Ecological Network Analysis of Urban Energy Metabolism - a Case Study of Fujian Province

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Abstract: This study develops an energy metabolic network to reveal the urban energy system's structural characteristics and identifying the inter-sectoral interactions based on the input-output analysis. A case study of Fujian Province, China, is conducted to illustrate the potential benefits of its use in urban energy metabolism system health diagnosis. It is found that the energy metabolic of Fujian is in the state of sub-health. The energy metabolism model of Fujian Province shows that the Ind sector directly consumes the most energy, reaching $6.57 \times 10^6$ tons of standard coal, but completely depends on the Tsp sector. The Tsp sector, however, consumed only $7.86 \times 10^6$ tonnes of standard coal directly, but it controlled all sectors. In this paper, there are only two interrelationships among the six sectors of Fujian Province, among which the exploitative relationship accounts for 87% and the competitive relationship accounts for 13%. And the Con sector benefits from the services provided by all other sectors, which is not conducive to the development of the Con sector. The results can provide scientific support to guide the improvement of urban energy metabolic system through adjusting energy structures and regulating energy strategies.

1. Introduction

With the evolution of urbanization, rapid economic and population growth, the world's energy demand is increasing rapidly [1]. According to BP's World Energy Statistics Review 2012, China remains the world's largest consumer of energy [2]. The decrease of available energy and the boost of utilization have brought great pressure to every region of our country. Fujian province is a coastal province in the southeast of mainland China, with the second longest coastline in China and developed foreign trade. Energy consumption is excessively dependent on coal, the proportion of clean energy consumption is small, and environmental protection is under great pressure. By calculating the energy expenditure, can help us to know we consume energy based on our needs and technologies [3].

Wolman was the first to come up with metabolism [4]. Many ways used in urban metabolic research. Among all the approaches, the IOA is one of the most powerful tools for uncovering the flow of indirect energy based on intersectoral exchange [5]. Zhang and Zheng et al. determined the energy’s movement process in Beijing, Tianjin, Hebei cluster with IOA method [6]. However, the IOA was unable to explain the energy utilization and complicated relationships in of production products [7]. In addition to IOA, ENA can track the energy utilization process to address the entire...
energy utilization involved in production of intermediate products [8]. Therefore, the combination of IOA and ENA to build a network model is helpful to a more broad and unified considerate of the energy flow in the system. For example, Chen et al. used the NCA to establish a dynamic network approach that can more comprehensively assess the effectiveness of carbon reduction [9].

Although previous studies have found a combination of the two methods. However, the combination methods to debate energy utilization in Fujian Province has not been seen in the earlier paper. Two methods based on ENA theory, NUA and NCA, was used analyze the ecological relationship in Fujian Province. The outcomes can bring reasonable basis for bolster the sustainable progress of energy metabolism in Fujian Province.

2. Methodology

2.1 Compile Input-Output Table

Firstly, merge table in terms of the major sectors. convert a value table to a physical table[10]. As in equation (1).

\[ \varepsilon = Q(Z - V)^{-1} \]  

(1)

Where \( \varepsilon \) means the implied energy coefficient matrix, Q means the matrix of energy used by each sector. \( Z = [z_{ij}]_{n \times n} \), the \( z_{ij} \) value is determined as follows: when \( i = j \), \( z_{ij} = X_i \). Otherwise, \( z_{ij} = 0 \) (\( X \) is the total output vector of the value table). \( V \) is the first quadrant matrix of the I-O table, where \( v_{ii} = x_{ii} \). Combining \( \varepsilon \) with the value table, we can figure out the physical table.

2.2 Ecological network analysis

From the physical tables, the energy flow network is established. \( f_{ij} \) means the energy flow from \( j \) to \( i \). \( z_i \) the flow into node \( i \) from the environs, then defined \( T_i \) (throughflow) as inputs to node \( i \) [11]. As in equation (2).

\[ T_i = \sum_{j=1}^{n} f_{ij} + z_i \]  

(2)

\( T_i^{in}, T_i^{out} \) which represent the total energy flow in and out of each sector [12]. This can be obtained from the ENA as follows:

\[ T_i^{in} = \sum_{j=1}^{n} f_{ij} + z_i \quad i = 1, 2, 3...n \]  

(3)

\[ T_j^{out} = \sum_{i=1}^{n} f_{ij} + y_i \quad j = 1, 2, 3...n \]  

(4)

Where \( y_i \) means the output of sector \( j \). and \( T_j^{in} = T_j^{out} \).

