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Article

Spatial Variation and Distribution of Urban Energy Consumptions from Cities in China

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Abstract: With support of GIS tools and Theil index, the spatial variance of urban energy consumption in China was discussed in this paper through the parallel comparison and quantitative analysis of the 30 provincial capital cities of mainland China in 2005, in terms of scale, efficiency and structure. The indicators associated with urban energy consumption show large spatial variance across regions, possibly due to diversities of geographic features, economic development levels and local energy source availability in China. In absolute terms, cities with the highest total energy consumption are mostly distributed in economic-developed regions as Beijing-Tianjin-Tangshan Area, Yangtze River Delta and Pearl River Delta of China, however, the per capita urban energy use is significantly higher in the Mid-and-Western regions. With regard to the energy mix, coal still plays the dominant role and cities in Mid-and-Western regions rely more on coal. In contrast, high quality energy carrier as electricity and oils are more used in southeast coastal zone and northern developed areas. The energy intensive cities are mainly located in the northwest, while the cities with higher efficiency are in southeast areas. The large spatial variance of urban energy consumption was also verified by the Theil indices. Considering the Chinese economy-zones of East, Middle and West, the within-group inequalities are the main factor contributing to overall difference, e.g., the Theil index for per capita energy consumption of within-group is 0.18, much higher than that of between group (0.07), and the same applies to other indicators. In light of the spatial variance of urban energy consumptions in China, therefore, regionalized and type-based management of urban energy systems is badly needed to effectively address the ongoing energy strategies and targets.

Keywords: urban energy system; spatial variance; Theil index; China

1. Introduction

China has great diversities not only in natural and geographical conditions, but also in population density and energy consumption patterns. Also, there is a sharp discrepancy of economic development between China's urban and rural areas, leading to corresponding differences in economic production, and energy consumption. Consequently, a dual structure has been formed in consuming energy resources in China, in which the majority of energy is used by cities. For example, it is reported that energy consumption in the cities in China accounted for 84% of China's total commercial energy usage in 2006 [1]. Particularly, urban residents use 3.7 times as much commercial energy, 5 times as much electricity, and 24.5 times as many oil and natural gas products as rural households, respectively [2]. Therefore, it is undoubtedly that urban energy system plays a predominant role in China's energy consumption profile and would be of great significance in achieving the country's national targets such as energy security and climate change impact mitigation. However, until now, most of the previous studies focused on national energy system, and there has been a great lack in reports on energy consumption patterns in Chinese cities [1–4].

Under the pressures of energy security and GHG emission commitment, China has initiated a number of measures and strategies to facilitate the identification of optimal energy structures in most Chinese cities. Due to spatial and economic diversities, it is normally unreasonable to put forward the same target of reducing energy consumption for all of the cities. Investigation and analysis of the spatial variance in energy consumptions across the entire country are thus necessary to facilitate the restructure energy systems in many cities in order to improve energy security, reduce energy induced air pollution and GHG emission. Therefore, the main objective of this paper is to investigate and analyze the spatial characteristics of energy consumption patterns (*i.e.*, quantity, efficiency and structure) in Chinese cities of certain scale. The provincial capital cities are highly urbanized and economic mostly important in China and they are often viewed as cities that set trends for popular life style and consumption patterns, as well as for new technology and policies. Additionally, these cities also take the lead in the implementation of key policy measures in urban energy [1].Therefore, the 30 provincial capital cities of mainland China were selected as case cities and the spatial variance derived from these case cities is to be discussed with the support of GIS tools and Theil index. Thus, a better understanding of the observed spatial variation and distribution in urban energy consumptions in China will be provided, which could be helpful in facilitating reorganization and management of energy management systems across China [5].

