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What Type of Energy Structure Improves Eco-Efficiency? A Study Based on Statistical Data of 285 Prefecture-Level Entities in China

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Abstract: Increasing environmental pollution, resource depletion, and climate change have led to policymakers paying increased attention to the environmental and ecological impacts of economic activities. To establish which type of energy structure is most conducive to improving eco-efficiency, we use the super-efficiency data envelopment analysis (DEA) model to quantify the relationship between the two, based on the panel data of 285 prefecture-level cities in China from 2005 to 2016. The heterogeneity and spatial spillover effect on different types of cities are further discussed. Our findings suggest that energy structure optimization by reducing the proportion of coal energy is beneficial to improving ecological efficiency. However, the effect is nonlinear, showing an inverted U-shaped nonlinear change. The influence of energy structure optimization on ecological efficiency has a stronger effect on its improvement of resource-based and old industrial cities. Moreover, it has an obvious "local–neighborhood" spatial spillover effect. Additionally, the energy structure could be improved according to local conditions in different regions, such as the level of economic development, industrial structure, and resource endowment conditions. Furthermore, regional cooperation and coordination should be strengthened and consolidated, along with the positive spatial effects of high eco-efficiency cities. Especially in city clusters and metropolitan areas, the strengthening of cross-city cooperation in emission trading, environmental governance, and compensation is vital.

Keywords: energy structure; urban eco-efficiency; spatial effect; coal consumption; China

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Citation: Zhang, F.; Luo, N.; Li, Y. What Type of Energy Structure Improves Eco-Efficiency? A Study Based on Statistical Data of 285 Prefecture-Level Entities in China. *Sustainability* **2023**, *15*, 9130. https://doi.org/10.3390/su15119130

Academic Editors: Attila Bai and Ştefan Cristian Gherghina

Received: 9 April 2023
Revised: 22 May 2023
Accepted: 30 May 2023
Published: 5 June 2023

1. Introduction

Since the Industrial Revolution in the 18th century, large-scale mechanized production has gradually replaced manual labor, improving the level of productivity and largely satisfying the material needs of human beings. The global acceleration of industrialization and urbanization and therefore of global energy consumption has led to a continuous increase in CO_2 emissions. Increasing environmental pollution, resource depletion, and climate change have led to policymakers paying increased attention to the environmental and ecological impacts of economic activities [1]. Schaltegger and Sturm [2] formally defined the connotation of ecological efficiency for the first time, that is, the ratio of economic growth to environmental impact. Specifically, by reducing the consumption of resources and energy in the production process, the impact on the environment can be reduced to meet human needs and improve the quality of life. The core concept of eco-efficiency is "produce more with less input", that is, obtain more economic benefits with less energy consumption and environmental damage. To comprehensively identify eco-efficiency, Kuosmanen and Kortelainen [3] used the data envelopment analysis (DEA) method in eco-efficiency evaluation for the first time. Rashidi [4] developed the DEA model that divides inputs into energy and non-energy and outputs into ideal (good) and undesirable (bad) outputs and developed a bounded adjustment measurement (BAM) based on green indicators to calculate the eco-efficiency of decision units (DMUs). When multiple economic outputs and environmental impacts are involved, the DEA can give more comprehensive evaluation results compared to the ratio method of a single index, and this has become the mainstream method for evaluating ecological efficiency [5].

This study built an ecological efficiency evaluation system, based on the DEA evaluation method. The DEA method was first proposed by Charnes et al. in 1978 [6]. The earliest DEA model was the classical multiplier model, namely CCR-DEA, and its bundle model, which assumed that all decision units were of constant scale efficiency. Banker et al., in 1984, proposed a DEA model based on the variable assumption of scale efficiency, namely the BBC-DEA model, which assumed that the scale of a decision-making unit could not be changed in the short term, and it could improve efficiency using calculation and technical efficiency improvement [7]. With the development of technology and research fields, DEA models were expanded and applied to different scenarios, such as the measurement DEA model based on relaxation [8,9], the efficiency model considering the game relationship between decision units [10], the network DEA model considering the complex production structure [11], the super-efficiency model solving the complete ordering problem [12,13], and a cross-efficiency model based on the "mutual evaluation model" [14]. These DEA models are widely used in different fields, such as technology management [15,16] and medical efficiency evaluation [17]. In addition, the network DEA model based on the network structure model was further developed to describe the inter-period efficiency changes and evaluate the performance [18].

Since the theory of ecological efficiency was introduced in China, the related issues of ecological efficiency have become a topic of concern for the government, enterprises, and scholars. Especially since the reform and opening in the late 1970s, due to China's development model of pursuing economic scale, environmental crisis has deepened with high emissions and energy consumption that causes severe pollution [19–21]. Scholars have studied the impact of energy structure adjustment due to the latest policy reform, termed "energy conservation and emission reduction". For example, Wu [22] found that the energy structure is highly correlated with CO_2 emissions. Zhou [23] proposed that energy carbon emission is the most important contributor to the global greenhouse effect and that the energy structure must be transitioned to achieve low-carbon development. Under the carbon intensity constraint and the increase in the proportion of non-fossil fuel energy, Dong [24] used the dynamic computable general equilibrium model to evaluate the energy-saving and emission reduction effects of all energy and economic sectors during 2012–2030 and concluded that the reduction in carbon emissions was higher than that of energy consumption. Chen [25] studied the ecological efficiency of 30 provinces and cities during 2012–2016 and found that the development level of the ecological economy of China tended to be overestimated when energy structure transition was not taken into account. Moreover, the ecological efficiency in China developed in a U-shaped curve, and the difference in development between provinces and cities showed an increasing trend, followed by a decreasing trend. Yan [26] constructed 3E-DEA models and determined that the performance of 3E targets in various regions of China during 2011–2013 was poor, with a notable difference between the East and West. Some studies have also investigated energy structure and economic development, as well as energy and ecological efficiency. Lin [27] developed an optimization model to determine the optimal energy structure under energy conservation and emission reduction constraints and assessed that a change in the energy structure, mainly coal, would cause an increase in the cost of clean energy inputs and certain negative macro-economic impacts on GDP and employment. Further simulation analysis illustrates that if the government wishes to further reduce emissions, it will need to adjust the energy structure and pay the corresponding energy costs. The emissions constraint decreases from 9.47 billion tons without planning to 8.4 billion tons when coal decreases from 68.7% to 53.2% of the primary energy structure.

In these studies, the issues of the energy structure, energy conservation, emission reduction, and ecological efficiency from different perspectives and involving diversified research methods and data support have been studied extensively, and a considerable amount of valuable research results has been obtained. To establish which type of energy structure is most conducive to improving eco-efficiency, we use the super-efficiency data envelopment analysis (DEA) model to quantify the relationship between the two, based on the panel data of 285 prefecture-level cities in China from 2005 to 2016. This study thus bridges the following remaining gaps in the abovementioned literature.

First, previous research has mainly focused on the relationship between energy and pollution emission but has not fully considered the effect of energy structure adjustment on the environment and economy—a relationship termed "ecological efficiency".

Second, existing research on the influencing factors of eco-efficiency is mainly conducted from the perspective of social and policy factors, including urbanization, city size, and environmental regulation, and few studies are conducted from the perspective of energy structure. Additionally, energy structure should not be regarded as the only factor affecting eco-efficiency, and a more comprehensive analysis of the relationship between energy structure and eco-efficiency is lacking.

Third, exploring and defining the type of energy structure most beneficial to promote ecological efficiency are significant for implementing the new concept of green development. Furthermore, this can assist in obtaining the maximum economic and social development benefits with the least resource consumption and pollution costs. In this regard, compared to the existing research, this study contributes by focusing on the correlation between energy structure and ecological efficiency, revealing both the influence effect and the embedded mechanism, and proposing the optimal energy structure conducive to the improvement of ecological efficiency.

