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

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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].

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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 socio-economic 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

sectors and components is performed to inspect the effect of sectoral aggregation on the energy consumption of the urban system from an input–output or network perspective. In addition, the process-based economic interactions in the city can be assessed and interpreted at different levels with these two configurations (component-based and sector-based).

2.2. Energy flow analysis (EFA)

Energy flow analysis (EFA) has been widely used for tracking the energy balance of nations [36,37], cities [18,38] and industrial units [39,40]. Both human activity and ecological processes are considered in some EFA studies to estimate the anthropogenic impact on ecosystems [41,42]. However, most EFAs concern energy flows concomitant with economic processes within a top-down assessment framework. The accounting of energy indicators in EFA often includes energy import, exports and socio-economic stocks based on society's biophysical structures [43]. EFA is also capable of tracking different types of fuels used by the city and urban sectors, which is important for understanding the energy infrastructure of cities [44,45].

Urban energy consumption is the focus of this study. The question being asked is how much energy is expensed by the city and its economic sectors. Direct energy use by the city was calculated based on the final energy use and energy transformation and loss. Final energy use included production-based consumption in the 7 components of the urban economy (Agriculture, Mining, Manufacture, Electricity, gas &water, Construction, Transport and Services) and household use (residential consumption). Energy transformation and loss included the energy input and output during transformation, physical loss and stock change within the city. According to the city's energy balance table, 11 types of fuel are investigated for their contributions to total urban energy consumption. Because different types of fuel have various heat values, the standard coal coefficients for these types of urban energy were provided to convert them into the same unit of measurement (i.e., standard coal equivalents in Mtce). The conversions of final energy use and energy transformation and loss of component i were formulated in Eqs. (1), (2), whereas the total direct energy was calculated by Eq. (3).

$$E_{\text{final}(i)} = \sum [\mathbf{U}_{\text{final}(i)} \boldsymbol{\rho}^T] \tag{1}$$

$$E_{\text{trans}(i)} = \sum [\mathbf{U}_{\text{trans}(i)} \boldsymbol{\rho}^T] \tag{2}$$

$$\mathbf{E}_{\text{direct}(1\times m)} = \mathbf{E}_{\text{final}(1\times m)} + \mathbf{E}_{\text{trans}(1\times m)} \tag{3}$$

where $i = 1, 2, \ldots, m$. $\boldsymbol{\rho}_{(1\times 20)}$ is the standard coal coefficients for 11 types of energy, $E_{\text{final}(i)}$ is the final consumption of component i, $E_{\text{trans}(i)}$ is the energy transformation and loss of component i, $\mathbf{E}_{final(1\times m)} = [E_{final(i)}]$ is the vector of final consumption for all components, $\mathbf{E}_{\text{trans}(1\times m)} = [E_{\text{trans}(i)}]$ is the vector of energy transformation and loss of all components and $\mathbf{E}_{\text{direct}(1\times m)}$ is the vector of direct energy use for all components.

2.3. Input–output analysis (IOA)

Input–output analysis (IOA) can assess the embodied energy consumption (both direct and indirect) required to produce goods and services in the city based on sectoral interactions and exchanges with other economies [46,47]. Embodied energy accounts for the energy required to support all the production activities of a product that is consumed locally, including *in situ* and upstream processes [48]. There have been no major methodological changes to IOA since it was proposed by Leontief [49,50]. However, before applying IOA for any embodied consumption analyses, it should be noted that several key assumptions have been made during the accounting of resource consumption (or limitations): First, imported goods and services from the rest of the world (either domestic or foreign) are analyzed based on the same embodied energy intensity as local products [13,51]. Second, traditional primary factors of economic production labor and capital are assumed to be independent and free from indirect energy costs, whereas solar energy input into the economy is ignored [35]. The latter assumption makes embodied energy analysis different from emergy analysis, which accounts for both natural and human work embodied in products based on the unit of solar energy (seJ) [52,53].

Because formulations for input–output energy analysis have been established [54–56], herein we present the accounting of embodied energy instantly without showing the detailed derivation process. Based on the IOA procedure, the energy consumption of urban sectors and the whole city were assessed individually. For a certain component or sector, indirect energy use embodied in the commodities was calculated from intermediate exchanges with other economic components or sectors based on the sector × sector Leontief Inverse. In terms of the whole city, indirect energy use accounted for the primary and final energy expensed outside the city's boundary that was needed to provide goods or services to local residents and governments. The direct and indirect energy consumption of urban components or sectors were calculated through Eqs. (4) and (5), whereas the direct and indirect energy consumption of the whole urban economy was calculated through Eqs. (6) and (7). The embodied energy is the combination of direct and indirect energy consumption.