2. Data and Methodology

2.1. Data Description

In China, cites and towns are rather politico-administrative units [1]. There are three commonly used concepts / names associated with cities in China, *i.e.*, *urban built-up areas*, *municipal districts* and *city regions* (covering both the *municipal districts* and other counties under administration of city [6,7]). The existing studies associated with urban systems could hardly clarify what their city boundary referred to, leading to conflicting and incomparable results. In fact, the *urban built-up area* can be an area with established infrastructure and surface buildings, usually referring to urban district with widespread and massive buildings. In terms of the urban function, it is close to the concept of city. In China, the *built-up area* of a city is expanding dynamically and rapidly. Comparatively, energy consumption data in this category is not available. Politically, the *city region* is administrative unit of a city in China, which also includes lots of municipal counties that have large proportion of rural areas besides its municipal districts. The *municipal district* is also an administrative unit but usually covers only the central part of the *city region* with a high level of urbanization. The adoption of *municipal district* as urban scope is a compromising solution in consideration of both data availability and urban function. The 30 provincial capital cities of mainland China except Lhasa (lacking data in Lhasa, the capital of Tibetan Autonomous Region) were chosen as case cities. The data used in this study mainly came from China city statistical yearbook [8], China energy statistical yearbook [9] and the corresponding statistical yearbooks for the 30 cities in 2006, which contain the urban energy information in 2005. The complete urban energy data for the 30 cities with regard to the uban concept of *municipal district* was unavailable. In detail, there were only 6 cities (Beijing, Tianjin, Chongqing, Shanghai, Guangzhou and Jinan) having energy balance tables, which illustrated general energy flow (production to end-use) of a region and are crucial to energy analysis. Other individual urban statistical yearbooks contained incomplete energy information in types for industrial sectors and electricity, gas and heating power data for residential use. The coal data for residential use and information of traffic energy usage were missed and have to be estimated. The former was estimated from the annual expenditure of urban households on purchasing coal, and the traffic energy data were obtained through multiplying the amount of passenger vehicles by per unit energy usage, the value of which was derived from the energy balance tables of the 6 cities mentioned above[10]. All the energy data were converted to standard coal through conversion coefficients provided by China energy statistical yearbook 2006.

2.2. Methodology

The main purpose of this research is to investigate and analyze the spatial difference of urban energy consumption in China with regard to the 30 provincial capital cities with the support of Geographical Information Systems (GIS) tools and Theil index. The first step involved the adoption of GIS mapping technology to represent urban energy consumption indicators in spatial form involving the 30 case cities of mainland China. GIS methods offer the opportunity to direct viewing the spatial difference associated with their consumption pattern on map, in addition to direct comparison of values of the related indicators. Then Theil index for each group was calculated to quantitatively demonstrate these spatial variances from the perspective of energy consumption scale, efficiency and structure of concerned case cities. Compared to other indicators as Gini index, Mean deviation and Atkinson index, the Theil index is an appealing inequality index measuring regional differences, since it can be easily broken down into two synthetic components, *i.e.*, within-group inequality component and between-group inequality component [11]. Alcantara and Duro proposed the use of Theil index to analyze international energy intensity differences among OECD countries, and found that the OECD countries reduced their differences in terms of energy intensity between 1971 and 1999 [12]. In this paper, the basic Theil index can be defined as follow:

$$T(I) = \sum_i y_i \ln(\frac{\bar{I}}{I_i}) \tag{1}$$

where I_i denotes the concerned indicator for city i; y_i stands for the GDP-share for city i; $\bar{I}$ is average value of the measured indicator. On this base, its sub-group decomposition would be computed through the following formula:

$$T(I) = T_B(I) + T_W(I) = \sum_i y_i \ln\frac{\bar{I}}{I_i} + \sum_i y_i I_i = \sum_i y_i \ln\frac{\bar{I}}{I_i} + \sum_i \sum_j y_i \left[y_{ij} \ln\frac{\bar{I}_i}{I_{ij}} \right] \tag{2}$$

where $T_B(I)$ is the aggregate between-group variance component, $T_W(I)$ is the aggregate within-group component, y_i is the GDP share of group i, y_{ij} is the GDP-share associated with city j in group i, $\bar{I}$ denotes average level of the i groups, finally $\bar{I}_i$ is the average of cities in group i. In the light of their locations, the 30 provincial capital cities involved was grouped into 3 categories with regard to the three Chinese economy-zones established in the *Seventh Five-Year Plan* and commonly used in China, *i.e.*, East, Middle, and West.

3. Result Analysis and Discussions

3.1. Energy Consumption Index

3.1.1. Energy Consumption Level

Figure 1 shows the total and the per capita urban energy consumption in 2005, with case cities arranged from left to right in a descending order of value of total energy consumption with regard to their associated groups of East, Middle and West. In addition, Figure 2 is the spatial distribution of total energy consumption on GIS platform, on which the locations of the 30 case cities as well as the three Chinese economy-zones are clearly indicated. There were great diversities both in total and per capita urban energy consumption level among the 30 cities in 2005. In the absolute terms, Shanghai had the largest total energy consumption of 7.04×10^7 tce, which was dozens of times of that of Haikou with a minimum amount of 0.23×10^7 tce. In consideration of spatial variation, cities with the highest total energy consumption are mostly distributed in economic-developed regions as Beijing-Tianjin-Tangshan Area, Yangtze River Delta and Pearl River Delta of China. Nevertheless, some cities located in Middle or West regions had consumed relatively larger amount of energy, one of which is Chongqing. In 2005, the energy consumption in Chongqing was 3.39×10^7 tce, much higher than those of cities in the East as Jinan and Fuzhou.