Fourth, existing studies regarding ecological efficiency and measurements of influencing factors usually stay at the national, provincial region, or specific city levels. Using prefecture-level cities as samples, we attempted to divide regions according to the level of economic development and resource conditions to analyze the regional differences and obtain a more specific and in-depth analysis and scientific and reliable conclusions.

The rest of the paper is structured as follows. Section 2 reviews the theoretical background and proposes a research hypothesis of the relationship between energy structure and ecological efficiency. Section 3 discusses the empirical model and data. Section 4 presents the baseline regression and the heterogeneity and robustness of the energy structure affecting ecological efficiency. Section 5 applies a spatial econometric analysis on the effect of the energy structure on ecological efficiency, followed by a characteristic analysis of the spatial effect of the energy structure on ecological efficiency. The final section draws the conclusions and policy recommendations.

2. Theoretical Background and Hypotheses

The influence of energy structure transition on eco-efficiency is uncertain. Reducing coal consumption and other fossil fuel resources in the energy structure reduces related pollution emissions, positively effecting ecological efficiency. In contrast, such an energy structure transition may increase energy costs and dampen economic growth, thus affecting ecological efficiency. Specifically, energy structure transition can have an impact via the paths discussed below.

2.1. Energy Structure Optimization for Pollution Emission Reduction and Ecological Efficiency Improvement

With accelerated industrialization and urbanization, global energy consumption (especially traditional fossil fuel energy consumption) sees continuous increase, along with an increase in total CO_2 emissions. First, the coal-dominated energy structure significantly affects the overall energy consumption of economic development. According to the National Bureau of Statistics, coal dominates China's energy consumption, which is not likely to change in the short term. Second, the carbon emission intensity of different energy consumption structures varies substantially, and different energy consumption structures will produce different ecological and environmental effects. The coal-based energy structure will inevitably lead to high carbon emissions and pollutants that consume the same energy, while the gradual decline of fossil fuels (such as coal) in the proportion of resources can effectively reduce greenhouse gas emissions in the production process and improve the level of green production. A decline in the proportion of coal resources can also bring about the extensive use of clean energy sources, effectively decreasing fossil fuel pollution emissions, affecting ecological efficiency. Lin [28] proposed that increasing clean energy consumption contributes to CO_2 and SO_2 emission reductions, which in turn has a significant positive effect on economic growth. Therefore, different energy structure forms can shape the corresponding overall energy efficiency, and energy structure transition can improve the ecological environment by reducing pollutant emissions, thus affecting the ecological efficiency.

2.2. Energy Structure Transition for Improvement of Energy Efficiency and Ecological Efficiency

Energy efficiency implies obtaining the same or more effective output with less energy input using technological innovation and improving management. As the country with the highest energy consumption in the world, China exhibits relatively low energy efficiency (Tao [29]; Wang and Xie [30]). Lv and Chen [31] calculated the total factor energy efficiency of 97 countries from 1980–2011, and the results indicated that total factor energy efficiency was relatively low in China and that a regression phenomenon existed due to the negative growth of technological progress and the decline of pure technical efficiency. Policies aiming at energy structure transition and reducing coal and other fossil energy consumption can facilitate or promote the development and utilization of new energy technologies while encouraging energy users to improve energy efficiency and reduce energy consumption. In this way, the energy consumption per unit of economic output can be reduced, while economic output per unit of energy input can be increased and ecological efficiency can be improved.

2.3. Energy Structure Transition Affects Economic Returns and Ecological Efficiency through Production Cost

The spatial distribution of clean energy in China is heterogeneous with the high price cost of development and consumption [32], so there are significant differences that the impact of energy restructuring in different regions will have on economic growth through the role of cost [33]. First, the economy of the main gas area is at an underdeveloped level, and for regions with strong economic strength and poor clean energy, the promotion of transmission facilities and equipment, technology research, and development investment are required to consume huge amounts of money, while the economic development is relatively lagging behind. In addition, there is the phenomenon of low cost of extraction and inefficient use in regions with relatively abundant resources, so increasing clean energy consumption will increase energy costs and reduce economic efficiency, thus affecting ecological efficiency. Second, industry is dependent on the consumption of fossil energy, and changing the energy structure requires technological innovation and industrial upgrading, which will also entail a greater economic cost. In conclusion, energy restructuring may increase energy costs and economic costs, which will have a negative impact on eco-efficiency. Therefore, the impact of energy restructuring on eco-efficiency depends on the trade-off and comparison between pollution reduction and economic efficiency reduction; when the pollution reduction effect is greater than the efficiency reduction effect, eco-efficiency is effectively improved, and vice versa.

The effect of energy structure on eco-efficiency is bidirectional and nonlinear. As the coal-based energy structure is constantly adjusted in China, clean energy use will reduce energy pollution emissions and promote ecological efficiency; however, it is constrained by the economic and technological development levels. In addition, the great coal energy reduction is not necessarily better. If coal consumption is reduced too rapidly, it will significantly increase energy and economic costs, resulting in a lower pollution reduction effect of the energy structure transition than the economic efficiency reduction effect, thus reducing the ecological efficiency. Having said so, it should be noted here that we consider the private economic cost of energy in this study, without referring to the social costs that are mainly due to negative externalities.

Based on the above analysis, we propose research hypotheses H1 and H2:

H1. *Energy structure optimization facilitates eco-efficiency. With the application of cleaner production technology innovation and environmental governance, it helps to reduce the intensity of resource consumption, promotes more efficient energy output, and has a significant positive effect on environmental pollution control.*

H2. *The influence of energy structure transition on eco-efficiency is non-linear and is an inverted U-shaped curve. Thus, reducing traditional energy use to a certain extent can improve eco-efficiency, whereas reducing it excessively or extensively will reduce eco-efficiency.*

2.4. Energy Structure Has a Spatial Spillover Effect on Eco-Efficiency

Through pollutant emission and energy efficiency improvement, energy structure has a spatial spillover and spatial interaction effect on environmental pollution in surrounding cities. In the energy structure transition process, pollutant discharge has a natural fluidity, which has impacted the previous governmental concept of "only sweeping your own snow". Both the energy structure and environmental pollution have spatial spillover effects. In the initial stage, each city will reduce pollutant emissions by transitioning and optimizing the energy structure. With clean energy use, the ecological environment of the region will be further optimized. However, inertia of the energy structure transition may also be generated, which directly leads to the beggar-thy-neighbor phenomenon of environmental pollution. Further, it is also expected that neighboring regions can optimize pollutant emissions in the whole region through energy structure transition. In contrast, there may be spatial interactions between the energy structure and environmental pollution, that is, local energy structure transition can promote the surrounding cities to carry out energy structure transition through competition, learning, and radiation driving effects, increase the scale of clean energy use and the investment in energy use technology, and improve energy efficiency and the ecological environment. The improvement of local ecological environment is accompanied by high-level environmental governance ability, technological innovation ability, and economic development strength, so as to attract industrial agglomeration, talent, and capital inflow and further promote economic development and improve the economic efficiency of energy structure transition.

Based on the above analysis, we propose research hypothesis H3:

H3. *There is a spatial spillover effect of energy structure transition on eco-efficiency.*

3. Methodology and Data

3.1. Model Specification

Based on the above mechanism analysis, we built the following basic model for the impact of energy structure on eco-efficiency:

$$EE_{it} = \alpha_0 + \beta_0 ES_{it} + \beta_k X_{i,k,t} + \delta_i + \mu_t + \varepsilon_{it}. \tag{1}$$

Here, EE is eco-efficiency, ES is the energy structure, i is the city, t is the year, δ_i is the regional fixed effect, μ_t is the time fixed effect, and ε_{it} is the random error term. $X_{i,k,t}$ includes industrial structure, technological innovation, opening to the outside world, and other K control variables that may affect ecological efficiency.

Considering that economic cyclical fluctuations, regional sudden events, and other unobservable factors will also affect ecological efficiency, we controlled the time and individual fixation effects. μ_t is the time fixation effect, i.e., the specific factors that do not affect the energy structure with individual changes. δ_i is the regional fixation effect, i.e., the specific factors that do not affect the energy structure over time.