$$\mathbf{V}_{(1\times m)} = \mathbf{E}_{\text{direct}(1\times m)} / \mathbf{X}^T_{(1\times m)} \tag{4}$$

$$\mathbf{E}_{\text{indirect}(1\times m)} = \mathbf{V}_{(1\times m)} (\mathbf{I} - \mathbf{A})^{-1}_{(m\times m)} \mathbf{X}^T_{(1\times m)} - \mathbf{E}_{\text{direct}(1\times m)} \tag{5}$$

$$E_{\text{direct}} = \sum_{i=1}^{m} \left[\mathbf{E}_{\text{direct}(1\times m)}\right] \tag{6}$$

$$E_{\text{indirect}} = \sum_{i=1}^{m} \left[\mathbf{V}_{(1\times m)} (\mathbf{I} - \mathbf{A})^{-1}_{(m\times m)} \mathbf{F}^T_{(1\times m)}\right] - E_{\text{direct}} \tag{7}$$

where $\mathbf{V}_{(1\times m)}$ is the vector of the energy intensities for all m components or sectors, $\mathbf{E}_{\text{direct}(1\times m)}$ is the vector of direct energy consumption for each component or sector, $\mathbf{X}_{(1\times m)}$ is the vector of gross monetary outputs for each component or sector, $\mathbf{I}$ is the identity matrix, $\mathbf{A}$ is the technology coefficient matrix ($m \times m$) with elements a_{ij}, representing the amount of direct intermediate flow from sector i to sector j, $\mathbf{F}_{(1\times m)}$ is the final monetary demand of residents and the government, $\mathbf{E}_{\text{indirect}(1\times m)}$ is the vector of indirect energy consumption for each component or sector, E_{direct} is the direct energy consumption of the whole urban economy, and E_{indirect} is the indirect energy consumption of the whole urban economy.

2.4. Ecological network analysis (ENA)

Ecological network analysis (ENA) emerges from a non-reductionist ideology and approach to understanding a system as the integration of smaller interconnected entities that exist because there are linkages from one to another [30,57,58]. ENA's concept of incorporating direct and indirect flows is homologous with IOA. In fact, Hannon [53] first adjusted the Leontief input–output model to the field of ecology to analyse direct and indirect element flows through the ecosystem based on the interrelationships of components. Patten and his co-workers [59,60] developed a line of network analysis called Network Environ Analysis (NEA), which divides the surroundings of each component into two environs (i.e., input/output environs). The ENA structure of input/output environs is also similar to the columns (production) and rows (consumption) of an input–output matrix in IOA.

Network control analysis (NCA), one of the key metrics in NEA, was developed to measure the control relationship (the dominance of one compartment over another) within an ecosystem [60,61]. In this sense, "control" is distributed among system components, determined by the combination of their input/output environs. Herein, we applied this concept to the energy consumption of an urban system to address how much energy is controlled by economic components (or sectors) and the city as a whole. For components (or sectors), this controlled energy specifies the flows that come into a sector through the process of consumption and are controlled by the sector in an integral way. With respect to city, this controlled energy considers the flows that are consumed by the city from outside the urban boundary (energy imports) and are controlled by urban activity (which therefore can be adjusted within the city). This can be an important metric because it distinguishes between embodied energy flows and integrally controlled flows by sectors. For example, the energy consumed by the transport sector but motivated by the activities in the service sector is considered the embodied energy of the Transport sector according to IOA because the fossil fuels used end up in the Transport sector, but it should be attached to the Service sector from a network control perspective.

Network control was primarily quantified by the ratio of pair-wise integral flows between components, indicating the control one component exerts over the others [62]. A variant metrics called control difference (CD) has been developed to implicate the absolute control intensity between components [63]. This metric is used in this study to calculate the controlled energy by sectors through their control relationships. The control intensity of sector i over sector j (cd_{ij}, Eq. (10)) is determined by the difference in the pair-wise integral flows between sector i and j (Eqs. (8), (9)). The calculations of controlled energy by sectors (Eq. (11)) and of the whole city (Eq. (12)) correspond to the embodied energy in Eqs. (5) and (7), replacing the Leontief inverse with CD.

