

Study on the impact of energy consumption structure index on energy intensity

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Abstract. The effects of the industrial structure of energy consumption structure and environmental regulations on energy consumption per unit of GDP are explored and empirically tested using the panel regression method based on panel data of 30 provinces and cities in China from 2000 to 2021. It is found that upgrading the energy consumption structure has a significant inhibitory effect on the energy consumption per unit of GDP, and the results are robust. The mechanism test shows that energy intensity is affected by the industrial structure upgrading effect and the environmental protection expenditure effect on energy consumption structure upgrading. Further discussion through the industrial heterogeneity test reveals that for regions with less coal resource endowment or higher GDP, low-carbon upgrading of energy consumption structure can significantly reduce energy intensity. Upgrading the energy consumption structure for the secondary and tertiary industries can significantly reduce energy intensity. In contrast, upgrading the energy consumption structure for the primary industry can increase energy intensity, but the effect is not significant.

Keywords: Energy consumption structure; energy intensity; heterogeneity; mechanism test.

1. Introduction

Fossil energy has always been the most critical energy source consumed globally because of its low difficulty in extraction and its mature application. However, fossil energy sources have long been extracted and utilized on a large scale, resulting in shrinking reserves. The annual report released by the Global Energy Industry Organization shows that the share of fossil fuels in the global energy supply reaches 82%, and the share of fossil energy consumption in China reaches 82.5%. In order to reduce carbon dioxide or other pollutant gases produced during fossil energy consumption, China has been vigorously advocating energy conservation and emission reduction in recent years in order to achieve "dual carbon" target. The advantages of coal, such as abundant reserves, low cost and multi-functionality, make its substitutes fewer, leading to the difficulty of adjusting and upgrading China's coal-dominated energy consumption structure, which has become a significant factor in the growth of China's carbon emissions. In view of this, China's energy structure has been continuously optimized, adjusted, transformed and upgraded in the direction of cleanliness, high efficiency, low carbon and diversified development, laying a good foundation for achieving carbon neutrality by 2060. At present, China's energy intensity continues to decline. However, it is still higher than the world average level, in which energy consumption is mainly concentrated in industry, so what is the impact of structural adjustment of energy consumption on the energy intensity of the industrial sector? Moreover, can it become an effective means to reduce energy consumption per unit of GDP? If yes, how does it maximize its inhibitory effect? To this end, this paper explores the theoretical mechanisms and impacts of upgrading the energy consumption structure on the energy intensity of the three major industrial sectors in the hope of synergizing the promotion of China's economic green development from the energy supply and demand sides.

2. Literature Review

2.1. Concept and Measurement of Energy Consumption Structure

Existing literature on energy consumption structure mainly focuses on three aspects: influencing factors, trend prediction and measurement of decarbonization level. The factors influencing the energy mix have been most studied. It is found that the factors such as industrial restructuring [1], finance, urbanization level, green economy development level, digital economy and so on all have an impact on the energy consumption structure [2]. As far as the trend prediction of energy consumption structure is concerned, scholars have mainly focused on the choice of methods, such as the use of improved Markov chains [3] or gray theory [4], macrosystem models [5], multi-objective decision-making methods [6], scenario analysis methods [7], or combinations of two or more ways [8], and so on. As far as the measurement of decarbonization of energy consumption structure is concerned, there are mainly two kinds of measurement standards: the first one is to measure the energy structure by a single indicator, such as the proportion of coal consumption or clean energy consumption in the total energy consumption [10]; The second is to construct comprehensive indicators using hierarchical analysis [12] or through data such as the rate of change in energy consumption [11].

2.2. Research on Energy Intensity

Energy intensity is also called energy consumption per unit of GDP, and studies on energy intensity mainly focus on the relationship between energy intensity and its convergence with other economic indicators and differences in energy intensity. Scholars have found that the degree of marketization and foreign direct investment are conducive to the convergence of China's energy intensity to a lower place within a specific range [13]; the level of China's digital economy development can be negatively correlated with the energy intensity [14], while the level of urbanization and the energy intensity are positively correlated [15]. Regarding the differences in energy intensity and specific decomposition, Liu Qilu et al. found that the energy intensity of cities continues to decline by using Dagum's Gini coefficient and spatial Markov chain analysis, and the changing trend shows spatial agglomeration and differentiation characteristics [16].