Second, to verify the nonlinear relationship of the influence of the energy structure on eco-efficiency, the quadratic term of energy structure was further introduced into Equation (1). The specific formula is as follows:

$$\mathrm{EE_{it}} = \alpha_0 + \beta_0 \mathrm{ES_{it}} + \beta_1 \mathrm{ES_{it}}^2 + \beta_k \mathrm{X_{i,k,t}} + \delta_i + \mu_t + \varepsilon_{it} \quad (2)$$

To further discuss the spatial spillover effect, the spatial interaction terms of the two and other control variables were introduced into Equation (2), which was expanded into a spatial panel econometric model:

$$\mathrm{EE_{it}} = \alpha_0 + \rho \mathrm{W_i EE_{it}} + \beta_0 \mathrm{ES_{it}} + \beta_1 \mathrm{W_i ES_{it}} + \beta_k \mathrm{X_{i,k,t}} + \delta_i + \mu_t + \varepsilon_{it}. \quad (3)$$

Owing to the possibility of spatial correlation between the energy structure and environmental pollution, we used the spatial Durbin model (SDM) to investigate the correlation. In Equation (3), ρ represents the spatial autoregressive coefficient, and $\mathrm{W_i}$ represents the space weight matrix. β_0 is the influence of the local city's energy structure on its own urban environmental pollution, namely the local effect. β_1 refers to the spillover effect of the energy structure of the city on environmental pollution of the surrounding cities, namely the neighborhood effect. The spatial economic correlations between different regions were realized by constructing different spatial weight matrices, which mainly have two aspects: geospatial matrix and economic spatial matrix. Among them, the geospatial matrix has two forms: 0–1 spatial proximity matrix and distance space matrix. For the geographical and economic spatial matrix, the proximity matrix represents the objective spatial distance, and the distance space matrix emphasizes the gap in economic development. Based on previous research experience, we constructed the weight matrix of geographic space and economic space and conducted a comparative analysis. In this study, the inverse distance matrix W1 was selected to represent the spatial weight effect between regions. To examine the influence of the economic gap, the method of Dong and Wang [34] was adopted to construct the economic distance weight matrix W2, which represents the economic gap by the difference in regional gross domestic product (GDP).

3.2. Measurement and Explanation of Variables

3.2.1. Explanation of Variables

- Ecological efficiency (EE)

Referring to the definition of ecological efficiency by Scholz and Wiek [35] and Cheng [36], we posit that ecological efficiency specifically represents the ratio of resource consumption, environmental impact, and economic output, focuses on the synchronous growth of economic growth and eco-environmental benefits, and can effectively reflect the environmental impact of economic activities. As a bridge connecting economic output and ecological environment, it is the input–output efficiency under the common constraint of resources and environment. In this study, the super-efficiency DEA model was used to measure the ecological efficiency of prefecture-level entities in China from 2005 to 2016.

The super-efficiency DEA model considering the undesired output is as follows:

$$\sigma = \min \frac{1 - \frac{1}{m}\sum_{j=1}^{m} \omega_m \alpha g_{mk}^{x} / x_{mk}}{1 + o_p \frac{1}{p}\sum_{p=1}^{p} \omega_p \beta g_{pk}^{y} / y_{pk} + o_t \frac{1}{t}\sum_{t=1}^{t} \omega_t \gamma g_{tk}^{e} / e_{tk}}$$

$$s.t.$$

$$\begin{cases} \sum_{j=1, j\neq k}^{n} \lambda_j X_j + \alpha g_{mk}^{X} + S^{+} \leq \sigma X_k \\ \sum_{j=1, j\neq k}^{n} \lambda_j Y_j - \beta g_{pk}^{X} - S^{g} \leq Y_k \\ \sum_{j=1, j\neq k}^{n} \lambda_j E_j + \gamma g_{tk}^{c} + S^{b} = \sigma E_k \\ \lambda_j \geq 0, j = 1, 2, \ldots, n; S^{+} \geq 0, S^{g} \geq 0, S^{b} \geq 0 \end{cases}$$

where ω_m, ω_p, and ω_t are the index weights of input factors, desired output, and undesirable output, respectively; x_{mk}, y_{pk}, and e_{tk} are the mth input factor, pth desired output, and tth undesirable output of the kth prefecture-level city, respectively. g^x_{mk}, g^y_{pk}, and g^e_{tk} are the direction vector of the mth input and the tth undesirable output in the kth prefecture-level city, respectively. α, β, and γ are the weights of the above direction vectors, respectively. S^+, S^g, and S^b are the relaxation vectors of input factors, desired output, and undesirable output, respectively. o_p and o_t are the total weights of all desired and all undesirable outputs, respectively. $\sum\limits_{p=1}^{p} \omega_p = p$, $\sum\limits_{t=1}^{t} \omega_t = t$, $\sum\limits_{m=1}^{m} \omega_m = m$, $o_p + o_t = 1$; we used λ as a constraint [37].

Based on the super-efficiency DEA model, resource consumption was considered as the input, economic development as the desired output index, and environmental pollution as the undesirable output index. On the basis of considering data availability, we selected energy consumption (in this study, the weighted synthesis of urban electricity consumption, liquefied petroleum gas, and natural gas was used to construct the energy input composite index, and we adopted the common entropy law), built-up area, urban water supply, fixed asset investment, and the number of employees per unit at the end of the year as input variables. The regional GDP (the flattening index was calculated to eliminate the calculation error caused by the price differences in different regions) was selected as the desirable output, and discharges of industrial wastewater, SO_2, and smoke (powder) dust were selected as the undesirable output variables. The undirected super-efficiency DEA model with constant return to scale was used for measurement.

3.2.2. Core Explanatory Variables

The core explanatory variable was the energy structure (ES). Previous studies defined the energy structure as the composition and proportion of various primary and secondary energy sources in total energy production or consumption, which can be specifically divided into production and consumption structures. The energy structure in this study refers to the energy consumption structure. According to the resource distribution and the proportion of coal in the energy production and consumption structure in China, the energy structure (which mainly relies on coal) will not change for an extended period of time. Consequently, we suggest that the proportion of coal consumption should be used to measure the energy structure. In terms of the feasibility of the index calculation, energy production and consumption of cities are unequal. Cities rich in energy resources should sell energy or transformed energy products to other regions. If energy production is taken into account, the energy production of some cities will be greater than their consumption, while the rest of the cities are correspondingly the opposite. In addition, it is difficult to make a unified analysis of energy production with urban economic efficiency and ecological environment. Further, using the method of Niu [38] to measure the total amount of urban energy consumption as a reference, we calculated the total amount of urban energy consumption based on the energy consumption per unit GDP or the total amount of energy consumption of 285 cities, deducted the standard coal consumption of urban electricity consumption, natural gas, and oil, and calculated the proportion of coal in urban energy consumption, i.e., the energy structure. Considering the energy situation of the municipal district before 2016 and the overall situation of the entire city since 2017, we conducted an empirical analysis based on the statistics from 2005 to 2016.

3.2.3. Control Variables

To more accurately analyze the impact of the energy structure on environmental pollution, it is also necessary to control the variables that may have an impact on environmental pollution. Combined with existing citations, a series of characteristic variables affecting eco-efficiency are controlled in the model: (1) Industrial structure (IS) is represented by the proportion of the secondary industry in GDP. (2) The degree of opening to the outside world is expressed by the proportion of the actual amount of foreign capital used in the current year and the GDP. The influence of foreign capital utilization on the economic development and ecological environment of the region has been proved by many studies. However, the conclusions differ. (3) The proportion of fiscal expenditure (PUBLIC) is expressed by the proportion of expenditure in the general budget of local finance and the GDP. The government has increased efforts to support regional industrial development and infrastructure construction, effectively improving the environment for economic development and the efficiency of the utilization of factors and easing the pressure on industries to save energy and reduce emissions. (4) Population density (PD) is determined by the number of the population per unit area at the end of the year. (5) Technology innovation (TECH). Generally speaking, the improvement of technology will promote environmental protection [15], which contributes to sustainable development transformation [39] and energy efficiency improvement [40]. Technological innovation refers to production efficiency improvement and reductions in unit resource and energy consumption, which will have a certain promoting effect on ecological efficiency. The proportion of expenditure in the financial science expenditure and the expenditure in the general budget of local finance was selected as the expression.