$$\mathbf{N} = (n_{ij}) = \sum_{m=0}^{\infty} \mathbf{A}^m = (\mathbf{I} - \mathbf{A})^{-1} \tag{8}$$

$$\mathbf{N}' = (n'_{ij}) = \sum_{m=0}^{\infty} \mathbf{A}'^m = (\mathbf{I} - \mathbf{A}')^{-1} \tag{9}$$

$$\mathbf{CD} = [cd_{ij}] \equiv \mathbf{N} - \mathbf{N}' \tag{10}$$

$$\mathbf{E}_{\text{control}(1\times m)} = \mathbf{V}_{(1\times m)}\mathbf{CD}_{(m\times m)}\mathbf{X}^T_{(1\times m)} - \mathbf{E}_{\text{direct}(1\times m)} \tag{11}$$

$$E_{\text{control}} = \sum_{i=1}^{m} [\mathbf{V}_{(1\times m)}\mathbf{CD}_{(m\times m)}\mathbf{F}^T_{(1\times m)}] - E_{\text{direct}} \tag{12}$$

where $\mathbf{A}'$ is the transpose of $\mathbf{A}$, $\mathbf{CD}$ is the sector × sector control intensity matrix, cd_{ij} is the difference in two dimensionless flows (i.e., the integral output flow (n_{ij}) and the dimensionless integral input flow matrix (n'_{ij})), $\mathbf{E}_{\text{control}(1\times m)}$ is the controlled energy matrix for urban sectors, and E_{control} is the controlled energy for the urban economy.

To determine the driving sectors of urban energy consumption, the control relationships within the system were further formulated from the controller's and observer's perspective using a control allocation matrix

$$\mathbf{CA} = [ca_{ij}] \equiv \begin{cases} n_{ij} - n'_{ji} > 0, & ca_{ij} = \frac{n_{ij} - n'_{ji}}{\sum_{i=1}^{m} n_{ij} - n'_{ji}} \\ n_{ij} - n'_{ji} \leqslant 0, & ca_{ij} = 0 \end{cases} \tag{13}$$

and dependence allocation matrix

$$\mathbf{DA} = [da_{ij}] \equiv \begin{cases} n_{ij} - n'_{ji} > 0, & da_{ij} = \frac{n_{ij} - n'_{ji}}{\sum_{j=1}^{m} n_{ij} - n'_{ji}} \\ n_{ij} - n'_{ji} \leqslant 0, & da_{ij} = 0 \end{cases} \tag{14}$$

CA is interpreted as how the economic sectors on the production side control the other sectors on the consumption side. In contrast, **DA** indicates how the economic sectors on the consumption side are dependent on the other sectors on the production side [64].

2.5. Case study and data

In this study, Beijing was used to exemplify the different calculations of urban energy consumption from EFA, IOA and ENA. With a rapidly growing population and expanding urban areas from urbanization, Beijing has an increasingly high demand for energy and resources. The base case investigated here is the energy consumption of Beijing in 2007. To manifest how the different perspectives will impact future judgment of urban energy consumption, three imaginary scenarios in 2020s were developed based on different performances regarding final demand and energy intensity (Table 2).

The Beijing input–output table for 2007 was derived from the Beijing Statistical Bureau [65]. The data for direct energy consumption for each sector came from the energy balance table in the Beijing Statistics Yearbook [66]. The standard coal coefficients used to convert the 11 types of energy (coal, coke, gasoline, kerosene, diesel oil, fuel oil, liquefied petroleum gas (LPG), natural gas, heat, electricity, and other energy) to standard coal equivalents (Mtce) were derived from the General Principles of Comprehensive Energy Consumption Calculation (GB/T 2589-2008) https://www1.zouch-eng.gov.cn/zcfiles/2009-3/20093914225799.doc.

3. Results and discussion

3.1. Sectoral energy flows of the city

Fig. 1 shows the proportions of 11 different types of fuel use (coal, coke, gasoline, kerosene, diesel oil, fuel oil, Liquefied petroleum gas (LPG), natural gas, heat, electricity, and other energy) in the direct energy consumption of the 7 urban components (agriculture, mining, manufacture, electricity, gas & water, construction, transport and services) of Beijing. The EFA result was the aggregation of the fuel flows of all 42 sectors in the urban economy. All energy types were transformed to the same unit of measurement for fair comparison. It is clear that coal (37%), diesel oil (16%) and gasoline (14%) were three important sources of energy in Beijing in general. In comparison, other types of energy, such as heat (8%), kerosene (7%) and electricity (4%), were much smaller. The development of the city is still highly dependent on fossil fuels (especially coal). Three economic components, electricity, gas and water; agriculture; and household, were most reliant on coal, with proportions of 82%, 60% and 37%, respectively. Gasoline was an important type of energy in services and households, whereas diesel oil was heavily consumed in construction, agriculture and transport.

Only part of primary energy coming into the city is eventually consumed by economic sectors due to energy loss during the inputs and outputs of transformation. Fig. 2 shows the constitution of primary energy consumption by urban component based on energy flow analysis of Beijing (Fig. 2), in which final energy consumption and energy transformation, stock change and loss are quantified. For the whole city, final consumption is only half of the primary energy input, leaving a large proportion lost during

Table 2
Scenario setting for urban energy consumption analysis.

