URBAN ENERGY METABOLISM USING ECOLOGICAL NETWORK ANALYSIS:

CASE STUDY OF FOUR CHINESE CITIES

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ABSTRACT

We develop an ecological network model for urban systems using throughflow and utility analyses. The model uses compartments based on five sectors (energy exploitation, energy transformation, industry, households, and recovery). The trophic levels include energy producers, primary consumers, secondary consumers, and decomposers. The goal is to understand the metabolic system's network structure and the ecological relations (i.e., mutualism, competition, etc.). The structure is derived from the weight distribution in the flow matrix, and the relations from the utility matrix. Four Chinese cities are used as examples (Beijing, Shanghai, Tianjin, and Chongqing). All four cities analyzed show an inverted pyramid structure in that producers were lower in total flow than consumers, which is consistent with the idea of cities as metabolic consumers on the landscape, and opposite to that of ecological systems which are supported by a large amount of producer flows. Regarding the ecological relations, Beijing had the highest mutualism index, followed by Shanghai, Tianjin, and Chongqing. Analyzing the structure and functioning of the urban energy metabolic system revealed suggestions for optimizing its structure and adjusting relationships among compartments, demonstrating how ecological network analysis can be used in future urban system research.

Keywords: urban metabolism; energy flow; network analysis; throughflow; utility analysis

1 Introduction

Cities are complex adaptive systems. Jacobs (1961) was an early pioneer into the study of urban systems as such in which the interconnections and design structure, as much as anything, influenced the socio-economic behavior and the subsequent life

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quality experienced by its inhabitants. She stated that urban planning is a problem in handling organized complexity, and viewed urban dynamics as an intricate and close-grained diversity of uses. In this manner, she was laying the groundwork for comparing urban system function with ecological system function. There has been much research over the past decades investigating organisms (e.g., Brown 1995) and ecosystems as complex adaptive systems (e.g., Patten et al. 2002) and the consequences that has for understanding and managing them. Specifically, one can focus on the energy-matter needs that ecosystems have and the dynamic tendencies they undergo during development. One useful aspect is when we assume that ecosystems are exemplar systems of sustainability, having adjusted, adapted, and persisted during long time periods under varying environmental conditions (which they themselves create). Therefore, a lesson to learn is to apply ecological design principles to urban and industrial systems. This refers to the respect for diversity and the structural patterns that ensure functional properties in terms of energy, matter, and information flows. This application of ecological principles to anthropogenic systems has been termed socio-metabolism to refer to the concept that societies are also ecological and resource dependent and resource consuming systems.

Urban systems concentrate the energy flows from surrounding areas in order to support the intense and diverse activities occurring within them. They are open systems, which continually require replenishment of energy and matter to sustain these activities. They acquire the resources through a complex network of channels delivering everything from food, fuels, water, air, materials, etc., and removing the wastewater, waste heat, solid waste, as well as the finished goods and services for export. With energy as the main driver for ecological and social systems, it is important to understand the energy flows within both. In ecological systems, one finds an abundance of primary producing organisms, whose role it is to capture and import external energy resources into the system. These stored solar energy resources are transformed and transferred to the primary and secondary heterotrophic consumers. The role of decomposers in the ecological system is to utilize remaining energy and provide closure in order to maximize the energy throughflow, cycling, and retention time (Fath et al. 2001). Urban systems have the same need for these energy carrying and transforming sectors. In this study, we apply ecological principles and network analysis to investigate the thermodynamic patterns in four Chinese cities.

2 City as a socio-metabolic system

As urbanization accelerates, energy use in urban areas is expected to increase rapidly. In the 11th Five-Year Plan (2006-2010), China considers reducing the country's energy consumption per unit GDP by 20%. As the main site of energy consumption, cities have become the focus of considerable attention, with the goal of adopting concrete measures to reduce urban energy consumption. At present, the most effective way to identify weak links in an urban energy system is to study energy consumption from the perspective of energy metabolism.

