

Multi-drivers and multi-mechanism analysis for city-level energy consumption in Suzhou based on the extended STIRPAT model

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Abstract. Examining the driving factors of energy consumption at city scale, is an important measure for effectively achieving energy saving and emission reduction. An extended STIRPAT model based on the classical IPAT identity is adopted to uncover the main drivers for total energy consumption in Suzhou, an important manufacturing city in China, during 2006 to 2016. The main conclusions are as follow: (1) Foreign trade, economic growth, and industrialization are the three dominant contributors to energy consumption increments. Furthermore, quite significant portion of Suzhou's foreign trade is processing exports. The export products are mainly high-energy consumption such as electromechanical, chemical, textile, etc. The export-oriented economy is accelerating the economic growth and industrialization, and also strengthening the energy intensive regional development mode. (2) Urbanization and population size are also the main driving factors for the rapid growth of energy consumption in Suzhou. The population scale effect exhibits the urban function of absorb employment and agglomerate population in Suzhou, it also demonstrates the growing energy demands caused by population growth and the accompanying urbanization process. (3) Energy consumption intensity and energy consumption structure are the important influencing factor in curbing energy consumption in Suzhou. Energy saving effects played by energy consumption intensity are stronger than energy consumption structure. The coal-based energy consumption structure has not been changed fundamentally during the research period. Therefore, the energy saving effect of energy structure has not been fully utilized. The current and future major strategies for controlling energy consumption in Suzhou should further improve energy utilization efficiency, optimize energy consumption structure, and reduce the proportion of coal consumption.

1. Introduction

As a common resource for human survival and socio-economic development, energy resources are basic material source for modern society, and the most powerful engine for regional development [1]. Especially since the industrial revolution, access to affordable, stable and cleaner energy supplies has been the cornerstone of world economic growth and social prosperity [2]. After the 1978 reform and opening up, the rapid industrialization and urbanization process have made China's total energy



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consumption growth too fast. At present, China has become the world's largest energy consumer. As of 2016, the global primary energy consumption reached 13276 million tons of oil equivalent (toe), of which China accounted for 23% of global energy consumption [3]. China's rapid economic growth and energy consumption have ensured the growth of energy supply and energy security pressures, which in turn has brought about a series of problems in the fields of ecology and environment [4]. In order to actively respond to energy issues [5], China announced that energy intensity (per unit GDP energy consumption) should decrease by 16% during 2011-2015 and by 15% during 2016-2020, and non-fossil fuel energy consumption should be 15% of the total primary energy consumption until 2020. Therefore, ecological energy, clean energy and efficient energy have become the core of China's energy strategies.

From the perspective of geographic analysis, research on country's energy consumption problem needs not only to assess from the changes of total amount, but also to grasp from the regional pattern changes. National energy saving and emission reduction strategies cannot be efficiently implemented without sufficient understanding of China's energy consumption status at the regional level [6, 7], especially the urban regions. Urban energy systems play an extremely important role in China's national energy system. Among energy-related carbon emissions sources in China, approximately 85% of emissions are contributed by energy consumption in cities, which is much higher than that experienced in the U.S. (80%) or in the EU (69%) [8, 9]. Therefore, understanding the growth trend of urban-scale energy consumption and its influencing factors is an important part of achieving energy saving and emission reduction strategies, as well as reducing energy consumption intensity. Wang et al. [10] adopted the STIRPAT (stochastic impacts by regression on population, affluence and technology) model to examine the influences of urbanization level, per capita GDP, industrialization level, tertiary industry proportion, energy intensity and R&D output on energy-related carbon emissions in Beijing. Wang et al. [11] used the STIRPAT model to reveal the effects of population size, per capita GDP, urbanization level and energy intensity on energy-related carbon emissions in Shanghai. Li et al. [12] employed the STIRPAT model to study the impacts of population size, urbanization level, industrialization level, per capita GDP, FDI, and energy intensity on energy-related carbon emissions in Tianjin. By comparing these three previous studies conducted at city level in China, the urbanization level, per capita GDP, and industrialization level played the most positive effects on carbon emissions in Beijing, while tertiary industry proportion and energy intensity performed the most important negative effects [10]. The population size, urbanization level, and per capita GDP would increase carbon emissions, but energy intensity would decrease, in Minhang district, Shanghai [11]. The urbanization level, industrialization level, per capita GDP, and FDI played important roles in energy-related carbon emissions growth, while energy intensity played minor but important negative effect on carbon emissions in Tianjin [12]. The impacts and influences of various factors on energy-related carbon emissions were different across different cities [10-12].