Scenario	Description	Valuables change	Observation
S1 2020	Energy technology as usual, and higher residential demand	Final demand +15% in 2020	Impact of residential demand on total energy consumption
S2 2020	Sustainable energy technology, and residential demand as usual	Energy intensity −10% in 2020	Impact of energy technology on total energy consumption
S3 2020	Sustainable energy technology, and higher residential demand	Final demand +15%, and energy intensity −10% in 2020	Mixed impact of residential demand and energy technology on total energy consumption

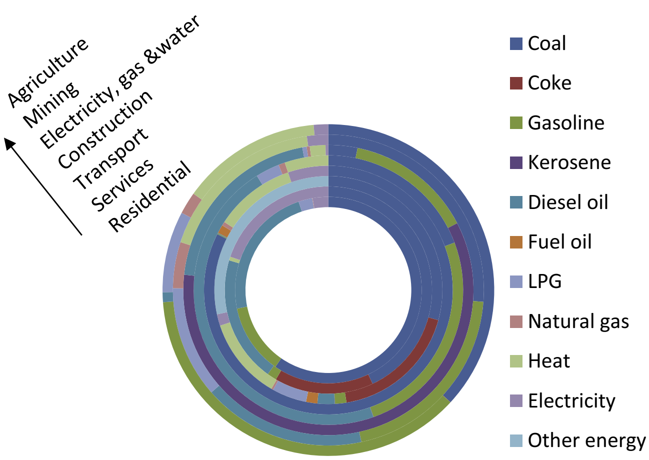

Fig. 1. Proportions of different types of fuel in the energy consumption of Beijing.

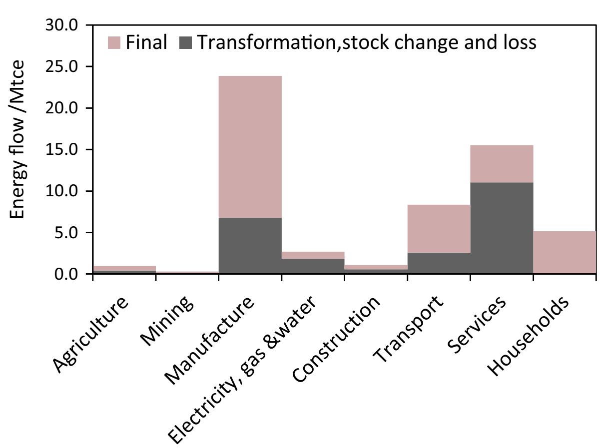

Fig. 2. Constitution of primary energy consumption based on energy flow analysis (EFA).

the transformation process. The shares of energy transformation and loss in urban components were different because they were associated with various fuel refinery and supply processes. The results suggest that most of the final energy was consumed directly by manufacture (17.1 Mtce), transport (5.8 Mtce), services (4.5 Mtce) and households (5.2 Mtce). The highest energy loss rates occurred in two components, services (71%) and transport (68%), where approximately 11.0 Mtce and 1.8 Mtce were lost in energy transformation, respectively. Taking the final energy transformation and loss allocated to the urban economy into consideration, the most energy-consuming components were manufacture (45% of total direct energy consumption), services (29%) and transport (16%).

The sectoral energy consumption from input–output and network control perspectives were analyzed for both the 42-sector and 7-component structures. Fig. 3 illustrates the energy consumption of urban sectors based on the 42-sector urban economy model, showing how different the energy results are between the calculation of IOA and ENA. The embodied energy consumption of sectors based on IOA (consisting of direct and indirect energy) is shown in Fig. 3a. Energy consumed in an indirect way by sectors can be much larger than the direct amount derived from EFA. For instance, the indirect energy consumption by electronic and telecommunication equipment was 16.6 Mtce, which was 26 times greater than the direct flow. The indirect consumption in the construction sector (32.7 Mtce) was 30 times greater when considering indirect flows from other economic sectors.

The controlled energy consumption of sectors based on ENA (consisting of direct and indirect energy) is shown by Fig. 3b. Controlled energy is often smaller than embodied energy. On average, the controlled energy in Beijing was 1.2-folds greater than the direct energy consumption, whereas indirect energy flow was 2.6 times greater than that. Some sectors had greater control on the energy flows, in which case the integral controlled energy (direct and controlled energy) approximated the embodied energy. For example, for the sector instruments, meters, cultural and office machinery, the integral controlled energy consumption (2.5 Mtce) was only slightly smaller than the embodied energy (1.1 Mtce), whereas for artware and other manufacturing products, the integral controlled energy consumption and embodied energy were the same (1.7 Mtce). This difference is determined by the actual energy dominance of a sector as a result of its interactions with other sectors, as reflected in the network control calculation. Considering the feedback effect of energy, one can figure out how much energy consumed by one economic sector is adjustable through the activities of this sector.