Figure 1. The total and per capita energy consumption of 30 provincial capital cities in China in 2005.

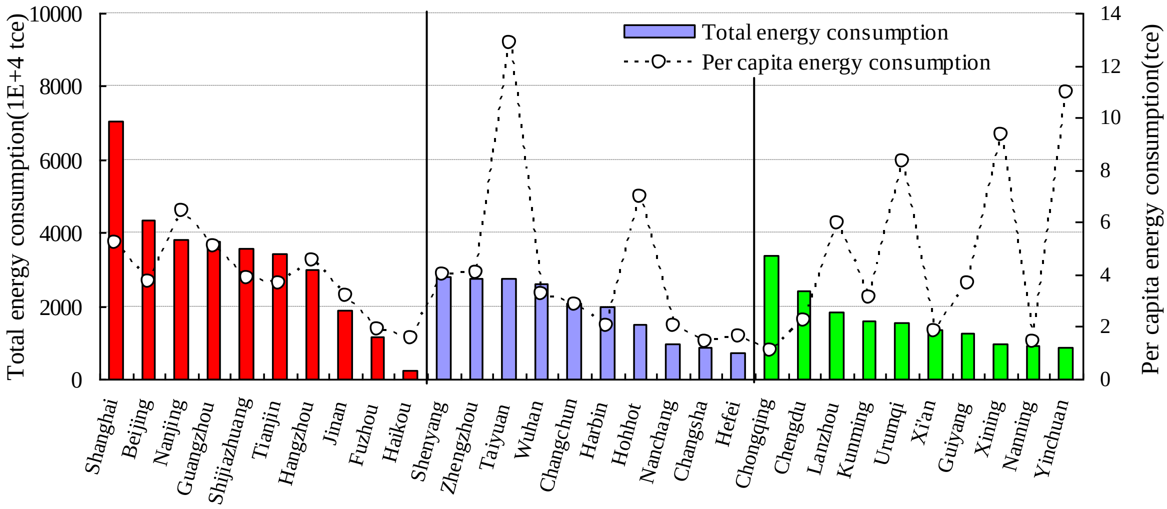
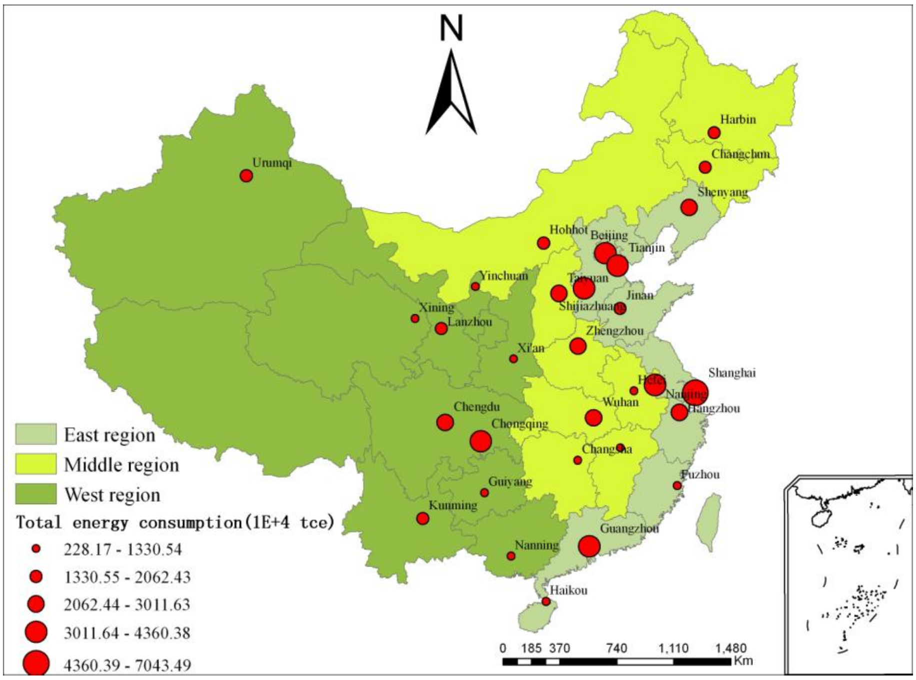
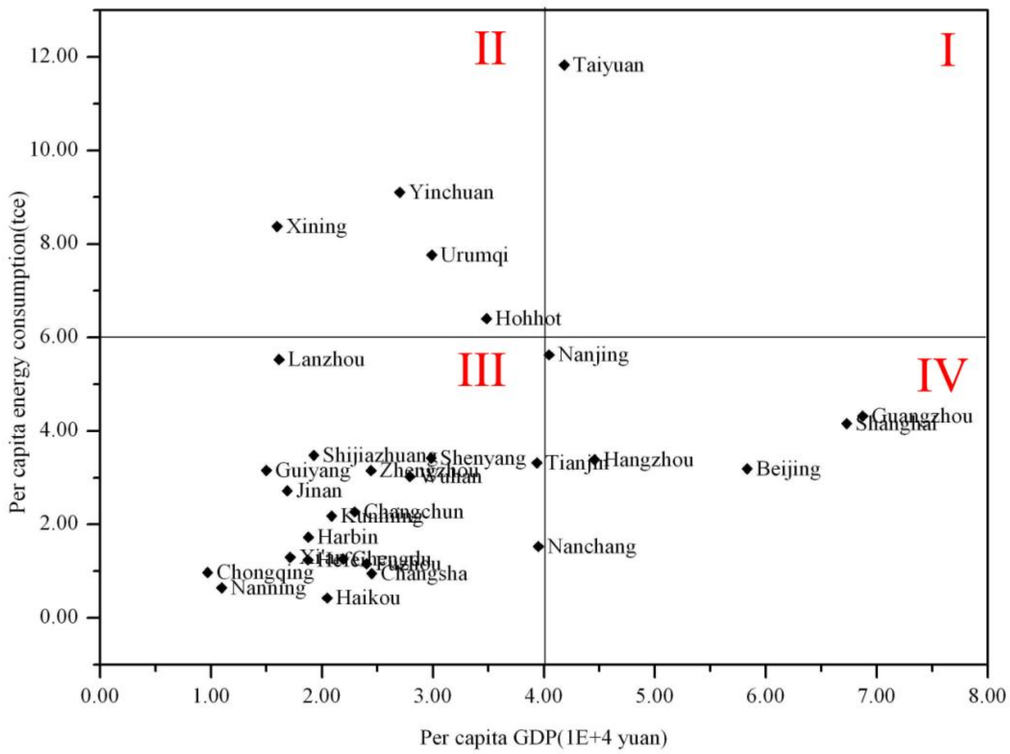