As a national manufacturing city, Suzhou is in a critical period of transformation, upgrading and innovation. In 2016, Suzhou's GDP ranked sixth in China in terms of city rankings, only behind Shanghai, Beijing, Guangzhou, Shenzhen, Tianjin, and Chongqing. But, the total energy consumption in Suzhou was much higher than Beijing, Guangzhou, Shenzhen, Tianjin, and Chongqing. Total energy consumption in Suzhou was 84.09 million tons of standard coal (tce) in 2016 [13], Beijing was 69.62 million tce [14], Guangzhou was 58.53 million tce [15], respectively. It is urgent to take a new road to sustainable development with low energy consumption and low emissions. As the second batch of low-carbon pilot cities in China, Suzhou announced that its total carbon emissions would peak around 2020. At the same time, Jiangsu province also issued a series of energy-saving and emission-reduction targets for Suzhou, that is a 18% reduction in energy intensity during the 12th Five-Year Plan period and a 19% reduction during the 13th Five-Year Plan period. Therefore, what are the main drivers for energy consumption in Suzhou? However, few studies provided an in-depth analysis of energy consumption in Suzhou. Therefore, Suzhou may serve as a demonstration of how to complete the strict energy conservation and emission reduction target, thereby highlighting the

representativeness of Suzhou city and the importance of studying its influencing factors of energy consumption in detail.

2. Research methodology and data sources

2.1. Research methodology

Taking the *IPAT* (Impact = Population × Affluence × Technology) model as the basic framework is one of the main methods of factor decomposition technique [16]. The *IPAT* identity was established in the early 1970s by Ehrlich and Holden [17, 18], has been considered as an understandable framework for measuring the drivers for environmental pressure, which can be described with the following equation:

$$I = PAT \quad (1)$$

Where, I is the environmental pressure indicator (i. e. energy consumption in this study); P represents the total population; A represents affluence; T represents technology.

In the *IPAT* model, I was affected by influencing factors P , A and T , respectively. However, *IPAT* identity was not a perfect solution for the proportional relationship between influencing factors and environmental pressure indicators. Then, York et al. [19, 20] established the STIRPAT (Stochastic impacts by regression on population affluence and technology) model with a stochastic form on the basis of the *IPAT* framework, which was performed as follows:

$$I = aP^b A^c T^d e \quad (2)$$

Where, a represents the model coefficient, b , c and d represent the exponents for independent variables, and e represents the model error term.

The STIRPAT model, which is a multivariable nonlinear model. By taking natural logarithm on both sides of Eq. (2):

$$\ln I = a + b \ln P + c \ln A + d \ln T + \ln e \quad (3)$$

Table 1. Description of variables used in the analysis in Suzhou city.

Variables	Symbol	Definition measuring method	Unit
Energy consumption	I	City level total energy consumption accounting	10000 tce
Population size	P	Total resident population	10000 people
Urbanization	U	Percentage of urban population in total population	%
Economic growth	A	Gross domestic product divided by total population	Yuan per capita
Industrialization	IS	Industry output added value	10000 Yuan
Energy consumption structure	ES	Percentage of coal consumption to total energy consumption	%
Technological progress	T	Energy consumption per unit gross domestic product	tce/10000 Yuan
Foreign trade	W	Total volume of import and export trade	Billions of dollars

In the newly constructed STIRPAT model, more and more influencing factors are allowed to be adopted for the analysis of energy consumption, based on the previous studies. In order to further fully examine the driving forces, a few more factors have been adopted to explain the changes of energy consumption. On the basis of the total population (P), urbanization level (U), which is described by the urban population proportion, is adopted to analyze the influence on energy consumption. The affluence (A), which is described by the GDP per capita, is adopted to analyze the influence of economic growth on energy consumption. T is characterized with the energy consumption per unit GDP, which is the influence of technological progress on energy consumption [21]. The factor IS is used to study the influence of industrialization level on energy consumption. The factor ES is used to study the influence of energy consumption structure change on total energy consumption. The

explanations of the specific variables are presented in Table 1, and the following equation was described as follows:

$$\ln I = a + b_1 \ln P + b_2 \ln U + d \ln A + f \ln IS + g \ln ES + h \ln T + j \ln W + \ln e \tag{4}$$

2.2. Data sources

Data resources, consisting of the total population including urban population, the gross domestic product (GDP) including industry output added value, total energy consumption, and the total import and export trades, covering the period from 2006 to 2016, are all available, as shown in Figure 1, Figure 2, and Figure 3. Energy, economy, population and trade data are all collected from the Suzhou Statistical Yearbook (2007-2017) [13]. Economic data was measured by GDP in Chinese Yuan during 2006-2016, taken in 2006 constant prices to avoid the inflation impacts.

