamic metabolic interactions containing a set of equilibrium equations from productive and consumptive perspectives in accordance with macroeconomic principles (Arto et al., 2019). CGE models have been widely applied to simulate energy emission and consumption on macroeconomic activities. Su et al. (2018) simulated and predicted dynamic relationships among urban energy, water and environment systems by a CGE-based integrated mode. Cao et al. (2019) combined CGE and dynamic material flow analysis to estimate the Chinese building stock under the socioeconomic metabolic framework. Pauliuk et al. (2015) proposed a general system structure of social-economic metabolism based on CGE model. Formulated in line with this, equilibrium equations can be built to elaborate dynamic inter-linkages within urban energy metabolic systems at the macro level. Furthermore, this analytical framework can provide additional insights into the potential impact of urban metabolic policy actions by assessing the feedback from the policy practice in advance. From the micro perspective, agent-based models (ABMs) can handle out-of-equilibrium dynamic problems by paying attention to agents (Semertzidis, 2015). The agents in the ABMs can be used to reflect the heterogeneity of components by considering multiple characteristics in the urban metabolic network. The behaviors of agents can be contextualized and imitated within the urban metabolic system by considering several alternative scenarios. Meanwhile, integrated network analysis methods with ABMs provide a decisive capability to incorporate uncertainty and can, therefore, be further used to simulate the urban energy metabolic activities.

5. Conclusion

In order to understand the status quo of urban energy metabolic studies and propose future directions, this study conducted a systematic bibliometric analysis based on the data from Web of Science Core Collection. The results revealed that urban metabolism publications could be divided into nascent, growth, and prosperous periods based on the number of co-cited literature. By conducting co-word analysis, the hot topics of urban metabolism have been summarized into three scopes, including study scale, environmental impact and management, and research methods. In particular, "energy" occupied much of the attention in urban metabolism research. The high citation keywords relating to network analytical methods in urban energy metabolism publications were analyzed based on the results of keywords cooccurrence network, including ecological network analysis, inputoutput analysis and the complex network. With the increasing of energy consumption and poor energy efficiency performance, more research attentions have been focused on Chinese energy metabolism by combining ecological network analysis with inputoutput analysis. Current research objectives of network analytical methods in UEM publications can be summarized from four parts, including descriptive analysis, comparative analysis, exploratory analysis, and optimization analysis. Though the literature review, future research directions for urban energy metabolic network analysis were suggested from two aspects: (1) the inclusion of both spatial and temporal dimensions of energy metabolic systems via Geographic Information System and big data; and (2) the ability to unravel the interactions of components in a dynamic manner based on the computable general equilibrium and agent-based models.

The main academic contribution of this study is to provide valuable insights into the knowledge of urban energy metabolism so that scholars can better understand current research progress, remained questions, emerging research methods and explore the research opportunities. Meanwhile, this study is also valuable for practitioners to evaluate and monitor the urban energy metabolic performance with suitable network methods.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors wish to express their sincere gratitude to the Fundamental Research Funds for the Central Universities (No. 2019CDSKXYJSG0041), the Natural Science Foundation of China (Grant No. 71801023), and Chongqing Science and Technology Commission (No. cstc2018jcyjAX0099) for funding this research project. Appreciation is also due to all members of the research team for their invaluable contributions.

References

Alcantara, V., Padilla, E., 2003. “Key” sectors in final energy consumption: an inputeoutput application to the Spanish case. Energy Pol. 31 (15), 1673e1678.
An, Q., An, H., Wang, L., Gao, X., Lv, N., 2015. Analysis of embodied exergy flow between Chinese industries based on network theory. Ecol. Model. 318, 26e35.
Arto, I., García-Muros, X., Cazcarro, I., Gonzalez-Eguino, M., Markandya, A., Hazra, S., 2019. The socioeconomic future of deltas in a changing environment. Sci. Total Environ. 648, 1284e1296.
Baccini, P., Brunner, P.H., 1991. Metabolism of the Anthroposphere. Springer Verlag, Berlin.
Bagheri, M., Guevara, Z., Alikarami, M., Kennedy, C.A., Doluweera, G., 2018. Green growth planning: a multi-factor energy input-output analysis of the Canadian economy. Energy Econ. 74, 708e720.