2.3. Energy Consumption Structure and Energy Intensity

There are fewer studies on the relationship between energy consumption structure and energy intensity, such as Wang Linhui and Yang Shanshan, who found that the energy bias of technological progress can be realized by adjusting the energy consumption structure to the energy intensity through the construction of a double nested CES production function [17]. Zhang Yinhao found that energy consumption structure significantly contributes to energy consumption intensity and has regional heterogeneity [18].

According to the existing literature, there is no literature on energy consumption structure on energy intensity of different coal endowment, GDP region, different industrial structures for heterogeneity analysis, industrial structure upgrading effect and environmental protection expenditure effect to make a specific analysis of the mechanism, and these on the structure of energy consumption or energy intensity has a great relevance to our country in the future of the industrial structure upgrading and energy emission reduction in the balance of trade-offs. It is crucial for China in the future industrial structure upgrading and energy emission reduction balance trade-off.

3. Experimental Design and Data Description

3.1. Model Settings

3.1.1. Benchmark Regression Model

Due to the lack of energy data statistics in Tibet, the estimation of this paper uses 30 provinces (cities and autonomous regions), 2000-2021 a total of 22 years of panel data model is set as follows:

$$\ln y^m = \alpha_0 + \alpha_1 \times \ln gecx + \alpha_2 \times control + \varepsilon \quad (1)$$

Where $m=0,1,2,3$ denotes the energy intensity of total industry, primary industry, secondary industry and tertiary industry, $\ln gecx$ denotes the decarbonization index of energy consumption, $control$ is a series of control variables, ε is a random perturbation term, and β_l is the coefficient of interest in this paper.

3.1.2. Mechanism Test Model

$$\ln y^0 = \beta_0 + \beta_1 \times \ln gecx + \beta_2 \times \ln gecx \times \ln iso + \beta_3 \times \ln iso + \beta_4 \times control + \varepsilon \quad (2)$$

$$\ln y^0 = \lambda_0 + \lambda_1 \times \ln gecx + \lambda_2 \times \ln gecx \times \ln eco + \lambda_3 \times \ln eco + \lambda_4 \times control + \varepsilon \quad (3)$$

Where iso and eco denote two mechanism variables, respectively, industrial structure upgrading effect and environmental protection expenditure effect.

3.2. Selection of Variables

3.2.1. Explained variable

The total energy consumption of the three industries in the i th province in year t is divided by the value added of the region as the energy intensity for the benchmark regression and the mechanism test and heterogeneity test. The energy consumption of primary, secondary, and tertiary industries in the i th province in year t is divided by the value added of the corresponding industry as the explanatory variable in the heterogeneity test.

3.2.2. Core explanatory variable

The types of energy consumption include coal, coke, petroleum, crude oil, natural gas, electricity, etc. The single energy share is not sufficient to represent the dynamic process of energy consumption, this paper draws on Fu Linghui's method[20] to construct an energy consumption structure index to measure the green and low-carbon transition process, so the definition of the energy structure decarbonization index is as follows: first of all, the energy unit is standardized as 10,000 tons of standard coal, and each subcategory of energy is uniformly divided into three categories: coal, oil, and gas, electricity and heat and other energy sources, and the proportion of energy consumption of the three categories of energy consumption of each province in the year t is taken as a component of the space vector, and the vector coordinates are constructed as follows:

$$X_0 = (x_{1,0}, x_{2,0}, x_{3,0}) \quad (4)$$

Then calculate separately the angle between the vector of energy consumption ranked from high carbon to low carbon and the vector of angle:

$$X^1 = (1, 0, 0), X^2 = (0, 1, 0), X^3 = (0, 0, 1) \quad (5)$$

The formula is as follows:

$$\theta_j = \arccos \left(\frac{\sum_{i=1}^3 (x_{i,j} \cdot x_{i,0})}{\left(\sum_{i=1}^3 (x_{i,j}^2) \right)^{1/2} \cdot \left(\sum_{i=1}^3 (x_{i,0}^2) \right)^{1/2}} \right) \quad (6)$$