3.3. Data Sources and Descriptive Statistics

Based on the power situation of the municipal district before 2016 and the overall situation of the whole city since 2017, the energy consumption of each city during 2005–2016 was evaluated and measured, and the energy structure of each city was calculated. China has 297 cities at or above the prefecture level. Owing to data continuity and comparability, some newly established prefecture-level cities were excluded (Kerber, Nyingchi, Shannan, and Qamdo in Tibet; Turpan and Hami in Xinjiang; Sansha and Danzhou in Hainan; Bijie and Tongren in Guizhou; Haidong in Qinghai; Tibet Lhasa City data are incomplete and thus were deleted). A total of 285 cities at the prefecture level and above were included in the calculation. In addition, in 2010, Xiangfan City in Hubei Province was renamed Xiangyang City and unified under this name. In 2007, Simao City in Yunnan Province was renamed Pu'er City and unified as such. Furthermore, China started with "the 11th Five-Year Plan" (2006–2010), with the planning quantitative indicators clearly divided into two categories: anticipation and constraint, among which the binding indicators further clarify and strengthen the target requirements for the related energy use structure and efficiency. Therefore, 285 cities from 2005 to 2016 were represented.

The samples used in this study were 285 prefecture-level or above entities (hereafter referred to as cities) from 2005 to 2016. The statistics are all from official documents such as *China Statistical Yearbook*, *China City Yearbook*, *China Environmental Yearbook*, and local statistical yearbooks of provinces and municipalities or were calculated and collated through basic statistics. The above statistical descriptions of explained, core explanatory, and other relevant variables are shown in Table 1. In addition, the data of three key variables in major Chinese cities are provided in Appendix A.

Table 1. Statistical description of main variables.

Main Variables	Number of Samples	Mean Value	Standard Deviation	Minimum Value	Maximum Value
EE	3420	0.605	0.123	0.320	1.258
ES	3420	0.785	0.148	0.041	0.9998
IS	3420	0. 490	0.109	0.09	0.910
OPEN	3420	2.355	2.405	0.001	16.476
PUBLIC	3420	0.501	1.302	0.006	24.956
PD	3420	425.844	326.508	5	2648
TECH	3420	0.126	0.0132	0.003	0.207

EE, ecological efficiency; ES, energy structure; IS, industrial structure; OPEN, openness to the outside world; PUBLIC, proportion of fiscal expenditure; PD, population density; TECH, technology innovation.

a. Overall situation

As shown in Figure 1, the ecological efficiency measurement showed that with the continuous improvement of China's economic efficiency and environmental benefits, the overall level of ecological efficiency of 285 entities in China showed a fluctuating upward trend from 2005 to 2016. During this period, the average ecological efficiency increased from 0.557 in 2005 to 0.668 in 2016, with an average annual growth rate of 1.66%. Figure 2 presents the average of three groups of cities based on their level of ecological efficiency. By comparing the two figures, it can thus be observed that the overall ecological efficiency of the country remained at a medium level of development.

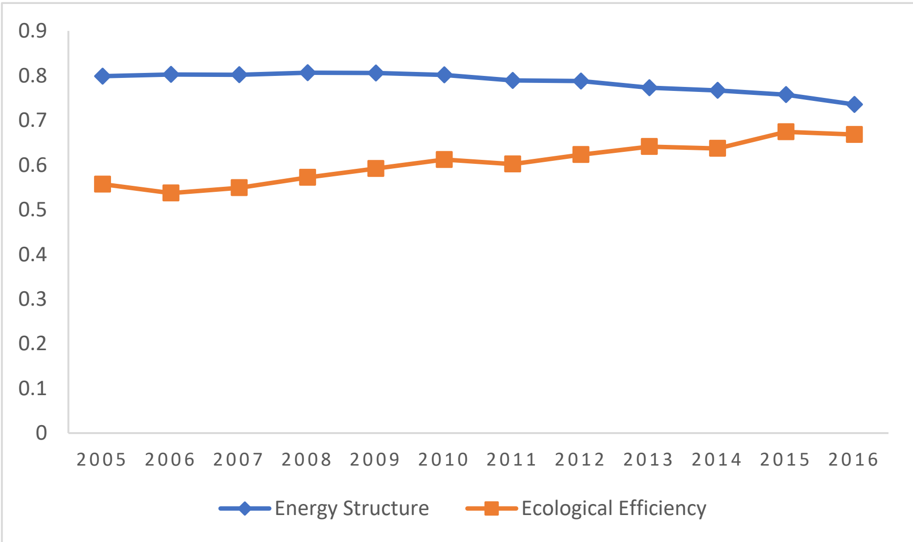

Figure 1. Overall urban ecological efficiency level in China from 2005 to 2016.

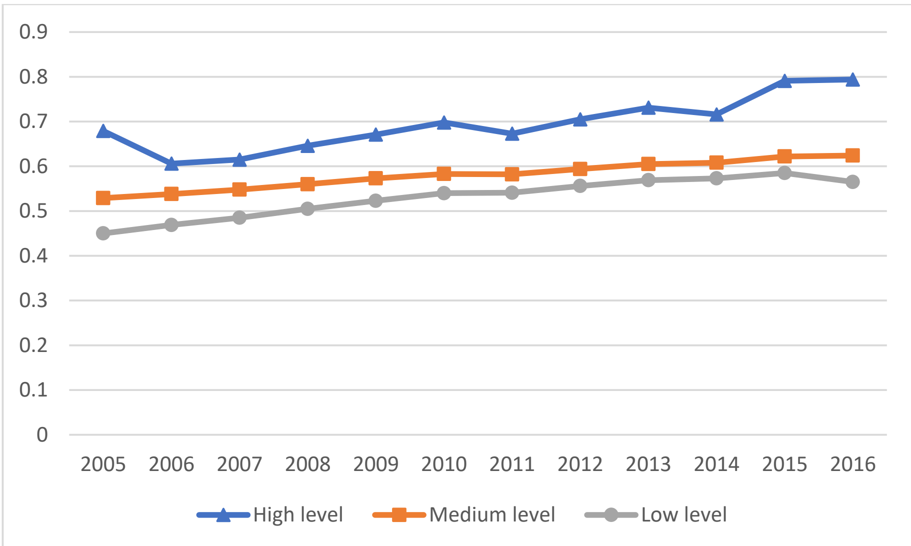

Figure 2. Average ecological efficiency of three groups of cities in China.

Accordingly, Figure 3 presents the energy structure changes in these three groups of cities in China. It can be seen that the group with better ecological efficiency levels has the best energy structure among the three groups. Since 2005, the mean value of the energy structure at the three levels has shown a downward trend, indicating continuous improvements of the energy structure in all groups.