2.2.1 Network utility analysis. NUA assesses the role of each sector in the energy flow. Zhang et al.’s [13] article describes the use of utility analysis in ENA. First, calculate the direct utility matrix \( D \), where the matrix element \( d_{ij} \) means the utility from node \( j \) to node \( i \).

\[ d_{ij} = \frac{f_{ij} - f_{ji}}{T_i} \]  

(5)

Integral utility matrix \( U \) among the sectors in the model can be calculated from the following formula:
The calculation of $U$ is similar to the Leontief inverse. Furthermore, the symbolic matrix (D) and symbolic matrix (U) are established. Each pair of sectors in the matrix has two symbols in opposite directions. The combination of these two symbols judgment the nature of the relationship between sectors. At the matrices, $(+,-)$ means mutualistic relationship, $(-,-)$ for competition $(+,-)$ for exploitation , and $(-,+)$ for exploited relationship.

2.2.2 Network control analysis. NCA introduced description of the control and dependency relationships between paired sectors[11].Therefore, direct flow matrix($G'$, $G$) and integral flow matrix($N'$, $N$) were first defined. As in equation (7) and (8).

$$g_{ij} = \frac{f_{ij}}{T_{ij}}$$ (7)

$$g_{ij} = \frac{f_{ij}}{T_{ji}}$$ (8)

Where $g_{ij}$ is the input-oriented flows from j to i. $g_{ij}$ is the output-oriented flows from node j to node i. $N(n_j), N(n_i)$ can be calculated from the following formula:

$$N' = (I - G')^{-1}$$ (9)

$$N = (I - G)^{-1}$$ (10)

Therefore, two kinds of control metrics, namely control allocation (CA) and dependency allocation (DA), are introduced [14]. As in equation (11) and (12).

$$CA = [ca_{ij}] = \begin{cases} n_j - n'_j > 0, ca_{ij} = \frac{n_j - n'_j}{\sum(n_j - n'_j)} \\ n_j - n'_j \leq 0, ca_{ij} = 0 \end{cases}$$ (11)

$$DA = [da_{ij}] = \begin{cases} n_j - n'_j > 0, da_{ij} = \frac{n_j - n'_j}{\sum(n_j - n'_j)} \\ n_j - n'_j \leq 0, da_{ij} = 0 \end{cases}$$ (12)

Where $0 \leq da_{ij}, ca_{ij} \leq 1$, $ca_{ij}$ means the control level of sector j on sector i, whereas $da_{ij}$ means the dependence level of sector j on i.

2.3 Research objects and data source
Investigate the influences of energy consumption, six energy types are analyzed, including raw coal, gasoline, diesel, fuel oil, LPG and electricity in this study because of the limitations of data. We then divided Fujian Province’s economy into 6 sectors( agriculture(Agr); industry(Ind); construction(Con); transport, storage and post(Tsp); wholesale, retail and catering(Wrc); and other services(Oth)). The input-output table and the energy consumption data are taken from China Statistical Yearbook and China Energy Statistical Yearbook.
3. Results and Discussion

3.1 Throughflow analysis

Table 1. Throughflow matrix F.

| 10^4 tons | f_{Agr} | f_{Ind} | f_{Con} | f_{Tsp} | f_{Wrc} | f_{Oth} | z | T_j |
|-----------|---------|---------|---------|---------|---------|---------|---|-----|
| f_{Agr}   | 70.74   | 460.49  | 12.14   | 20.56   | 11.08   | 24.42   | 283.11 | 882.55 |
| f_{Ind}   | 433.07  | 11502.69| 17.98   | 906.83  | 260.80  | 249.81  | 6569.01 | 19940.19 |
| f_{Con}   | 14.60   | 1772.76 | 33.60   | 222.42  | 37.27   | 41.82   | 176.66  | 2299.13 |
| f_{Tsp}   | 1.57    | 424.42  | 16.71   | 20.56   | 17.67   | 125.62  | 786.21  | 1392.76 |
| f_{Wrc}   | 61.27   | 230.19  | 3.74    | 20.07   | 25.44   | 140.30  | 333.45  | 814.46  |
| f_{Oth}   | 6.16    | 610.05  | 12.69   | 79.13   | 123.36  | 278.34  | 527.07  | 1636.80 |
| y         | 295.14  | 4939.59 | 2202.26 | 123.19  | 338.84  | 776.50  |         |      |
| T_j       | 882.55  | 19940.19| 2299.13 | 1392.76 | 814.46  | 1636.80 |         |      |

