Decrease in urban energy intensity: Is there a role for urban spatial structure?

Yong Liu1 | Cuihong Long2

1School of Economics, Sichuan University, Chengdu, China
2School of Economics, East China Normal University, Shanghai, China

Abstract
Using satellite remote sensing data and the threshold panel model, this research explores the impact of urban spatial structure on urban energy intensity. The evaluation index of urban spatial structure includes compactness and elongation rate. Results from empirical studies of 30 cities in China from 1996 to 2016 indicate that urban spatial structure has a significant impact on urban energy intensity. There is a positive correlation between urban spatial structure elongation rate and urban energy intensity. However, with the increase in urban fixed assets investment, there is a negative correlation between elongation rate and energy intensity, which implies an inverted-U relationship. The results also indicate that urban compactness is negatively correlated with urban energy intensity. Therefore, proper management of urban spatial structure can effectively promote the reduction in urban energy intensity. The elongation of urban suburb space and the compactness with the internal space of the city can be developed simultaneously. While playing the role of a spatial agglomeration economy, the negative effects of over agglomeration are avoided, which jointly promote the reduction in urban energy intensity.

KEYWORDS
China, energy intensity, energy policy, urban environment, urban form

1 | INTRODUCTION

Energy intensity can be defined as the ratio of energy consumption to output. Higher energy intensity means lower energy efficiency. Therefore, with the rapid development of science and technology, energy intensity should generally show a downward trend. However, because of the differences in levels of technology and in the energy structures of specific regions, energy intensity exhibits different trends. Decreasing energy intensity and improving energy efficiency is one of the main objectives of energy policies in many countries.

Especially for large energy-consuming and energy-intensive country such as China, the reduction in energy intensity is of great significance. In fact, the Chinese government has formulated many policies to reduce energy intensity. These policies include the development of new energy technologies, new energy vehicles, and financial support policies.

The reduction in energy intensity is affected by a variety of factors including industrial structure, technology level, and energy structure, which are intertwined with a range of guiding policies. However, aside from these factors, does the spatial structure of specific regions affect energy intensity? What kind of spatial structure should be designed to promote the reduction in energy intensity?

This study aims to analyze these problems. Taking the cities of the provincial capital and municipalities directly
under the central government of China as a case, a quantitative analysis of the relationship between the spatial structure of Chinese cities and their energy intensity is carried out using remote sensing and panel data analysis methods. The conclusion will help put forward a guiding policy to promote the reduction in energy intensity from a perspective of urban spatial structure management.

2 | LITERATURE REVIEW

Energy intensity has been studied extensively in the existing literature. The literature review can be divided into three sections based on the research content of this study.

First, many studies have analyzed the factors that influence energy intensity. (a) Income and capital. For example, research has explored the capital-energy substitution effect that causes a decline in energy intensity in China. Energy intensity, determinants, and trends have also been studied in Iran, suggesting a relationship between energy intensity indices and income, as well as a capital-output ratio. (b) Economic structure and urbanization rate. According to Dong et al., economic structure and urbanization rate are the determining factors for the increase in energy intensity, whereas R&D investment reduces it. (c) Technological factors. Research also indicates that technological factors, such as information and communication technology, have a significant impact on energy intensity. (d) Geographical factors and population. It is interesting to find that geographical location and city population size have a significant impact on energy intensity in China, which partly echo the result of Mahmood and Ahmad. European countries have been able to economize on the use of energy due to stable, and in some cases declining, populations.

Secondly, existing research has also analyzed policies for reducing energy intensity. Huang, Du and Tao recommend to consider the characteristics and situations of technology spill overs to decrease China's energy intensity. Meanwhile, Soni, Mittal, and Kapshe analyzed policies to reduce India's energy intensity. Other related policies also have been proposed, including an increase in energy prices, R&D investment, and industrial concentration. A decrease in state-owned enterprises may reduce the energy intensity of the industry. Previous literature also suggested policies for reducing energy intensity in specific sectors. For example, for the road transportation sector in Thailand, Winyuchakrit and Limmeechokchai proposed traffic control for different vehicles as a means of reducing energy intensity.

