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Urban energy consumption: Different insights from energy flow analysis, input–output analysis and ecological network analysis

Shaoqing Chen, Bin Chen *

State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, PR China

HIGHLIGHTS

- Urban energy consumption was assessed from three different perspectives.
- A new concept called controlled energy was developed from network analysis.
- Embodied energy and controlled energy consumption of Beijing were compared.
- The integration of all three perspectives will elucidate sustainable energy use.

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ABSTRACT

Energy consumption has always been a central issue for sustainable urban assessment and planning. Different forms of energy analysis can provide various insights for energy policy making. This paper brought together three approaches for energy consumption accounting, i.e., energy flow analysis (EFA), input–output analysis (IOA) and ecological network analysis (ENA), and compared their different perspectives and the policy implications for urban energy use. Beijing was used to exemplify the different energy analysis processes, and the 42 economic sectors of the city were aggregated into seven components. It was determined that EFA quantifies both the primary and final energy consumption of the urban components by tracking the different types of fuel used by the urban economy. IOA accounts for the embodied energy consumption (direct and indirect) used to produce goods and services in the city, whereas the control analysis of ENA quantifies the specific embodied energy that is regulated by the activities within the city's boundary. The network control analysis can also be applied to determining which economic sectors drive the energy consumption and to what extent these sectors are dependent on each other for energy. So-called "controlled energy" is a new concept that adds to the analysis of urban energy consumption, indicating the adjustable energy consumed by sectors. The integration of insights from all three accounting perspectives further our understanding of sustainable energy use in cities.

1. Introduction

Energy consumption is a central concern for urban scientists, stakeholders and planners. Approximately 67% of the total global energy consumption and 70% of greenhouse gas emissions are caused by activities in urban areas [1,2]. Cities are considered the source of many environmental problems and key to addressing the challenges from global change [3,4]. The rapid urbanization worldwide has begged the question of how to manage energy use in cities in pursuit of sustainable socioeconomic development [5,6].

Urban energy planning is usually developed later than urban land use planning, resulting in a lack of systematic strategies for balancing environmental and energy-related development and policy implementation [7,8]. The primary step of enhancing energy planning is to provide meaningful energy accounting results by including economic, environment and energy sectors in the urban energy analysis [9]. Accounting for energy consumption is important for sustainable energy planning of cities in many ways. First, it provides insight into how much energy we are consuming in different urban activities and what the performance may be in the future based on our demand and technology. Second, it also facilitates our understanding of the driving forces of energy consumption and relationships between urban sectors. Finally, urban energy accounting provides methods and tools for selecting the optimal energy importing and generation systems for the city's energy demand attendance considering environmental and economic objectives over time [10].

* Corresponding author at: No. 19, Xinjiekouwai St., Beijing 100875, PR China. Tel./fax: +86 10 58807368.

E-mail address: chenb@bnu.edu.cn (B. Chen).

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There are plenty of studies looking into urban energy consumption from production- or consumption-based perspectives [11–14]. And it has been clear that the boundary and methodology used in the urban energy study are important in designing an environmentally friendly energy profile [15]. There has been a wide debate on how to account for energy consumption in a way that can be both legitimate and policy relevant [16–18]. Different accounting approaches for energy consumption in cities need to be justified to better interpret the urban energy profile. Among all the approaches, energy flow analysis (EFA) has been widely used in assessing urban metabolism (the study of the technical and socioeconomic processes that occur in cities) [19,20]. EFA indicators parallel the metrics in material flow analysis (MFA), which are strong tools for tracking urban energy flows and indexing the energy intensity of economic sectors from the production perspective [21–23].

In addition to EFA, two other approaches, input–output analysis (IOA) and ecological network analysis (ENA) have also been applied to urban energy analysis. IOA has become one of the strongest tools for modeling the consumption of natural resources by humanity with increasingly accessible data on the different scales of the economies around the world [24,25]. IOA is capable of uncovering indirect energy flows based on sectoral intermediate exchanges. The modeling of regional and local energy use and emissions based on IOA is now a standard practice for many economic consultants, although sometimes little primary data on exports and imports are available [26–29].