By studying urban energy metabolic processes using network analysis, we can track all the key links in a city's energy metabolism. *Ecological network analysis* is currently one of the main methods for analyzing the interactions between an ecosystem's structure and function. By quantifying the metabolic fluxes, analyzing the relationships between metabolic components, and analyzing the structure and function of the urban energy metabolic system, it becomes possible to define the status and function of the urban metabolic components. Ecological network analysis has been widely applied to study natural ecosystems, but has seldom been used in the analysis of urban ecosystems (Bodini and Bondavalli, 2002; Bailey et al., 2004a, b; Zhao, 2006, Zhang et al. 2010).

In this paper, we develop an ecological network model of an urban energy metabolic system by collecting, sorting, and analyzing the available energy consumption data. The model can reflect the whole process of energy consumption from resource development, exploitation, transformation, and consumption to recovery. Using the model, we developed a new method for studying the internal characteristics of an urban energy metabolic system, with the goal of providing both theoretical and practical methods for optimizing and managing energy in Chinese cities. An extended version of this analysis is published in Zhang et al. (2010).

3 Methodology and data used

3.1 Processes involved in urban energy metabolism

The match between ecological functions and social functions is not isomorphic, but here we assume that the urban system sectors energy exploitation, energy transformation, household and industrial consumers, and recovery represent relevant analogous ecological roles. Specifically, the energy exploitation sector mirrors the primary producers, the energy transformation sector represents the primary consumers, the household and industrial sectors are secondary consumers and the energy recovery sector represents the decomposers as shown in the conceptual model in Figure 1.

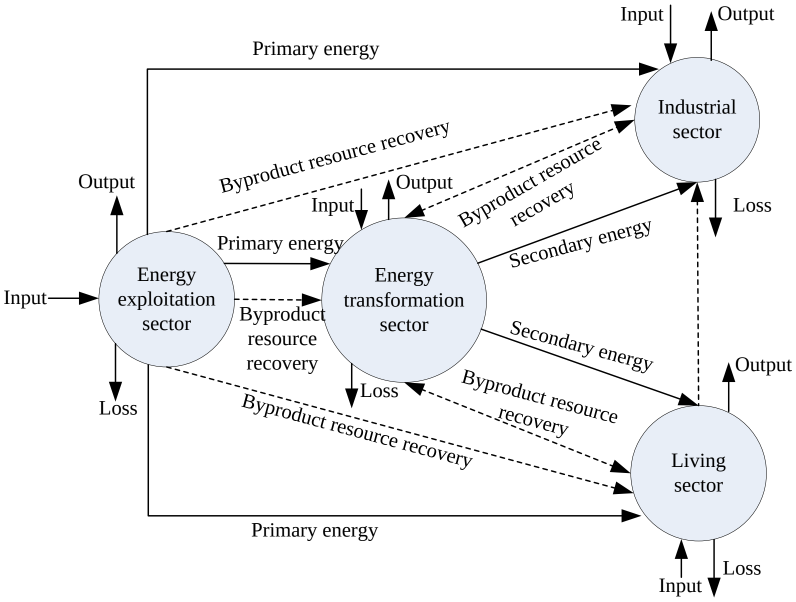

Figure 1. Conceptual model of urban energy metabolic processes.

3.2 Ecological network model of the urban energy metabolism

By analyzing urban energy metabolism processes in the conceptual model, it is determined that the sectors are linked together by a network of 16 flows that reflect the metabolic pathways among these five compartments (Figure 2). According to the direction of the energy flow, all energy flows among compartments can be represented by directional lines that connect the nodes in the network, resulting in an ecological network model for the urban energy metabolism system (Zhang et al., 2009a, b).

Using the standard coal equivalent coefficient (*Co*) values, we converted all energy types that flowed among compartments into standard coal equivalents (kgce), and based on these values, calculated the direct metabolic flows for each compartment in the model. Table 1 presents the resulting matrices for the direct metabolic flows for Beijing (F_B), Shanghai (F_S), Tianjin (F_T), and Chongqing (F_C).

Note that in this diagram, f_{ij} represents the flow from compartment j to compartment i, z_i represents the flow into compartment i from outside of the energy metabolic system, and y_i represents the boundary outflows from compartment i.

