Research Paper

Urban Building Scale and Energy Consumption: Scaling Laws and Temporal Dynamics in 70 Chinese Cities

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Abstract

Today, cities are growing rapidly and their populations are expanding. This causes many problems. The key to sustainable cities is how they obtain, share and manage their energy and material resources. Drawing upon open-source data and the established urban scaling law, the study puts forward and examines a conceptual framework for urban building scale and energy consumption. The findings indicate that urban building scale is predominantly horizontal, with an increasing vertical expansion, and that the scale of energy consumption is unevenly distributed, with its power law being more stable in relation to the size of the urban building than to the population. The study provides a novel perspective on understanding the mechanisms driving the development trends in urban building scale and urban energy consumption patterns, and offers theoretical references for urban planning policies.

Keywords

Urban system, Scaling law, Urban energy use

1. Introduction

Rapid urban expansion and population growth have created many urban problems(Steurer and Bayr, 2020),and concern about these problems has fuelled the study of urban systems and urban science, with complexity science seen as an excellent tool for understanding urban systems(Sugar and Kennedy, 2021). The complexity of cities is reflected not only in the individual city itself as a complex system, but also in the macro-urban complex system composed of cities, where features not present in the individual are often expressed by simple laws(Li et al., 2017). Urban scaling and Zipf's law are representative (Luís M A Bettencourt et al., 2007). The Urban Scaling Law uses a power law to explain the relationship between urban scale and urban characteristics, and to summarise the laws governing the operation of urban systems. For instance, a number of studies have identified the proportional characteristics of area(Zhao et al., 2018) economic output and population in China's major cities and within cities(Lei et al., 2021). The Urban Scaling Law has also been used to assess the efficiency of urban land use (Jiao et al., 2020), urbanisation process (Liu et al., 2022), Urban carbon emissions, etc. (Rao et al., 2023).

Zipf's law is an important theory for characterising the size distribution of cities, and its academic origins can be traced back to the rank-order size law proposed by Auerbach(Auerbach, 1913). The law posits that the product of the city's positional order and its population size is approximated as a constant. This theoretical foundation forms the basis for the study of city size distribution. Zipf's interdisciplinary analyses revealed that the relationship between positional order and size is not only present in urban systems, but that analogous patterns prevail in several disciplinary fields(Human, 1949). It is particularly noteworthy that this phenomenon exhibits a unique scalar property as the parameter α tends to 1, which

is known as Zipf's law. This significant discovery not only extends the boundaries of the original theory's application, but also promotes a paradigm shift in the study of urban size distribution, establishing it as a classic analytical tool in regional economics and urban geography(Sun et al., 2022).

The urban scaling law and Zipf's law represent foundational principles within the domain of urban science. These laws facilitate the articulation of non-linear characteristics inherent in urban systems, including the non-linear dynamics of energy consumption and carbon dioxide emissions(Batty, 2013)(Gudipudi et al., 2019). The relationship between urban building energy consumption and city size must be examined in light of the rapid expansion of modern cities. This research will contribute to effective integrated emission reduction strategies, which are pivotal to combating climate change. (Pachauri et al., 2014). It is important to study the relationship between energy patterns in cities and urban development and city size, and to focus on the link between urban expansion and energy consumption, in order to understand and manage energy in cities (Kennedy et al., 2015). The focus of research in the field of urban building energy consumption is predominantly oriented towards simulation and empirical research methodologies. The scope of simulation research encompasses the modelling of energy consumption assessment at the level of individual buildings and urban blocks. The energy consumption of a building unit is hypothesised to be contingent on the configuration of the unit and the pattern of utilisation and occupancy by building personnel.(Loeffler et al., 2021)(Chen et al., 2021)(Azar and Menassa, 2012). Modelling of energy consumption in urban buildings focuses on the meso-scale, the impact of density, compactness and height of the building stock on the energy consumption of the urban building stock.(Resch et al., 2016)(Perera et al., 2023)(Wang et al., n.d., n.d.) . Empirical studies focus more on the macro scale, studying the pattern of urban size and urban energy consumption from the perspective of urban agglomerations (Hu and Fan, 2020). Exploring the macro-correlations and micro-correlations between energy and urban building stock in urban systems by studying resource flows in megacities. (Kennedy et al., 2015)