Beloin-Saint-Pierre, D., Rugani, B., Lasvaux, S., Mailhac, A., Popovici, E., Sibiude, G., Benetto, E., Schiopu, N., 2017. A review of urban metabolism studies to identify key methodological choices for future harmonization and implementation. J. Clean. Prod. 163, S223eS240.
Blondel, V.D., Guillaume, J.L., Lambiotte, R., Lefebvre, E., 2008. Fast unfolding of communities in large networks. Journal of Statistical Mechanics 2008 (10), 155e168.
Bohle, H.G., 1994. Metropolitan food systems in developing countries: the perspective of "urban metabolism. Geojournal 34 (3), 245e251.
Borrett, S.R., Sheble, L., Moody, J., Anway, E.C., 2018. Bibliometric review of ecological network analysis: 2010e2016. Ecol. Model. 382, 63e82.
Bristow, D., Kennedy, C., 2015. Why Do Cities Grow? Insights from Nonequilibrium Thermodynamics at the Urban and Global Scales. J. Ind. 19 (2), 211e221.
Brockway, P.E., Steinberger, J.K., Barrett, J.R., Foxon, T.J., 2015. Understanding China′s past and future energy demand: an exergy efficiency and decomposition analysis. Appl. Energy 155, 892e903.
Brown, M.T., Ulgiati, S., 2010. Updated evaluation of exergy and emergy driving the geobiosphere: a review and refinement of the emergy baseline. Ecol. Model. 221 (20), 2501e2508.
Brown, M.T., Ulgiati, S., 2016. Assessing the global environmental sources driving the geobiosphere: a revised emergy baseline. Ecol. Model. 339, 126e132.
Bühler, F., Nguyen, T.-V., Elmegaard, B., 2016. Energy and exergy analyses of the Danish industry sector. Appl. Energy 184, 1447e1459.
Cao, Z., Liu, G., Zhong, S., Dai, H., Pauliuk, S., 2019. Integrating dynamic material flow analysis and computable general equilibrium models for both mass and monetary balances in prospective modeling: a case for the Chinese building sector. Environ. Sci. Technol. 53 (1), 224e233.
Cespedes Restrepo, J.D., Morales-Pinzon, T., 2018. Urban metabolism and sustainability: precedents, genesis and research perspectives. Resour. Conserv. Recycl. 131, 216e224.
Chen, B., Dai, J., Sciubba, E., 2014. Ecological accounting for China based on extended exergy. Renew. Sustain. Energy Rev. 37, 334e347.
Chen, B., Li, J.S., Wu, X.F., Han, M.Y., Zeng, L., Li, Z., Chen, G.Q., 2018. Global energy flows embodied in international trade: a combination of environmentally extended inputeoutput analysis and complex network analysis. Appl. Energy 210, 98e107.
Chen, C., 2004. Searching for intellectual turning points: progressive knowledge domain visualization. Proc. Natl. Acad. Sci. U. S. A. 101 (Suppl. l), 5303e5310.
Chen, S., Chen, B., 2015. Urban energy consumption: different insights from energy flow analysis, inputeoutput analysis and ecological network analysis. Appl. Energy 138, 99e107.
Chen, Z.M., Chen, G.Q., Zhou, J.B., Jiang, M.M., Chen, B., 2010. Ecological inputeoutput modeling for embodied resources and emissions in Chinese economy 2005. Commun. Nonlinear Sci. Numer. Simulat. 15 (7), 1942e1965.
Cui, X., 2018. How can cities support sustainability: a bibliometric analysis of urban metabolism. Ecol. Indicat. 93, 704e717.
Dai, J., Fath, B., Chen, B., 2012. Constructing a network of the social-economic consumption system of China using extended exergy analysis. Renew. Sustain. Energy Rev. 16 (7), 4796e4808.
de Jong, M., Joss, S., Schraven, D., Zhan, C., Weijnen, M., 2015. Sustainable-smartresilient-low carbon-eco-knowledge cities; making sense of a multitude of concepts promoting sustainable urbanization. J. Clean. Prod. 109, 25e38.
Decker, E.H., Elliott, S., Smith, F.A., Blake, D.R., Rowland, F.S., 2000. Energy and material flow through the urban ecosystem. Annu. Rev. Energy Environ. 25 (25), 685e740.