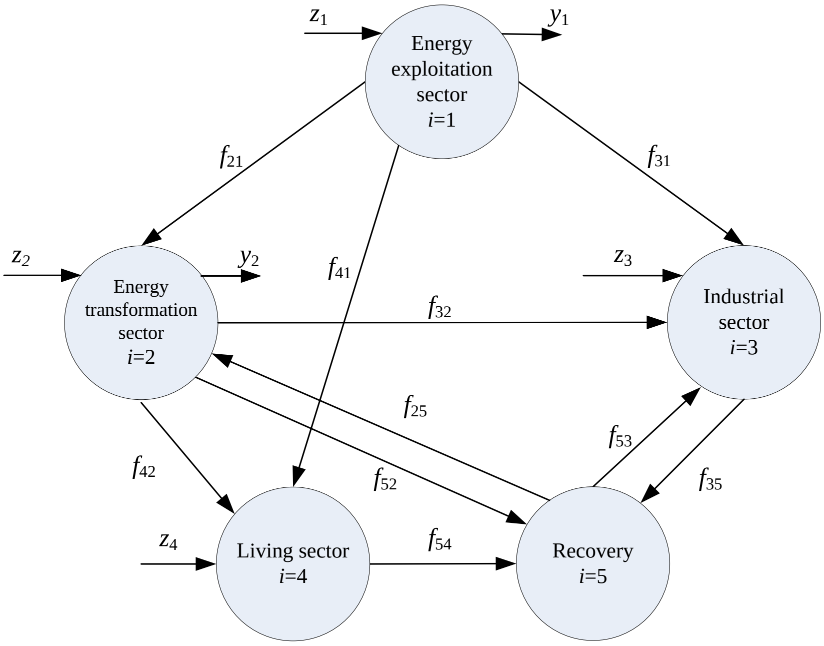

Figure 2. The ecological network model of urban energy metabolism system used in the present study.

Table 1. Matrices for the direct ecological flows among compartments (units: 10^7 t standard coal equivalent). For the five components, the *i* values are in the first column of the table, and the *j* values are across the top of the table.

Beijing (F_B)

	1	**2**	**3**	**4**	**5**	***T***
1	0	0	0	0	0	0.459
2	0.087	0	0	0	0	3.466
3	0	1.929	0	0	0	4.629
4	0	0.080	0	0	0	0.729
5	0	0	0	0	0	0

Shanghai (F_S)

	1	**2**	**3**	**4**	**5**	***T***
1	0	0	0	0	0	0.459
2	0.093	0	0	0	1.036	3.466
3	0.009	2.946	0	0	0.008	4.629
4	0	0.143	0	0	0	0.729
5	0	0.004	1.032	0.008	0	0

Tianjin (F_T)

	1	**2**	**3**	**4**	**5**	***T***
1	0	0	0	0	0	2.916
2	0.517	0	0	0	0.080	6.438
3	0.024	1.045	0	0	0.119	3.107
4	0	0.175	0	0	0	0.369
5	0	0	0.199	0	0	0.199

Chongqing (F_C)

	1	**2**	**3**	**4**	**5**	***T***
1	0	0	0	0	0	3.906
2	1.425	0	0	0	0.082	1.515
3	1.514	0.627	0	0	0.346	3.152
4	0.106	0	0	0	0	0.328
5	0	0.001	0.427	0	0	0.427

3.3 Network utility analysis

Network utility analysis is an ecological network approach that was first introduced by Patten (1991) to express the relative benefit to cost relations in networks. In this method, a direct utility matrix is constructed and used to analyze the network functions (Fath, 2007). From the urban network structure that we derived, we analyzed the mutual relationships between elements of the network. In the network utility analysis, d_{ij} represents the utility of an inter-compartment flow from compartment *j* to compartment *i*, and can be expressed as:

$$d_{ij} = (f_{ij} - f_{ji}) / T_i \qquad (1)$$

where f_{ij} represents the flow from compartment *j* to compartment *i*, f_{ji} represents the flow from compartment *i* to compartment *j*, and T_i is the sum of the intercompartmental and boundary inputs into compartment *i*. From the matrix *D*, which contains all d_{ij} values, a dimensionless integral utility intensity matrix $U = (u_{ij})$ can be computed from the following convergent power series:

$$U = (u_{ij}) = D^0 + D^1 + D^2 + D^3 + ... + D^k + ... = (I - D)^{-1} \qquad (2)$$

where *I* is the identity matrix, u_{ij} represents the integral dimensionless value of d_{ij}, which is calculated using a Leontief inverse matrix, and the matrix *U* represents the intensity and pattern of integrated relations between any of the five compartments in the network (i.e., the utility, u_{ij}).

In network utility analysis, the sign of an element in matrix *U* can be used to determine the interaction pattern between compartments in the network to derive a mutualism index (*M*). The mutualism index of the urban energy metabolic system can be expressed as follows:

$M = J(U) = S_+/S_-$ (4).

Here, $S_+ = \sum_{ij} \max(sign(u_{ij}),0)$ and $S_- = \sum_{ij} (-\min(sign(u_{ij}),0))$ (Fath, 2007; Lobanova *et al.*, 2009). If the matrices have more positive signs than negative signs, this means that the urban ecological system exhibits mostly positive relationships between compartments and thus represents network mutualism (Fath, 2007).

During the analysis of urban metabolic relationships based on the sign distribution and the ratio of the numbers of positive and negative signs in the network utility matrix, we can therefore identify five intercompartmental ecological relationships: competition, exploitation, control, mutualism, and neutrality. Using the results of this analysis, we can identify potential directions for optimizing a city's energy metabolic system toward greater mutualism.

4 Results and Discussion

4.1 Urban metabolic structure

Based on the energy metabolic flows among the compartments, we calculated the integral output flow matrices and the weight matrices for Beijing, Shanghai, Tianjin, and Chongqing, respectively. Based on these results, the role, status, and function of each compartment can be defined.

Chongqing had the highest weight for energy production (compartment 1), followed by Tianjin, Beijing, and Shanghai, which indicates that the city's energy supply capability is high (Figure 3). Beijing had the highest weight for primary consumers (compartment 2), followed by Tianjin, Shanghai, and Chongqing, which means that inputs for the energy transformation sector in Beijing are relatively large. Shanghai had the highest weight for secondary consumers (compartments 3+4), followed by Beijing, Tianjin and Chongqing, which means that Shanghai's energy demand is relatively large. Shanghai had the highest weight for recovery (compartment 5), followed by Chongqing, Tianjin, and Beijing, which reflects the city's relatively strong self-regulation ability. Shanghai had the highest weight for industrial consumption (compartment 3), followed by Beijing, Tianjin, and Chongqing. Beijing had the highest weight for households consumption (compartment 4), followed by Shanghai, Chongqing, and Tianjin.

A healthy structure for an urban energy metabolism should be a clear pyramidal structure, with sufficient energy producers at the bottom of the ecological structure, followed by primary consumers (here, the energy transformation sector), and with a smaller weight of secondary consumers at the top. However, the ecological structure of Shanghai represented an inverted pyramid, and the structures of Beijing and Tianjin represented irregular inverted pyramids. In contrast, Chongqing showed an irregular pyramidal structure, but with producers and secondary consumers roughly in balance, and a lesser weight of primary consumers.

Urban energy metabolism systems change the energy flow patterns since they typically have little self-regulation ability. In the present study, the weight of the decomposers component was ≤5% for all four cities. The proportion of decomposers can reflect the self-regulation ability of such systems, and in terms of the recovery weights, Shanghai had the highest self-regulation ability, followed by Chongqing, Tianjin, and Beijing, which means that Shanghai had the strongest recovery ability and Beijing had the weakest.