However, current research on energy consumption and urban size has an uncommon focus on time series, with most articles focusing on the relationship between urban size and urban energy consumption in a given year (Hu and Fan, 2020), and do not go into depth on the relationship between changes in urban size and energy consumption over the years. The relationship between urban building energy consumption and urban development and planning is complex and under-researched. Research is needed to explore scaling characteristics between urban building size and energy consumption during urban development, and whether these can be applied to future assessments. Is urban building energy consumption non-linearly proportional to urban size? What are its spatio-temporal dynamics? How can the performance of the evolution of energy consumption in urban buildings be understood and assessed in the context of sustainable development and urban size? Overall, the knowledge and understanding of the relationship between energy consumption in urban buildings and urban size at the urban system level is necessary and important, but remains unclear and needs to be explored in further depth.

The study selected 70 Chinese cities to explore the differences and similarities between urban size and energy consumption using the urban scaling law to combine historical changes in population, economy, urban building footprints and urban building energy consumption. The objective of this study is to provide an in-depth understanding and assessment of the dynamic patterns and performance of urban building energy consumption in China through a systematic perspective. To this end, the power-law relationship between urban building energy consumption and urban building footprints is to be quantified. The research in this paper could inform urban science, planning and management, helping to achieve sustainable urban development.

2. Methodology

This study presents a novel insight into the use of open-source data to establish the relationship between urban size and energy consumption in urban buildings, and proposes a framework for interpreting

the laws of urban systems from data analysis(Figure 1). Study aims to reveal the relationship between urban size and urban building energy consumption based on the urban scaling law and Zipf's law by using end-use energy consumption data and urban building footprint data. The methodology starts with data acquisition and creation of an analytical framework, followed by data patching. Finally, the data is analysed to obtain a power law relationship between urban size and energy consumption in urban buildings.

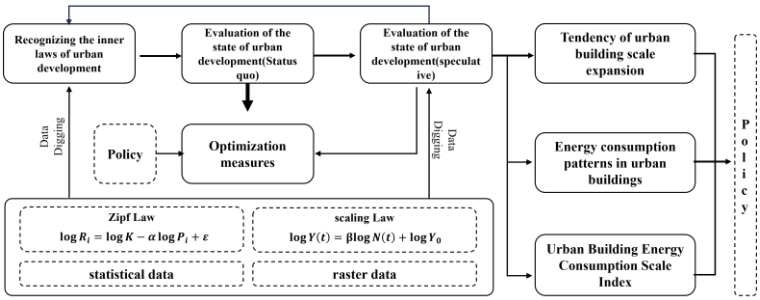


Figure 1: Methodology for Conceptual Framework of Power Law Relationship between Urban Building Size and Energy Consumption in Urban Buildings. Source: Drawn by the author

Urban building data

The acquisition of historical and current data, including urban land use data, urban building footprint (surface data), urban building volume data (volume data), was conducted at five-year intervals from 1990 to 2020. The data set also includes building footprint data (m^2) and building volume data (m^3). The resolution of the data is 3arc. (Schiavina et al., 2022).

Urban building energy consumption data

Source China Urban Statistical Yearbook("National Bureau of Statistics," 2024).Calculation of Urban building energy consumption, does not take into account the urban transport energy, Urban building energy consumption proxy data with residential electricity, living gas data, living liquefied petroleum gas data (public building energy consumption operation cooling heating, etc. to use electricity, so do not take into account the public building gas energy consumption), will be these data through the conversion coefficients in Table 1, converted to standard coal, the proxy Urban building energy consumption data.

Table 1: Conversion Coefficients.

Energy Type	Average Lower Heating Value	Reference Conversion Coefficient for Standard Coal
Electricity	860 kcal/kWh	1.229 TSC/10,000 kWh
Gas	7700-9300 kcal/m^3	13.3 TSC/10,000 m^3
Liquefied Petroleum Gas (LPG)	12000 kcal/kg	1.7143 TSC/ton

Population and economic data

Obtain population data for 1990-2020 from the China Urban Statistical Yearbook.("National Bureau of Statistics," 2024). The target data were obtained, and the presence of outliers and error records in the data was identified. The data were then subjected to a process of elimination, with any missing parts of the data being filled in using linear interpolation and extrapolation. Through the above steps, the completeness and consistency of the data were ensured, providing a reliable database for the study.