Díaz-Alvarez, A.E., Francos, J., Crochet, P., Cadierno, V., 2014. Recent advances in the use of glycerol as green solvent for synthetic organic chemistry. Curr. Green Chem. 1 (1), 51e65.
Du, H., Wei, L., Brown, M.A., Wang, Y., Shi, Z., 2013. A bibliometric analysis of recent energy efficiency literatures: an expanding and shifting focus. Energy Efficiency 6 (1), 177e190.
Duvigneaud, P., Smet, S.D.-D., 1977. L′ecosysteme Urbain Bruxellois.
Eisenmenger, N., Warr, B., Magerl, A., 2017. Trends in Austrian resource efficiency an exergy and useful work analysis in comparison to material use, CO2 emissions, and land use. J. Ind. Ecol. 21 (5), 1250e1261.
Facchini, A., Kennedy, C., Stewart, I., Mele, R., 2017. The energy metabolism of megacities. Appl. Energy 186, 86e95.
Fan, Y., Fang, C., 2020. Evolution process analysis of urban metabolic patterns and sustainability assessment in western China, a case study of Xining city. Ecol. Indicat. 109, 105784.
Fan, J.L., McConkey, B.G., Janzen, H.H., Miller, P.R., 2018. Emergy and energy analysis as an integrative indicator of sustainability: a case study in semi-arid Canadian farmlands. J. Clean. Prod. 172, 428e437.
Fang, D., Chen, B., 2018. Linkage analysis for water-carbon nexus in China. Appl. Energy 225, 682e695.
Fath, B.D., 2007. Network mutualism: positive community-level relations in ecosystems. Ecol. Model. 208 (1), 56e67.
Fragkias, M., Lobo, J., Strumsky, D., Seto, K.C., 2013. Does size matter? Scaling of CO2 emissions and U.S. Urban areas. PloS One 8 (6), e64727.
Fu, Y., Zhang, X., 2017. Trajectory of urban sustainability concepts: a 35-year bibliometric analysis. Cities 60, 113e123.
Gao, C., Su, B., Sun, M., Zhang, X., Zhang, Z., 2018. Interprovincial transfer of embodied primary energy in China: a complex network approach. Appl. Energy 215, 792e807.
Geng, Y., Chen, W., Liu, Z., Chiu, A.S.F., Han, W., Liu, Z., Zhong, S., Qian, Y., You, W., Cui, X., 2017. A bibliometric review: energy consumption and greenhouse gas emissions in the residential sector. J. Clean. Prod. 159, 301e316.
Gentleman, D.J., 2009. Jacques buffle: complex insight and environmental solutions. Environ. Sci. Technol. 43 (19), 7165e7169.
Ghisellini, P., Zucaro, A., Viglia, S., Ulgiati, S., 2014. Monitoring and evaluating the sustainability of Italian agricultural system. An emergy decomposition analysis. Ecol. Model. 271, 132e148.
Grosskurth, J., Rotmans, J., 2005. The scene model: getting A grip on sustainable development in policy making. Environ. Dev. Sustain. 7 (1), 135e151.
Guevara, Z., Domingos, T., 2017. The multi-factor energy inputeoutput model. Energy Econ. 61, 261e269.

Han, J., Chen, W.-Q., Zhang, L., Liu, G., 2018a. Uncovering the spatiotemporal dynamics of urban infrastructure development: a high spatial resolution material stock and flow analysis. Environ. Sci. Technol. 52 (21), 12122e12132.
Han, W., Geng, Y., Lu, Y., Wilson, J., Sun, L., Satoshi, O., Geldron, A., Qian, Y., 2018b. Urban metabolism of megacities: a comparative analysis of Shanghai, Tokyo, London and Paris to inform low carbon and sustainable development pathways. Energy 155, 887e898.
Hanya, T., Ambe, Y., 1977. A Study on the Metabolism of Cities. Science for Better Environment. Pergamon, pp. 228e234.
Hao, Y., Zhang, M., Zhang, Y., Fu, C., Lu, Z., 2018. Multi-scale analysis of the energy metabolic processes in the BeijingeTianjineHebei (Jing-Jin-Ji) urban agglomeration. Ecol. Model. 369, 66e76.
Hendriks, C., Obernosterer, R., Müller, D., Kytzia, S., Baccini, P., Brunner, P.H., 2000. Material Flow Analysis: a tool to support environmental policy decision making. Case-studies on the city of Vienna and the Swiss lowlands. Local Environ. 5 (3), 311e328.