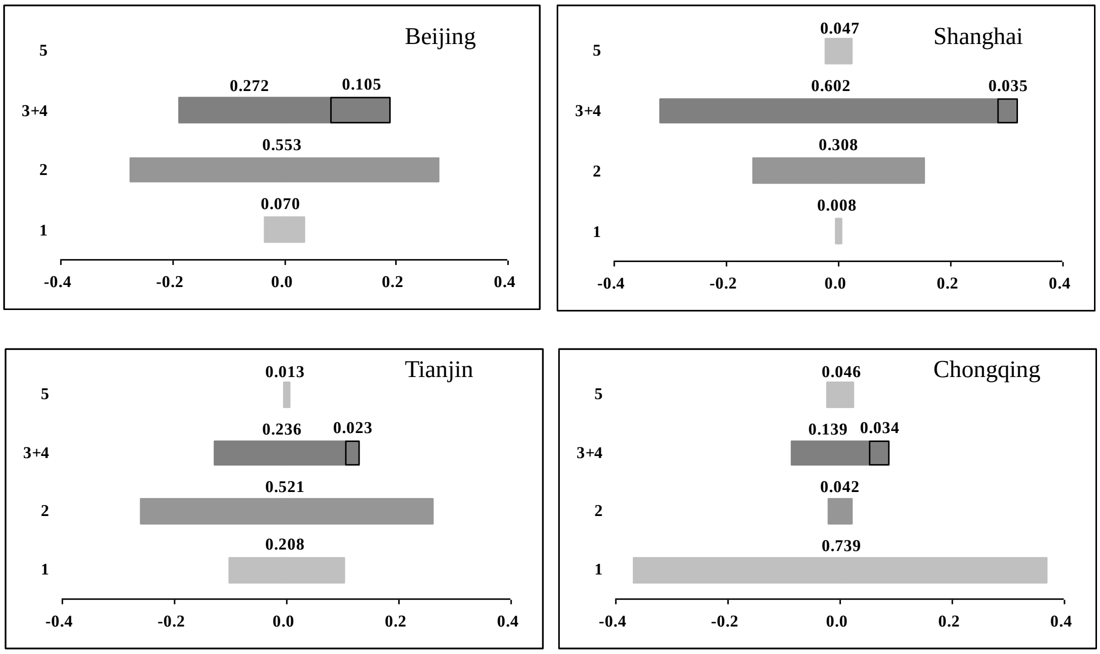

Figure 3. The ecological structure of the urban energy metabolic system for the four Chinese cities used in the case studies. Compartments: 1, energy exploitation sector; 2, energy transformation sector; 3, industrial sector; 4, households sector; 5, recovery sector. The lengths of the bars have been normalized so that each bar or segment of a bar represents the proportion of the total flow (which equals 1.0) for that component.

4.2 Metabolic relationships

Using the metabolic flows among compartments, we calculated the integral utility matrices among compartments for Beijing, Shanghai, Tianjin, and Chongqing (U_B, U_S, U_T, and U_C, respectively) using network utility analysis. Based on the signs of the elements in the U matrices for the four cities, we have also presented the sgn(U) values for each city in Table 2. We have presented this discussion for Beijing to illustrate how the data in Table 2 should be interpreted. Readers can easily use the same approach we have used for Beijing to examine details of the relationships for the other three cities.

For Beijing, the ecological relationship between the energy exploitation and transformation sectors, between the industrial and energy transformation sectors, and between the households and energy transformation sectors, were exploitation, with (su_{21}, su_{12}) = (+, –), (su_{32}, su_{23}) = (+, –), and (su_{42}, su_{24}) = (+, –). This indicates that local energy has been used to meet the demand for secondary transformation of energy, and likewise, the transformed energy was subsequently used in mass consumption by the industrial and households sectors. Increased pressure on the energy supply and transformation results.

Table 2. The integral utility matrices and the corresponding sign matrices for the urban energy metabolic systems of the four cities. For the five components, the *i* values are in the first column of the table, and the *j* values are across the top of the table.

