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# A Method for Evaluating Structural Changes of Energy Flow Process with the Case Study of China from 2005-2015

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In response to climate change and to achieve global sustainable development, countries should accelerate the transition of their energy systems. In order to clearly understand the underlying mechanism of the transition, it is necessary to investigate the structural changes along energy flow processes and find the driving factors. This paper proposes a quantitative method based on energy allocation Sankey diagrams and index including total amount change, relative growth rate and occupation ratio change (TRO) to evaluate the structural changes of energy flow process and presents a case study of China from 2005 to 2015. Firstly, China's energy flow process in 2015 was mapped from energy sources, intermediate conversion, end-use devices, passive systems to final services in the form of a Sankey diagram. Secondly, based on TRO index, this diagram was compared with a previous one of 2005 to reveal and evaluate structural changes in the past decade. Finally, the driving factors of these changes were discussed from different perspectives. The main changes from energy sources level are the reduction of coal and the increase of natural gas, from final services level are the reduction of thermal comfort demand and the increase of structural materials (especially that from chemical industry). The key factors driving these changes are the infrastructure construction of natural gas, rapid urbanization, improvement of energy efficiency of buildings and the people's pursuit of high-quality life.

## 1. Introduction

In recent years, climate change has become a major global issue of general concern to the international community. In order to cope with the problems and challenges brought by climate change, and achieve the goal of sustainable development, all countries should endeavour to control the total amount of $CO_2$ emission, reduce $CO_2$ emission intensity and improve energy efficiency while achieving healthy economic development (IPCC, 2014). To achieve this goal, a series of countermeasures can be taken. Among them, optimizing the energy structure is not only a policy choice to achieve coordinated development of the energy industry, ensure national energy security, but also a measurement to directly and effectively reduce carbon intensity (Wang et al., 2011). Many countries have proposed a package of plans and targets to promote the transition of the energy system. As time goes by, how many of these goals have been achieved, and what changes have taken place in the energy structure need to be systematically analysed.

Before discussing the changes in energy structure, it's important firstly to have a clear overall picture for a country's energy system. Based on this, there will be sufficient evidence regarding structural changes. Sankey diagram (Schmidt, 2008) is one of the effective tools to study energy systems proposed by an Irish engineer named Riall Sankey in 1898. It's popular because it can measure and visualize the energy utilization in an energy system in different parts and sectors. In previous study, Cullen and Allwood (2010) considered the second law of thermodynamics, distinguished energy grades and plotted 2005 global energy allocation diagram. They divided the energy flow process into four sections, showed the overview of global energy flow in detail. Ma et al. (2011) referred to Cullen and Allwood's research on global energy systems to make a more detailed division of China's energy structure and draw the 2005 China exergy allocation diagram which combined the first and second law of thermodynamics and introduced the demand driver. Based on the first law of thermodynamics, Davis et al. (2018) used Sankey diagrams to interpret the energy flow from primary fuel to end use in all of the provinces and territories in Canada for the year 2012.

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Through literature research, it’s found that in the study of energy system based on Sankey diagram, researchers often focus only on the situation of a certain year and lack comparative analysis of structural changes on long-term scales. Part of the reason is that the structure of the energy flow diagram is complex and it’s difficult to analyse structural changes by frequently-used indicators or decomposition methods. Considering this, a new method for systematic analysis of energy Sankey diagram is needed.
Taking the China’s energy system as a case, this study selects two time points in 2005 and 2015, maps the 2015 China exergy allocation diagram and compares it with a previous one of 2005 (Ma et al., 2011). The energy flow process is divided into 5 sub-sections: energy sources, intermediate conversion, end-use conversion devices, passive systems and final services. This is the latest Sankey diagram showing the energy flow process of China’s energy system. Then the TRO index is put forward to analyse the structural changes of Sankey diagram. Finally, conclusions and policy implications are proposed from different aspects.