The building footprint (BU) with building volume data (BUVOL) and land use data(LULC) at a resolution of 100m was obtained using the resampling method in the GISpro platform. The average building height

(AGBH) within the 100m (S_x) grid was calculated according to equation (1);

$$AGBH_X = BUVOL_x / S_x \quad (1)$$

BU, BUVOL and LULC worked together to find out about the buildings in the built-up area and to calculate the total BU and the total BH for each city.

Zipf's law

The regression model employed is of the form given by equation (2). In this model, R_i denotes the rank order of city i, P_i is the population size of city i, α is often referred to as the Pareto index, K is a constant, and ε is a disturbance term. It is assumed that a Pareto index α of 1 implies compliance with Zipf's law; a larger α implies a more dispersed urban size distribution(Human, 1949).

$$log\ R_i = log\ K - \alpha\ log\ P_i + \varepsilon \quad (2)$$

Urban scaling index

The urban scaling law is a manifestation of the nonlinear aggregation effect of urban size and urban characteristics. The majority of urban characteristics $Y(t)$ follow an approximate power-law scaling law.(Bettencourt et al., 2010)(Luis M A Bettencourt et al., 2007)(Batty, 2008)(Chowell et al., 2003),as shown in equation (3), where Y_0 is the normalisation constant, $N(t)$ is the urban size at time t, and β is the scaling index. Thus, for each fraction increase in urban size (*DN=N*), the relative increase in the number of per capita *y*(*t*): $Y(t)$= N increases, and according to equation (4) when $\beta \approx 1$, $\Delta y \approx 0$, y does not change, and Y is linearly related to N .

$$log\ Y(t) = \beta log\ N(t) + log\ Y_0 \quad (3)$$

$$\Delta y/y \approx (\beta - 1)\Delta N/N \quad (4)$$

3. Result

This section shows and analyses the changes in building size and urban building energy consumption in 70 Chinese cities over the past three decades, and the power-law relationship between building size and urban building energy consumption in these cities, based on building footprint data urban building energy consumption data and population data from 1990-2020.

3.1. Evolution of urban building size indicates changes in urban size

Between 1990 and 2020, China will be in a process of rapid urbanisation, with rapid population and economic growth and expansion of the size of cities. Figure 2 illustrates the growth of building coverage (BU) and urban building height (BH) in the selected typical cities from 1990 to 2020. Using 1990 as the base year for comparison, between 1990 and 2020, the growth rate of horizontal expansion and the vertical growth rate in urban centres are lower than those in peripheral areas, indicating that urban areas are expanding outwards. As is evident from the distribution of relative growth rates, the intensity of Shenzhen's expansion between 1990 and 2000 was notably high, which is consistent with the reform and opening-up phase of vigorous development in Shenzhen. The urbanisation process in China has been divided into five distinct stages (Jia, 2018) namely the steady increase stage (1979-1995), the rapid growth stage (1996-2011), and the high-quality development stage (2012-present). These stages are consistent with the time span of this study. The process of horizontal expansion in cities such as Shenzhen and Jinhua coincided with a period of rapid development, during which major cities were characterised by horizontal expansion. In the post-2010 phase, cities such as Beijing and Jinhua have undergone a gradual vertical expansion of urban size and the evolution of a more compact urban form.