ENA is a system-oriented method evolved from input–output analysis, which is often used in examining the structure of energy/materials flows in ecosystems [30–32]. ENA has been applied to evaluating energy flows and carbon emissions in cities and determining inter-sector relationships in the urban metabolic processes [33,34]. The indirect effect in ENA has been used differently from that in IOA: the integral flows (the integration of direct and indirect flows in ENA) have been utilized to quantify not only the flows that accumulate in the transformation process but also the relationships between economic sectors from a systems perspective. The "control strength", determined by the combination of the input/output environs of the sectors, is potentially useful in identifying which sectors play a more dominant role in urban energy consumption than others.

In this study, we aim to develop a more comprehensive and balanced understanding of urban energy consumption by integrating various accounting perspectives. Using Beijing as a case study, EFA, IOA and ENA were applied to the assessment of sector-level and city-level energy consumption. Essentially, IOA- and ENA-oriented energy flow analyses were developed based on the results derived from EFA. However, they were used to provide insights associated with the embodied energy consumed by the urban economy. IOA included the direct and indirect energy flows of Beijing, whereas the control analysis of ENA reduced the embodied energy to the amount that can be controlled within urban sectors. The "controlled energy" is a new term derived from ENA in contrast with embodied energy. Two versions of the urban energy model (42-sector and 7-component) were considered to evaluate the impact of model structure on IOA and ENA results. In addition, three future scenarios were constructed to address the potential of EFA, IOA and ENA in sustainable energy planning. Finally, the policy relevance of merging the three accounting perspectives was discussed.

2. Materials and Methods

2.1. System boundary and model structure

In this study, both the activities within the urban economy and boundary interactions between the city and the rest of the world (such as energy inputs/outputs) were considered for energy consumption analysis. Although in most published statistical books, energy consumption is monitored from the perspective of production, it is important to know how much energy is consumed by citizens because their purchase of products often comes from outside a city's boundary. The selection of system boundaries is very important because it distinguishes between net inputs and internal transitions of resources [35]. Therefore, we explain the system boundaries based on different energy accounting methods in the following sections.

To understand an energy flow profile, the urban economy can be modeled as the aggregation of a set of interconnected economic sectors. To be consistent with the structure in the urban I–O table and material flows accounting [13,34], the urban economy was divided into 42 economic sectors. These sectors were then aggregated into 7 larger components (agriculture, mining, manufacture, electricity, gas & water, construction, transport and services) based on their common activities in the industry (Table 1). This setting of

Table 1
Components and sectors of urban economy.

Component	Sector	Sector code
Agriculture	Agriculture, forestry, animal husbandry and fishery	1
Mining	Coal mining and dressing	2
	Petroleum and natural gas extraction	3
	Metal ore mining	4
	Non-metal minerals mining	5
Manufacture	Manufacture of food products and tobacco processing	6
	Textiles	7
	Wearing apparel, leather, fur, down and related products	8
	Sawmills and furniture	9
	Paper and products, printing and record medium reproduction	10
	Petroleum processing, coking and nuclear fuel processing	11
	Chemical industry	12
	Nonmetallic mineral products	13
	Metal smelting and pressing	14
	metal products	15
	General and special purpose machinery	16
	Transport equipment	17
	Electric equipment and machinery	18
	Electronic and telecommunication equipment	19
	Instruments, meters, cultural and office machinery	20
	Artware and other manufacturing products	21
	Scrap and waste	22
Electricity, gas &water	Electricity, steam and hot water production and supply	23
	Gas production and supply	24
	Water production and supply	25
Construction	Construction	26
Transport	Transport and storage	27
Services	Post services	28
	Telecommunication, computer services and software	29
	Wholesale and retail trade services	30
	Accommodation and food serving services	31
	Finance and insurance	32
	Real estate	33
	Rental and business services	34
	Scientific research	35
	Polytechnical services	36
	Water resources, environment and public facilities management	37
	Residential services and other social services	38
	Educational services	39
	Health, social security and welfare	40
	Cultural, sporting and recreational services	41
	Public management and social organization	42