Figure 2. Spatial distribution of total energy consumption of the 30 case cities in China in 2005.



Regarding the quantum of urban energy consumption, per capita rather than total is used in consideration of the disparities of population and administrative area. In the year 2005, the per capita urban energy consumption varied from 1.07 to 12.82 tce among the 30 provincial capital cities of mainland China. Relatively low per capita urban energy consumption is found in Chongqing, Changsha, Nanning, Haikou and Hefei, see Figure 1. Unlike the total energy consumption, the per capita urban energy use is significantly higher in the Mid-and-Western regions. The top 5 cities with high per capita energy consumption are Taiyuan, Yinchuan, Xining, Urumchi and Hohhot, ranging from 12.82 to 7.00 tce, much higher than the average level 3.6 of the 30 case cities considered.

Figure 3. Per capita energy consumption and per capita GDP in 30 case cities in China in 2005.



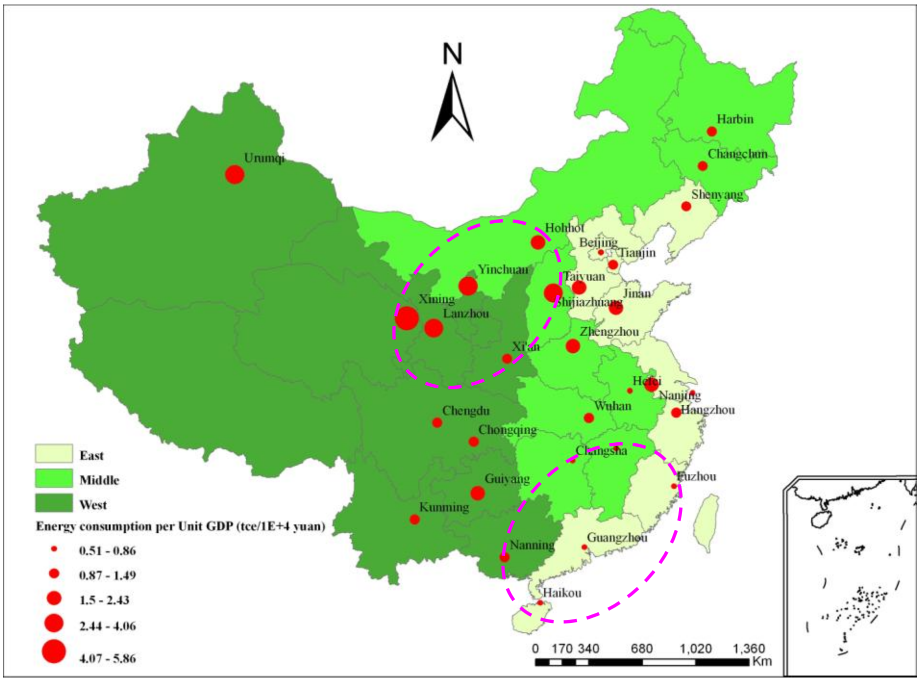
In the comparison of per capita energy consumption and per capita GDP among the 30 provincial capital cities of mainland China, there are evident spatial differences among them. In the schematic diagram associated with per capita energy consumption and per capita GDP (Figure 3.), it can be found that Taiyuan is located in the I quadrant with high energy consumption level and high economic output. In contrast, the II quadrant was occupied by Yinchuan, Xining, Urumqi and Huhhot, with high energy consumption level but low economic output. These cities are all located in northwest less developed areas with energy intensive industrial structure and obsolete technical facilities. Nevertheless, most of the case cities are located in III quadrant, suggesting that both the urban energy consumption and economic development are still in relatively low levels. However, it is worthwhile to note that urban energy demand would inevitably increase rapidly with the speed up of economic development and urbanization, and it is very crucial to control evolvement of urban energy system into right pathway, *i.e.*, ideally low energy consumption and high economic output path adopted by cities like Beijing, Guangzhou and Shanghai.