Other noteworthy research focused on a method for energy intensity calculation. For example, Alghandoor et al. used multivariate regression analysis to analyze the decomposition of aggregate energy intensity in the U.S. manufacturing industry. Structural Decomposition Analysis (SDA) requires a greater amount of data, whereas the Index Decomposition Analysis (IDA), being less complicated and more flexible, is a more popular method. Zaim, Gazel, and Akkemik consider all inputs used in production and correct the bias in traditional energy intensity measure. A restricted VARX model, a data envelopment analysis, the Malmquist index approach, the autoregressive distributed lagged model, and a panel augmented mean group were also used.

The literature review points to a lack of empirical research regarding the relationship between the urban energy intensity and urban spatial structure, particularly in China. One of the contributions of this study, therefore, is providing an analysis of the impact of the urban spatial structure on the urban energy intensity. Another contribution of this study is providing an analysis of energy intensity using a combination of GIS and remote sensing technologies with a threshold panel analysis model. Therefore, the aim of this study is to analyze the issue by employing indicators for urban spatial structure and urban energy intensity. The findings provide valuable information for energy policy-making to decrease urban energy intensity through urban spatial structure management.

3 | METHODOLOGIES

3.1 | Theoretical framework and research hypotheses

Economic theories related to energy intensity indicate that geographical location and city population size have a significant impact on energy intensity, which partly echoes the results of Mahmood and Ahmad. The agglomeration of population and other factors of production in cities can produce a positive agglomeration effect, such as transaction cost savings. In particular, agglomeration can improve the energy efficiency of cities, for example, through sharing energy infrastructure. We, therefore, propose the following hypothesis:

Hypothesis 1: Urban compactness is negatively correlated with urban energy intensity.

Given a continuous concentration of population, the scale of urban space will gradually expand. Continuous urban spatial structure elongation accompanied by a large number of urban infrastructure constructions, especially by the expansion of urban traffic networks, will lead to the consumption of a large amount of energy. In addition, in a new urban area, the economic effect takes some time, which leads to an increase in urban energy intensity. However, with the gradual development of new urban areas and the agglomeration of various factors of production, an economy can grow and achieve positive spatial agglomeration effects, and the energy...
intensity of the city can decrease. The relationship between urban spatial elongation and urban energy intensity has a dynamic trend. This research therefore proposes a second hypothesis.

Hypothesis 2: There is an inverted-U relationship between the urban spatial structure elongation rate and urban energy intensity.

3.2 | Urban energy intensity

This study is based on data from 30 provincial capitals and municipalities in China. Lhasa and Taipei are not included because of missing data. Evaluation indicators for quantitative analysis of urban spatial structure were designed using remote sensing technology to collect urban spatial structure data. The panel data model was then used to analyze the mechanism of urban energy and urban spatial structure.

There are 2 commonly used methods of computing energy intensity: (a) energy consumption per unit of gross domestic product (GDP), and (b) energy consumed per unit value. Considering the instability of the output value as a benchmark, the unit GDP energy consumption is used to calculate energy intensity. The index decomposition method represents a complete analysis for exploring the trend of energy intensity. This research used the Logarithmic Mean Divisia Index (LMDI) method. According to findings of Ang,21 the LMDI method has 4 characteristics: (a) the result of factorization does not have unexplained residual terms, (b) the decomposition results have addition characteristics, (c) the sum of the effects of the sector is consistent with the total effect, and (d) the results obtained by multiplicative decomposition and additive decomposition can transform each other. The calculation formula is as follows:2:

\[
EI_i = \frac{E_i}{Y_i} = \sum_i \sum_j E_{ij} Y_{ij} E_{ij} Y_{ij}
\]  

\[
(1)
\]

\[EI_i = \frac{E_i}{Y_i} = \frac{\sum_i E_{ij}}{Y_i}
\]  

\[
(2)
\]

EI, is the energy intensity of a city in t year. Ei is the total amount of energy consumption in a city in t year. Eij is the energy consumption for the sector in t year. Ej is the energy consumption j in the i sector. Yi is the GDP of a city in t year, and Yij is the outputs of i sector in t year. When calculating the energy intensity of each city, the formula is simplified (t = 1):

\[
EI_i = \frac{E_i}{Y_i} = \frac{\sum_i E_{ij}}{Y_i}
\]  

\[
(2)
\]

The data used in this research are GDP, the total amount of electricity consumption, gas (artificial and natural) supply, and the total amount of liquefied petroleum gas supply of 30 cities in 1996, 2000, 2007, 2010, and 2016. According to the definition of energy intensity, GDP was chosen as an index. Other indexes were selected on the basis of (a) the major components of urban energy consumption and (b) data availability. Data on urban energy statistics are scarce in China and available energy data are also limited.