## 2. Methodology

### 2.1 The framework for systematic analysis of energy flow process

#### 2.1.1 Method of energy measurement-Exergy

The method currently used for measuring energy is enthalpy based on the first law of thermodynamics. The drawback of this method is that it only considers the amount of energy but ignores the differences in grade between different forms of energy. The exergy method used in this study introduces the second law of thermodynamics based on the first law. The energy grade is also taken into account while considering the amount of energy. When calculating the exergy of different energy types, it’s necessary to multiply the energy value measured by the lower heating value (LHV) in the energy balance sheet by a factor to obtain its exergy. Because the exergy contains the energy embodied in water and other vapour generated by fuel combustion, it’s slightly higher than LHV. The specific conversion factor is shown in Table 1 (Saidura, et al. 2007).

*Table 1: The conversion factor from LHV to exergy*

| Energy carrier | Electricity | Oil | Biomass | Gas | Coal | Coke |
|---|---|---|---|---|---|---|
| Conversion factor | 1.00 | 1.06 | 1.11 | 1.04 | 1.06 | 1.05 |

#### 2.1.2 Process of energy flow

This study divides the energy flow process into five sub-sections: energy sources, intermediate conversion, end-use conversion devices, passive system and final services. The concept and scope of each section can refer to the previous study (Ma et al., 2011). The specific structure is shown in Figure 1.

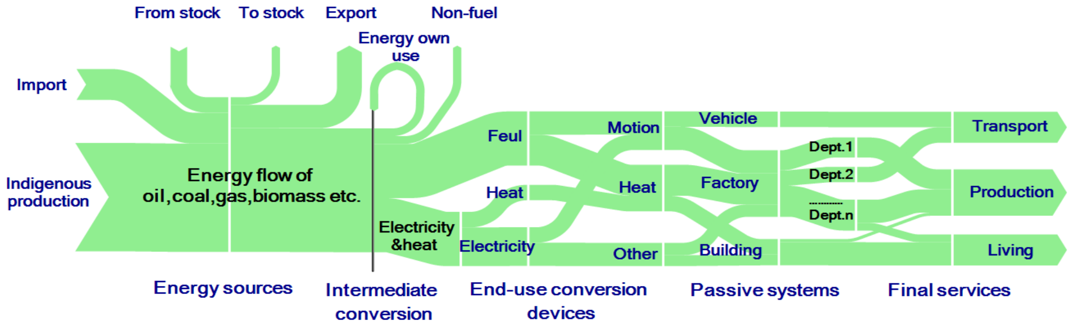


*Figure 1: The framework for analysis of energy flow structure*

The initial sources of energy data are China’s 2015 Energy Balance Sheet (NBSPRC, 2016), 2015 Energy Data (Wang, 2016), 12th Five-Year Plan for Energy Development (CSC, 2013), etc. Referring to this framework, data reflecting the details of China’s energy system in 2015 was calculated and updated. Then 2015 China’s exergy allocation Sankey diagram was mapped.
How should we look at the exergy allocation diagram? Except the clear demonstration of the exergy flow process distinguished in different categories, different departments and different links, one of the great advantages of this map is an effective combination of the three levels of supply-technology-demand: looking from the left side, it’s the distribution of supplies(such as energy sources), from the right side, it’s the distribution of demands (such

as final services), while in the middle is the condition of specific technical departments (such as end-use conversion devices). These are also the key links to be discussed in the following text.

### 2.2 Method for comparison and analysis of energy flow structure-TRO index

In previous work, the energy flow Sankey diagram was mainly used to show an overview of energy allocation in energy systems. The analysis of relevant changes was also focused on the incremental decomposition of a single sector based on statistic while separated from the diagram itself. The analysis of the structural changes of the Sankey diagram itself was still limited. Because there are too many detailed data and complex departments in the energy Sankey diagram from different industries, it’s difficult to analyse them in detail under the same framework. In order to solve this difficulty, this study proposes a method for analysing Sankey diagrams. Using this method, systematic comparison and analysis can be made for each link and part of the Sankey diagram between different years. Three indexes are mainly used as follows.