3.1.2. Energy Efficiency

Concept, definition and the importance of energy efficiency have been widely discussed by many scholars [13–16], which is an important indicator with regard to commercial and industrial competitiveness, energy security as well as environmental benefits [17]. It is one of the criteria for regional performance assessment of the ongoing energy-saving and emission-reduction strategy, which has been actively promoted by Chinese government recently. The energy intensity expressed by energy/GDP ratio is the most commonly used aggregate measure of a nation's or a sector's energy efficiency, although there has been widespread criticism of the use of this indicator for this purpose. This paper also employed this index to roughly assess city's energy consumption efficiency, and the larger the values of this index, the lower the energy efficiency.

As shown in Figure 4, the energy consumption efficiency in term of energy consumption per unit GDP varies tremendously in urban level across China. The average value of energy consumption per 10^4 yuan(¥) GDP is 0.51 tce, for the high-efficient cities ranked before ten among the 30 cities in 2005. In contrast, average value of the most low-efficient cities ranked last ten is 2.62 tce among the 30 cities in 2005. Correspondingly, the maximal and minimum ones were Nanchang of 0.21 tce/10^4 yuan and Xining of 5.25 tce/10^4 yuan respectively. It can also be found that large gaps may also exist between two cities in the same region, for example, Tianjin and Shijiazhuang are both located in Bohai Economic Rim, however, the latter's energy consumption per 10^4yuan GDP in 2005 is 1.8 tce more than two times of that of former. In consideration of spatial distribution, the high and low energy consumption efficiency group are concentrated in southeast and northwest of China respectively, while the middle ones area are mostly in northeast and southwest. As to the cities with higher efficiency in southeast areas, they are closer to the coast and having strong services industries and a relative warm climate.

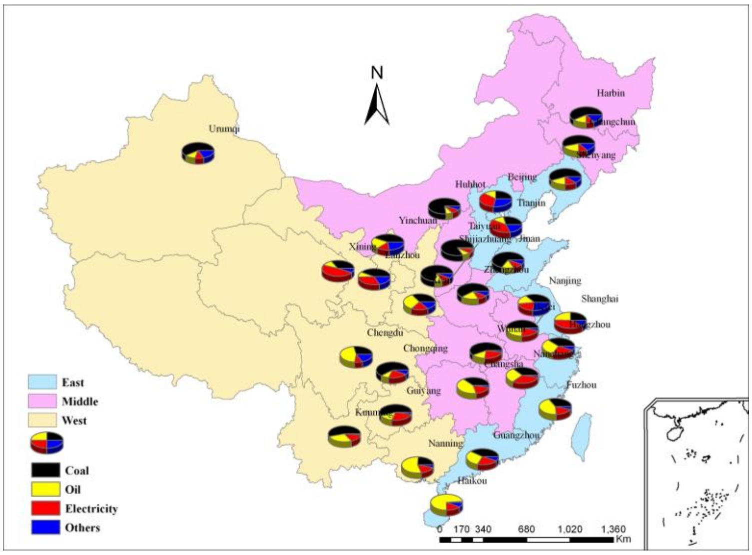
Figure 4. Energy efficiency for the 30 provincial capital cities of mainland China in 2005.



