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Research Article

Keywords: Urbanization, Population, Space, Industry, Energy consumption, Effects decomposition

Posted Date: April 12th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-346736/v1>

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Multidimensional effects decomposition of urbanization on energy consumption based on a modified LMDI model

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Abstract: Urbanization is important for population transfer, it triggers the coordination and adaptation process among population, space and industries, which in turn have multiple effects on energy consumption (EC). This paper conducted multidimensional effects decomposition of EC change in China (1998-2017) based on a modified LMDI model. The findings revealed that urbanization has a greater pulling effect on EC of production side over life side. Household consumption effect is the leading factor stimulating the increase in EC at production side. The convergence of urban and rural residents' consumption behaviors has increasingly contributed to EC fluctuation at life side, and become the handicap for energy sustainable development with population expansion. Unreasonable land utilization from space aspect has intensified EC, however, the scale effect produced by population agglomeration negatively caused fluctuation of living EC. The transformation and upgrading of traditional energy-driven industries and technological progress have alleviated energy pressure, and the consumption inhibiting effect has an inverted U-shaped effect on EC (promote first, decrease later). Thus, this paper further proposed that when the development from industry aspect encounters bottleneck, more attention should be paid to improve residents' consumption habits at population aspect, and release resource allocation momentum from space aspect to reduce EC.

Key words: Urbanization; Population; Space; Industry; Energy consumption; Effects decomposition

1. Introduction

At present, China's urbanization has entered a period of rapid growth. The total number of large-scale cities has reached the first place in the world, and the urban population has accounted for 60% of the country's total population. With the arrival of non-agricultural industries in urban areas and the migration of rural populations to urban areas, urbanization has not only promoted the dual transformation of manufacture and lifestyle, but has also led to an increasingly prominent problem of energy consumption (EC) in urban development. From 1998 to 2017, China's urbanization rate increased by 1.75 times, but behind it there is a 3.29 times increase in total EC. Related research shows that urbanization exerts a number of influences on EC (Jones, 1991; Mrabet et al., 2019), as the changes of consuming behaviors, expansion of land space and transformation of production mode in China, creates increasing pressure on energy supply and the natural environment (Wang, 2014; Yu et al., 2020), the EC level of an agricultural population transferred to a city will increase to more than three times the original (Zhang et al., 2011). It can be seen that the current urbanization model in China is characterized by high EC, and the energy problem is still a shackle that restricts sustainable development. From a cross-country comparison, although China has had over 660 million people relocating to cities and towns during its 40 years of rapid development, there is still a gap of about 20 percentage points compared with the 80% urban rate in developed countries. At the same time, the EC of Chinese residents is much lower than the world average, only 1/3 of the high level of urbanization in the United States and 1/2 of the United Kingdom (Wei and

Shen, 2019). It is expected that by 2030, one billion, or 70% of Chinese people will settle in the cities, and will certainly produce much more EC (Normile, 2008). Therefore, some scholars pointed out that the energy demand of developing countries is far from being saturated, and energy rebound is more likely (Jeroen, 2011).

From the current literature, urbanization is an important way of population transfer, and it also triggers a process of coordination and adaptation among population, space, and industries, which in turn can have multiple effects on EC. So whether the impact of urbanization development on EC is reflected in a negative agglomeration effect or a positive promotion effect, or there is a nonlinear relationship (Wang and Yang, 2019), the current academic research conclusions are not unified (Sheng et al., 2017). For answer this question accurately, it is necessary to identify the affecting factors and its mechanisms that drive EC in the process of urbanization in combination with the specific development scenarios of the research samples, and to further quantify the direction and intensity of different factors.

The contribution of this paper can be summarized in three aspects.

First, in terms of research perspectives, this research believes that the impact on EC should not be considered only from a certain aspect of the urbanization process, but should be combined with realistic development scenarios and consider the influence transmission mechanism of multiple factors. Therefore, this research expands the existing research and constructed the impact mechanism of population, space and industry on EC in the process of urbanization, discussed the interaction path between them to support and supplement the existing economic development and transformation theories, and can accurately identify EC trends, trends under urbanization and the driving factors behind, and then further provide an analysis framework for subsequent in-depth research.

Second, in terms of research models, the factor decomposition method has been widely adopted in the literature of energy economics and environmental economics because of its applicability. However, the existing research generally uses the form of "single multiplication and sum", which limits the content covered by the expression to a certain extent, causes the homogeneity of the effect analysis, and ignores more influencing factors. Therefore, this paper divides the total EC into production EC and domestic EC, and combines the characteristics of the dual structure of urban and rural areas and the difference in consumption between urban and rural residents, and innovatively constructs a vector form based expanded Kaya identity model. This method improves the LMDI method to the form of "multiple multiplication and summation", and analyzes the dynamic contribution of population, space, and industry to the fluctuation of EC in the process of urbanization in China.

Third, in terms of research data, some literatures use cross-sectional data to make static and horizontal comparisons of EC between regions at a certain point in time, lacking a time series of phased EC evolution analysis, and ignoring the nature of the dynamic changes of urbanization. Therefore, this study adopts the panel data in China in the past two decades and conducts the empirical analysis which uncovers the reasons of the dynamic changes in EC during the process of urbanization. On the one hand, it can provide scientific basis and policy recommendations for analyzing EC issues under China's new urbanization. On the other hand, the dynamic trends and

characteristic laws in the Chinese case can provide realistic experience for other countries in transition that are in the early stages or in the process of urbanization.