Fig. 4 shows the energy consumption of urban components for the 7-component urban economy model based on IOA and ENA. The calculation of both indirect energy (from IOA) and controlled energy (from ENA) was based on the integral economic flows between sectors. Therefore, this calculation was not equal to the simple aggregation of the 42-sector results. For example, for the embodied energy in manufacture, the aggregation result from the 42-sector model was 100.6 Mtce, whereas the result based on the 7-component model was 82.9 Mtce. Similarly, the integral controlled energy of manufacture was 24.3 Mtce according to the 7-component model, much smaller than the aggregation of sectoral consumption (63.2 Mtce).

The embodied energy results in the 7-component urban economy model showed that Manufacture was the largest sector (82.9 Mtce), which was consistent with the EFA results. However, unlike the direct energy accounting, Transport was more energy consuming than Services due to its large indirect energy flow (14.7 Mtce). There was a huge gap between the network control and embodied energy perspectives. The controlled energy for the 7 components was only 1.1 Mtce on average, much smaller than the indirect energy (13.0 Mtce). For such components as manufacture, electricity, gas and water, and services, the controlled energy was insignificant because they are mostly controlled by other components (not the other way around).

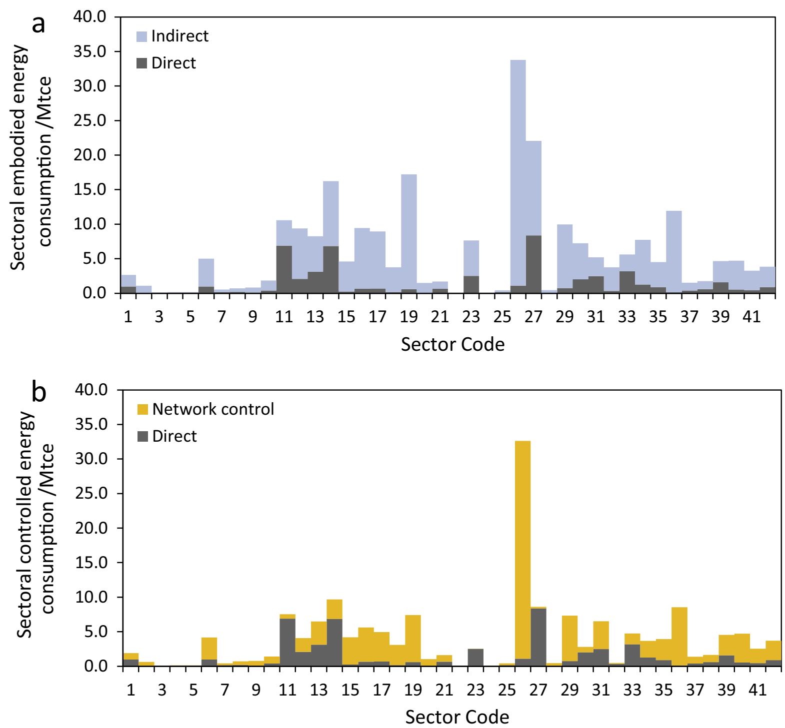

Fig. 3. Sectoral energy consumption for 42-sector urban economy model based on (a) input–output analysis (IOA) and (b) ecological network analysis (ENA).