3.1.3. Energy Mix

In this study, the main energy carriers were integrated and reclassified into four categories, *i.e.*, coal, oils (diesel, kerosene, gasoline and fuel oils), electricity and the others (natural gas, coal gas, LPG as well as heat power).

Figure 5. Energy mix for the 30 provincial capital cities of mainland China in 2005.



Regional disparities in the structure of urban energy consumption are also tremendous. Figure 5 shows the urban energy components for the 30 provincial capital case cities of mainland China in the year 2005. The coal still plays the dominant role for most cities, especially for the cities in the north of China rich in coal resources. With regard to the coal proportion, there are 13 cities over 50% and 6 cities below 30%, with the Taiyuan the largest 82.70% while Haikou only 1.18%. Oils are the second major energy resource for urban systems with the average proportion was 23% in 2005, and half of the cities' proportion of oils was above 20%. Electricity accounted for a little smaller proportion than oils in urban energy consumption structure and the average was 21% in 2005. Natural gas, coal gas, LPG and heat power remained a quite low proportion in the urban energy mix, with average proportion for all close to 10%.

(a) Coal

China is a country rich in coal resources, which could definitely affect the China' overall energy mix as well urban sector. As shown in Figure 5, the proportion of coal consumption for the case cities involved presents a spatial trend of higher in north than in south, and west than east, which is well in concordance with the distribution of coal resources in China. Therefore, cities rich in coal resources, e.g., Taiyuan, Huhhot, Shijiazhuang, Jinan, Chongqing and Zhengzhou have a large share of coal use, accounting for more than 60%. In contrast, coal accounts for a relative smaller ratio in southeast coastal area, which possesses a relative diverse energy structure and depend less on coal.