At last, the formula for defining the decarbonization of the energy consumption structure is as follows:

$$gecx = \sum_{k=1}^3 \sum_{j=1}^k \theta_j \quad (7)$$

3.2.3. Mechanism Variables

There are two mechanism variables, one is the industrial structure upgrading effect, and the ratio of the value added of the tertiary industry to the value added of the secondary industry in the i th province in year t is selected to represent the industrial structure upgrading. The larger the $lniso$, the larger the industrial structure upgrading effect. The second one is environmental protection expenditure effect. The investment in industrial pollution control of the i th province in the t th year is chosen to represent the investment. The larger $lneco$ is, the larger the effect of environmental protection expenditure is.

3.2.4. Control Variables

The variables of per capita purchasing power (aop), inflation index (inf), government intervention (fin), energy supply ($output$), and the level of green innovation (gre) are set to affect the energy consumption or GDP, and are taken as per capita disposable income of urban residents in each province, consumer price index, general budget expenditure, energy production, green patent authorization, and so on. Expenditures, energy production, and the number of green patents authorized are expressed, and logarithms are taken in the subsequent empirical tests in order to reduce the influence of heteroskedasticity.

Due to the lack of data in Tibet, Hong Kong, Macao and Taiwan, this paper selects the panel data of 30 provinces (municipalities and autonomous regions) in China from 2000 to 2021 for analysis, and the data come from China Statistical Yearbook, China Energy Statistical Yearbook, China Research Data Service Platform (CNRDS), wind database, China Marketization Level Report, and China Environmental Statistical Yearbook.

4. Empirical Results and Analysis

4.1. Benchmark Results

Table 1 reports the regression results of model (1). The regression results in Columns (1)-(4) show that the effects of upgrading the decarbonization of the energy consumption structure on energy consumption are all significantly negative regardless of the addition of control variables or the inclusion of time province fixed effects.

Table 1. Benchmark regression results.

Variables	(1)	(2)	(3)	(4)
Ingecx	-0.679*** (0.188)	-0.987*** (0.173)	-0.660*** (0.177)	-0.948*** (0.170)
Inoutput		0.147*** (0.0163)	0.166*** (0.0192)	0.147*** (0.0159)
Inaop		-0.466*** (0.0538)	-0.315* (0.163)	-0.369*** (0.0497)
lninf		0.667* (0.385)	-2.171** (0.924)	0.581 (0.390)
Infin		0.0467*** (0.0145)	0.0173 (0.0150)	0.0345*** (0.0126)
Ingre		-0.103*** (0.0204)	-0.114*** (0.0238)	-0.137*** (0.0189)
Provinces Fixed	Y	Y	Y	N
Year Fixed	Y	N	Y	N
Observations	650	602	602	602
R ²	0.853	0.843	0.862	

statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

4.2. Heterogeneity Test

Since both energy intensity and energy consumption structure are affected by resource endowment and economic development level, and there are significant differences among provinces, the heterogeneity analysis of different provinces is conducted, and the results are shown in Table 2. In this paper, the coal production data in the energy statistics report from 2000 to 2022 are arranged in ascending order. The top ten provinces (autonomous regions and municipalities directly under the central government) are regarded as the group with higher resource endowment (Column 1). The remaining regions are categorized as the regions with lower resource endowment (Column 2), and regression analyses are conducted. The results show that the statistics of the more resource-endowed regions are not significant, and the estimated coefficients are smaller than those of the less resource-endowed regions. The possible reason is that although the energy consumption structure in regions with higher coal resource endowment has been upgraded, the industrial system on which the economic development of these regions is based has yet to realize the low-carbonization transformation. Hence, the inhibition effect on energy intensity is not apparent. Regions with less coal endowment are dominated by low-energy-consumption industries, with higher elasticity of demand for various types of energy, so the industrial structure can be adjusted faster to realize the reduction of energy intensity under the guidance of market price or national policy. The total GDP of provinces (autonomous regions and municipalities directly under the central government) from 2000 to 2021 is ranked in ascending order, with the top ten regions classified as the higher GDP group (Column 3), and the remaining regions are classified as the lower GDP group (Column 4) for regression analysis. The results show that the regression coefficients of the higher GDP group are significant, and the coefficients are significantly larger than those of the lower GDP group. On the one hand, it may be due to the lack of high-carbon resources such as coal in the regions with higher GDP, and people are more inclined to buy new energy and other low-carbon products, which leads to the development of low-carbon industries. On the other hand, it may be that the higher GDP regions have more increased environmental regulations and higher levels of research and development, which will motivate enterprises to improve the efficiency of energy use to a greater extent, so the development of a low-carbon energy consumption structure can significantly reduce energy intensity.