Figure 1 exhibited the process of population growth and urbanization level during 2006 to 2016 in Suzhou. Total resident population of Suzhou has grown rapidly from 8.08 million in 2006 to 10.65 million in 2016, with an average annual growth rate of 2.77%. In the same period, the registered population of Suzhou increased from 6.16 million in 2006 to 6.78 million in 2016, indicating the strong population agglomeration capacity of Suzhou. Registered population is the population that has obtained the local household registration. The resident population contains a large number of floating population. Compared with the registered population, the resident population can reflect the population size of a city more accurately. Along with the capacity of population agglomeration and the ability to absorb employment, the agglomeration effect and structural changes of its population have led to a rapid increase in the level of urbanization in Suzhou, from 65.08% in 2006 to 75.50% in 2016 (Figure 1).

Figure 1 shows the process and urbanization process in Suzhou.

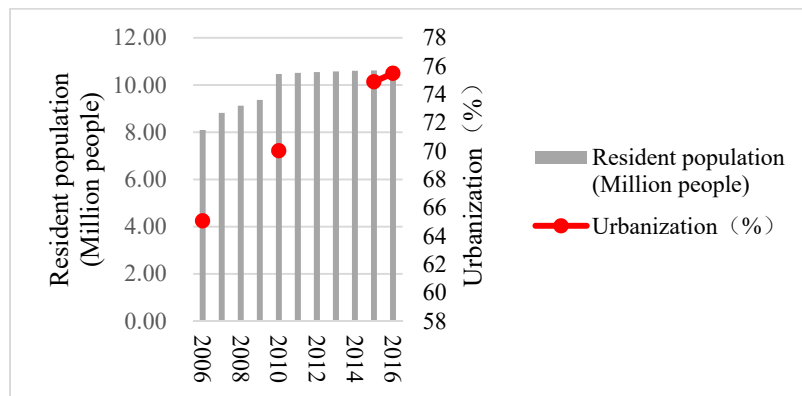


Figure 1. Population size and urbanization in Suzhou from 2006 to 2016.

Industrialization was represented by industry output added value in Suzhou. With the constant price treatment in 2006, the industrial added value of Suzhou increased from 301.832 billion yuan in 2006 to 608.631 billion yuan in 2016, with an average annual growth rate of 7.27%; per capita GDP increased rapidly from 61097.84 yuan/person in 2006 to 130507.95 yuan/person in 2016, with an average annual growth rate of 7.86%.

As we know, Suzhou is a city with developed foreign trade [22]. The total volume of foreign trade imports and exports during the 11th Five-Year Plan period has increased by an average of 14.3%. During the 12th Five-Year Plan period, the global economy was still in the post-financial crisis era. Although the annual average growth rate of Suzhou's foreign trade was 2.2%, it still accounted for more than 55% of Jiangsu's total foreign trade volume, as well as 7% of the national total foreign trade volume. As shown in Figure 3, the foreign trade dependence in Suzhou was more than 140% per year. In addition, Suzhou's foreign trade was mainly based on export trade.

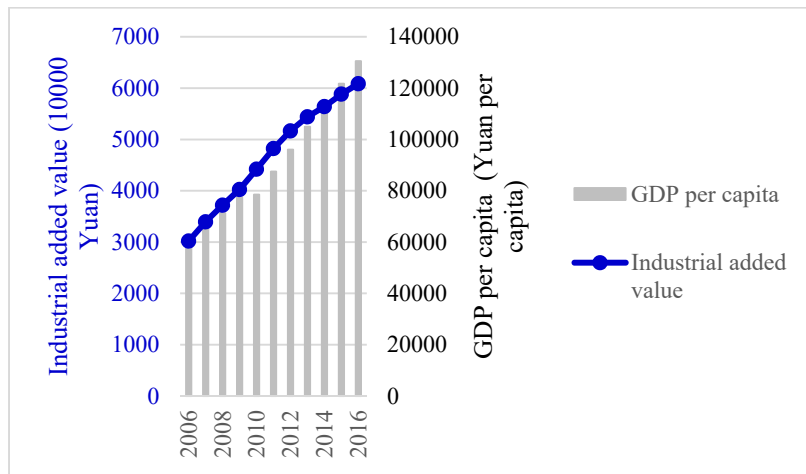


Figure 2. Economic growth and industrialization in Suzhou during 2006-2016.