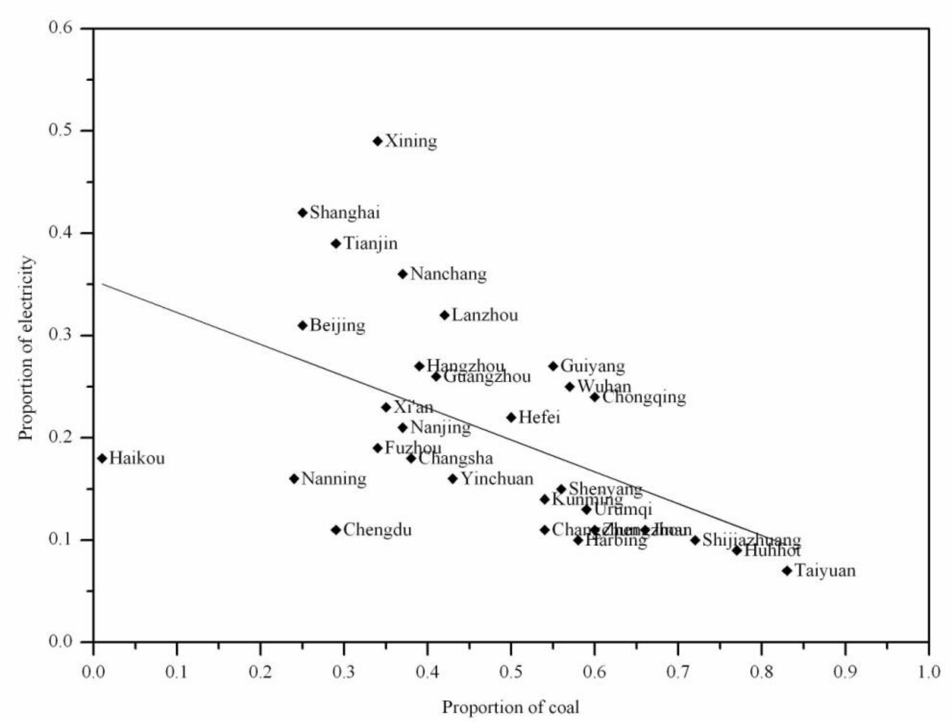
(b) Oil products

In urban areas, oils are mainly used for industrial purpose and traffic vehicles. The cities involved in this study have different oil consumption shares due to diversified industrial structures and different urbanized stages with respect to the holding of motor vehicles. Therefore, the highest proportion of oil consumption is found in Haikou, a city mainly engaged in tourism industry, while the least in Lanzhou, a city with heavy industrial characteristic and largely depending on coal. In fact, the average share of oil consumption among the 30 cities is only 23.33%. In contrast to coal resource, the consumption of oil is not affected by the distribution of petroleum resource but largely influenced by the economic development level. In general, the more developed cities, the more oil consumed, although not necessarily with higher proportion.

(c) Electricity

At first sight of the Figure 5, it seems that there are no discernable distribution rules by geographic region with regard to proportion of electricity. However, it can be found that the spatial distributions of coal and electricity showed a certain converse relationship, which means the proportion of electricity is descending with the ascending of that of coal. The correlation coefficient (r) is 0.52 and the *p*-value is 0.003($p < 0.05$). This relationship is more clear and obvious in coal-dependent cities as Shijiazhuang, Hunhot and Taiyuan. In addition, the developed cities are more likely to use electricity in southeast coastal zone and northern developed areas than the less developed cities in west and middle regions of mainland China.

Figure 6. The relation between the percentage of coal in energy consumption and that of electricity in China provincial capital cities in 2005.



3.2. Theil Index Measure of the Spatial Disparity

3.2.1. Spatial Variance of Urban Energy Consumption Level

In correspondence with the analysis of urban energy consumption level described above, the Theil indices associated with per capital energy use and per household energy use were calculated and presented in Table 1.

Table 1. Theil index for energy consumption level across the 30 provincial capital cities of mainland China in 2005.

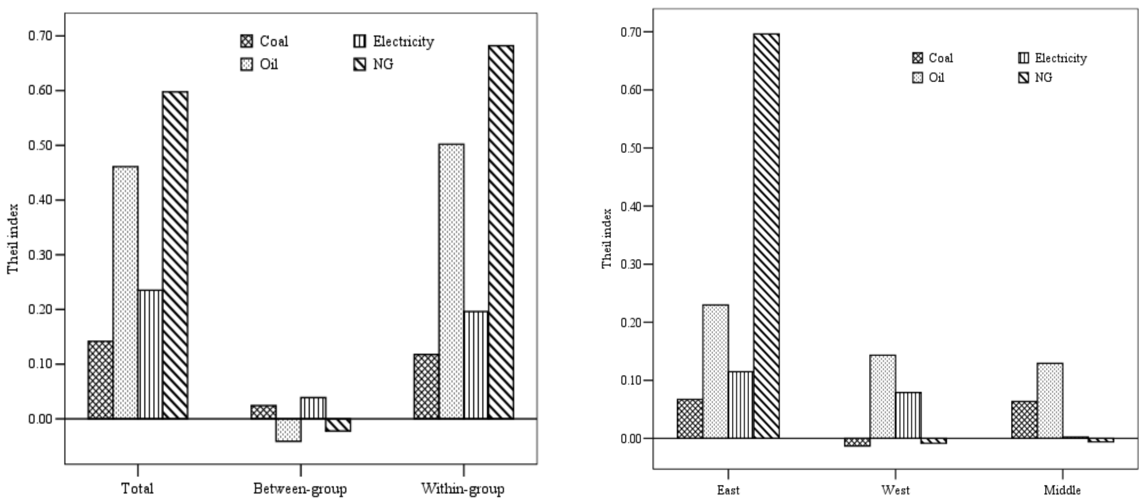
		Total	Between-group	Within-group	East	Middle	West
Per capita energy use	Theil index	0.25	0.07	0.18	−0.06	0.09	0.14
	Contribution (%)	100.00	28.65	71.35	−24.05	37.98	57.42
Per household energy use	Theil index	0.14	0.03	0.11	−0.08	0.05	0.14
	Contribution (%)	100.00	23.29	76.71	−57.34	35.09	98.96

From Table 1, it is evident that within-group differences are currently the most important factor explaining per capita energy consumption level variance across the 30 cities involved in this study, which accounts for nearly 71.35% of total inequalities. The contributions of three groups for within-group difference in order, from high to low, are West > Middle > East, indicating energy consumption level of cities in the same region also varies greatly and West is the one having the largest contribution for overall variance. The average of per capita energy use of cities in West is 5.12 tce, however, the two lowest ones Nanning (1.4 tce) and Chongqing (1.1 tce) do not reach the half of average level and the two highest ones Yinchuan (10.97 tce) and Xining (9.35 tce) are almost two times the average and ten times the lowest level. In addition, great disparity is also found in the per capita household energy use among western cities.