Table 2. Heterogeneity test results: resource endowment and GDP.

Variables	(1) lny ⁰	(2) lny ⁰	(3) lny ⁰	(4) lny ⁰
Ingecx	-0.107 (0.326)	-0.859*** (0.209)	-1.335*** (0.278)	-0.0751 (0.236)
Control variables	Y	Y	Y	Y
Provinces/Year	Y/Y	Y/Y	Y/Y	Y/Y
N	201	401	191	411
R ²	0.880	0.870	0.860	0.886

statistics in parentheses

*p<0.05, **p<0.01, ***p<0.001

Many studies have shown the correlation between energy intensity and industrial structure, so this paper divides the industries into three major categories for heterogeneity analysis. Table 3 shows the relationship between energy intensity and energy consumption structure index of the three major categories of industries, and the results show that the secondary (Column 2) and tertiary industries (Column 3) are negatively significant, and the primary sector (Column 1) is positively insignificant. The development process of decarbonization of energy consumption structure can promote the secondary industry sector to adjust the production structure of products, introduce green and low-carbon products, and maintain the stable growth of GDP while reducing the total amount of energy consumption. Due to the large base of energy use in the secondary industry, the marginal inhibitory

effect of the adjustment of energy consumption structure on the energy intensity is significantly more significant than that of the tertiary sector, which are consistent with the test results.

Table 3. Heterogeneity test results: Industrial structure.

Variables	(1) lny ¹	(2) lny ²	(3) lny ³	(4) lny ⁰
Ingecx	0.0293 (0.339)	-1.258*** (0.275)	-0.574** (0.251)	-0.660*** (0.177)
Control variables	Y	Y	Y	Y
Provinces/Year	Y/Y	Y/Y	Y/Y	Y/Y
N	603	603	602	602
R ²	0.619	0.718	0.676	0.862

statistics in parentheses

*p<0.05, **p<0.01, ***p<0.001

4.3. Robustness Test

This paper uses two methods to test robustness. The first is to replace the core explanatory variables (Column 1) by replacing the composite index of energy consumption structure with the share of coal in total energy use, as is done in most literature. The second is to add the omitted variable (Column 2). Since large variability is found in testing the heterogeneity of the impact of different industrial structures on the empirical results, the ratio of the value added of the province's secondary industry to the province's GDP from 2000 to 2021 is used as the measure. The results are shown in Table 4, consistent with the benchmark regression results, and the results are still robust. As the meanings of coal proportion and energy consumption structure index are opposite, they both indicate that the more the energy consumption structure develops in the direction of decarbonization, the more energy intensity can be reduced significantly.

Table 4. Robustness test results.

Variables	(1) lny ⁰	(2) lny ⁰
Ingecx		-0.666*** (0.176)
coal	0.160*** (0.0193)	0.164*** (0.0191)
industry		-0.0390** (0.0158)
Control variables	Y	Y
Provinces/Year	Y/Y	Y/Y
N	608	602
R ²	0.861	0.864

statistics in parentheses

*p<0.05, **p<0.01, ***p<0.001

4.4. Mechanism Test

In the decarbonization of energy consumption structure, the tertiary industry represented by low carbon emission industries, such as the service industry will be driven, while the secondary industry with high carbon emission such as iron and steel and plastic manufacturing will be suppressed. In this paper the interaction term between the energy consumption structure index and the industrial structure upgrading index is added to the model to test the impact of industrial structure upgrading. According to the estimation results in column (1) of Table 5, the coefficient of the interaction term is significantly negative, which is because the decarbonization development of the energy consumption structure will be transferred to the low-carbon and high-efficiency tertiary industry through the effect of upgrading