The remainder of this paper is organized as follows. A brief overview of the existing literature regarding EC in the process of urbanization is presented in section 2 with respect to three aspects of population, space and industry, further reveals the effect mechanism between them. The proposed Methodology is elaborated in section 3 for a modified LMDI model and a definition of the new data source and variables. Our main findings are demonstrated and discussed with an empirical analysis in Section 4. Finally, we conclude in Section 5 with three policy recommendations.

2. Literature review and effect mechanism reveal

2.1 Literature review

The effect of urbanization on EC cannot be simply limited to the impact of changes in the proportion of urban and rural populations, as there must be a complex transmission mechanism formed by the interaction of many factors (Avtar et al., 2019). By reviewing the existing literature, it is found that industrial structure, spatial arrangement and household consumption are the three main factors.

The study literature in population aspect shows that urbanization is not only the simple process of residents moving from rural to urban areas, but more significantly the process of changes in consumer behavior and improvement of human capital, of which the influences on EC can be roughly divided into two categories: on the one hand, the development of population urbanization, as an intensive development method, has a clustering effect and a scale effect on the improvement of energy efficiency and the promotion of efficient energy utilization technologies (Chen et al., 2019), further lower the original rural EC structure which mainly based on the fuel wood and straw (Yang et al., 2019), which can reduce EC to a certain extent. At the same time, the improved awareness of energy conservation and the rising energy prices can also lead to a continuous decrease in energy intensity (Kambara, 1992). On the other hand, population urbanization has promoted the increase of residents' consumption levels. Khuong et al., (2019) pointed that the way in which urbanization impacts EC depends strongly on the income level of the country studied. Cities have richer energy equipment and consumption types, which greatly changed the EC behavior and lifestyle of the immigrant families (Liu and Lei, 2018). With the upgrading of the consumption structure of urban residents, the EC in the production of goods and services has been indirectly promoted (Bin and Dowlatabadi, 2005), which has gradually become a major factor in the EC of Chinese residents (Wang and Fu, 2017). In addition, various factors including the promotion of educational qualifications and population quality (Liddle, 2011), the smaller family scales and increased housing areas (Hu et al., 2017) will all drive the consumption growth of electricity and oil. For a long time in the future, as the new generation of urban consumers become more economically independent, and their desire and demand for consumption being stronger than those of the previous generation, the growth of China's urban population and its structural changes will cause long-term pressure on EC (Pfaff et al., 2004; Liu et al., 2017).

Research based on the spatial perspective shows that EC is related to the spatial structure and scale of urban and rural areas (Parikh and Shukla, 1995; Yang and Shi, 2017), the questions such as low utilization of land resources, low density of urban planning, scattered distribution between living and manufacture areas, high exclusiveness of infrastructural service functions and redundancy of building area, have all led to an increase in urban EC (Karathodorou et al., 2010; Lin

and Ouyang, 2014; Zhao et al., 2017). While larger cities with reasonable spatial density can also reduce traffic EC (Chang et al., 2019). For example, increasing the high-density layout of cities can shorten commuting distances, reduce energy transmission and distribution losses, and achieve economies of scale in public facilities in order to achieve the purpose of energy saving and emission reduction (Burton, 2000; Leibowicz, 2020). Lin and Du (2017) found that the construction of urban rail transit can reduce automobile EC by 5.5% and vehicle EC per capita by 6.6%. Yu et al. (2020) indicated that an increase in metro operation intensity has the effect of improving traffic EC. On the basis of drawing on and comparing the development experience of other countries, Chinese scholars pointed out that energy conservation should not only consider industrial structure and technology, but should integrate actual national conditions and start with space conservation to achieve energy conservation and low carbon (Gu et al., 2009; Han et al., 2019). However, in real life, the negative benefits caused by traffic congestion and exhaust emissions are greater than the positive benefits brought by the scale effect. The phenomenon of high-density urban development leading to rising EC has also caused scholars to question the development of compact space (Rudlin and Falk, 1999).

Research from the perspective of industrial development shows that productive EC in urban areas is significantly higher than that in rural areas (Li and Lin, 2015), and changes in industrial structure at different stages of urbanization have different paths to EC (Mukhopadhyay and Forssell, 2005): the biggest influencing factor affecting China's urbanization process is the industrial structure (Lu, 1999), of which the secondary industry accounts for the largest proportion of total EC (Lv et al., 2019), with the development of urbanization, the ratio of light industry to heavy industry has changed significantly. The industrial focus has shifted from energy-dependent manufacturing to environmentally friendly high-end technology industries. The upgrading of industrial structure causes energy intensity to decline continuously over time (Fishervanden et al., 2004). However, some scholars pointed out that the effect of industrial structure changes on energy efficiency has gradually disappeared since the mid-1990s, and it is difficult to cope with the current huge energy pressure by structural adjustment alone (Shi and Zhang, 2003). Further studies showed that the influences of industry technological advance on EC present noticeable differences in different development phases (Ji and Chen, 2017). At present, we should depend on technological innovation to realize the energy intensity reduction and energy efficiency improvement (Adom and Kwakwa, 2019). But if technological progress drives the development of other economic units, which makes the energy saved by technology less than the energy demand of economic growth, there will be a rebound effect in the total EC (Birol and Keppler, 2000; Yan and Cheng, 2017). Then the change in the total EC will depend on the net effect of technological progress.