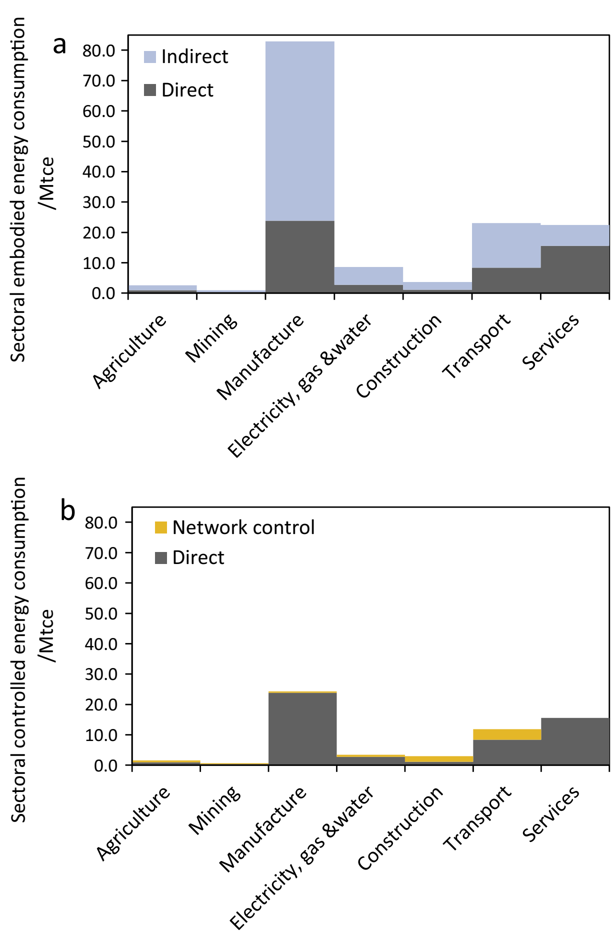

Fig. 4. Sectoral energy consumption for 7-sector urban economy model based on (a) input–output analysis (IOA) and (b) ecological network analysis (ENA).

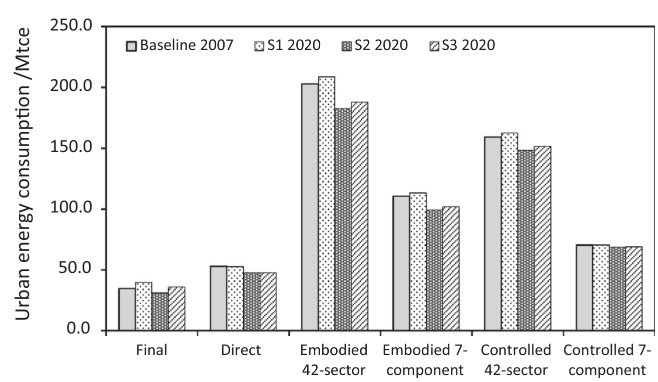

Fig. 5. Total energy consumption of Beijing for different scenarios in 2020 based on energy flow analysis (EFA), input–output analysis (IOA) and ecological network analysis (ENA).

The aggregation of economic sectors into larger sectors (components) impairs the intermediate flow pathways because some of the inter-sector flows merge into one single flow between components. The sector-level analysis has the most complete consideration of intermediate flows, whereas the component-level analysis helps us understand the comparison in energy usage among different urban industries. Setting the model structure is crucial to interpreting sectoral energy consumption.

3.2. Total energy consumption of the city

Based on the investigation of energy use by sector, the total energy consumptions of Beijing based on different approaches were accounted for (Fig. 5). To evaluate future energy use in the city and how different measurements address it, the base case (Beijing in 2007) and three other scenarios in 2020 were compared for the total urban energy consumption. The EFA results showed that only 34.6 Mtce out of the direct energy input (52.8 Mtce) turned into final use for the urban economy in 2007. This result is not dependent on how the system is divided. In contrast, there was a wide gap between the energy consumption calculated from the 42-sector and 7-component models regarding IOA and ENA. For example, the total embodied energy via 42-sector urban model (202.9 Mtce) was almost 2 times of that in the 7-component model (110.4 Mtce). The integral controlled energy of the city was 159.3 Mtce if the interactions of 42 sectors were considered but diminished to 70.4 Mtce when those interactions were integrated into 7 components.

Overall, the embodied urban energy consumption was significantly larger than the controlled energy in both the 42-sector and 7-component models and for all scenarios. This difference is because IOA captures both direct and indirect energy consumed by the city (whether inside or outside the city's boundary), whereas ENA can identify how much of this embodied energy was integrally regulated by urban activity. Both calculations indicate larger urban energy consumption than the EFA results (i.e., direct energy consumption) due to their incorporation of upstream energy costs to different extents. There are two main urbanization trends associated with energy use in Beijing: growing residential demand for energy (larger population) and a renewing process of energy facilities (e.g., the elimination of backward production capacity). These factors clearly have a major impact on the energy consumption in the city. For instance, according to the 42-sector model, the embodied energy consumption will reach 208.7 Mtce if the energy demand increases by 15% (S1 2020) and will be reduced to 182.6 Mtce if the energy intensity decreases by 10% (S2 2020). When both energy demand and energy intensity change to this degree, the total embodied energy consumption still decreases to 187.8 Mtce. Similarly, the integral controlled energy of the city will be 162.7 Mtce in S1 2020 but decreased to 148.6 Mtce and 151.7 Mtce in other energy intensity scenarios (S2 2020 and S3 2020).

It has been reported in several studies that the complexity of analytical models (how a system is divided by sector) changes the accounting results of the system [33,67]. Not only the sectoral energy use but also the total energy consumption is influenced by the model structure of an urban economic system. The more aggregated the intermediate flows between sectors are, the more underestimated the boundary energy imports will be. Under these circumstances, one should be careful in choosing the appropriate model for assessing and managing urban energy consumption.