#### 2.2.1 Total amount change-T

Total amount change (T) refers to the change of the total energy consumption (or total carbon emissions, the same below) in corresponding sections between two years. To a certain degree, total amount change reflects the change in the size of the industry’s production capacity. The calculation formula is Eq(1).

Total amount change=The energy consumption of a certain section in the observed year−The energy consumption of the same section in the base year (1)

#### 2.2.2 Relative growth rate-R

Relative growth rate (R) refers to the ratio of the energy consumption change of a relevant section during the observed years to the base year energy consumption. It can make up for the shortcomings when T index is used for the industry that used to be small and unconcerned but has rapid development in recent years. Therefore, R index also reflects the orientation of relevant policies and changes of market demand to some extent. The calculation formula is Eq(2).

Relative growth rate=Total amount change of a certain section/The energy consumption of the same section in the base year (2)

#### 2.2.3 Occupation ratio change-O

Occupation ratio change (O) refers to the change of the proportion of relative links in the corresponding sector during observed years. It reflects the actual changes of energy flow structure and it’s the actual impact the policies, markets, and technologies have on the energy system structure. The formula is Eq(3).

Occupation ratio change = The proportion of a certain section in the corresponding link in the observed year – The proportion of the same section in the same link in the base year (3)

## 3. Results and discussion

### 3.1 Exergy allocation Sankey diagrams

This study plotted 2015 China’s exergy allocation Sankey diagram as Figure 2, which is the latest Sankey diagram that reflects exergy flow process of China’s energy system.
All the detailed data and departments about China’s energy system are visually displayed in the figure, and the unit is EJ (1E+18 J).

### 3.2 Discussion on the structural changes of the energy flow

Comparing the 2015 China’s exergy allocation Sankey diagram with the previous one of 2005 (Ma et al., 2011), it seems that there is not much difference between the two diagrams intuitively, this just illustrates the necessity of TRO analysis. This study analyses the TRO indicators for each section of the diagram, but only the conclusions of some important sections are discussed here. This manuscript selects energy sources, three passive systems (vehicle, building and factory) and final energy services as research objects. The results of the TRO index decomposition of each section are shown as Table 2 and Figure 3. (The colour of the dots represents the total amount of energy used by related sections in 2015).

#### 3.2.1 The energy sources level

From the perspective of energy sources, although the coal is still the source with the largest amount as well as the largest increase in China (total amount increased by 32.7 EJ), however, its proportion conversely decreased the most (by 6.42 % of O index). It can be seen that the effect of coal reduction work in China during the decade from 2005 to 2015 is very significant. On the one hand, it's related to the national efforts to increase the proportion of natural gas and non-fossil energy consumption, on the other hand, it's also closely related to the industrial upgrading and technological progress of the coal industry itself. Specific technical measures are eliminating old units, promoting clean coal combustion technology, accelerating the development of ultra-supercritical units, and reducing coal consumption per kWh. In contrast, the natural gas has become an important energy source for replacing coal in the transition of China's energy structure (the O index increased by 4.32 %), which is closely related to China's strong investment in natural gas infrastructure construction and deep international cooperation. For example, in 2009, China cooperated with Russia and Central Asian countries to build the first natural gas pipeline for the introduction of long-distance natural gas delivery from Central Asia. In 2013, China-Myanmar natural gas pipeline was established in cooperation with Myanmar, which became the second onshore natural gas pipeline. In the meantime, the liquefied natural gas (LNG) business is also booming, LNG importing countries have expanded from Australia, Indonesia and Malaysia to Qatar and Brunei. The wind power is also worth mention, which has become the energy source with fastest relative growth rate (by 55.7 times) in the decade and contributed a lot of increase of the proportion (increased by 1.1 %). This is related to China's coordination and promotion of wind power development as the second core task of renewable energy development during the 12th Five-Year Plan period (NDRC, 2013), with measurements like accelerating the development of wind power in the central-east region and south region, orderly building the "Three North" large-scale wind power bases, promoting offshore wind power, improving wind power capacity and so on.