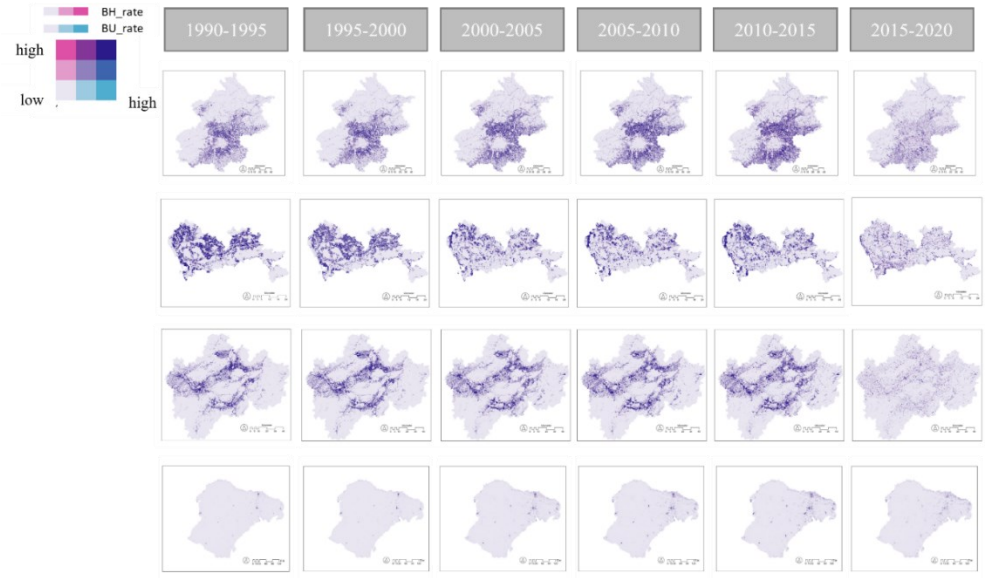


Figure 2: Relative growth rates of urban BU and BH, 1990-2020 (Beijing, Shenzhen, Jinhua, Edors). Source: Drawn by the author

Figure 3 illustrates the relative growth rates of building coverage (BU) and building height (BH) in each city from 1990 to 2020. In general, the growth rate of BU is higher than that of BH, and urban expansion is dominated by horizontal growth. The relative growth rate of BU in Erdos is 2,100%, which is significantly higher than that of large cities such as Beijing (about 159%) and Shanghai (about 280%). This suggests that cities such as Erdos have increased their urban size primarily through horizontal expansion over the past three decades. In contrast, Jinhua's BH growth rate is higher than the BU growth rate, at approximately 430 % and 500 %, respectively, with a more significant expansion in the vertical direction.

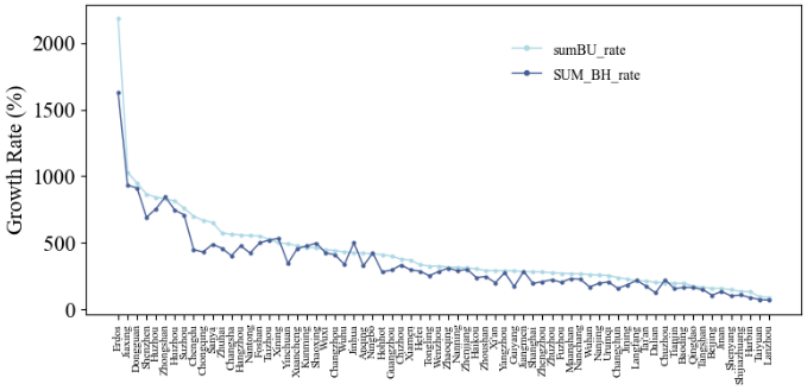


Figure 3: Relative growth rates of total BU to total BH, 1990-2020. Source: Drawn by the author

The observed overall trend demonstrates a preponderance of horizontal expansion in small and medium-sized cities, accompanied by a gradual increase in the growth rate of vertical expansion. The growth rates of BU in Kunming and BH in Zhongshan exhibit a similar trend, with rates of approximately 470 % and 830 %, respectively, while BH demonstrates a slightly higher rate of approximately 845 %. This phenomenon can be interpreted as a response to the increasing scarcity of land resources, as urbanisation progresses, prompting small and medium-sized cities to expand horizontally while their urban size gradually increases vertically.