Data were taken from China urban statistical yearbook. To ensure the uniformity and comparability of statistical results, according to the general principles of comprehensive energy consumption calculation,22 different types of terminal energy consumption were converted to standard coal.23 Power conversion coefficient = 1.229. Coal gas conversion coefficient = 6.143. Liquefied petroleum gas conversion coefficient = 1.7143.22

3.3 | Urban spatial structure

No recognized indicators for measuring urban spatial structure were identified and thus indicators are open to varying interpretations. Therefore, 2 indicators representing urban spatial structure were chosen. The spatial structure elongation ratio (SE) measures the extended degree of a city:

\[
SE = \frac{LA}{SA}
\]  

\[\text{(3)}\]

LA is the long axis of a city and SA is the short-axis of a city. Meanwhile, Cole23 proposed a method for measuring spatial compactness (SC) based on the following formula:

\[
SC = \frac{U}{C'}
\]  

\[\text{(4)}\]

U represents the urban area and C’ represents the smallest circumscription of the city. Because of the strong feasibility of the 2 indicators, they have been successfully used in many studies.24 An urban area is defined as that within the urban land boundary, based on Landsat images and thematic maps. ERDAS IMAGING 9.1 and ArcGIS9.3 were employed for data processing. Figure 1 presents examples in Tianjin and Taiyuan.

3.4 | Threshold panel model

The impact of urban spatial structure on urban energy intensity is not always the same. At different points in time, there may be different effects. As proven by existing literature, urban spatial agglomeration can bring about agglomeration economies.25,26 However, the continuous increase in agglomeration could also result in uneconomic agglomeration.27,28 Therefore, to effectively analyze the different effects of various stages of urban spatial structure on urban energy intensity, this paper adopts the threshold panel analysis model.29 This model can effectively classify the core variables and their phased effects on dependent variables, which has been successfully used in many fields of research.30-32 First, the model needed to set the threshold variable and the indicator function. The choice of the threshold variable was based on both theoretical and empirical bases. The alternative threshold variables were usually
determined by theoretical analysis, and then, the threshold variable was determined by calculation. Next, the panel regression equation was constructed. The whole calculation process could be executed using econometric software such as Stata. A more detailed exposition of the calculation process can be found in the research of Wang.\textsuperscript{33} 

\[ y_{it} = \alpha_i + \beta_1'x_{it}U(z_{it} \leq \gamma) + \beta_2'x_{it}U(z_{it} > \gamma) + \mu_{it}, \quad i = 1 \ldots N, \quad t = 1 \ldots T \] 

\( y_{it} \) denotes the size of the cross-section (30 cities) and \( t \) (1996, 2000, 2007, 2010, and 2016) denotes the dimension of time series, \( \alpha_i \) is a scalar, \( \beta_1 \) and \( \beta_2 \) are \( k \times 1 \) coefficient and vectors, \( \beta_1' \) and \( \beta_2' \) are the transpose of \( \beta_1 \) and \( \beta_2 \), \( x_{it} \) is \( 1 \times k \) vectors of observations of the independent variable, and \( y_{it} \) is the observation of the dependent variable for individual \( i \) at time \( t \). \( z_{it} \) is the threshold variable and \( U(.) \) is the indicator function. \( \mu_{it} \) represents the effect of other factors that are not only unique to individual units, but also to time periods, and that can be characterized by an independently and identically-distributed random variable with zero mean and variance (\( \sigma^2 \)). The construction of an urban spatial structure is a long-term process that undergoes change slowly, so taking measurements at an interval of every few years ensures that there is sufficient variation for identification.\textsuperscript{34} Furthermore, depending on the image quality and cloud cover, 30 Landsat TM/ETM+ images for each of the five years (1996, 2000, 2007, 2010, and 2016) were used.