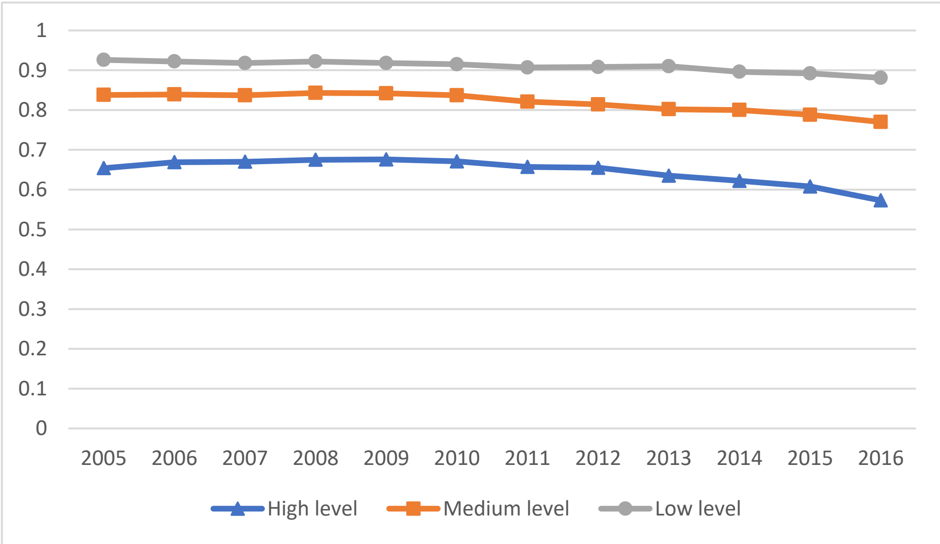

Figure 3. Energy structure changes in the three groups of cities in China.

b. City-level situation

The dynamic evolution process of the urban energy structure was visually displayed through the kernel density curve (Figure 4). From the four-time node positions from 2005 to 2016, the kernel density curve gradually moved to the left, and the energy structure dominated by coal resources was continuously optimized. Specifically, compared to 2005, the overall density distribution shifted to the left in 2010, and the density distribution was further shifted to the left in 2015–2016, shrinking from about 0.9 in 2005 to about 0.8 in 2016, which further verified the optimization of urban energy structure since 2005. From the point of kurtosis, the peak density of urban energy structure was decreasing gently, and the energy structure gradually became different between cities, which was most likely because with the economic and technological development and an increase in environmental protection investment, part of the developed region and areas with relatively scarce coal resources vigorously improved clean energy usage and further widened the gap in the energy structure between cities. In addition, over time, the drag-tail part of the energy structure density function shortened, indicating that the gap in the energy structure between cities had a narrowing trend.

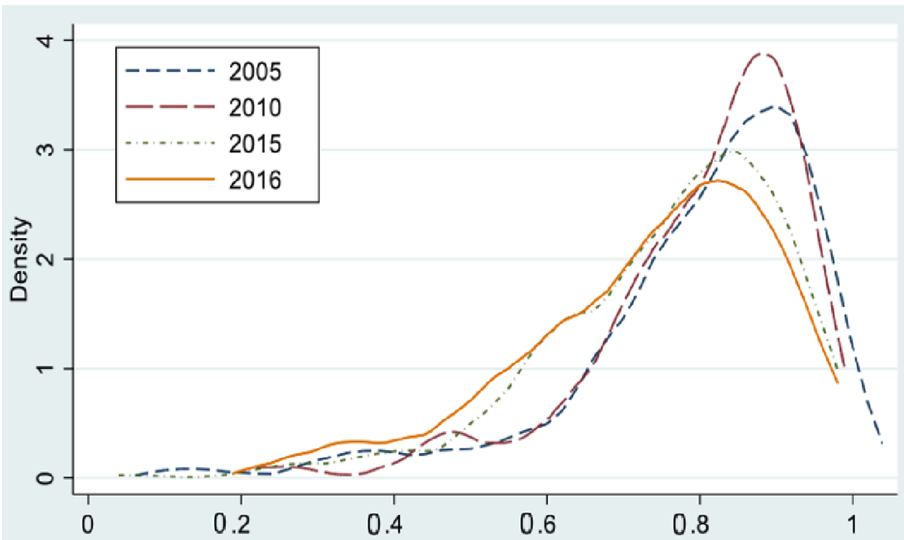

Figure 4. Urban energy structure level in China from 2005 to 2016.

The kernel density curve of urban ecological efficiency (Figure 5) gradually moved to the right and improved. From the perspective of kurtosis, a relatively stable single-peak pattern was presented in 2005, and the urban ecological efficiency mainly converged to approximately 0.5; the peak density increased rapidly from 2005 to 2010, and there were two peaks. The ecological efficiency was mainly concentrated at 0.6; however, there was a bulge at 1.05 and signs of polarization. Subsequently, the density function mainly presented the distribution pattern of "one main and one pair". Observing the right tail of the kernel density curves from 2010 to 2016, the amplitude of the bulge was enhanced, indicating a certain increase in the middle- and high-level cities. However, on the trend characteristic surface of the right tail, the number of high-efficiency cities remained small, and growth was slow. In addition, the peak density was gradually reduced, indicating that the ecological efficiency gap between cities was significantly expanding and still converged at different levels. From the perspective of shape, the flat and wide kernel density curve in 2005 (peak reduction, width increase) indicated that the degree of difference between the cities was relatively large. The density function of urban ecological efficiency in the four years did not differ considerably in the right extension of the horizontal axis. The tail part then experienced a small increase or decrease process, and the overall change was minimal.

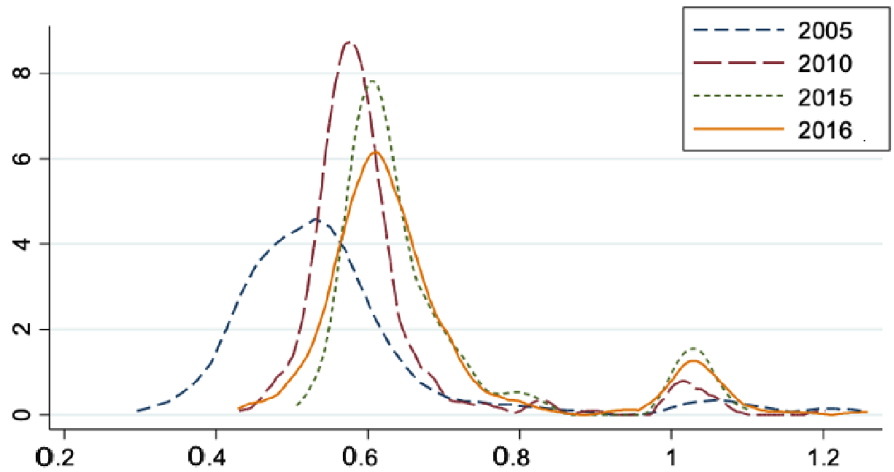

Figure 5. Urban ecological efficiency level in China from 2005 to 2016.

4. Empirical Results and Analysis

(1) Baseline regression results

Table 2 (column 1) reports the estimated results of fixed effects. The estimated value of the ES parameter of energy structure passed the significance level test of 1%, indicating that the increase in coal consumption in energy structure had a negative effect on the improvement of urban ecological efficiency. Reducing coal consumption and optimizing energy structure have become an important driving force to improve urban ecological efficiency. The above results provide empirical support for H1 in this paper, i.e., the transition of the energy structure significantly improved urban ecological efficiency.

Table 2. Baseline regression results.

	FE (1)		FE (2)
ES	−0.1777 *** (−7.7261)	−0.1170 *** (−5.2347)	−0.1143 *** (−5.1030)
IS		−0.0838 *** (−2.6962)	−0.0903 *** (−2.8843)
OPEN		0.0004 (0.5944)	−0.0007 (−0.5458)

Table 2. *Cont.*

	FE (1)		FE (2)
PUBLIC		0.0106 *** (6.3820)	0.0107 *** (6.4313)
lnPD		0.3706 *** (10.3055)	0.3738 *** (10.3903)
TECH		1.3168 *** (8.0395)	1.3980 *** (8.1622)
ES × TECH			2.5446 * (1.6526)
Two-way fixed effect	Yes	Yes	Yes
_cons	0.7450 *** (41.1105)	−1.4063 *** (−6.7717)	−1.4208 *** (−6.8401)
R^2	0.4244	0.1103	0.1110
N	3420	3420	3420

Note: *** and * indicate that the statistical test was passed at a significance level of 1% and 10%, respectively. FE, fixed effect; ES, energy structure; IS, industrial structure; OPEN, openness to the outside world; PUBLIC, proportion of fiscal expenditure; PD, population density; TECH, technology innovation.