Hong, J., Shen, G.Q., Mao, C., Li, Z., Li, K., 2016. Life-cycle energy analysis of prefabricated building components: an inputeoutput-based hybrid model. J. Clean. Prod. 112, 2198e2207.
Hong, J., Tang, M., Wu, Z., Miao, Z., Shen, G.Q., 2019. The evolution of patterns within embodied energy flows in the Chinese economy: a multi-regional-based complex network approach. Sustainable Cities and Society, 101500.
Hoornweg, D., Freire, M., 2013. Building sustainability in an urbanizing world: A partnership report, 2013.
Hu, G., Mu, X., 2018. Dominants in evolution of urban energy metabolism: a case study of Beijing. Ecol. Model. 385, 26e34.
Hu, G., Mu, X., 2019. Analysis of urban energy metabolic system: an ecological network framework and a case study for Beijing. J. Clean. Prod. 210, 958e969.
Huang, S.-L., Wu, S.-C., Chen, W.-B., 1995. Ecosystem, environmental quality and ecotechnology in the Taipei metropolitan region. Ecol. Eng. 4 (4), 233e248.
Huang, Q., Zheng, X., Liu, F., Hu, Y., Zuo, Y., 2018. Dynamic analysis method to open the "black box" of urban metabolism. Resour. Conserv. Recycl. 139, 377e386.
Kamalski, J., Kirby, A., 2012. Bibliometrics and urban knowledge transfer. Cities 29, S3eS8.
Kennedy, C., Cuddihy, J., Engel-Yan, J., 2007. The changing metabolism of cities. J. Ind. Ecol. 11 (2), 43e59.
Kennedy, C., Pincetl, S., Bunje, P., 2011. The study of urban metabolism and its applications to urban planning and design. Environ. Pollut. 159 (8e9), 1965e1973. Kennedy, C.A., Bachmann, C., 2017. The energy structure of the Canadian economy. J. Ind. Ecol. 21 (5), 1301e1311.
Kennedy, C.A., Stewart, I., Facchini, A., Cersosimo, I., Mele, R., Chen, B., Uda, M., Kansal, A., Chiu, A., Kim, K.-g., Dubeux, C., Lebre La Rovere, E., Cunha, B., Pincetl, S., Keirstead, J., Barles, S., Pusaka, S., Gunawan, J., Adegbile, M., Nazariha, M., Hoque, S., Marcotullio, P.J., Gonzalez Otharan, F., Genena, T., Ibrahim, N., Farooqui, R., Cervantes, G., Sahin, A.D., 2015. Energy and material flows of megacities. Proc. Natl. Acad. Sci. Unit. States Am. 112 (19), 5985e5990.
Kucukvar, M., Onat, N.C., Haider, M.A., 2018. Material dependence of national energy development plans: the case for Turkey and United Kingdom. J. Clean. Prod. 200, 490e500.
Lee, C.-L., Huang, S.-L., Chan, S.-L., 2009. Synthesis and spatial dynamics of socioeconomic metabolism and land use change of Taipei Metropolitan Region. Ecol. Model. 220 (21), 2940e2959.
Lehmann, D.S., 2011. Resource recovery and materials flow IN the city: zero waste and sustainable consumption as paradigm in urban development. Journal of Green Building 6 (3), 88e105.
Li, H., Kwan, M.-P., 2018. Advancing analytical methods for urban metabolism studies. Resour. Conserv. Recycl. 132, 239e245.
Liang, S., Wang, C., Zhang, T., 2010. An improved inputeoutput model for energy analysis: a case study of Suzhou. Ecol. Econ. 69 (9), 1805e1813.
Liu, L., Huang, G., Baetz, B., Huang, C.Z., Zhang, K., 2018b. A factorial ecologicallyextended input-output model for analyzing urban GHG emissions metabolism system. J. Clean. Prod. 200, 922e933.
Liu, B., Wang, D., Xu, Y., Liu, C., Luther, M., 2018a. A multi-regional inputeoutput analysis of energy embodied in international trade of construction goods and services. J. Clean. Prod. 201, 439e451.