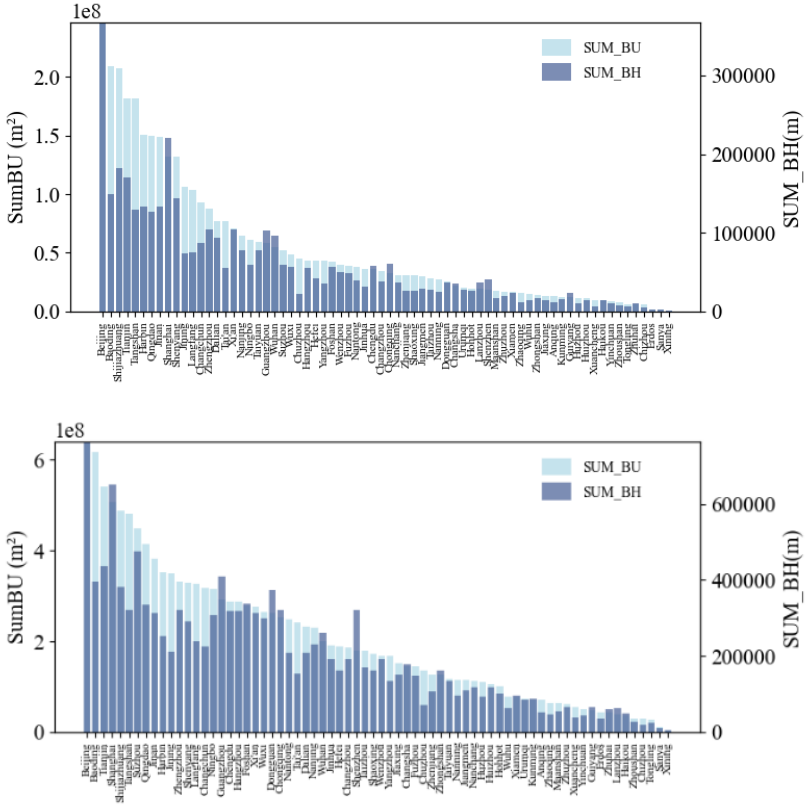


Figure 4: Total BU rank order and corresponding total BH in 1990, 2020. Source: Drawn by the author

Figure 4 presents a visual representation of the relationship between the total amount of building coverage (BU) and building height (BH) for a selection of 70 cities in 1990 and 2020. The comparison reveals that the rank order of urban building sizes is not entirely consistent between BU and BH; specifically, cities with larger BUs do not necessarily also have higher BHs. For Beijing and Shanghai, in 1990, the rank order of BH compared to BU is more advanced in these two cities, ranking first and second respectively, indicating that the building form in these two cities is dominated by height. By 2020, the rank order of the total BH of these two cities remains the same, while the rank order of the total BU of Shanghai rises to 4th (1990 BH rank was 9th), with a more significant increase in BU, indicating a greater expansion of urban size in the horizontal direction.

In 1990, the cities at the bottom of the urban size rankings mainly included some small and medium-sized cities, such as Xining, Yinchuan, Lanzhou, Guiyang, Nanning and Haikou. These cities have relatively low building coverage (BU) and building height (BH), with total BU ranging from 524,767 to 196,929,957(m^2) which is lower than the average value of 5363,625,250(m^2), and total BH ranging from 845 to 37,166(m), which is lower than the average value of 66,961(m), with a relatively lagging process of urbanisation and a smaller building scale. In 2020, these cities generally show significant horizontal expansion, with a significant increase in building coverage (BU) and a relatively small increase in building height (BH). The urban form of these cities in 2020 is dominated by the horizontal dimension, with the vertical dimension lagging behind in terms of urban size, and the urban form remains relatively loose.

3.2. Evolution of urban building energy consumption over the last three decades

Figure 5 provides energy consumption patterns for the city in 1990 and 2020. Overall, urban building energy consumption has increased significantly over the past three decades. In 1990, the total energy

consumption of Beijing was 593,574.98 tonnes of standard coal(TSC). By 2020, this figure had increased significantly to 4,808,977.39 tonnes of standard coal(TSC), indicating a substantial growth in energy consumption over the period. Erdos in 1990 energy consumption rank order in the 70th, the total urban building energy consumption is 4340.44 TSC, by 2020, the total urban building energy consumption grows to 188946.31.