Other control variables showed that IS, degree of openness to the outside world (OPEN), PUBLIC, and TECH had positive effects on ecological efficiency. (1) The IS coefficient of the industrial structure was negative, i.e., when the proportion of the secondary industry in the industrial structure increased, the ecological efficiency decreased. (2) The coefficient of openness to the outside world was positive but not significantly. This may have been because the increase in foreign capital investment mainly drives development of the urban economy. However, it may also transfer related industries to China as a result of pollution; therefore, the level of openness to the outside world in this region did not significantly promote improvement of regional ecological efficiency. (3) The PUBLIC effectively improved the operating environment of the urban economy and the utilization efficiency of resource endowment. (4) The PD coefficient was significantly positive, indicating that an appropriate increase in population means improvement of human capital, which is conducive to economic and social development, technological upgrading, rational resource allocation, efficiency of resource utilization, ecological environment improvement, and ecological efficiency improvement. (5) The TECH coefficient was considerably positive, indicating that the higher the technology level, the lower the dependence of economic development on energy, the lower the resource consumption and pollutant emission, and the higher the ecological efficiency, and that the ecological coefficient was greater than the energy structure. To further verify the optimization of energy structure, driven by technological innovation and the improvement of ecological efficiency indirectly brought by it, an interactive analysis was conducted with the energy structure. To make the original core explanatory variables still have economic significance, we carried out centralized processing on the interaction terms. As shown in Table 1 (column 2), the estimated coefficient of the interaction term between the energy structure and local eco-efficiency was significantly positive at the 10% significance level, indicating that the influence of the energy structure on eco-efficiency will be enhanced with the improvement of technological innovation ability and that the interaction effect coefficient of the two was much larger than that of energy structure and technological innovation, which is conducive to the improvement of eco-efficiency.

(2) Nonlinear effect analysis

To further verify Hypothesis 2, we analyzed whether the impact of the energy structure on urban eco-efficiency level was consistent or whether the impacts were different at different stages of the energy structure. In this study, the square term of the energy structure was added to the baseline regression model for the empirical test. Table 3 showed that with or without the addition of control variables, the primary term factor of the energy structure on eco-efficiency was significantly negative, and the coefficients of the secondary term were significantly negative at the 1% statistical level. In other words, there was an inverted U-shaped nonlinear relationship between energy structure and ecological efficiency, that is, when the cost of energy structure transition was smaller than the environmental effect and economic effect, it had a significant positive effect on ecological efficiency improvement. Specifically, the energy structure dominated by coal energy consumption has been continuously improved with the development of the economic and technological level and the requirement of ecological environment protection, and the overall coal consumption in cities has been reduced to varying degrees. This maintained sustained and stable economic growth, reduced pollutant emissions, and improved the ecological environment. However, blindly optimizing the energy structure by replacing coal with clean energy and reducing coal consumption will continuously increase the energy consumption cost of urban economic and social development and ultimately shut down enterprises with high energy consumption to reduce emissions. Furthermore, this will affect sustainable and stable economic development considerably, and the influence of energy structure transition on ecological efficiency will change to inhibition.

Table 3. Test results of nonlinear correlations.

	EE	
ES	−0.0758 *** (−2.7952)	−0.0525 ** (−2.0194)
ES2	−0.1609 *** (−6.9717)	−0.1192 *** (−5.3291)
IS		−0.0534 * (−1.7083)
OPEN		0.0005 (0.7189)
PUBLIC		0.0104 *** (6.2839)
lnPD		0.3523 *** (9.8346)
TECH		1.2770 *** (7.8463)
Two-way fixation	YES	YES
_cons	0.7974 *** (40.9101)	−0.2686 *** (−6.1187)
R^2	0.1236	0.1236
N	3420	3420

Note: ***, **, and * indicate that the statistical test was passed at a significance level of 1%, 5%, and 10%, respectively. EE, ecological efficiency; ES, energy structure; IS, industrial structure; OPEN, openness to the outside world; PUBLIC, proportion of fiscal expenditure; PD, population density; TECH, technology innovation.

(3) Heterogeneity analysis

Considering the imbalance of regional economic development, cities have great differences in location, endowment, policies, and other development conditions, and the influence of urban energy consumption structure on ecological efficiency may also differ, resulting in regional heterogeneity. Referring to the Notice of the State Council on the Issuance of the National Sustainable Development Plan for Resource-based Cities (2013–2020) and the National Plan for the Adjustment and Transformation of Old Industrial Bases (2013–2022), in this study, numerous resource-based and/or heavy industrial cities were excessively dependent on energy resources and traditional energy-consuming industries, especially those with a rich coal resources endowment. Due to the excessive development of resource-based industries in natural resource-rich areas, it is difficult to adjust the energy structure; however, the adjustment effect will be more significant. We divided Chinese cities into city categories: resource-based industrial (112), non-resource-based (173), heavy industrial (94), and non-heavy industrial (191). According to the results listed in Table 4, the energy structure of different types of cities contributes to improve eco-efficiency, which was significant at the 1% level; however, there was a significant difference in the effect. First, as for the similarities, overall, the energy structure coefficient of all types of cities was negative, indicating that the reduction in coal consumption could well promote ecological efficiency improvement and that the promoting effect of control variables on the ecological efficiency of different cities was maintained within a certain range. Second, specifically looking at the differences between cities, the energy structure of resource-based and heavy industrial cities had a substantially greater effect on eco-efficiency than that of non-resource-based and non-heavy industrial cities. In fact, as a main coal consumer, resource-based industrial cities in China are also mostly coal-based cities. For a long time, vigorous development of coal resources has supported economic and social development in China and formed traditional industries such as iron, steel, and chemical industries. This has also led to dependence on the development of coal resources, involving high energy consumption and severe environmental pollution. The cost and benefit of a regional transition in the energy structure restrain its motivation of active adjustment. Furthermore, the different energy structures between regions have a certain influence on the industrial development focus. The different energy structures of regions induce the introduction of industries, and the adjustment and upgrading of different industries will also promote the energy structure transition, resulting in ecological efficiency improvement. There was a certain overlap between resource-based industrial and heavy industrial cities. In recent years, China has provided strong support to the transformation and upgrading of the two types of cities, extending the industrial chain and increasing the added value, which plays a significant role in promoting the improvement of ecological efficiency.

Table 4. Influence of the energy structure of cities with different characteristics on eco-efficiency.

	Resource-Based Cities	Non-Resource-Based Cities	Heavy Industrial Cites	Non-Heavy Industrial Cities
ES	−0.1297 *** (−3.9268)	−0.0996 *** (−3.3297)	−0.1252 *** (−3.7979)	−0.1081 *** (−3.7336)
IS	−0.1955 *** (−4.6973)	0.0137 (0.3056)	−0.0838 ** (−2.0000)	−0.0926 ** (−2.1865)
OPEN	0.0014 (1.3199)	−0.0003 (−0.2863)	0.0008 (0.8100)	0.0003 (0.3144)
PUBLIC	0.0108 *** (2.6588)	0.0108 *** (5.6954)	0.0155 *** (4.3103)	0.0100 *** (5.1449)
lnPD	0.4722 *** (8.5232)	0.3197 *** (6.7853)	0.4674 *** (8.2647)	0.3487 *** (7.6424)
TECH	1.2125 *** (4.9836)	1.4607 *** (6.6752)	1.8317 *** (7.0363)	1.1468 *** (5.5219)
_cons	−0.7739 *** (−5.9041)	−0.2366 *** (−4.3751)	−0.9623 *** (−6.0583)	−0.2762 *** (−4.8285)
Two-way fixation	Yes	Yes	Yes	Yes
R^2	0.3579	0.2629	0.5604	0.2223
N	1344	2076	1128	2292

Note: ***, ** indicate that the statistical test was passed at a significance level of 1%, 5%, respectively. ES, energy structure; IS, industrial structure; OPEN, openness to the outside world; PUBLIC, proportion of fiscal expenditure; PD, population density; TECH, technology innovation.