Maranghi, S., Parisi, M.L., Facchini, A., Rubino, A., Kordas, O., Basosi, R., 2020. Integrating urban metabolism and life cycle assessment to analyse urban sustainability. Ecol. Indicat. 112, 106074.
Marx, K., 1887. Capital: A Critique of Political Economy, 1. Frederick Engels.
Meerow, S., Newell, J.P., Stults, M., 2016. Defining urban resilience: a review. Landsc. Urban Plann. 147, 38e49.
Mei-PoKwan, 2012. How GIS can help address the uncertain geographic context problem in social science research. Geographic Information Sciences 18 (4), 245e255.
Mellino, S., Ulgiati, S., 2015. Mapping the evolution of impervious surfaces to investigate landscape metabolism: an EmergyeGIS monitoring application. Ecol. Inf. 26, 50e59.
Newcombe, K., Kalma, J.D., Aston, A.R., 1978. The metabolism of a city: the case of Hong Kong. Ambio 7 (1), 3e15.
Newell, J.P., Cousins, J.J., 2015. The boundaries of urban metabolism: towards a political-industrial ecology. Prog. Hum. Geogr. 39 (6), 702e728.
Newell, J.P., Goldstein, B., Foster, A., 2019. A 40-year review of food-energy-water nexus literature and its application to the urban scale. Environ. Res. Lett. 14 (7), 18.
Newman, P.W.G., 1999b. Sustainability and cities: extending the metabolism model. Landsc. Urban Plann. 44 (4), 219e226.
Odum, H., 1995. Environmental Accounting: Emergy and Environmental Decision Making. Wiley.
Pan, L., Liu, P., Li, Z., Wang, Y., 2018. A dynamic inputeoutput method for energy system modeling and analysis. Chem. Eng. Res. Des. 131, 183e192.
Pauliuk, S., Majeau-Bettez, G., Muller, D.B., 2015. A general system structure and accounting framework for socioeconomic metabolism. J. Ind. Ecol. 19 (5), 728e741.
Persson, O., Gl€anzel, W., Danell, R., 2004. Inflationary bibliometric values: the role of scientific collaboration and the need for relative indicators in evaluative studies. Scientometrics 60 (3), 421e432.
Pincetl, S., Bunje, P., Holmes, T., 2012. An expanded urban metabolism method: toward a systems approach for assessing urban energy processes and causes. Landsc. Urban Plann. 107 (3), 193e202.
Po€rtner, H., 2008. Ecosystem effects of ocean acidification in times of ocean warming: a physiologist's view. BMC Biotechnol. 373 (22), 203e217.
Pulido Barrera, P., Rosales Carreon, J., de Boer, H.J., 2018. A multi-level framework fo r metabolism in urban energy systems from an ecological perspective. Resour. Conserv. Recycl. 132, 230e238.
Qi, W., Deng, X., Chu, X., Zhao, C., Zhang, F., 2017. Emergy analysis on urban metabolism by counties in Beijing. Phys. Chem. Earth 101, 157e165. Parts A/B/C.
Ravalde, T., Keirstead, J., 2017. Comparing performance metrics for multi-resource systems: the case of urban metabolism. J. Clean. Prod. 163, S241eS253.
Rocco, M.V., Colombo, E., 2016. Internalization of human labor in embodied energy analysis: definition and application of a novel approach based on Environmentally extended Input-Output analysis. Appl. Energy 182, 590e601.
Rocco, M.V., Forcada Ferrer, R.J., Colombo, E., 2018. Understanding the energy metabolism of World economies through the joint use of Production- and Consumption-based energy accountings. Appl. Energy 211, 590e603.
Rosales Carreon, J., Worrell, E., 2018. Urban energy systems within the transition to sustainable development. A research agenda for urban metabolism. Resour. Conserv. Recycl. 132, 258e266.
Sahely, H.R., Dudding, S., Kennedy, C.A., 2003. Estimating the urban metabolism of Canadian cities: greater Toronto Area case study. Can. J. Civ. Eng. 30 (2), 468e483.
Semertzidis, T., 2015. Can energy systems models address the resource nexus? Energy Procedia 83, 279e288.
Shahrokni, H., Arman, L., Lazarevic, D., Nilsson, A., Brandt, N., 2015a. Implementing smart urban metabolism in the stockholm royal seaport: smart city SRS. J. Ind. Ecol. 19 (5), 917e929.