The structure of urban building energy consumption pattern has also undergone significant change. Compared to 1990, the share of electricity consumption rises in 2020. Beijing's electricity consumption increased from 88,365.1 TSC to 25,187,770.36 TSC, with its share rising from 14.9 % to 52 %; Shanghai increased from 138,262.5 TSC to 29,666,672.039 TSC, with its share rising from 13.8 % to 53.5 %. Concurrently, there was a decline in the consumption of LPG. In the city of Beijing, the consumption of LPG fell from 40 % to 3.8%; in Shanghai, it fell from 8.6 % to 4.7 %, with an average decrease of 25 % across all sample cities.

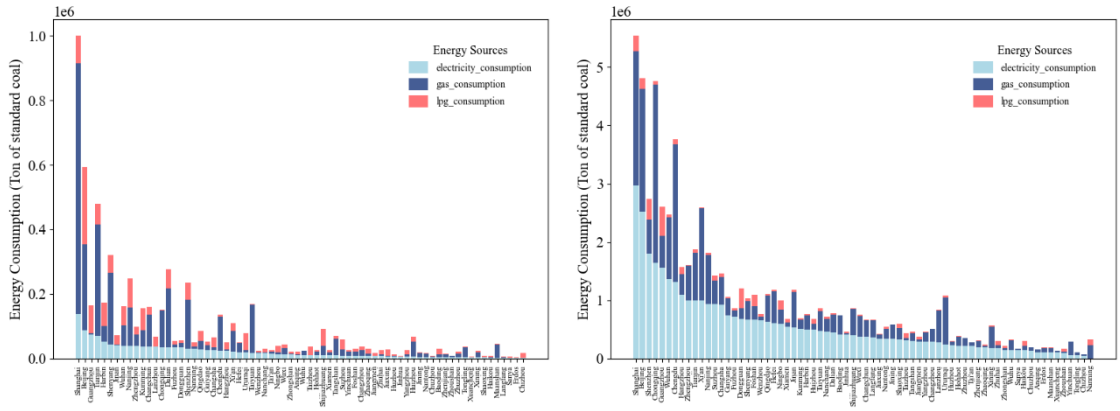


Figure 5: Urban building energy consumption distribution patterns, in 1990,2020. Source: Drawn by the author

In comparison with older metropolises such as Beijing and Shanghai, the urban building energy consumption pattern of post-development cities has increased in rank order over the last three decades. Shenzhen, which was ranked 17th in 1990 in terms of total energy consumption, is projected to rise to 5th place in 2020. Shenzhen's urban building energy consumption pattern has followed the same trend of growth in urban building size over the last three decades of development. Since the reform and opening up after 1980, Shenzhen has developed into a first-tier city, absorbing a large number of foreigners and expanding urban building size, and urban building energy consumption has risen sharply, about 8 times.

Urban building energy consumption is unevenly distributed, with a few cities consuming higher levels of energy. Large cities such as Beijing, Shanghai, Tianjin and Nanjing have significantly higher total energy consumption in 1990 and 2020. The total energy consumption of all these cities exceeded 200,000 TSC in 1990 and 1,500,000 TSC by 2020, while many small and medium-sized cities have a relatively low total energy consumption and a small growth rate.

3.3. Distribution patterns of urban building energy consumption

Figure 6 illustrates the bit-order-size double logarithmic change in urban building energy consumption from 1990 to 2020. The overall trend of the urban size distribution exhibited a continuous rightward and upward shift during the period 1990-2020, indicating an increase in urban building energy consumption over time and a gradual increase in city size. It is worth noting that the urban size distribution curve for the urban place order is not a straight line as expected by theory, but rather a left-to-right - i.e., a gradual shift

from flat to sloping curve from smaller cities to mega-cities. Utilising Zipf's law with a slope of 1 as a reference point, it is evident that the extremities of the urban size distribution deviate from the predominant linear distribution, exhibiting a downward collapse. In summary, the urban building energy consumption for the sample of study cities is lower than the expected value of Zipf's law for both small and large sized cities. In essence, this suggests that the urban size distribution can be represented by a straight line with a slope of 1 on a double logarithmic plot of rank order-size, which is a fundamental tenet of Zipf's law. Early studies, mainly in the United States, basically found that the slope of the urban size distribution is 1(Lotka, 1925)(Goodrich, 1926). However, a growing number of studies for other countries and at different scales of urban characteristics show that the slope of the urban size distribution is not always 1(Carroll, 1982)(Rosen and Resnick, 1980)(Nitsch, 2005). The bit-order-size double logarithmic analysis of urban building energy consumption has been shown to be consistent with the general behaviour of Zipf's law.