In addition to the 2 key variables for measuring the urban spatial structure, this research also adds control variables. The selection of control variables was based on theoretical and empirical research as well as the availability of data. There is a close relationship between industrial development and energy consumption. Especially with the development of secondary industry, energy consumption usually increases gradually. The proportion of employees in a secondary industry is a variable that can represent the scale of the secondary industry. Moreover, industry is a key economic sector that consumes energy in China.\textsuperscript{35,36} Therefore, the proportion of employees in the secondary industry (%) was selected as a control variable. According to the definition of energy intensity,\textsuperscript{20,21} energy-processing conversion efficiency is a variable that directly affects the efficiency of energy consumption and energy intensity. Thus, the energy processing conversion efficiency (%) was selected as a control variable. Investments will stimulate economic development, and then affect the energy consumption of the industry. In China, the total investment in fixed assets indirectly stimulates energy consumption by stimulating investment in fixed assets, which then affects the energy intensity.\textsuperscript{37,38} Finally, control variables include the proportion of employees in the secondary industry, the energy-processing conversion efficiency, and the total investment in fixed assets.

4 | RESULTS AND DISCUSSION

4.1 | RESULTS

According to data from China’s urban statistical yearbook, calculation results indicate that urban energy intensity has generally been declining. The average value of urban energy intensity decreased from 1.83 in 1996 to 0.09 in 2016. The gap between the energy intensity of each city is narrowing. Furthermore, the range value declined from 6.66 in 1996 to 0.14 in 2016, and the standard deviation value decreased from 1.34 in 1996 to 0.04 in 2016 (Table 1).

The calculation results of urban spatial structure indicate that the urban space is evidently expanding. The spatial elongation results show that the mean increased from 1.67 in 1996 to 9.13 in 2016. Meanwhile, the degree of expansion of different cities has obvious differences. For example, standard deviation expanded from 0.61 in 1996 to 14.85 in 2016 (Table 2). Data sources of other variables include China’s urban statistical yearbook and China Statistical Yearbook. The conversion efficiency of energy processing is based on the average data of various provinces and municipalities. The result indicates an increasing overall trend.

On the basis of the theory of energy economics and numerous computer experiments, the total investment in fixed assets was identified as a threshold variable. In fact, the most important driving force in the change in urban spatial structure is the promotion of investment in China,\textsuperscript{39} such as in...
the construction of various infrastructure. \(^{40}\) Urban spatial extension rate was identified as a core variable and calculation results show that the choice of threshold variables is significant \((P = 0.1)\) (Table 3). The value of the threshold can be used to determine the reasonable scale of urban fixed asset investment, providing a reference for the expansion of urban space.

The results also indicate a significant positive correlation between urban spatial elongation and urban energy intensity. However, after a particular degree of investment in urban fixed assets, there is a significant negative correlation between urban spatial elongation and urban energy intensity. Thus, the impact of urban spatial structure on urban energy intensity has a threshold effect (Table 4).

To test for multivariate outliers, the Mahalanobis distances of the predicted variables were used. The maximum absolute values of the skewness and kurtosis for the variables were below 2 and 8, respectively, which were acceptable. \(^{41}\) The Durbin–Wu–Hausman test of endogeneity \(^{42}\) also indicated that the variables were not endogenous. Variance inflation factors were used to test for multicollinearity and the results were below 7, which were acceptable. \(^{43}\)

### Table 1
Descriptive statistics for urban energy intensity

|    | Range | Minimum | Maximum | Std. Deviation | Mean |
|----|-------|---------|---------|----------------|------|
| 1996 | 6.66  | 0.62    | 7.28    | 1.34           | 1.83 |
| 2000 | 0.41  | 0.12    | 0.53    | 0.12           | 0.24 |
| 2007 | 0.95  | 0.07    | 1.02    | 0.22           | 0.21 |
| 2010 | 0.31  | 0.06    | 0.37    | 0.07           | 0.14 |
| 2016 | 0.14  | 0.05    | 0.19    | 0.04           | 0.09 |