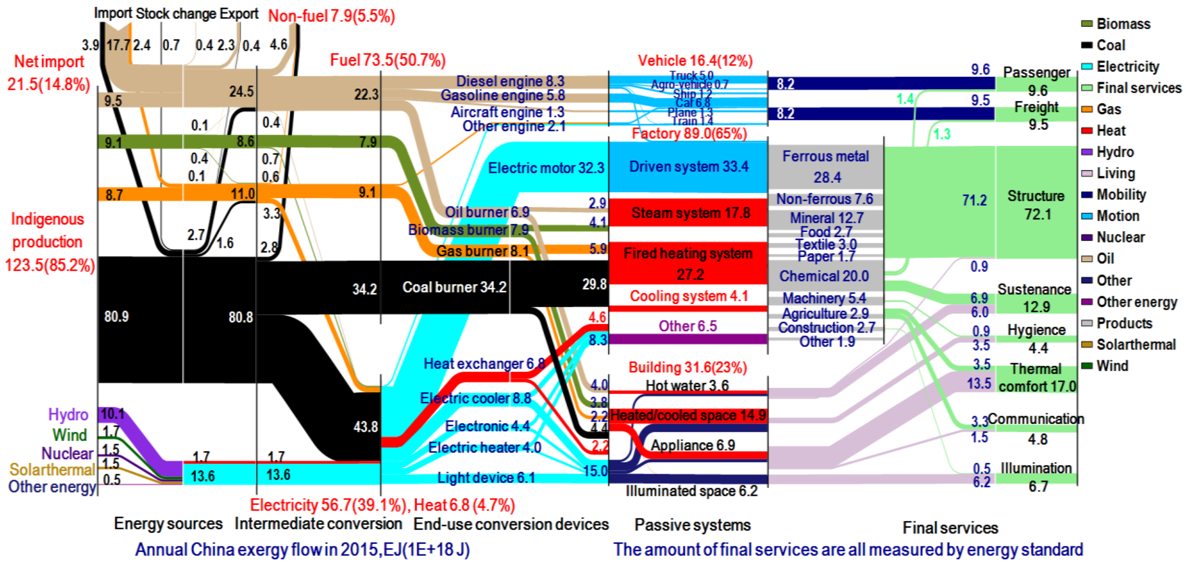


*Figure 2: 2015 China's exergy allocation Sankey diagram*

*Table 2: The TRO index decomposition of relative sections*

| Item | Section | T/EJ | R | O/% | Section | T/EJ | R | O/% | Section | T/EJ | R | O/% |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Energy sources | Oil | 11.4 | 0.72 | -0.83 | Gas | 8.5 | 3.27 | 4.32 | Biomass | 3.4 | 0.60 | -0.78 |
| | Coal | 32.7 | 0.62 | -6.42 | Hydro | 5.5 | 1.12 | 1.23 | Wind | 1.67 | 55.70 | 1.10 |
| | Nuclear | 0.9 | 1.50 | 0.28 | Solar | 1.5 | 5.00 | 0.88 | Other | 0.4 | 4.00 | 0.22 |
| Vehicle | Car | 4.3 | 1.72 | 11.7 | Truck | 1.6 | 0.47 | -10.0 | Agro-V | 0.4 | 1.33 | 0.7 |
| | Plane | 0.8 | 1.60 | 1.9 | Ship | 0.1 | 0.09 | -5.8 | Train | 0.8 | 1.33 | 1.4 |
| Building | Hot water | 2.2 | 1.57 | 4.9 | Cooled/ Heated | 4.5 | 0.43 | -0.9 | Appliance | 1.1 | 0.19 | -5.1 |
| | ILL | 2.2 | 0.55 | 1.1 | | | | | | | | |
| Factory | Steel | 14.1 | 0.99 | 0.3 | Non-Fe | 4.7 | 1.62 | 2.1 | Mineral | 5.3 | 0.72 | -2.0 |
| | Food | 1.1 | 0.69 | -0.5 | Textile | 0.9 | 0.43 | -1.2 | Paper | 0.3 | 0.21 | -1.2 |
| | Chemical | 11.4 | 1.33 | 3.5 | Machinery | 2.5 | 0.86 | -0.3 | Agriculture | 1.0 | 0.53 | -0.9 |
| | Constr. | 1.7 | 1.70 | 0.8 | Other | 0.7 | 0.58 | -0.5 | | | | |
| Final services | PASS | 5.9 | 1.59 | 2.1 | Freight | 3.4 | 0.56 | -1.2 | Structure | 38.1 | 1.12 | 7.4 |
| | SUST | 3.8 | 0.42 | -2.7 | Hygiene | 2.0 | 0.83 | 0.0 | Thermal-CMFT | 4.1 | 0.32 | -4.7 |
| | COMM | 2.0 | 0.71 | -0.2 | ILL | 2.4 | 0.56 | -0.8 | | | | |