Shahrokni, H., Lazarevic, D., Brandt, N., 2015b. Smart urban metabolism: towards a real-time understanding of the energy and material flows of a city and its citizens. J. Urban Technol. 22 (1), 65e86.
Shi, J., Li, H., Guan, J., Sun, X., Guan, Q., Liu, X., 2017. Evolutionary features of global embodied energy flow between sectors: a complex network approach. Energy 140, 395e405.
Stylos, N., Koroneos, C., Roset, J., Gonzalez-Sanchez, C., Xydis, G., Mun~oz, F.S., 2018. Exergy as an indicator for enhancing evaluation of environmental management performance in the hospitality industry. J. Clean. Prod. 198, 1503e1514.
Su, M., Zhang, M., Lu, W., Chang, X., Chen, B., Liu, G., Hao, Y., Zhang, Y., 2017. ENAbased evaluation of energy supply security: comparison between the Chinese crude oil and natural gas supply systems. Renew. Sustain. Energy Rev. 72, 888e899.
Su, Q., Dai, H., Lin, Y., Chen, H., Karthikeyan, R., 2018. Modeling the carbon-energywater nexus in a rapidly urbanizing catchment: a general equilibrium assessment. J. Environ. Manag. 225, 93e103.
Sun, X., An, H., 2018. Emergy network analysis of Chinese sectoral ecological sustainability. J. Clean. Prod. 174, 548e559.
Sun, X., An, H., Gao, X., Jia, X., Liu, X., 2016. Indirect energy flow between industrial sectors in China: a complex network approach. Energy 94, 195e205.
Tan, L.M., Arbabi, H., Brockway, P.E., Densley Tingley, D., Mayfield, M., 2019. An ecological-thermodynamic approach to urban metabolism: measuring resource utilization with open system network effectiveness analysis. Appl. Energy 254, 113618.
Tan, L.M., Arbabi, H., Li, Q., Sheng, Y., Densley Tingley, D., Mayfield, M., Coca, D., 2018. Ecological network analysis on intra-city metabolism of functional urban areas in England and Wales. Resour. Conserv. Recycl. 138, 172e182.

Tang, M., Hong, J., Liu, G., Shen, G.Q., 2019a. Exploring energy flows embodied in China's economy from the regional and sectoral perspectives via combination of multi-regional inputeoutput analysis and a complex network approach. Energy 170, 1191e1201.
Ukidwe, N.U., Bakshi, B.R., 2007. Industrial and ecological cumulative exergy consumption of the United States via the 1997 inputeoutput benchmark model. Energy 32 (9), 1560e1592.
Velasco-Fernandez, R., Ramos-Martín, J., Giampietro, M., 2015. The energy metabolism of China and India between 1971 and 2010: studying the bifurcation. Renew. Sustain. Energy Rev. 41, 1052e1066.
Venkatesh, G., Sægrov, S., Brattebø, H., 2014. Dynamic metabolism modelling of urban water services e demonstrating effectiveness as a decision-support tool for Oslo, Norway. Water Res. 61, 19e33.
Voskamp, I.M., Sutton, N.B., Stremke, S., Rijnaarts, H.H.M., 2020. A systematic review of factors influencing spatiotemporal variability in urban water and energy consumption. J. Clean. Prod. 256, 120310.
Wang, C., Wang, Y., Geng, Y., Wang, R., Zhang, J., 2016. Measuring regional sustainability with an integrated social-economic-natural approach: a case study of the Yellow River Delta region of China. J. Clean. Prod. 114, 189e198.
Wang, R., Li, F., Hu, D., Larry Li, B., 2011a. Understanding eco-complexity: socialeconomic-natural complex ecosystem approach. Ecol. Complex. 8 (1), 15e29.
Wang, R., Zhou, T., Hu, D., Li, F., Liu, J., 2011b. Cultivating eco-sustainability: socialeeconomicenatural complex ecosystem case studies in China. Ecol. Complex. 8 (4), 273e283.
Wang, S., Cao, T., Chen, B., 2017. Urban energyewater nexus based on modified inputeoutput analysis. Appl. Energy 196, 208e217.
Warren-Rhodes, K., Koenig, A., 2001. Ecosystem appropriation by Hong Kong and its implications for sustainable development. Ecol. Econ. 39 (3), 347e359.