3.3. Driving sectors of urban energy consumption

To understand what drives urban energy consumption most, the control and dependence relationships between economic sectors/components were identified based on ENA. The control strengths of sectors on the production side (column) over others on the consumption side (row) are displayed in Fig. 6. Using a heat map of two ENA-oriented indicator, control allocation (CA) and dependence allocation (DA), it is easy to locate the strongest control and dependence relationships within the urban system.

From the control perspective (Fig. 6a), the relationships between different components are assessed. Water resources, environment and public facilities management (Sector code 37, in services component) controlled 65% of energy consumption in water production and supply (Sector code 25, in the electricity, gas and water component). Within the same component, textiles (Sector code 7) and artware and other manufacturing (Sector code 21) had strong control over wearing apparel, leather, fur, down and related products (Sector code 8). From the dependence perspective (Fig. 6b), the energy use in electricity, steam and hot water production and supply (Sector code 23) was dependent on gas production and supply (Sector code 24) and coal mining and dressing by 70% and 30%, respectively. Another interesting result is that transport and storage (Sector code 27) is more reliant on transport equipment (58%) than electricity, steam and hot water production and supply (36%).

Based on the same indicators, the control and dependence relationships between the 7 components were also uncovered (Fig. 7). For example, from the network control angle, electricity, gas and water controlled the energy consumption activities in agriculture, construction and transport by 42%, 36% and 22%, respectively. In terms of energy dependence, electricity, gas and water depended most on two other economic components, manufacture (51%) and services (35%). It was evident that construction was among the most reliant on other components in the urban economy because all other sectors had control over it to certain extents. Manufacture and services were two dominant components driving urban energy consumption because all the other components of the city were highly dependent on them.

3.4. Policy implication and limitation

Accounting for urban energy profile based on EFA, OIA and ENA provides different insights for energy assessment and accounting. In Beijing's case, the EFA-based energy consumption of the city was 34.6 Mtce in 2007, while the calculation in OIA and ENA is 5

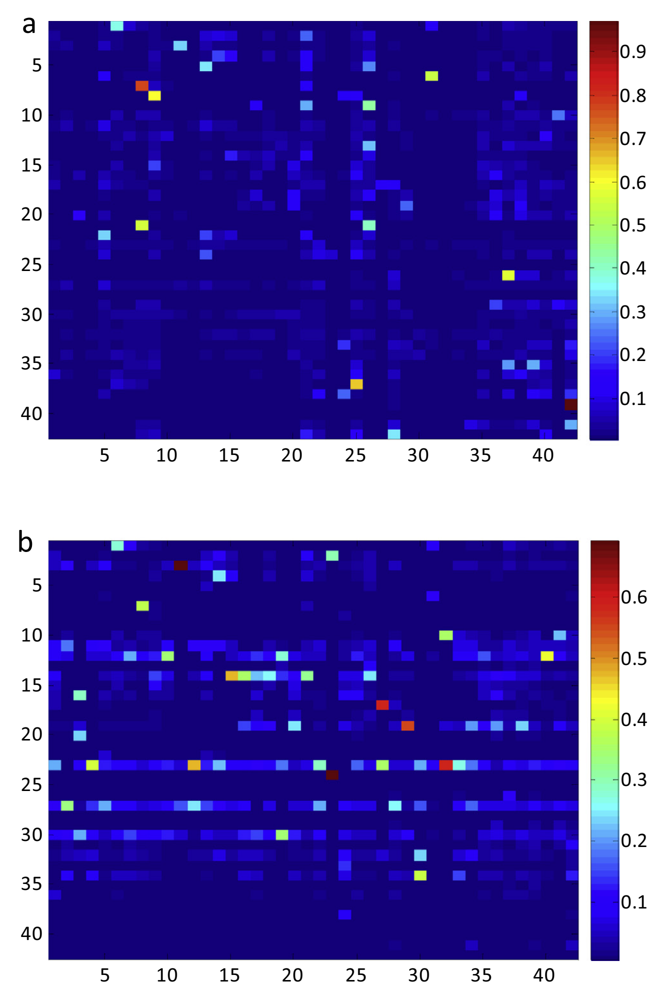

Fig. 6. (a) Network control and (b) network dependence between 42 urban sectors based on ecological network analysis (ENA). Note: The control/dependence relationships between sectors are presented from the production side (matrix column) to others on the consumption side (matrix row).