Table 1 reveals the energy flows between the six sectors, as well as the energy flows from the external environs into the sector and the energy output from each sector to the outside environs. It can be seen from Table 1 that energy flows exist between the six sectors, and Ind sector’s flow to Con sector is up to 17.7 × 10^6 tons of standard coal, while Agr sector’s flow to Tsp sector is only up to 15.7 × 10^3 tons of standard coal. Table 1 indicates that Ind received the largest amount of external energy inflow, with 65.7 × 10^6 tons of standard coal. Among them, 58% of the energy obtained by Ind is consumed in Ind, and 25% of the energy flows into the final product. Moreover, the energy flow of industrial sector to other 5 sectors is far greater than that of other sectors. However, Con only received 1.77 × 10^6 tons of standard coal from the outside, but it sent out 23 × 10^6 tons of standard coal to the outside. The reason for the above phenomenon is that the industrial sector contains the largest number of sub-sectors and is the pillar industry of Fujian Province, which needs to consume a lot of energy to produce and provide intermediate products for other sectors. For the construction sector, the amount of energy directly consumed in the production process is not much, and most of the energy consumed comes from intermediate products of other sectors.

3.2 Network utility analysis

Table 2. Network utility matrix.

| Agr     | Ind     | Con     | Tsp     | Wrc     | Oth     |
|---------|---------|---------|---------|---------|---------|
| Dimensionless direct utility intensity matrix D |
| Agr     | 0.000000| 0.031069| -0.002780| 0.021522| -0.056866| 0.020685|
| Ind     | -0.001375| 0.000000| -0.088002| 0.024193| 0.001535| -0.018066|
| Con     | 0.001067| 0.763234| 0.000000| 0.089473| 0.014585| 0.012668|
| Tsp     | -0.013638| -0.346366| -0.147699| 0.978873| -0.001724| 0.033384|
| Wrc     | 0.061620| -0.037586| -0.041172| 0.002947| 0.000000| 0.020806|
| Oth     | -0.011153| 0.220091| -0.017794| -0.028406| -0.010353| 0.000000|

| Dimensionless integral utility intensity matrix U |
| Agr     | 0.995949| 0.025543| -0.006091| 0.020784| -0.056866| 0.020685|
| Ind     | -0.001354| 0.927015| -0.083562| 0.015414| 0.001535| -0.018066|
| Con     | -0.000438| 0.672273| 0.925567| 0.099020| 0.014353| 0.003175|
| Tsp     | -0.013543| -0.413815| -0.108663| 0.978873| -0.003535| 0.038424|
| Wrc     | 0.061157| -0.057921| -0.036314| -0.001040| 0.995672| 0.022532|
| Oth     | -0.011647| 0.204135| -0.031330| -0.026397| -0.009733| 0.994591|

Direct utility sign matrix (Sign(D)) and integral utility sign matrix (Sign(U))
Table 2 displays the direct and integral relationships (Sign(D)/Sign(U)) among sectors of Fujian Province, which are isolated by “/”. Table 2 provides the main calculations leading up to these results. The ‘+/−’ signs in the U matrix sporadically vary from those in the D matrix, suggesting that the sector relationship in the two matrices has changed. For example, in direct utility sign matrix, the relationship between Con sector and Agr sector, Wrc sector and Tsp sector is (+, -), and their relationship in integral utility sign matrix is (-, -). This shows that the indirect role of sectors turns the exploitative relationship between them into a competitive relationship. The combination of the two symbol matrices can enable decision makers to have a more comprehensive understanding of the relationship between sectors.