Beijing sgn(U_B)

	1	**2**	**3**	**4**	**5**
1	+	–	+	+	0
2	+	+	–	–	0
3	+	+	+	–	0
4	+	+	–	+	0
5	0	0	0	0	0

Shanghai sgn(U_S)

	1	**2**	**3**	**4**	**5**
1	+	–	+	+	–
2	+	+	–	–	+
3	+	+	+	–	–
4	+	+	–	+	+
5	–	–	+	+	+

Tianjin sgn(U_T)

	1	**2**	**3**	**4**	**5**
1	+	–	+	+	–
2	+	+	–	–	+
3	+	+	+	–	–
4	+	+	–	+	+
5	–	–	+	+	+
6	+	–	+	+	–

Chongqing sgn(U_C)

	1	**2**	**3**	**4**	**5**
1	+	–	–	–	–
2	+	+	–	–	+
3	+	+	+	–	–
4	+	–	–	+	–
5	–	–	+	+	+
6	+	–	–	–	–

The ecological relationship between the industrial sector and the households sector was competition, with (su_{43}, su_{34}) = (–, –), indicating both sectors are vying to utilize primary and secondary energy. This competition between the households and industrial sectors occurred in all four cities, which could create further stress for urban development if energy supplies are not adequately available for both sectors.

The ecological relationships between the industrial and energy exploitation sectors and between the households and energy exploitation sectors for Beijing were (su_{31}, su_{13}) = (+, +), and (su_{41}, su_{14}) = (+, +), reflecting the mutualisms between the industrial sector and local energy exploitation and between the households sector and local energy exploitation; this means that the industrial and households sectors mainly utilize the energy transformation sector.

The ecological relationships between the recovery and energy exploitation sectors, between the recovery and energy transformation sectors, between the recovery and industrial sectors, and between the recovery and households sectors, were neutral for Beijing, with (su_{51}, su_{15}) = (0, 0), (su_{52}, su_{25}) = (0, 0), (su_{53}, su_{35}) = (0, 0), and (su_{54}, su_{45}) = (0, 0), reflecting the lack of a recovery sector in Beijing and the resulting lack of interactions between this sector and the other sectors.

Based on the integral utility intensity matrix (*U*) values, Beijing’s mutualism index (2.20) was higher than that of Shanghai and Tianjin (both 1.78), and much higher than that of Chongqing (0.92). The reason Chongqing’s mutualism index was less than 1 is because of the greater frequency of exploitation relationships between sectors. Thus, the urban energy metabolic processes of three of the four cities reveal an overall degree of mutualism, with mutualism indices greater than 1, but differences in the ecological relationships among the compartments lead to large differences in these indices.

5 Conclusions

Using ecological network analysis, we constructed a simple network model for urban energy metabolism, and used the model to analyze the urban energy metabolic system of four Chinese cities. The approach let us analyze the processes inherent in the urban energy metabolic system from the perspective of energy flows, thereby providing insights into the ecological relationships between compartments of the model. The results show that this method can be used in future studies of other urban systems. The main conclusions from the analysis are: 1) the e*nergy trophic structure* of the four cities was largely inverted, and 2) three of the four cities showed *mutualism relationships*. Furthermore, some of the energy metabolic relationships between sectors were similar for all four cities, whereas others differed.

Based on the detailed insights provided by our results, we have the following recommendations to improve energy utilization by the four cities. Chongqing should improve the energy utilization efficiency of the secondary consumers, whereas Tianjin and Shanghai should restrict the currently excessive development of their energy transformation sectors, and Beijing should adjust its energy structure to promote the utilization of recovered energy, which is currently nonexistent. The cities should all reduce their excessive exploitation of local energy by the primary and secondary consumers, and reduce competition for energy between the industrial and households sectors. They should also reduce the excessive exploitation of the external environment's resources by the industrial and energy transformation sectors, and should promote the recovery of local energy and the exploitation of renewable energy.

Although metabolic paths in urban energy metabolic systems are more complex than the ecological network model developed in this study, the model nonetheless provides a useful way of analyzing the system's main components and their functional relationships. Using throughflow and utility analyses, we revealed the structures of the systems and the types of ecological relationships between their components, and were able to use the results to interpret the problems facing a given urban system and recommend directions for future management. Future optimization of the model should provide a more precise simulation of the complexity of real urban energy systems.

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