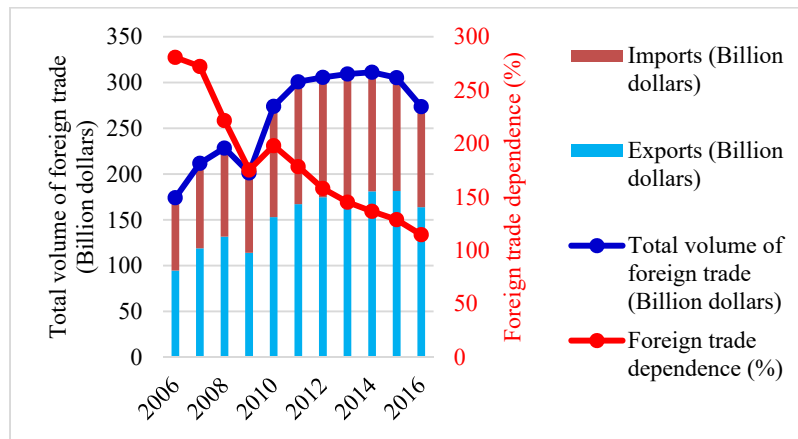


Figure 3. Imports and exports and the foreign trade dependence in Suzhou.

3. analysis of the results

3.1. Multicollinearity testing

Before performing the correlation test between variables, the variables first underwent the logarithmic treatment to eliminate the influence of the dimension between the variables. It can be seen from Table 2 that the correlation coefficients between the variables P , U , A , IS , ES , T and W are both high. Therefore, it can be judged that there is a high correlation between variables, and there may be severe multicollinearity.

Table 2. Correlation test results.

	$\ln P$	$\ln U$	$\ln A$	$\ln IS$	$\ln ES$	$\ln T$	$\ln W$
$\ln P$	1.000	.878	.921	-.779	.833	-.868	.915
$\ln U$	.878	1.000	.968	-.936	.966	-.920	.933
$\ln A$	.921	.968	1.000	-.938	.969	-.954	.936
$\ln IS$	-.779	-.936	-.938	1.000	-.969	.890	-.839
$\ln ES$	.833	.966	.969	-.969	1.000	-.918	.897
$\ln T$	-.868	-.920	-.954	.890	-.918	1.000	-.920
$\ln W$	.915	.933	.936	-.839	.897	-.920	1.000

In order to determine whether there is multicollinearity between the dependent variable *I* and the explanatory variables *P*, *U*, *A*, *IS*, *ES*, *T* and *W*, the ordinary least squares estimation (OLS) is first performed on each variable. OLS was used to evaluate their variance inflation factor (VIF). As shown in Table 3, the VIF of the variable is much higher than the maximum tolerance of 10, indicating that there is severe multicollinearity between the explanatory variables. The reliability of the regression coefficient of the OLS is low and cannot be effectively explained by the energy consumption impact factor.

Table 3. OLS regression.

Variables	Unstandardized coefficients	t-Statistic	Sig.	VIF
<i>c</i>	-9.21034	-5158091.21	1.61E-20	
<i>lnP</i>	1.000	4295198.71	2.78E-20	289.28392
<i>lnU</i>	-1.1E-13	0.00	1.000	184.07995
<i>lnA</i>	-6.7E-14	0.00	1.000	3318.4855
<i>lnIS</i>	1.000	4462175.40	2.48E-20	785.87908
<i>lnES</i>	1.000	3719454.62	4.29E-20	2742.8702
<i>lnT</i>	9.84E-14	0.00	1.000	103.92969
<i>lnW</i>	2.44E-14	0.00	0.999999	34.832895