2.2 Effect mechanism reveal

Based on the literature review, in the process of urbanization, population migration promotes the transfer and interaction of people and materials between regions. To be specific, at the micro level, urbanization directly affects people's lifestyles such as consumption, shopping, transportation and travel, and promotes the coordinated development of low-energy-consumption tertiary industries. At the macro level, urbanization also resets the spatial layout of the elements required for industrial development, provides input of manpower, land and other elements for industrial development, and broadens the consumer market for products. It is also helpful for large-scale planting after the land is transferred, and provides an opportunity for the development of modern agriculture. Thus, there will be the following complicated effect transmission mechanism of EC in urbanization process

under the interactions of population, space and industry, as Figure 1 shown.

Fig. 1. Effect mechanism of population-space-industry on energy consumption in the process of urbanization

Specifically, the agglomeration effect caused by population migration to cities and towns can improve energy efficiency, and the improvement of consumption structure and living standards optimizes EC structure to a certain extent, and solves the problems from rural residents of scattered energy use, backward technology and low efficiency. However, as urban residents are closer to the market, domestic demand is stimulated, which indirectly increases production EC. Moreover, the scale effect brought by the compact development of land space can reduce EC, but problems such as repeated construction of supporting infrastructure and urban traffic congestion also consume a large part of energy. Furthermore, industrial restructuring and technological progress have improved energy efficiency, while also helping to develop new energy and reduce the cost of energy use. Yet, the side effect is that while feeding back the development of other economic units, it will also cause a rebound in total energy demand.

To sum up, academia has done extensive and useful research in the field of urbanization on EC and its influencing factors, but there is still some gap for further research. This study believes that the impact on EC should not only be considered from a certain aspect of the urbanization process, but should be combined with realistic development scenarios and consider the interaction transmission mechanism of multiple factors. Hence, based on the multidimensional mechanism of urbanization for EC established above, the traditional effects decomposition method needs to be improved to cover more influence factors to quantify and decompose the influential effect of three aspects including population, space and industry on EC in urbanization process, further compare and dissect the directions and intensities of various effects.

3. Methodology

3.1 Research model

Logarithmic Mean Divisia Index (LMDI) has been widely used in the research literature of energy economics and environmental economics because it does not produce residual terms when the

effects are decomposed, and the results are easy to explain. (Wei and Shen, 2019). In order to combine the characteristics of the dual structure of urban and rural areas and the differences in consumption between urban and rural residents, and to comprehensively reflect the interaction of the development of the production-side industry, the changes in the consumption behavior of the life-side population, and the expansion of spatial land on the EC, and to compare the contribution of different dimensional driving factors, this research is firstly extended on the basis of the classic Kaya identity (Kaya,1989), then improved the LMDI method proposed by Ang (2004) to further enrich the influencing factors covered by the function. The EC impact model constructed based on the influence and effect transmission mechanism as in Equation (1):

$$E = EP + EL = \sum_i \alpha_i EP_i + (EL_u + EL_r) \quad (1)$$

$$= \sum_i \alpha_i \frac{EP_i}{G_i} \cdot \frac{G_i}{G} \cdot \frac{G}{HC} \cdot HC + \sum_{\xi} \frac{\alpha_{\xi} EL_u}{\xi P_u} \cdot \frac{P_u}{P} \cdot \frac{P}{A} \cdot A + \sum_{\xi} \frac{\alpha_{\xi} EL_r}{\xi P_r} \cdot \frac{P_r}{P} \cdot \frac{P}{A} \cdot A$$

E is the total energy consumption, EP is the amount of EC in production ($i=1, 2, 3$ respectively represent the primary industry, secondary industry and tertiary industry), EL is the amount of EC in daily life ($u, r=$ respectively represent the urban and rural), G is the gross domestic product (GDP), HC is the household consumption, P is population quantity, and A is land area. Household consumption is incorporated into the production EC impact formula in order to reflect the impact of consumption demand on the indirect EC of the production side. Additionally, space expansion is also incorporated into the EC impact formula to reflect the impact of space layout on the direct EC of residents. Considering the differences of separate urban-rural structure in urbanization process of China, the further vector decomposition of household consumption is shown as Equation (2):

$$HC = HC_u + HC_r = HC_u \cdot \frac{\alpha P_u}{\xi P} \cdot \frac{P}{P_u} \cdot \frac{\ddot{\alpha}}{\xi} + HC_r \cdot \frac{\alpha P_r}{\xi P} \cdot \frac{P}{P_r} \cdot \frac{\ddot{\alpha}}{\xi} = \frac{\alpha P_u}{\xi P} \cdot \frac{HC_u}{P_u} + \frac{\alpha P_r}{\xi P} \cdot \frac{HC_r}{P_r} \cdot \frac{\ddot{\alpha}}{\xi} \cdot P$$

$$= \frac{\alpha P_u}{\xi P} \cdot \frac{P}{P} \cdot \frac{\ddot{\alpha}}{\xi} \cdot \frac{\alpha HC_u}{\xi P_u} + \frac{\alpha P_r}{\xi P} \cdot \frac{P}{P} \cdot \frac{\ddot{\alpha}}{\xi} \cdot \frac{\alpha HC_r}{\xi P_r} \cdot P = (PS_u \quad PS_r) \cdot \frac{\alpha hc_u}{\xi hc_r} \cdot \frac{\ddot{\alpha}}{\xi} \cdot P \quad (2)$$