Wolman, A., 1965. The metabolism of cities. Sci. Am. 213 (3), 179e190.
Wu, X.F., Chen, G.Q., 2017. Energy use by Chinese economy: a systems cross-scale input-output analysis. Energy Pol. 108, 81e90.
Xiao, Z., Yao, M., Tang, X., Sun, L., 2019. Identifying critical supply chains: an inputoutput analysis for Food-Energy-Water Nexus in China. Ecol. Model. 392, 31e37.
Xiong, S., Ma, X., Ji, J., 2019. The impact of industrial structure efficiency on provincial industrial energy efficiency in China. J. Clean. Prod. 215, 952e962.
Yang, X., Wang, Y., Sun, M., Wang, R., Zheng, P., 2018. Exploring the environmental pressures in urban sectors: an energy-water-carbon nexus perspective. Appl. Energy 228, 2298e2307.
Yao, L., Liu, J., Wang, R., Yin, K., Han, B., 2015. A qualitative network model for understanding regional metabolism in the context of SocialeEconomiceNatural Complex Ecosystem theory. Ecol. Inf. 26, 29e34.
Yeow, L.W., Cheah, L., 2019. Using spatially explicit commodity flow and truck activity data to map urban material flows. J. Ind. Ecol. 23 (5), 1121e1132.
Zhai, M., Huang, G., Liu, L., Su, S., 2018. Dynamic input-output analysis for energy metabolism system in the Province of Guangdong, China. J. Clean. Prod. 196, 747e762.
Zhang, B., Chen, B., 2017. Sustainability accounting of a household biogas project based on emergy. Appl. Energy 194, 819e831.
Zhang, Y., Li, S., Fath, B.D., Yang, Z., Yang, N., 2011. Analysis of an urban energy metabolic system: comparison of simple and complex model results. Ecol. Model. 223 (1), 14e19.
Zhang, Y., Li, Y., Zheng, H., 2017. Ecological network analysis of energy metabolism in the Beijing-Tianjin-Hebei (Jing-Jin-Ji) urban agglomeration. Ecol. Model. 351, 51e62.
Zhang, Y., Xia, L., Fath, B.D., Yang, Z., Yin, X., Su, M., Liu, G., Li, Y., 2016a. Development of a spatially explicit network model of urban metabolism and analysis of the distribution of ecological relationships: case study of Beijing, China. J. Clean. Prod. 112, 4304e4317.
Zhang, Y., Yang, Z., Fath, B.D., Li, S., 2010. Ecological network analysis of an urban energy metabolic system: model development, and a case study of four Chinese cities. Ecol. Model. 221 (16), 1865e1879.
Zhang, Y., Yang, Z., Yu, X., 2009. Ecological network and emergy analysis of urban metabolic systems: Model development, and a case study of four Chinese cities. Ecol. Model. 220 (11), 1431e1442.
Zhang, Y., Zheng, H., Yang, Z., Li, Y., Liu, G., Su, M., Yin, X., 2016b. Urban energy flow processes in the BeijingeTianjineHebei (Jing-Jin-Ji) urban agglomeration: combining multi-regional inputeoutput tables with ecological network analysis. J. Clean. Prod. 114, 243e256.
Zhang, Y., Zheng, H., Yang, Z., Su, M., Liu, G., Li, Y., 2015. Multi-regional inputeoutput model and ecological network analysis for regional embodied energy accounting in China. Energy 86, 651e663.
Zhao, Y.-B., Yang, M.-Z., Ni, H.-G., 2018. An emergy-GIS method of selecting areas for sponge-like urban reconstruction. J. Hydrol. 564, 640e650.
Zheng, H., Fath, B.D., Zhang, Y., 2017. An Urban Metabolism and Carbon Footprint Analysis of the JingeJineJi Regional Agglomeration.J. Ind. Ecol. 21 (1), 166e179.
Zheng, H., Wang, X., Li, M., Zhang, Y., Fan, Y., 2018. Interregional trade among regions of urban energy metabolism: a case study between Beijing-Tianjin-Hebei and others in China. Resour. Conserv. Recycl. 132, 339e351.
Zucchetto, J., 1975. Energy-economic theory and mathematical models for combining the systems of man and nature, case study: the urban region of Miami, Florida. Ecol. Model. 1 (4), 241e268.