3.2. Ridge regression

In order to ensure the validity and accuracy of the model results, overcome the influence of multicollinearity between variables on the regression results, improve the stability and reliability of traditional least squares estimation, Ridge regression is adopted to estimate the impact factor. The ridge regression estimation is essentially an improved method of least squares estimation, which can reduce large standard errors significantly among related independent variables, is one of the most effective solutions for the model estimation and reliability of the regression coefficients [23]. The ridge regression coefficient is selected according to the relationship between *R* square and *K*. When *K*=0.220, *R* square is almost stable in this case study in Table 4. Therefore, ridge regression coefficients are selected as follows:

$$\begin{aligned}
 LnI = & 0.118LnP + 0.146LnU + 0.184LnA \\
 & + 0.169LnIS - 0.123LnES - 0.128LnT + 0.190LnW
 \end{aligned}
 \tag{5}$$

Table 4. Ridge regression results.

Parameters	Regression coefficients	Parameters	Regression coefficients
<i>lnP</i>	0.118	<i>lnT</i>	-0.128
<i>lnU</i>	0.146	<i>lnW</i>	0.190
<i>lnA</i>	0.184	<i>R</i> ²	0.998
<i>lnIS</i>	0.169	<i>F</i> test	4.999
<i>lnES</i>	-0.123	<i>K</i>	0.220

Based on the results of the regression equation, foreign trade (*W*), economic growth (*A*), industrialization (*IS*), urbanization (*U*) and population size (*P*) are the main contributors to the growth of energy consumption, while technological progress (*T*) and energy consumption structure (*ES*) are the main contributors to curbing energy consumption growth. The descending order on the degrees of the positive influencing factors was: foreign trade > economic growth > industrialization > urbanization > population size. The negative influencing factors could be ranked according to their influencing degrees: technological progress > energy consumption structure.

Foreign trade (W): Since the reform and opening up, Suzhou, relying on the favorable location advantages of the Yangtze River Delta, gave full play to the traditional advantages of cooperation between agriculture and industry, has made great efforts to develop an export-oriented economy. Especially since entering the WTO in 2002, the export-oriented economy of Suzhou has entered a new stage. The import and export products of Suzhou were mainly energy intensive products such as electromechanical, chemical and textile. In 2016, the total import and export volume of electromechanical, chemical and textile products accounted for 74.33%, 8.28% and 6.65% of the total import and export volume of the city, respectively. While import and export trade were driving economic growth in Suzhou, its energy intensive processing exports trade mode has become the most important contributor to the growth of energy consumption.

Economic growth (A) and industrialization (IS): Since entering the WTO, Suzhou's export-oriented development mode has rapidly grown into a national industrial city and a global manufacturing base. Industrial activities were mainly focused on the *electronic information industry, equipment manufacturing industry, smelting and pressing of ferrous metals, chemical and textile*. At present, it is already the second largest industrial city in the country. In 2016, the total output value of industrial enterprises above designated size in Suzhou was 3071.399 billion yuan, only lower than Shanghai's 3108.272 billion yuan.

The rapid development of the industrial economy continued to drive the rapid development of their associated energy-intensive industries. At the same time, foreign direct investments in Suzhou were dominated by energy-intensive processing export trade, and foreign-invested industrial clusters were formed to further strengthen the energy-driven industrialization and economic growth mode. However, the driving force of industrialization for energy consumption growth is weaker than economic growth. Especially since 2010, the growth rate of industrial fixed asset investment has declined. The average annual growth rate of energy-intensive steel, textile and chemical industries has declined. The equipment manufacturing industry, which represents the direction of advanced manufacturing, has replaced the steel industry, as the second leading industry in the city. This phenomenon indicated that Suzhou's industrial structure was continued to be optimized and was entering a key transition period of high-quality development.

Urbanization (U) and population size (P): The continuous growth of population size and the continuous improvement of urbanization level have also played significant effects on the growth of energy consumption. In the process of rapid population growth and urbanization, a large number of foreigners and rural residents have flooded into cities, resulting in continued growth in consumption needs, such as real estate demands, transportation demands, power consumption demands, etc. These growing demands in turn played a significant impact on the growth of energy consumption.