In Equation (2), P_u and P_r indicate the number of urban and rural populations respectively, $PS_u = P_u/P$ and $PS_r = P_r/P$ indicate the proportions of urban and rural population in the total population respectively. HC_u and HC_r indicates the total consumption of urban and rural residents respectively, $hc_u = HC_u/P_u$ and $hc_r = HC_r/P_r$ indicates the per capita consumption of urban and rural residents respectively. Substituting equation (2) into equation (1), we can get Equation (3):

$$E = \sum_i \alpha_i \frac{EP_i}{G_i} \cdot \frac{G_i}{G} \cdot \frac{G}{HC} \cdot (PS_u \quad PS_r) \cdot \frac{\alpha hc_u}{\xi hc_r} \cdot \frac{\ddot{\alpha}}{\xi} \cdot P + \sum_{\xi} \frac{\alpha_{\xi} EL_u}{\xi P_u} \cdot \frac{P_u}{P} \cdot \frac{P}{A} \cdot A + \sum_{\xi} \frac{\alpha_{\xi} EL_r}{\xi P_r} \cdot \frac{P_r}{P} \cdot \frac{P}{A} \cdot A \quad (3)$$

Equation (3) can be simplified to Equation (4):

$$E = \sum_i \alpha_i T_i \cdot S_i \cdot C \cdot (PS_u \quad PS_r) \cdot \frac{\alpha hc_u}{\xi hc_r} \cdot \frac{\ddot{\alpha}}{\xi} \cdot P + (LP_u \cdot PS_u + LP_r \cdot PS_r) \cdot D \cdot A \quad (4)$$

Equation (4) includes energy consumption at both production side and life side. In production: $T_i = EP_i/G_i$ is the EC intensity of the i industry, which reflects the development of industrial

technology. $S_i = G_i/G$ is the proportion of i industry output value in GDP, which reflects the adjustment of industrial structure. $C = G/H_C$ is the ratio of GDP to total household consumption, which indicates the inhibition degree of consumption. In daily life: $LP_u = EL_u/P_u$ and $LP_r = EL_r/P_r$ indicate per capita EC in urban and rural areas respectively, as $PS_u = P_u/P$ and $PS_r = P_r/P$ indicate the urbanization rate and rural population rate, $D = P/A$ is the density of urban and rural population. Perform differential conversion on the left side and right side of the plus sign in equation (4), and the following functional formulas can be obtained:

P_u and P_r indicate the number of urban and rural populations respectively,

$$d \ln EP = d \ln \sum_i T_i' S_i' C' PS_u^{\alpha'} PS_r^{(1-\alpha)'} hc_u^{\alpha'} hc_r^{(1-\alpha)'} P \quad (5)$$

$$\begin{aligned} d \ln EL &= d \ln (EL_u + EL_r) = d \ln (LP_u' PS_u' D' A + LP_r' PS_r' D' A) \\ &= d \ln \left((LP_u' PS_u + LP_r' PS_r)' D' A \right) \end{aligned} \quad (6)$$

In Equation (5), $\alpha = \frac{PS_u hc_u}{PS_u hc_u + PS_r hc_r}$, $(1 - \alpha) = \frac{PS_r hc_r}{PS_u hc_u + PS_r hc_r}$, respectively indicate the proportions of urban and rural residents' total consumption in total residents' consumption. The influence equation of total energy consumption can be derived as Equation (7) which can reflect the urban-rural dual structure of energy consumption in the process of urbanization.

$$E = \sum_i T_i' S_i' C' PS_u^{\alpha'} PS_r^{(1-\alpha)'} hc_u^{\alpha'} hc_r^{(1-\alpha)'} P + (LP_u' PS_u + LP_r' PS_r)' D' A \quad (7)$$

Based on previous work (Li and Yang, 2014), we decompose Equation (7) through the LMDI model using polynomial multiplication and summation, this practice analyses the effect of each driving factor on EC changes, while avoiding the situation where other decomposition models have residual items and zero values affecting the analysis results. Let 0 and t denote the base period and the investigation period respectively, and the expressions of the contribution value of each energy consumption effect are as follows:

Technological Progress Effect: $IT = \sum_i \frac{EP_i^t - EP_i^0}{\ln EP_i^t - \ln EP_i^0} \ln \frac{T_i^t}{T_i^0} \quad (8)$

Structural Adjustment Effect: $IS = \sum_i \frac{EP_i^t - EP_i^0}{\ln EP_i^t - \ln EP_i^0} \ln \frac{S_i^t}{S_i^0} \quad (9)$

Consumption Inhibiting Effect: $IC = \sum_i \frac{EP_i^t - EP_i^0}{\ln EP_i^t - \ln EP_i^0} \ln \frac{C^t}{C^0} \quad (10)$

Production Effect:

$$IP = \sum_i \frac{EP_i^t - EP_i^0}{\ln EP_i^t - \ln EP_i^0} \left(\alpha' \ln PS_u^t - \alpha^0 \ln PS_u^0 + (1 - \alpha') \ln PS_r^t - (1 - \alpha^0) \ln PS_r^0 \right) \quad (11)$$