The integral utility sign matrix (U) reveals 15 pairs of sector relationships in Fujian Province. Among them exploitation relationships manage the system, occupy 87% and then competition relationship is up to 13%. The outcomes suggest need to improve reciprocity relationship. In detail, regarding sector Con, it exploits energy flow from Ind, Tsp, Wrc, and Oth, and is in competition with Agr (i.e., reducing Con inputs will indirectly increase inputs of Agr). This is because the raw materials used in the construction industry are supplied by other sectors. Therefore, the formulation of Fujian's energy policy should consider the interrelationship between different sectors comprehensively.

3.3 Network control analysis

The control and dependence situation of the sectors in the energy metabolism network are illustrated in Table 3. In view of network control, the control degree of Agr sector on Con sector, Wrc sector and Oth sector is respectively 69%, 29% and 2%. Ind sector has control effect on other sectors except Tsp sector, and the control ability of Ind sector on Con sector is up to 81%, which is consistent with our troughflow analysis. However, the Con sector has no control over any sector, which means that it benefits from the services of other sectors (i.e. the Con sector exploits other sectors). Table 3 also shows that the Wrc sector has control over only the Con sector, while the Tsp sector has control over all sectors.

In view of network dependence, all sectors rely on Tsp sector, among which Agr sector and Ind sector rely on Tsp transportation sector up to 89% and 100%, indicating that the development of Agr sector and Ind sector cannot be separated from convenient Tsp transportation service, and Tsp sector has restricted the development of other sectors. The dependence of Wrc sector on Agr sector, Ind sector, Tsp sector and Oth sector is 68%, 5%, 19% and 8% respectively. Wrc sector has the highest dependence on Agr sector, which indicates that the development of Wrc sector needs Agr sector's products.

|   | Agr | Ind | Con | Tsp | Wrc | Oth |
|---|-----|-----|-----|-----|-----|-----|
| Control allocation matrix CA |     |     |     |     |     |     |
| Agr | 0.00 | 0.02 | 0.00 | 0.03 | 0.00 | 0.00 |
| Ind | 0.00 | 0.00 | 0.00 | 0.68 | 0.00 | 0.00 |
| Con | 0.69 | 0.81 | 0.00 | 0.26 | 1.00 | 0.94 |
| Tsp | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Wrc | 0.29 | 0.02 | 0.00 | 0.01 | 0.00 | 0.06 |


|       | Oth | 0.02 | 0.16 | 0.00 | 0.00 | 0.00 | 0.00 |
|-------|-----|------|------|------|------|------|------|
| Agr   | 0.00| 0.11 | 0.00 | 0.89 | 0.00 | 0.00 | 0.00 |
| Ind   | 0.00| 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 |
| Con   | 0.15| 0.25 | 0.00 | 0.33 | 0.15 | 0.12 | 0.00 |
| Tsp   | 0.00| 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Wrc   | 0.68| 0.05 | 0.00 | 0.19 | 0.00 | 0.08 | 0.00 |
| Oth   | 0.08| 0.72 | 0.00 | 0.20 | 0.00 | 0.00 | 0.00 |

3.4 Discussion
In the flow analysis: the value of Ind is always the highest, which indicates that the Ind sector shows an irreversible part in developing the energy development in Fujian Province. The amount of energy flowing out of Con is far greater than the amount flowing in. This can be associated to the effects of indirect influences that are vital to each sector but are easily neglected. The pair-wise control effects exist sectors represent that Tsp has not a pillar industry in Fujian Province, it can control other sectors. This shows that the development of Fujian Province is related to each sector. Besides, sectoral relationships in Fujian's Energy System need to change. In general, the development of energy and ecological relations between sectors still faces many challenges, threatening future energy security.

4. Conclusions
This paper examines the impact of sectoral energy flows on energy metabolism and inter-sector ecological relationships in Fujian Province. We have established a network model in conjunction with ENA and IOA to calculate and compare the ecological relationships between different sectors to analyze energy use.

Throughflow analysis shows that the energy flow between various sectors is unbalanced, which leads to the development imbalance of various sectors, thus slowing down the development speed of the Fujian. The NUA indicate that disadvantage of exploitation relations between the sectors, which indicates a need to increase reciprocity relationship. The result of NCA indicates that Ind, the pillar industry of Fujian Province, is totally dependent on the service of Tsp, which seriously restricts the development of Ind sector. According to the analysis results, provide scientific basis for developing the sustainable progress of energy metabolism system in Fujian Province.

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