Technological progress (T) and energy consumption structure (ES): Technological progress and energy consumption structure are the main contributors to curbing the growth of energy consumption, which has slowed down the rapid growth of energy consumption to a certain extent, but the impact degrees of technological progress and energy consumption structure on the total energy consumption (in absolute terms) are significantly lower than other positive factors (except population size). Representing technological progress with energy consumption intensity, the energy consumption intensity of Suzhou dropped from 0.96 tons of standard coal per 10000 yuan in 2006 to 0.53 tons of standard coal per 10000 yuan in 2016. The continued decline in energy consumption intensity has become the most important contributor to mitigate the rapid growth of energy consumption during this period. However, the energy consumption intensity of Suzhou in 2016 was much higher than Shenzhen's 0.191, Beijing's 0.254, and Shanghai's 0.394. The reasons for the relative high energy consumption intensity in Suzhou were mainly due to the low energy utilization efficiency of these energy-intensive industries, such as electricity, thermal, metal, paper, textiles, and chemicals.

From 2006 to 2016, energy consumption structure of Suzhou has always been characterized by coal. Natural gas, oil, electricity and other renewables have also played important positive but relatively minor effects on the optimization of end-use energy consumption structure in Suzhou. In 2016, the proportion of coal consumption was 62.63%, and the proportion of natural gas consumption was

8.11%. Although the coal-based energy consumption structure has not undergone fundamental changes, the proportion of raw coal and coal products in total energy consumption in Suzhou has shown a downward trend year by year. The proportion of coal (raw coal + clean coal + coke) in total energy consumption continued to drop from 70.83% in 2006 to 62.63% in 2016. The energy consumption structure adjustment in Suzhou achieved initial progresses, especially in reducing the total coal consumption at the current stage.

4. Discussions and conclusions

In order to uncover the main drivers for total energy consumption in Suzhou, an important manufacturing city in China, an extended STIRPAT model based on the classical IPAT identity is adopted, during 2006 to 2016. The main discussions and conclusions are as follows:

4.1. Discussions

We compare our results in Suzhou with the previous studies carried out in Beijing, Shanghai, and Tianjin at the city levels [10-12]. The comparison further highlights the previous conclusions that energy consumption intensity is the most important factor to curbing total energy consumption both at the city level.

However, results carried out from the perspective of energy consumption drivers are different. Urbanization level is the most significant contributor to energy consumption increments in Beijing and Tianjin. The effect on energy consumption played by urbanization level was relative weak than the effects played by economic growth and industrialization level, respectively. Suzhou's urbanization level was significantly lower than Shanghai [24], Beijing [14] and Tianjin [25]. Urbanization levels in Suzhou, Shanghai, Beijing, and Tianjin in 2016 were 75.80%, 87.70%, 86.50%, and 82.93%, respectively.

4.2. Conclusions

Foreign trade, economic growth, and industrialization are the three dominant contributors to energy consumption increments, while technological progress and energy consumption structure are the main contributors to curbing energy consumption growth. The descending order on the degrees of the positive influencing factors was: foreign trade > economic growth > industrialization > urbanization > population size. The negative influencing factors could be ranked according to their influencing degrees: technological progress > energy consumption structure.

The export-oriented economy is accelerating the economic growth and industrialization, and also strengthening the energy intensive regional development mode. Foreign trade is the most important driver for energy consumption in Suzhou. That was mainly due to the development models of each city were very different. The rapid development of the industrial economy continued to drive the rapid development of their associated energy-intensive industries. In the future, Suzhou should make great efforts to reduce the proportion of energy-intensive products in import and export trade.

Urbanization and population size are also the main driving factors after the foreign trade for the rapid growth of energy consumption in Suzhou. The population scale effect exhibits the urban function of absorb employment and agglomerate population in Suzhou, it also demonstrates the growing energy demands caused by population growth and the accompanying urbanization process.

Energy consumption intensity and energy consumption structure are the important influencing factor in curbing energy consumption in Suzhou. Energy saving effects played by energy consumption intensity are stronger than energy consumption structure. The coal-based energy consumption structure has not been changed fundamentally during the research period. Therefore, the energy saving effect of energy structure has not been fully utilized. Therefore, the current and future major strategies for controlling energy consumption in Suzhou should further improve energy utilization efficiency, optimize energy consumption structure, and reduce the proportion of coal consumption, especially in its energy intensive industries.

In order to fully meet energy and climate targets of Suzhou, more efforts should be made to reduce the proportion of energy-intensive products during the development of foreign trade. Furthermore, energy consumption intensity should be effectively improved, energy consumption structure should be further optimized along with the decline of coal consumption.

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