Household Consumption Effect:

$$PC = \sum_i \frac{EP_i^t - EP_i^0}{\ln EP_i^t - \ln EP_i^0} \left(\alpha' \ln hc_u^t - \alpha^0 \ln hc_u^0 + (1 - \alpha') \ln hc_r^t - (1 - \alpha^0) \ln hc_r^0 \right) \quad (12)$$

$$250 \quad \text{Population Scale Effect:} \quad PS = \frac{EP_i^t - EP_i^0}{\ln EP_i^t - \ln EP_i^0} \ln \frac{P^t}{P^0} \quad (13)$$

$$251 \quad \text{Per Capita Living Effect:} \quad PL = \frac{EL_u^t - EL_u^0}{\ln EL_u^t - \ln EL_u^0} \ln \frac{LP_u^t}{LP_u^0} + \frac{EL_r^t - EL_r^0}{\ln EL_r^t - \ln EL_r^0} \ln \frac{LP_r^t}{LP_r^0} \quad (14)$$

$$252 \quad \text{Urbanization Structure Effect:} \quad PU = \frac{EL_u^t - EL_u^0}{\ln EL_u^t - \ln EL_u^0} \ln \frac{PS_u^t}{PS_u^0} + \frac{EL_r^t - EL_r^0}{\ln EL_r^t - \ln EL_r^0} \ln \frac{PS_r^t}{PS_r^0} \quad (15)$$

$$253 \quad \text{Agglomeration Density Effect:} \quad AD = \frac{EL_u^t - EL_u^0}{\ln EL_u^t - \ln EL_u^0} + \frac{EL_r^t - EL_r^0}{\ln EL_r^t - \ln EL_r^0} \frac{\ddot{\circ}}{\ddot{\circ}} \ln \frac{D^t}{D^0} \quad (16)$$

$$254 \quad \text{Space Expansion Effect:} \quad AE = \frac{EL_u^t - EL_u^0}{\ln EL_u^t - \ln EL_u^0} + \frac{EL_r^t - EL_r^0}{\ln EL_r^t - \ln EL_r^0} \frac{\ddot{\circ}}{\ddot{\circ}} \ln \frac{A^t}{A^0} \quad (17)$$

255 Total Effect:

$$256 \quad \begin{aligned} \Delta E &= E^t - E^0 = \Delta EP + \Delta EL = (EP^t - EP^0) + (EL^t - EL^0) \\ &= (\Delta IT + \Delta IS + \Delta IC + \Delta IP + \Delta PC + \Delta PS) + (\Delta PL + \Delta PU + \Delta AD + \Delta AE) \end{aligned} \quad (18)$$

257 3.2 Data source and definition

258 On the basis of guaranteeing the availability and continuity of data, panel data of China from 1998
 259 to 2017 is selected for empirical analysis. The data generally comes from *China Statistical Yearbook*
 260 and *China Energy Statistical Yearbook*, and relevant economic data are deflated with year 1998 as
 261 the base period in order to remove the influence of price factors. The consumption inhibiting effect
 262 value is the inverse of the household consumption rate, as the accounting of the GDP expenditure
 263 method consists of household consumption, government purchases, investment expenditures, and
 264 net exports. When GDP is constant, the consumption inhibiting effect develops in the same direction
 265 as the three economic components of fixed asset investment, government purchases and net export,
 266 this not only reflects the operating status of the regional economy, but also reflects changes in the
 267 environment, concepts and policies of EC. Urbanization is usually reflected through the proportion
 268 of urban population in the total population. In terms of regional spatial expansion, this study selects
 269 the built-up area as a measure of spatial change (Yang and Shi, 2017). In order to deal with zero
 270 values while performing log transformation of variable in the process of LMDI effect decomposition,
 271 a small positive constant value (10^{-15}) is added to each of value of the relevant parameters.

272 4. Empirical results and analysis

273 The urbanization rate of China risen from 33.35% to 58.52% between 1998 and 2017, 397 million
 274 people moved to cities during the period, with an average annual growth rate of 3.59%.
 275 Correspondingly, the total EC has grown from 1361.84 million tons of standard coal to 4485.29
 276 million tons of standard coal, with the growing range of 3123.45 million tons of standard coal and
 277 the average annual growth rate of 6.47%, which is higher than the growth rate of urbanization. It
 278 can be preliminarily judged that the process of urbanization in China has accelerated EC, which
 279 echoes the research conclusion of Zhang et al. (2011). However, it's worth noticing that in the total
 280 EC, the increased multiple in daily life (3.89) is higher than production (3.22). Therefore, it is

necessary to further calculate the total EC change during the research period based on the model constructed above, decompose the effects and evaluate the change rate of each impact effect from the current year to the previous year. The specific results are shown in Table 1 and Figure 2. Population EC includes the household consumption effect, population scale effect, per capita living effect and urbanization structure effect. Spatial EC includes the density agglomeration effect and space expansion effect. Industry EC includes technological progress effect, structural adjustment effect, consumption inhibiting effect and production effect.

Tab 1 Effects and contributions of China's energy consumption from 1998 to 2017

Effect	Contribution of EC (million tons of standard coal)	Percentage of Total EC (%)
ΔIT	-1675.55	-50.17
ΔIS	-281.20	-8.42
ΔIC	206.77	6.19
ΔIP	643.31	19.26
ΔPC	3750.47	112.30
ΔPS	267.61	8.01
$\Delta Total-P$	2911.40	87.18
ΔPL	363.18	10.87
ΔPU	31.13	0.93
ΔAD	-272.68	-8.16
ΔAE	306.66	9.18
$\Delta Total-L$	428.29	12.82
$\Delta Total-EC$	3339.70	100.00