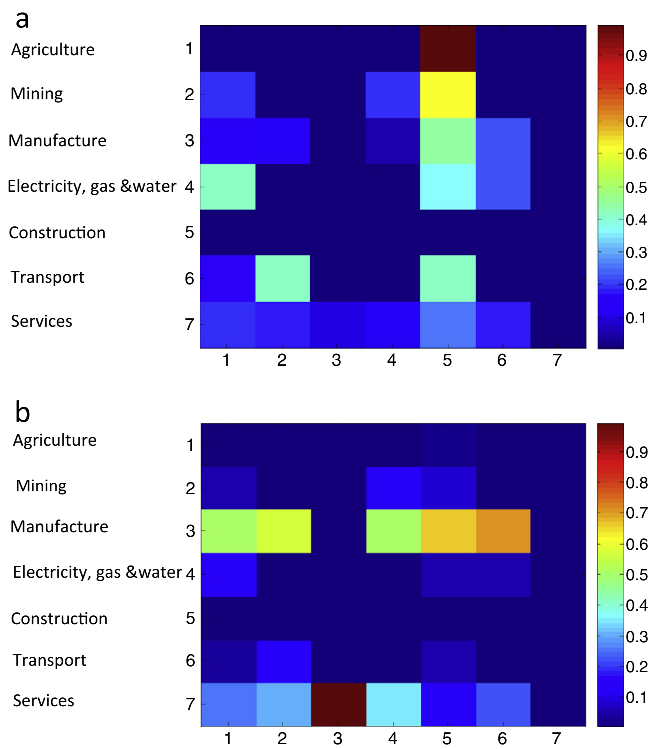

Fig. 7. (a) Network control and (b) network dependence between 7 urban components based on ecological network analysis (ENA). Note: The control/dependence relationships between sectors are presented from the production side (matrix column) to others on the consumption side (matrix row)

and 3.5 time bigger, respectively. This implies that city is highly reliant on other economics for energy and a lot of energy was consumed by importing of products and services from outside the city's boundary. The difference between OIA and ENA is that ENA neglects the energy flows that are not controlled by sectors with the city. In this study, ENA results indicate that 78% of the embodied energy of Beijing is adjustable by manipulating the activities of its urban sectors.

It is clear that OIA and ENA have a broader boundary of energy accounting than EFA since they consider energy use embodied in electricity generated and products imported from outside the city. The consideration of energy consumption caused by all urban activities is a more holistic way to assess the energy "metabolism" or "footprint" of city than direct energy consumption [68,69]. In comparison to EFA, OIA and ENA deliver insights from the consumption's perspective and therefore have the potential to be better linked with an environmentally friendly energy planning [4]. In addition to distinguishing controlled energy from embodied energy, ENA is also helpful in locating which sectors in the urban economy control others they connect to. This is essential for recognizing the driving factors of changing urban energy profile and designing urban energy strategies at sectoral level.

Urban form and land use pattern, and impact of urbanization on energy demand are also important issues to be considered when designing urban energy systems [70–72]. There have been studies working on developing an energy structure of compact energy demand and reasonable energy supply to achieve low energy consumption in the urban planning stage [7,8,73]. Unfortunately, current frameworks of IOA and ENA are limited to sectoral level analysis and do not provide indicators that are directly linked to land-use based urban planning. This makes them difficult to be applied to assessing urban planning projects. Future study should work on achieving an environmentally friendly urban energy development by integrating embodied and controlled energy accounting to land use and infrastructure planning of cities.

4. Conclusions

Managing urban energy use is an important task for sustainable socio-economic development in the face of rapid urbanization globally [5,74,75]. In this study, using Beijing as a case study, three accounting approaches, energy flow analysis (EFA), input–output analysis (IOA) and ecological network analysis (ENA) were compared on the basis of their different insights into sectoral and total energy consumption. The EFA results showed that excluding transformation and loss, 34.6 Mtce out of the direct energy input turned into final use for Beijing in 2007. IOA indicated that the total embodied energy of the city was 202.9 Mtce based on 42-sector structure, including direct energy use and indirect consumption from importing products from outside the city's boundary. ENA revealed the integral controlled energy of the city was 159.3 Mtce if the interactions of all 42 sectors were considered. The controlled energy was smaller than embodied energy consumption for all scenarios because that ENA excluded the energy flows that were not integrally controlled by any sectors from the embodied flows. The model structure of the urban economy is also important in both IOA and ENA, given that embodied energy and controlled energy accounted for in 42-sector urban model were nearly 2 times of those in 7-component model. Based on ENA, the driving economic sectors of energy consumption and the control/dependence relationships between sectors were also uncovered. By introducing the new concept of "controlled energy" to the analysis of urban energy consumption, this study will further our understanding of sustainable energy use in cities from all the three perspectives.

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