### Table 2
Descriptive statistics for variables

|                | Range | Minimum | Maximum | Std. Deviation | Mean  |
|----------------|-------|---------|---------|----------------|-------|
| Spatial elongation (SE) |       |         |         |                |       |
| 1996           | 3.03  | 0.99    | 4.02    | 0.61           | 1.67  |
| 2000           | 2.95  | 1.06    | 4.01    | 0.65           | 1.77  |
| 2007           | 15.38 | 1.61    | 16.99   | 3.17           | 4.07  |
| 2010           | 4.07  | 1.03    | 5.10    | 0.71           | 1.61  |
| 2016           | 82.51 | 1.86    | 84.37   | 14.85          | 9.13  |
| Spatial compactness (SC) |       |         |         |                |       |
| 1996           | 0.44  | 0.05    | 0.49    | 0.11           | 0.20  |
| 2000           | 0.27  | 0.07    | 0.34    | 0.07           | 0.18  |
| 2007           | 0.35  | 0.09    | 0.45    | 0.08           | 0.24  |
| 2010           | 0.22  | 0.07    | 0.28    | 0.06           | 0.18  |
| 2016           | 0.53  | 0.01    | 0.54    | 0.13           | 0.21  |
| The proportion of employees in the second industry (%) |       |         |         |                |       |
| 1996           | 25.00 | 29.60   | 54.60   | 6.09           | 43.55 |
| 2000           | 36.60 | 19.20   | 55.80   | 8.28           | 44.52 |
| 2007           | 27.16 | 26.03   | 53.19   | 7.63           | 43.06 |
| 2010           | 34.42 | 19.25   | 53.67   | 8.23           | 41.48 |
| 2016           | 43.92 | 18.50   | 62.42   | 10.41          | 41.83 |
| Total investment in fixed assets (Ten thousand Yuan) |       |         |         |                |       |
| 1996           | 9.94E6 | 1.06E5  | 1.00E7  | 1.91E6         | 1.37E6|
| 2000           | 1.66E7 | 3.81E5  | 1.70E7  | 3.19E6         | 2.26E6|
| 2007           | 4.25E7 | 1.10E6  | 4.36E7  | 1.03E7         | 1.14E7|
| 2010           | 5.56E7 | 2.54E6  | 5.81E7  | 1.57E7         | 2.09E7|
| 2016           | 1.60E8 | 1.27E7  | 1.72E8  | 3.43E7         | 5.20E7|
| Energy processing conversion efficiency (%) |       |         |         |                |       |
| 1996           | 70.19 |        |        |                |       |
| 2000           |       | 69.0    | 71.2    | 72.5           | 73.7  |
The results of threshold panel analysis indicate that urban spatial structure is significantly related to urban energy intensity. The relationship between urban spatial elongation and urban energy intensity has 2 stages. First, with the rapid urbanization and urban spatial elongation, the transportation network, housing, and business centers can be established quickly, which has driven substantial investments and the expansion of urban space. However, considerable amount of energy is consumed. Although these new urban areas have wide roads and tall buildings, due to inadequate supporting facilities, such as hospitals and schools, the agglomeration of labor force is limited, especially high-quality labor. These new urban areas lack popularity, and have even seen the emergence of an “empty city”. The economic benefits are either limited or not sufficient to compensate for the increase in energy consumption. Therefore, at this stage, with the expansion of urban space, the city's energy intensity is likewise increasing.

This situation changes after a particular amount of investment. Considering the lack of popularity in the new urban area, given the increase in various costs in the city center, population will gradually migrate to the new urban area. The government has also formulated various policies to attract people to new urban areas, including simple “Hukou” handling procedures, entrepreneurial subsidies, and so on. New public infrastructure, including schools and hospitals, have been established. The economic benefits of these new urban areas are showing up, and the ratio of energy consumption has changed. As a result, urban energy intensity has decreased.

It is worth noting that these conclusions do not mean that the urban space can continue to spread. This is because conclusions also show that the compactness of urban space is negatively correlated with urban energy intensity. The agglomeration of space and the increase in compactness can reduce energy intensity of cities through the agglomeration of economic effects. Thus, the relationship between urban spatial structure and urban energy intensity is dynamic. We cannot emphasize only the agglomeration of urban space, as excessive agglomeration leads to agglomeration diseconomy, which, in turn, leads to the reduction in energy efficiency. In this case, the extension of urban space will have a significant effect, but this will not be immediately apparent. There will be a lag, especially in the absence of sufficient population density.