Fig. 2. Cumulative contribution of energy consumption effects

The fluctuation range of production EC is 6.80 times that of living EC, and shows a trend of decreasing year by year. Specifically, the total EC of the production side contributed 2911.40 million tons of standard coal, accounting for 87.18% of the total EC variation. Among them, the effects of industrial technological progress and structural adjustment have appeared, which have a

significant inhibitory effect on EC, and the negative contribution of technological progress is as high as -50.17%. Consumption inhibiting effect, production effect, household consumption effect and population scale effect are all positive contributions to the changes in production EC. Among them, the added value of production EC driven by residential consumption is the largest, and its positive contribution to total EC is 112.30%. The cumulative contributions of EC of other influencing factors are ranked as follows: 19.26% of production effect, 8.01% of population scale effect and 6.19% of consumption inhibiting effect. The growth of EC in daily life has reached 428.29 million tons of standard coal, taking up 12.82% of total EC variation. The per capita living effect of residents contributes 363.18 million tons of standard coal. Although it only accounts for 10.87% of the total EC change, it accounts for 84.80% of the change in life EC, and its positive influence rate is the highest. The second is the increase of 306.66 million tons of standard coal caused by the space expansion effect, which accounts for 9.18% of the total EC change, which is the second growth point of life EC. The structural effect of urbanization is 0.93% of the total effect, with a cumulative increase of 31.13 million tons of standard coal, with the smallest positive impact. The increase in population density has a contribution of -8.16% to EC, and the cumulative effect of density agglomeration saves 272.68 million tons of standard coal. Based on the parameters in the formula mentioned above, the following will analyze the impact of urbanization on EC from the three aspects of population, space and industry in-depth.

4.1 Effects decomposition from population aspect

The four energy consumption effects from population aspect within the research period are shown in Figure 3. The demographic changes in the process of urbanization have contributed 132.12% of total EC, among which 128.82% of the rise of EC in production comes from the domestic demand driven by household consumption. The scale effect of the population has a steady increase in the impact of fluctuations in production EC, contributing 9.19% of the total EC and only accounting for 7.14% of the household consumption effect. Affected by the economic environment, the positive contribution rate of the per capita living effect to the EC of life is 10.87% which has an overall upward trend of fluctuations. However, changes in the urbanization rate have little positive impact on EC in daily life, accounting for merely 0.93% of the total fluctuations in EC.

Fig. 3. Trends of various effects in population aspect

Based on specific analysis of the impact of demographic factors on the fluctuation of EC at the production-side, after the Asian financial crisis in 1997, China introduced related fiscal and taxation policies focusing on issuing additional treasury bonds and increasing government spending, the inhibited household consumption had slackened off the energy demands to certain extent. Since 2003, economic and fiscal policies implemented had stimulated the household consumption, and made the EC keep growing. Although under the influence of the global financial crisis in 2008, EC experienced a short-term decline, but on the whole, the impact of residential consumption on the EC at the production end during the inspection period still showed a fluctuating upward trend. Meanwhile, the increase in the income of urban residents is accompanied by the continuous expansion of the urban-rural consumption gap. In 2017, the consumption expenditure of urban residents in China accounted for 78.6% of total consumption expenditure, while the consumption expenditure of rural residents, which accounted for 41.4% of the total population, accounted for only 21.4% of total consumption expenditure, and the ratio of consumption expenditures between urban and rural residents has increased from 1.6:1 in 1998 to 3.7:1 in 2017. With the development of urbanization, the household consumption of urban and rural residents in China is increasingly biased towards energy-dependent products, which made the Engel coefficient drop from 49% in 1998 to 29.3% in 2017. If we benchmark against the 20% level of European and American countries, we can predict that with the deepening of urbanization, more urban residents will expand their demand for non-food commodities. This will undoubtedly become the main factor to promote EC at the production end in the future.

From specific analysis of the impact of demographic factors on EC fluctuations at life-side, the difference in lifestyles and living standards between urban and rural residents in the early days resulted in very different energy utilization and consumption behaviors. In 1998, the ratio of urban and rural living EC per capita was as high as 3.07, however, the improvement of residents' living standards is accompanied by the homogenization of consumption behaviors between urban and rural areas. The substantial increase in rural EC has caused the urban rural per capita EC ratio to drop year by year to 0.99 in 2017, and the EC gap in living has almost disappeared^①. Therefore, the urbanization structure effect is not the major influence factor, but the per capita life effect (national EC per capita) has the highest contribution to the variation of life EC. In addition, due to the previous one-child policy, the rate of population change was relatively low, and the growth rate remained at around 0.5% for many years, thus the current positive contribution to production EC is low. However, with the implementation of China's two-child policy in 2016, a substantial increase in population is likely to provide a broader consumer market for industrial development, and thereby provide a stronger driving force for EC.

4.2 Effects decomposition from space aspect

^① Non-commercial energy such as firewood, straw, and biogas in rural may account for a large proportion of the EC structure, and this part is not reflected in official statistics, thus the rural life EC may be underestimated.

The time series energy consumption fluctuations caused by two space effects during the research period are shown in Figure 4, the accumulated positive contribution degree of 1.01%. The agglomeration density effect of space is accumulated to contribution degree of -8.16% to the total EC. The scale effect of energy utilization caused by the population agglomeration is apparent, which relieves energy pressure to a certain extent. On the contrary, the positive contribution of the spatial expansion effect to the total EC is 9.18%, which exceeds the EC saved by the density agglomeration effect. On the whole, the space expansion in urbanization process of China has promoted the EC.