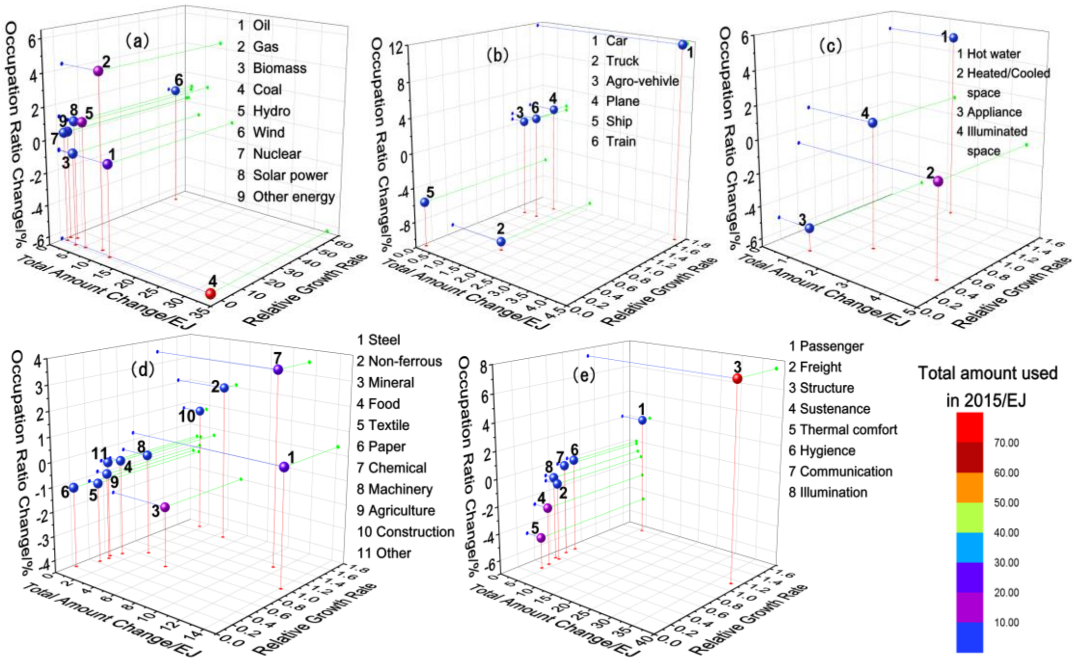


*Figure 3: The TRO index decomposition of 5 sections including (a) energy sources, (b) vehicle, (c) building, (d) factory and (e) final services*