the industrial structure, which promotes the overall reduction of the energy intensity of the industry, which is in line with the conclusions of the existing studies. In addition, since the development of energy consumption structure will promote the development of emerging green industries, including industrial pollution control through the upgrading effect of industrial structure, the deepening of the government's attention to the environment and the significant investment in industrial pollution control will also inevitably lead to changes in energy intensity. In this paper, the interaction term between the energy consumption structure index and the environmental protection expenditure index is added to the model to test the effect of differences in environmental protection expenditures. According to the estimation results in column (2) of Table 5, the coefficient of the interaction term is significantly positive. The more pronounced the role of environmental protection expenditure is, the weaker the inhibitory effect of the decarbonization development of the province's energy consumption structure on the province's energy intensity, compared with the provinces with less investment in industrial pollution control. The reason may be that industrial pollution control technology still needs to be mature and requires energy sources such as electricity for operation and services, thus weakening the inhibitory effect of energy consumption structure on energy intensity.

Table 5. Mechanism test results.

Variables	(1) lny ⁰	(2) lny ⁰	(3) lny ⁰
Ingecx×lniso	-0.692*** (0.230)		
Ingecx×lneco		0.150** (0.0639)	
lniso	1.245*** (0.403)		
lneco		-0.208* (0.115)	
Ingecx	-0.361* (0.202)	-0.795*** (0.187)	-0.660*** (0.177)
Control variables	Y	Y	Y
Provinces/Year fixed	Y/Y	Y/Y	Y/Y
N	602	602	602
R ²	0.865	0.869	0.862

statistics in parentheses

*p<0.05, **p<0.01, ***p<0.001

5. Conclusions and Implications

5.1. Conclusions

The study finds that (1) Low-carbon upgrading of energy consumption structure significantly suppresses energy intensity, and the conclusion still holds after a series of robustness tests. (2) Heterogeneity analysis reveals that low-carbon upgrading of energy consumption structure significantly reduces energy intensity in regions with less coal resource endowment or higher GDP. In comparison, low-carbon upgrading of energy consumption structure has a certain inhibitory effect on energy intensity in regions with more resource endowment or lower GDP, but the effect is insignificant. Upgrading the energy consumption structure for the primary industry will increase energy intensity. However, the effect is not significant, while for the second and third industries, upgrading the energy consumption structure can significantly reduce energy intensity and the degree of influence of the second industry is greater, the effect is more significant. (3) Empirical test on the transmission mechanism of energy intensity affected by the low-carbon transformation of energy consumption structure, the study found that the energy consumption structure can affect the regional

energy intensity by upgrading the industrial structure and the effect of environmental protection expenditures.

5.2. Implications

(1) Establish an energy adjustment policy based on a tailor-made approach. For regions with more mineral endowments, the relevant government departments should focus on structural reform of the energy supply side in order to realize the low-carbon development of the region; for regions with fewer mineral endowments, efforts should be made from the energy demand side, and the government departments can use fiscal and financial policies such as taxes and subsidies to reduce the demand for low-energy-efficiency traditional fossil fuels in the industrial and living sectors and to encourage the use of low-emission, low-energy-consumption and high-energy-efficiency clean fuels.

(2) Promote the rational development of industrial structure according to local conditions. Provinces (municipalities directly under the central government and autonomous regions) should formulate industrial policies by the characteristics of the local industrial structure and the goal of energy conservation and carbon reduction and make gradual adjustments to different industrial problems rather than pursuing the advanced industrial structure, i.e., transferring the secondary industry to the tertiary industry.

(3) Promote the low-cost, low-carbon transformation of technology innovation enterprises' scientific and technological achievements. The Government should increase investment in low-carbon innovation activities through innovation funds, innovation subsidies, equity investment, loans and other forms of investment and intensify its efforts to eliminate barriers to the transformation of scientific and technological achievements so that the results of scientific and technological innovation can significantly reduce the energy intensity of society as a whole.

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