Fig. 4. Trends of various effects in space aspect

The reason is that with the expansion of population activity space in the process of urbanization, both the natural and socio-economic attributes of the land will change. Since 1998, the China has continued to optimize and adjust urban housing and land-use policies, the urban built-up area increased by 162.98% during the inspection period, which was much higher than the 95.51% increase in urban population. Land urbanization is faster than population urbanization. Due to the strong dependence of space expansion on capital, the contribution to EC fluctuations around 2008 financial crisis reached the lowest value. Afterwards, the country's policy of expanding domestic demand and infrastructure construction has continued to promote the impact of EC on the space aspect. Specifically, on the one hand, the spatial layout of the industrial structure in the process of urbanization in China is not highly coordinated. The space dislocation between the consumer market and the original resources, the separation of production areas and living areas, resulting in unreasonable allocation of elements, caused long-distance transportation of materials, increased commuting distances, long-term traffic congestion, repeated infrastructure construction, and many other problems that have increased economic operating costs and further consumed a lot of energy. On the other hand, during the expansion of land in the old urbanization stage, local governments over-relied on land transfer income and land mortgage financing in order to maintain growth, resulting in spatial “spreading” of low-density spread. To sum up, problems such as scattered land layout, low development intensity and strong exclusiveness of infrastructure functions have caused poor space comprehensive carrying capacity and unreasonable energy utilization patterns.

4.3 Effects decomposition from industry aspect

From 1998 to 2017, the cumulative contribution of China's industrial development to EC fluctuations was -33.14%, which verifies the previous opinions raised by Lu (1999) and Mukhopadhyay and Forssell (2005) that industrial development has a greater impact on EC in the urbanization process. The specific trend is shown in Fig 5, the accumulated contribution degree of technological progress effect is -50.17%, the total contribution degree of structural adjustment effect -8.42%, both of this two effects have had the mitigative effect on the total EC. On the contrary, changes in the urban-rural population ratio during the research period had a greater impact on production EC, with a cumulative positive contribution of 19.26%, which keeps growing in general. The consumption inhibiting effect has the positive contribution degree of 6.19% to production EC in total, but from the overall trend, the inhibiting effect on EC is increasingly enhancing. An important point that should not be ignored is that the effects of technological progress and structural adjustment have rebounded in recent years, and the effectiveness of alleviating EC is weakening.

Fig 5. Trends of various effects in industrial aspect

From industry-analysis perspective, since China's accession to the WTO, the country has successively promulgated a number of industrial technology policies, coupled with the addition of 400 million urban populations during the inspection period, the huge emerging market has formed a forceful effect, resulting in the transformation and upgrading of traditional energy-resource dependent industries, and further improved the energy efficiency. During the inspection period, the EC intensity was reduced from 1.60 to 0.99 year by year (calculated at the price in 1998). Although dramatic rise has appeared due to the financial crisis in 2008, technological progress effect had the biggest contribution to the reduction of production EC on the whole. Moreover, China's industrial structure had been actively adjusted and optimized as the ratio among three industries has been changed from 17.2:45.8:37.0 in 1998 to 7.6:40.5:51.9 in 2017, which thoroughly shows that the share of primary industry has been gradually replaced by the secondary and tertiary industries. Especially since 2005, the decline in the proportion of traditional industries and the rise in the proportion of modern service industries have reduced the dependence of industrial development on energy, which has caused significant downward fluctuations in EC. However, it should not be overlooked that there are varying degrees of diminishing marginal utility in technological progress effects and structural adjustment effects, on the one hand, this conclusion is consistent with the research by Shi and Zhang (2003). On the other hand, it also shows that the inhibitory effect of

technological and structural improvements at the industrial aspect on EC will be a bottleneck in the short term, so industrial development must never be the only way to reduce EC.

The production effect in the process of urbanization has promoted EC. This is mainly due to the expansion of the consumption market after the migration of rural populations to cities, which indirectly stimulated EC at the production side. This point is in sharp contrast with the conclusion of the urbanization structure effect on the life side mentioned above, indicating that the urbanization rate has a much greater effect on the EC of the production side than on the daily life side. The consumption inhibiting effect has an obvious phased inverted U-shaped impact on EC, because in the beginning of the research period, the economic components of China's GDP (including government purchases, investment, and net exports) was mainly concentrated in construction, transportation, and resources, this type of resource-driven development model has high EC characteristics. Especially in the late 2008, the "Four Thousand Trillion Economic Stimulate Package" plan proposed by the national policy to expand the domestic demand stimulated infrastructure construction, thus the early consumption inhibiting effect has promoted the increase of EC. Afterwards, the country has paid more and more attention to the green environmental protection industry, and the development of other economic components except consumer expenditures are all restricted by EC, thus the traditional extensive "three highs" development model (high EC, high material consumption, high pollution) has been improved, and the digital economy and sharing economy are in the ascendant, which has increased the efficiency of social energy use, thus, the consumption inhibiting effect has slowed the increase in overall EC to a certain extent in recent years.

5. Conclusions and policy recommendations

5.1 Conclusions

This study constructs a Kaya expansion model in vector form, and improves the traditional LMDI method into the form of polynomial multiplication and summation, the impact of urbanization on energy consumption in China from 1998 to 2017 is decomposed from the three aspects of population, space, and industry. The specific conclusions are as follows:

- (1) On the whole, with the development of urbanization, the total energy consumption of China has been rising. The average annual growth rate of urbanization in China within the inspection period is higher than the average annual growth rate of total energy consumption, and the process of urbanization in China has accelerated energy consumption. From the perspective of variation range, although the variation amount of production energy consumption is 6.80 times of the one of living energy consumption, it presents the tendency of decreasing year by year. From the perspective of growth multiples, the growth rate of energy consumption from daily life is higher than that from production side, and the gap is increasing year by year. Therefore, the domestic energy consumption in the process of urbanization in China is more worthy of attention.
- (2) From the population aspect, we conclude that the rise of energy consumption in production side mainly result from the expansion of domestic demand caused by residential consumption in the urbanization process. The impact of population scale effect on the fluctuations of production

energy consumption rises steadily. With the homogenization of consuming behaviors between urban and rural, the urbanization structure effect caused by the urban-rural population ratio is not the main influencing factor of living energy consumption, and the per capita living effect produced by per capita living energy consumption has the highest contribution to the change in living energy consumption.