### 4.2 DISCUSSION

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### 5 CONCLUSIONS AND SUGGESTIONS

Based on remote sensing data and statistical data, this research analyses the relationship between urban spatial structure and urban energy intensity. Considering the complexity and the dynamic nature of this relationship, the threshold panel model has been used for analysis. The results indicate that

| Table 3 | Threshold estimator (level = 95) and threshold effect test |
|---------|----------------------------------------------------------|
| Model   | Threshold | Lower | Upper  |
| Th-1    | 13.9      | 13.5  | 14.4   |

| Table 4 | Threshold regression results (fixed effects) |
|---------|------------------------------------------------|
| Dependent variable | Coef. | $P > t$ | 95% Conf. Interval |
| Urban energy intensity | 1.51** | 0.0 | 0.8 | 2.2 |
| Spatial elongation (SE) | 0     | 1.51** | 0.0 | 0.8 | 2.2 |
| 1     | -0.34** | 0.0 | -0.6 | -0.1 |
| Other variables | Spatial compactness (SC) | -0.2* | 0.1 | -0.6 | 0.1 |
| The proportion of employees in the second industry | 1.1* | 0.1 | -0.1 | 2.2 |
| Energy processing conversion efficiency | -0.2** | 0.0 | -0.3 | -0.1 |

$R = 0.51; F = 24.38**$

Variance inflation factors <7

*Indicates statistical significance at the 10% level; **Indicates statistical significance at the 1% level t-values in parentheses.
with the expansion of urban spatial structure, urban energy intensity demonstrates a rise-and-decline trend (inverted-U relationship). The urban compactness ratio is negatively correlated with the urban energy intensity. These conclusions can help establish a policy for reducing urban energy intensity from an urban space management perspective.

With overcrowding in downtown areas, the costs are rising. Furthermore, under the impetus of urbanization in developing countries, the expansion of urban spatial structure is a general trend. To avoid rising energy intensity in the early expansion stage, public infrastructure should be promoted simultaneously with real estate and road development. In particular, government policies to attract population to new urban areas should be implemented early. In this way, the construction of a new urban area is aligned with the rate of migration. The recommendation is to shorten the “empty city” period to allow for positive effects of urban expansion as soon as possible.

However, this does not mean that urban spatial structure can expand without a limit, since conclusions also show that compact urban spatial structure will be conducive to the reduction in urban energy intensity. A more reasonable policy is to find a balance between the compactness and expansion of urban spatial structure. This can reduce urban energy intensity brought about by the agglomeration economy and avoid the crowding effect of excessive agglomeration. In the process of urban expansion, the “empty city” period of the new urban area can be minimized and positive effects brought by space evacuation can be achieved, thus reducing energy intensity.

To achieve the objectives of these policies, to find a reasonable “balance point” between compactness and expansion, urban fixed asset investment can be used as an alternative monitoring and adjustment index. According to data on Chinese cities, when a city’s fixed asset investment reaches 12 billion yuan, it has reached the “balance point”. We should control the continued growth of investment and restrain the further expansion of urban space. An increase in investment and the promotion of urban space extension can address the issues of overcrowding, expensive housing, and congestion in the central urban areas. Reduction in investment and curbing excessive expansion of urban spaces are to be deployed whenever the urban spatial structure expands beyond a certain threshold. The dynamic relationship between urban spatial structure and urban energy intensity implies that the expansion of urban suburb space and the compactness of urban inner space can be developed simultaneously. It can inhibit blind expansion, meanwhile bringing the economic benefits of agglomeration into play. As a result, urban energy intensity can be decreased. However, the specific data vary from country to country, so using the threshold panel regression method and the index system proposed in this study can help find the “balance point”. First, we need to calculate urban energy intensity, and urban spatial structure. And then, control variables should be selected, and the Threshold panel model also should be established. Finally, we run the computer program, such as STATA, and get the results.

Some limitations of this research are worth mentioning. There are no uniform criteria for evaluating urban spatial structure and this study only chooses some of the indicators. However, this explorative research provides a starting point for further research on urban form and urban energy intensity in China.

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ENDNOTE

The data used to support the findings of this study are available from the corresponding author upon request.

ORCID

Cuihong Long  https://orcid.org/0000-0001-7778-9829

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