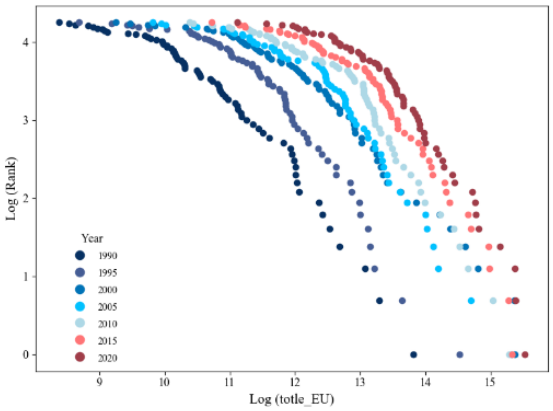


Figure 6: Changes in Zipf law for energy consumption in urban buildings. Source: Drawn by the author

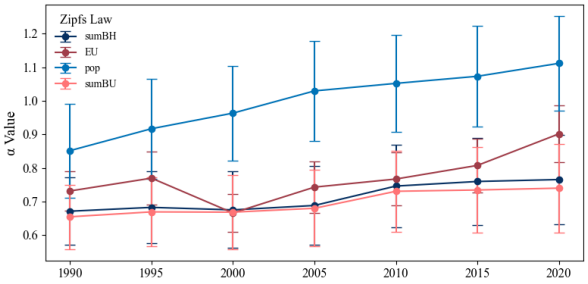


Figure 7: Changes in Zipf law with BU,BH,POP,EU. Source: Drawn by the author

Figure 7 illustrates the evolution of the Zipf's law parameter α for urban building size, urban population size and urban building energy consumption. The change in the slope of the fit shows that the size distribution of urban building energy consumption is relatively balanced from 1990, when a small number of cities accounted for the vast majority of energy consumption, to 2020, when the size distribution of urban building consumption is relatively balanced. Although still showing a few cities occupying high urban energy consumption, urban building energy consumption is more homogeneous in size than in 1990.

The study also performs a bit-order-size double logarithmic analysis of urban building size and urban size. Figure 7 shows that both urban scaling data and urban building energy consumption have tended to

follow Zipf's law over the last three decades. From 1990 onwards, urban building size and urban building energy consumption scale have gone from extreme fragmentation to gradual agglomeration. It is evident that until the year 2020, the α-value remains below 1, thus indicating a failure to comply with Zipf's law. This finding suggests that the urban scaling data and urban building energy consumption in these cities have not yet attained the optimal level of agglomeration. With regard to the urban scaling law distribution, it increases to 1 in 2005, and in the development from 2005 to 2020, the Pareto index α has become greater than 1, and the urban scaling law distribution gradually deviates from the optimal Zipf's law distribution.

Overall, population, economic activity and urban size have shown a gradual trend towards agglomeration. Between 1990 and 2020, many countries have experienced a significant increase in urban size, in line with the overall trend of accelerating urbanisation. The comparison of urban building size, urban building energy and urban population size is indicative of a consistent trend, with a certain degree of intrinsic linkage.

3.3. Scaling index of urban building size and urban building energy consumption

Figure 8 illustrates the power law relationship between urban building size and urban building energy consumption scale in 2020. Relationship between urban building coverage (sum_BU), urban building height (sum_BH) and total urban building energy consumption (totle_EU). Urban building coverage area (sum_BU), urban building height (sum_BH) and total urban building energy consumption show a sub-linear relationship, indicating that the increase in building coverage area has a certain impact on the increase in total energy consumption , but not completely synchronised, the sub-linear relationship indicates that the growth of actual total energy consumption is lower than the growth of urban building coverage area (sum_BU), urban building height (sum_BH).