(3) The spatial aspect conclusions show that the scale effect of energy utilization produced by population aggregation has reduced the pressure of energy in some extent. The space expansion effect has promoted the rise of total energy consumption, and exceeded the energy consumption amount saved from the density agglomeration effect. Therefore, the space expansion in urbanization process of China has promoted the energy consumption. The problems such as scattered land layout, low development intensity and strong exclusiveness of infrastructure functions have caused the poor comprehensive carrying capacity of space and unreasonable patterns of energy utilization.

(4) The conclusions in the industry aspect show that technological progress and industrial structure adjustment have alleviated the total energy consumption. The production effect has promoted energy consumption, and the consumption suppression effect has an inverted U-shaped effect on energy consumption that first promotes and then decreases. What cannot be ignored is that there are different degrees of rebound trends in both technological and structural effects, indicating that the restraining effect of these two factors will be bottlenecked in the short term. Therefore, industrial development must not be the only way to reduce energy consumption.

5.2 Policy Recommendations

After referring to the conclusions of effect decomposition in three aspects including population, space and industry, this study further proposes three policy recommendations about how to promote the efficiency of energy utilization in urbanization process as follows:

(1) In terms of population, it is suggested that to advocate the green energy use, and optimize energy consumption structure. Residents are both consumers and producers, and the implementation of two-child policy also means that the population scale will probably intensify the pressure of energy in the future. Thus, on the one hand, it is advisable to improve the awareness of energy conservation and consumption reduction, cultivate green consumption habits, and give full play to the market regulation role of price leverage, promote energy-saving consumption through price adjustments, guide the transformation of consumption structure from non-clean energy to clean energy, and from fossil energy to non-fossil energy; On the other hand, by promoting energy-saving technologies and products such as green buildings and energy efficiency labeling products to the demand side, the supply-side industry is forced to adjust, so as to research and development the energy-saving products, improve the energy-saving manufacture system, and promote the recycling energy model.

(2) In the aspect of space, optimizing the urban spatial structure and realizing a low-carbon sharing model is recommended. We should not blindly seek sustainable development of energy from the industrial structure and technology, instead we should arrange the space reasonably on the basis of examining many "big city diseases" to improve the efficiency of urban operation: on the one hand, strictly abide by the red line of land development, preserve the ecological

environment base, and realize a compact space layout that organic combines production, life and ecology; On the other hand, we suggest to revitalize the space inventory, release industrial space through urban renewal, and at the same time, to expand infrastructure compatibility, improve the utilization rate of public facilities, avoid dysfunction and repeated construction, develop a sharing economy, reduce commuting energy consumption, and reduce infrastructure energy consumption and promote intensive living energy consumption.

(3) In the aspect of industry, it is advisable to strengthen resource and environmental constraints and develop high value-added industries. The industries in the early stages of urbanization were mainly labor-intensive and depended strongly on resources and the environment. The influx of low-end labor and extensive industrial development have made the energy intensity much higher than that of European and American countries, but the proportions of secondary industry in GDP of those developed countries during the urbanization process have surpassed 55%, and theirs high-tech industries have a prominent proportion and low energy consumption. Therefore, the industrial development under the new urbanization process cannot simply reduce the proportion of the secondary industry, instead, we must strengthen the environment and resource restrains, upgrade development models, focus on industrial quality and efficiency, develop high-tech industries and high-end service industries, and strive to achieve the decoupling of economic development and energy consumption.

-Ethical Approval and Consent to Participate

Not applicable, this manuscript does not report on or involve the use of any animal or human data or tissue.

-Consent to Publish

Not applicable

-Authors Contributions

Xiang Yan contributed to the conception of the study, analysis and manuscript preparation.

Yongchun Huang helped perform the analysis with constructive discussions.

All authors read and approved the final manuscript.

-Funding

This work was supported by the Humanities and Social Sciences Foundation of the Ministry of Education of China [Grant No. 20YJC630180], the Chinese Postdoctoral Science Foundation [Grant No. 2020M681471], the Postdoctoral Research Funding Program of Jiangsu Province [Grant No. 2020ZZ264].

-Competing Interests

The authors declare that they have no competing interests.

-Availability of data and materials

The datasets used and/or analysed during this study are available from the corresponding author on reasonable request.

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Highlights

- Builds transmission mechanism of urbanization on energy consumption from three aspects: population, space and industry.
- Constructs a Kaya expansion model in vector form, and modifies the traditional LMDI method into the form of polynomial multiplication and summation.
- Decomposes multidimensional effects of urbanization on energy consumption from three aspects of population, space, and industry.
- Inhibiting effects of technological progress and structure adjustment from industry aspect appear diminishing marginal utility.
- More attention should be paid in population and space aspects.

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Figures

Figure 1

Effect mechanism of population-space-industry on energy consumption in the process of urbanization

Figure 2

Cumulative contribution of energy consumption effects

Figure 3

Trends of various effects in population aspect

Figure 4

Trends of various effects in space aspect

Figure 5

Trends of various effects in industrial aspect