### 3.2.2 The passive system of the vehicle level

From the perspective of the passive system of vehicles, the most significant growth is brought by the passenger car, which has the largest growth in all three dimensions (T increased by 4.3 EJ, R by 1.72 times, O by 11.7 %), while the truck is the department with the most significant reduction. On the one hand, this is due to China's highway infrastructure which has been gradually improved in the past decade (in 2015, the total length of China's highways reached 4.5773 M km, the total length of freeway reached 123,500 km, the proportion of towns with roads reached 99.99 %), and due to the rapidly increase of the number of civilian vehicles (reached 163 million in 2015, which is ten times more than that in 2005). On the other hand, it is closely related to the transition of the economic structure. In 2015, the proportion of increased GDP in the tertiary industry exceeded 50 % for the first time, while the tertiary industry has a smaller proportion of physical goods compared with the primary and secondary industry. The overall freight demand and the growth rate of the road freight industry slowed down in 2015.

### 3.2.3 The passive system of the building level

From the perspective of the passive system of buildings, the most amazing discovery is the remarkable growth of the hot water system (R increased by 1.57 times and O by 4.9 %). At the spiritual level, this is related to a significant improvement of the residents' living standards, the constantly increasing demand for quality of life and the increasing demand for bathing, cleaning, drinking, etc. At the physical level, it is directly related to the continuous improvement of the regional hot water supply system. While the significant reduction comes from the household appliance (O reduced by 5.1 %) which is related to the alternatives of traditional home appliances (such as electric cookers, gas stoves replaced coal-fired and firewood stoves) and the improvement of appliances' efficiency (such as the improvement of air conditioning, refrigerator, etc.).

### 3.2.4 The passive system of the factory level

From the perspective of the industrial passive system, the ferrous metal mining industry is still the sector with the largest total energy consumption and increment (T increased by 14.1 EJ). This is related to the excess capacity inertia of the steel industry, and it is impossible to achieve de-capacity in short term. The chemical industry has become a new leading industry (R increased by 1.3 times, O increased by 3.5 %). The improvement of macroeconomics, industrialization and urbanization have provided a good economic environment for the rapid development of manufacture of raw chemical materials and chemical products. And the significant profit growth of chemical industry (in 2015, the profit increased by 7.7 %, the largest increase in all industrial sectors) brought great opportunities for the development of chemical related enterprise.

### 3.2.5 The final services level

From the perspective of final services, which is also the demand side, the most significant growth comes from structure materials (R increased by 1.12 times, O by 7.4 %) and passenger services (R increase by 1.59 times, O by 2.1 %). The increase of demand for structure materials is closely related to the rapid urbanization process and the rapid development of the infrastructure construction industry in China in the past decade. During 2006-2011, the total output value of the construction industry maintained a super-high-speed growth of more than 20 % for six consecutive years, which became the pillar industry of economic growth. The increase in passenger service demand has been explained previously in the discussion of the passive system of vehicles. In contrast, the thermal comfort and sustenance demands are significantly reduced, which is mainly related to the construction of urban centralized heating pipe network, the replacement of traditional heating methods (such as charcoal fire and firewood heating) and traditional stoves (such as firewood stoves), the improved efficiency of air conditioners and refrigerators, as well as the reduction of proportion of the primary industry. This also reflects the people's life pursuit has risen from food and clothing to high-quality life.

## 4. Conclusions

The framework for systematic analysis of energy flow process based on the Sankey diagram has been developed. A Sankey diagram mapping the exergy flow process of China's energy system in 2015 based on the second law of thermodynamics has been drawn. A method based on the TRO index for comparison and analysis of energy flow structure between different Sankey diagrams has been proposed. Using these methods, the detailed energy flow process of a regional energy system can be clearly depicted and the structural changes during the transition of energy systems can be systematically discussed. The significant conclusion about the structural changes of China's energy flow process from 2005 to 2015 is as follows: from the supply perspective, the proportion of coal was greatly reduced while natural gas became the main energy source to fill this gap; from the demand perspective, the construction and the passenger transport service became two main drivers of the energy consumption and further became the main drivers of the economic growth. In future work, with this method, we can further analyse the allocation of energy-related carbon emission and the change of emission structure.


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