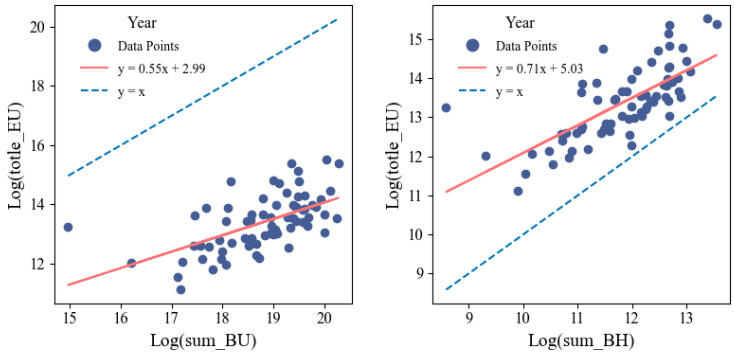


Figure 8: Scaling patterns of urban building size and urban building energy consumption. Source: Drawn by the author

Figure 9 provides the changes in the β-value of the scale index between 1990 and 2020. From 1990 to 2020, the trend of the β-value of scaling_BH and scaling_BU is more consistent, both fluctuating between 0.6 and 0.8, indicating that the scale indexes of the two indexes are relatively stable, which suggests that the relationship between the building heights and the building covered areas in the urban size of the buildings is more fixed and less influenced by other factors. The scaling law for POP is more volatile. It ranges from 0.4 to 1.2, indicating that the impact of population size on urban building energy consumption is complex and unstable.

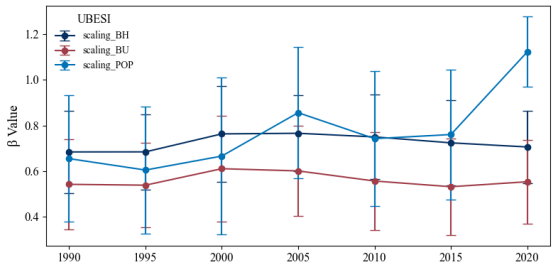


Figure 9: Changes in scaling index. Source: Drawn by the author

The relationship between BH, BU and EU is more stable, indicating the relative stability of building size and building energy use efficiency. It is not significantly affected by POP; that is to say, changes in building height and covered area have a more direct and stable effect on energy consumption.

4. Conclusion

The present study explores the relationship between urban size and energy use patterns. Firstly, it provides a detailed explanation of the direction and pattern of expansion of urban size in the last three decades. Among the 70 cities, urban building size is dominated by horizontal expansion, which is consistent with the stage of urbanisation of Chinese cities and reflects a gradual narrowing of the gap between urban building sizes and a tendency for urban building size to expand in a consistent manner. Secondly, total urban building energy consumption has increased significantly, indicating growing energy demand in the context of urbanisation. The structure of energy consumption shifted towards cleaner energy sources, with the share of electricity and natural gas consumption increasing and the share of LPG consumption decreasing. During the expansion of urban building size from 1990 to 2020, the scaling law between urban building size and urban building energy consumption is more stable, suggesting a more direct effect between them, while the effect of population size on urban building energy consumption is more complex and unstable.The study shows the framework of the laws of urban systems is feasible, the data sources are authoritative, and the data is reliable.

The results of the analysis of urban size and energy consumption provide an important reference for urban planning to understand the law of urban development, and help to formulate a more scientific and reasonable energy management strategy in promoting the optimisation of urban energy consumption structure and improving energy efficiency.

The framework established in this study has high feasibility and application potential, and can provide an important reference for urban planning and energy management. Future research can further validate the feasibility of the framework, expand the scope of the study to other countries and regions, compare the relationship between urban building energy consumption and urban building size in different countries, and explore the urban development model in the context of globalisation. Consider additional influencing factors, such as the level of economic development, policy support, and the level of technology in the city, in order to more fully understand the relationship between urban size and energy consumption.

The study is subject to certain limitations; firstly, the cities selected do not include all cities worldwide and therefore may not fully reflect global urban trends. The process of data acquisition may result in the omission of data for individual years. The interpolation of missing data may introduce error to the results, and it is necessary to expand the research sample and ensure data completeness in future studies.

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