(4) Robustness test

The process of energy structure transition involves reducing the proportion of coal consumption in the total energy consumption, expanding clean energy consumption, optimizing the technical level of energy consumption, and finally improving the ecological efficiency. As shown in Table 5, to further ensure the reliability of the research conclusions, the robustness test of the regression results of instrumental variables was conducted in various ways in this study:

a. Excluding the influence of some outliers. Firstly, the mean values of the urban energy structure and eco-efficiency in the whole sample period were calculated, and then the top and bottom 10% of cities were excluded to obtain 266 cities. The instrumental variable regression was then carried out. The research results remained basically unchanged, and the regression coefficient of the energy structure was always negative at the 1% significance level.
b. The influence of provincial capitals and municipalities was excluded. Due to the particularity of administrative and economic status of provincial capitals and municipalities directly under the Central Government, to eliminate their interference in the regression results, we removed 27 provincial capitals (e.g., Shijiazhuang and Taiyuan) and four municipalities directly under the Central Government (including Beijing, Shanghai, Tianjin, and Chongqing) from the whole sample and conducted an instrumental variable regression. The regression results remained robust, which reconfirmed the reliability of the empirical results in this study.
c. The full-log model was used for empirical analysis. Natural logarithms were taken for explained, core explanatory, and control variables, and econometric regression was then performed to investigate the sensitivity of regression results to the model setting. The promoting effect of the energy structure on urban ecological efficiency remained significant. Although there were differences in the relevant estimation coefficients, there was a negative relationship between the energy structure and the urban eco-efficiency level, which was manifested in that the improvement of the energy structure (namely the reduction in energy with coal consumption as the core) played a promoting role in the improvement of urban ecology. In conclusion, the above research conclusions are robust and reliable.

Table 5. Robustness tests results.

	(1)	(2)		(3)
	Elimination of Outliers	**Elimination of Provincial Capitals and Municipalities**		**Taking the Logarithm**
ES	−0.1280 *** (−8.6027)	−0.1412 *** (−5.8830)	lnES	−0.0455 *** (−2.9347)
IS	0.0425 *** (2.8520)	−0.0561 * (−1.7795)	lnIS	−0.0768 *** (−4.1850)
OPEN	0.0001 (0.1717)	0.0008 (1.1297)	lnOPEN	0.0093 *** (5.2452)
PUBLIC	0.0055 *** (6.8897)	0.0145 *** (5.5371)	lnPUBLIC	0.0327 *** (15.6706)
lnPD	0.2112 *** (12.1853)	0.4227 *** (10.7831)	lnPD	0.3292 *** (6.5362)
TECH	0.8892 *** (11.2967)	1.1945 *** (6.7625)	lnTECH	0.0347 *** (11.1914)
_cons	−0.5523 *** (−5.4584)	−1.6710 *** (−7.4841)	_cons	−2.2514 *** (−7.6819)
Two-way fixation	Yes	Yes	Two-way fixation	Yes
R^2	0.1733	0.1144	R^2	0.2219
N	3192	3048	N	3420

Note: *** and * indicate that the statistical test was passed at a significance level of 1% and 10%, respectively. ES, energy structure; IS, industrial structure; OPEN, openness to the outside world; PUBLIC, proportion of fiscal expenditure; PD, population density; TECH, technology innovation.

5. Spatial Spillover Effect Test

(1) Moran's index

Before the spatial econometric analysis, we firstly conducted a Moran's bilateral test on the eco-efficiency and energy structure of 285 cities to preliminarily investigate whether the two had spatial effects. According to the test results shown in Table 6, the Moran's index of urban eco-efficiency and energy structure from 2005 to 2016 under the weight of inverse geographical distance was significantly positive at the 1% significance level, indicating that the urban eco-efficiency and energy structure of Chinese cities have positive spatial autocorrelation during the study year. Urban eco-efficiency and energy structure had a spatial relationship of "space spillover" and "competition, learning and radiation-driven", which provided the basic support for the spatial econometric analysis of this study.

Table 6. Spatial Moran's index of eco-efficiency and energy structure.

	Efficiency of Ecology	Energy Structure
	Moran Z Value	**Moran Z Value**
2005	0.037 *** (6.549)	0.041 *** (7.103)
2006	0.054 *** (9.300)	0.043 *** (7.498)
2007	0.045 *** (7.927)	0.035 *** (6.242)
2008	0.038 *** (6.705)	0.031 *** (5.632)
2009	0.038 *** (6.720)	0.035 *** (6.218)
2010	0.027 *** (4.952)	0.026 *** (4.795)
2011	0.046 *** (8.005)	0.011 *** (2.368)
2012	0.037 *** (6.604)	0.019 *** (3.611)
2013	0.042 *** (7.341)	0.028 *** (5.087)
2014	0.021 *** (3.910)	0.041 *** (7.143)
2015	0.022 *** (4.124)	0.048 *** (8.221)
2016	0.023 *** (4.255)	0.048 *** (8.211)

Note: *** indicate that the statistical test was passed at a significance level of 1%.

(2) Spatial baseline regression

Table 7 reports the spatial regression results of the energy structure on eco-efficiency under two different spatial weight matrices using Equation (3). The spatial metrology in this study should adopt the SDM. To more accurately measure the impact of the energy structure on eco-efficiency, as shown in Table 7 (columns 1 and 2), the local–neighborhood effects of the energy structure on eco-efficiency of 285 Chinese cities were measured by using spatial weight matrix tests of inverse distance and economic distance. Moreover, the direct and indirect effects of the neighborhood effect were further investigated. As shown in models (3) and (4), to ensure robustness of the empirical results, the regression results of the spatial autoregressive model (SAR) are also reported. From the log-likelihood function value (LogL) and Akaike information criterion value (AIC) of the four models, the SDM was superior to the spatial autoregressive model, and its LogL value was relatively large and AIC value was small.

Table 7. Test of spatial effect of energy structure on urban eco-efficiency.

	SDM		SAR	
	(1)	**(2)**	**(3)**	**(4)**
	Inverse Distance	**Economic Distance**	**Inverse Distance**	**Economic Distance**
ES	−0.0355 * (0.0201)	−0.0398 ** (0.0200)	0.0326 (0.0201)	0.0340 * (0.0200)
W × ES	−0.1378 (0.2266)	−0.0284 (0.0493)		
Control variables	YES	YES	YES	YES
rho	0.2787 ** (0.1214)	0.1685 *** (0.0321)	0.4158 *** (0.1086)	0.1650 *** (0.0317)
sigma2_e	0.0047 *** (0.0001)	0.0047 *** (0.0001)	0.0048 *** (0.0001)	0.0047 *** (0.0001)
Direct effect	0.0358 * (0.0206)	0.0402 * (0.0206)	0.0334 (0.0206)	0.0348 * (0.0206)
Indirect effect	−0.1851 (0.346)	−0.0256 (0.0611)	0.027 (0.0246)	0.0069 (0.0046)
Total effect	−0.1493 (0.3471)	0.0146 (0.0662)	0.0604 (0.0418)	0.0417 * (0.0249)
Two-way fixation	Yes	Yes	Yes	Yes
R^2	0.0338	0.0286	0.0564	0.0496
N	3420	3420	3420	3420
Log L	4316.302	4322.5124	4291.325	4297.779
AIC	−8580.603	−8593.0247	−8542.649	−8555.558

ES, energy structure; SDM, spatial Durbin model. Note: ***, **, and * indicate that the statistical test was passed at a significance level of 1%, 5%, and 10%, respectively.