3.2.2. Spatial Variance of Urban Energy Consumption Structure

With regard to Theil index for energy mix, percentages of the coal, oil, electricity and natural gas (NG) were calculated respectively and then Theil indices of each type was obtained and the results are shown in Figure 7 (a) and (b).

Figure 7. (a) Energy consumption pattern variance shown by fuel types; (b) The contributions of three regions for within-group difference with regard to the four fuel types.



Firstly, the overall Theil indices of four fuel types considered are NG (0.6), Oil (0.46), Electricity (0.24) and Coal (0.14), revealing that the consumption of coal and electricity is more balanced than that of oil and NG. Secondly, within-group inequalities are also the main factor behind overall variance (account for nearly 80%). Figure 7(b) presents the decomposition analyses for within-group difference among regions with regard to the four fuel types considered and East group has the most significant contribution for the overall within-group variance. Specifically, the natural gas of East group presents a largest contribution since some of the cities in eastern area have no access to natural gas. It is worthwhile to note that the project of natural gas transmission from West to East is being built to satisfy the natural gas demand in some eastern developed cities areas.

3.2.3. Spatial Variance of Urban Energy Consumption Efficiency

Table 2 Theil index for energy utilization efficiency across 30 case cities in 2005.

	Total	Between-group	Within-group	East	Middle	West
Theil index	0.54	0.22	0.32	0.13	0.06	0.12
Contribution (%)	100.00	41.10	58.90	24.48	11.26	23.16

As shown in Table 2, the Theil index also shows that within-group difference are currently the main driving force for overall spatial variance of energy consumption efficiency. This component accounts for nearly 59% of global difference associated with urban energy efficiency. In addition, the energy intensity variance of West and East group has the larger contribution than that of Middle. However, it is not an easy task to interpret this characteristic in this paper, in view of coupled interactions among industrial structure, resource mix, geographical position as well as lifestyles.

4. Conclusions

The 30 provincial capital cities of mainland China were adopted as case cities to make analysis of spatial characteristics of urban energy systems with regard to energy consumption scale, structure and efficiency. Several concrete conclusions and deductions are drawn as follows:

(1) The indicators associated with urban energy consumption show high diversities and large spatial variances with regard to scale, structure and efficiency. In consideration of spatial distribution, cities with the highest total energy consumption are mostly distributed in economic-developed regions as Beijing-Tianjin-Tangshan Area, Yangtze River Delta and Pearl River Delta of China. Unlike the total energy consumption, however, the per capita urban energy use is significantly higher in the Mid-and-Western regions, and the top 5 cities with highest per capita energy consumption are Taiyuan, Yinchuan, Xining, Urumchi and Hohhot. As to the energy mix, coal still plays the dominant role and cities in Mid-and-West regions rely more on coal while high quality energy carrier as electricity and oils are more used in southeast coastal zone and northern developed areas. The overall consumption efficiency in terms of energy consumption per 10^4 yuan GDP present a spatial pattern of lower in northwest region and higher in the developed coastal areas.

(2) In consideration of decomposition analyses of Theil index for the overall difference among the three Chinese economy-zones, *i.e.*, East, Middle and West, the within-group differences are the

dominant factor contributing to the overall variance for all the indicators of scale, efficiency and structure. It is improper to arbitrarily attribute these to a certain factors before in-depth analysis. Nevertheless, it can be regarded that resources endowment (local availability), economic development (purchasing power) and economic structure (final demand) are important factors having influence on these inequalities.

(3) As far in China, the framework of urban energy management is from top to bottom and based on administrative divisions. The management goal such as energy saving target was assigned compulsorily into administrative areas without considering the regional disparities. Therefore, regionalized and type-based management of urban energy systems is badly needed in light of the spatial variances of urban energy consumption in China. This highlights the fact that these urban regions with higher energy consumption deserve considerable attention for better technology, more investment, and improved urban energy system and infrastructure.

(4) The study also suffered from the unavailability and incomplete of energy data of cities, which is very essential for in-depth analysis. There is a large scope to improve and carry out for further detailed as a follow-up of this study, since this is an area that is less-studied but badly needed.

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