SDM regression coefficients from (1) to (2) can be seen as follows: First, optimization of the energy structure had a significant effect on the improvement in local eco-efficiency. Among them, the regression coefficients of the energy structure to local eco-efficiency were significant at the significance level of 10% and above, which were −0.0355 and −0.0398, respectively, indicating that the local effect was significant. Second, the influence of the energy structure on the eco-efficiency of neighboring cities was consistent with that of local cities, i.e., the energy structure transition in one city was conducive to improvement of the eco-efficiency of neighboring cities; however, the empirical results obtained using the inverse distance and economic distance matrix were not significant, which may have been because the mutual relationship with neighboring space was unable to well reflect the influence of the energy structure on the eco-efficiency, or the performance was weak. Third, the partial differential regression results of direct and indirect effects also confirmed that the energy structure had a certain positive effect on both local and neighboring eco-efficiency. In addition, based on the consideration of robustness, the regression results of SAR core variables were basically consistent with the SDM.

Based on the above empirical results, energy structure transition improved ecological efficiency, promoted spatial spillover and competitive learning, and produced certain spatial spillover effects on surrounding areas. The influence of the energy structure on the eco-efficiency of neighboring cities was notably different from that of local cities. This indicated that when the local government and residents regard environmental protection as important, polluting enterprises may disperse to surrounding areas. In the short term, energy restructuring will force industries with high energy dependence to move out of the vicinity. The regions that undertake the transfer of related industries will have increased income, while also an increase in carbon-intensive energy consumption and the doubling of environmental cost, resulting in a relative reduction in ecological efficiency. Generally, even if an insignificant relationship is found in the econometric analysis, it does not necessarily imply that there is no relationship and may be because the influence is weak. To further investigate and verify the neighborhood effect, the direct and indirect effects of the neighborhood effect presented in Table 7 showed that among the direct effects, the energy structure had a significant impact on the neighborhood ecological effect. Among them, under the spatial weight of economic distance, the influence of the energy structure on neighboring cities was greater than the influence coefficient of the inverse distance spatial weight matrix and was significant at the 10% significance level. This indicated that the closer the economic connection between two places, the more notable the influence of the local energy structure on the ecological efficiency of neighboring cities. This may be due to the transfer of related industries brought by the energy structure transition and brings more pollution from the industries transferred to neighboring cities.

6. Discussion

In sum, our results reveal the effect and influence mechanism of energy structure on ecological efficiency. This will further contribute to the literature on the upgrading of energy structure and the improvement of ecological efficiency, deepen the understanding of the characteristics of their relationship, and better propose effective policy solutions. In terms of research samples, existing studies typically rely on the measurement of ecological efficiency and the analysis of influencing factors at the national level or provincial level. Here, prefecture-level data of cities were used as samples, and the division of regions was conducted according to the level of economic development and resource conditions, so as to analyze the regional differences in the abovementioned influence, which will make the analysis more specific, in-depth, scientific, and reliable. Therefore, we conclude that the energy structure and ecological efficiency is an inverted U-shaped relationship. As such, this study further revealed the optimal choice of energy structure under the current conditions in China and explained why China needs to gradually reduce the use of coal energy to improve ecological efficiency. However, not too much or too rapidly, but rather gradually.

In China, coal consumption reduction reflects the energy structure transition, and the improvement in ecological efficiency goes in tandem with green development. The influence mechanism of the energy structure on eco-efficiency was discussed and analyzed in this study, taking 285 cities across China as examples, and the impacts of the energy structure on ecological efficiency, including influence relationship and spatial effects, were specifically investigated.

The main findings compared to the literature are summarized as follows:

(1) We explored the relationship between energy structure and eco-efficiency with more cities as objects. Further, Zhang [41] and Zhang [42], based on provincial data, refined the research object and enriched the discussion on the influencing factors of ecological efficiency by Shah [39] and Hu [40]. These studies held that the overall trend of urban energy structure adjustment and ecological efficiency improvement is good, supporting the conclusion of Chen [25], which is also based on provincial data. The difference is that they concluded that carbon dioxide emissions can be reduced through energy structure adjustment, which can be expressed as the increase in the coal-based energy structure had a negative effect on the improvement of urban eco-efficiency. This study finds that such results remain valid after a series of robustness tests, including a replacement regression model and outlier. However, based on the analysis of regional

heterogeneity, the influence of energy structure on eco-efficiency varies substantially in space. Resource-based and old industrial cities have greater difficulty in energy structure adjustment, but the effect of such adjustment is more significant. Reducing coal consumption and optimizing energy structure has become an important driving force for improving urban ecological efficiency.

(2) The effect of energy structure on eco-efficiency meets the nonlinear change characteristic of an inverted U-shape. According to model (2), this study finds that in Table 3, the primary term factor is significantly negative, but the secondary term coefficient is significantly positive. In other words, continuous substitution of clean energy and reduction in coal consumption to optimize the energy structure will eventually raise the cost of urban operation and development, notably affect the sustainable and stable economic development, and inhibit the improvement of ecological efficiency. Lin [27] concluded that the increase in energy cost caused by the change in energy structure would have a certain negative impact on the macro-economy. Wang [43] proposed that the adjustment of energy consumption structure had no significant effect on the improvement of energy efficiency.

(3) The change in energy structure among cities and the level of urban eco-efficiency have spatial interaction effects and heterogeneity. Cities may race to the bottom and to the top simultaneously. The spillover effect of eco-efficiency on neighboring areas is obvious: when the eco-efficiency of the neighboring area increases, the eco-efficiency of the local area also tends to increase. Geographical and economic spatial effects have an important influence on the change in eco-efficiency between cities. Further study of the local–neighborhood spillover effect shows that the local and neighborhood effects of energy structure on eco-efficiency are different in the inverse and economic distance matrices, indicating that the energy structure reflects more local effects. However, looking at the direct and indirect effects of economic distance, we found that the energy structure in the direct effect has a significant impact on the ecological efficiency, indicating that the closer the economic connection between two places, the more noticeable the impact of local energy structure on the ecological efficiency of neighboring cities. It has a certain spatial spillover effect, which provides support for local governments and other relevant institutions to understand and improve ecological efficiency. Such is an important complementary finding to the existing literature, which rarely provides such evidence.

7. Conclusions and Policy Recommendations

7.1. Conclusions

Exploring the relationship between energy structure and eco-efficiency and revealing what kind of energy structure is most conducive to promoting eco-efficiency is the key to implementing green development. The answers to these questions will enable us to obtain the greatest economic and social development benefits with the least resource consumption and pollution costs. Existing studies either focus on the relationship between foreign investment, industrial structure, environmental regulation, and energy use efficiency or explore the idea of energy structure optimization in industries. This study re-examined the relationship between energy structure and eco-efficiency with new evidence from China. As the world’s largest developing country, China’s rapid industrialization and urbanization are bound to bring about high energy consumption and corresponding environmental problems. It will provide a reference for other countries, especially developing countries, on how to handle the correlations between urban economic development and energy structure, in order to achieve sustainable development. It will also provide implications on how to deal with the interacted economic interests and the eco-friendly energy supply system of cities, with the proper formation of coordinated collaborations between cities in urban agglomerations. The study demonstrated that for every 1% reduction in the structure of coal as a share of energy consumption, eco-efficiency would increase by 0.1170; meanwhile, further validation argued that as the share of coal decreases, the cost of energy consumption rises and has a suppressive effect on eco-efficiency improvement.

7.2. Policy Recommendations

First, clean energy, especially renewables such as hydro, wind, and photovoltaic, should be vigorously developed and used, so as to improve the energy structure, while paying close attention to its U-shaped relationship with eco-efficiency. In this regard, policy should not only just pay attention to how to promote clean energy but also consider an optimal pathway of phasing out the historical assets of west-to-east coal transport infrastructure, which has existed for a long time and until now is still the biggest pillar of energy supply in China. The policy of adjusting production capacity should be improved, the reform of the energy supply should be deepened, the market regulations of both supply and demand should be exerted through further reforming the energy pricing, and reasonable sharing of pollution costs should be promoted. In the policy language of China, this composite basket of policies could be dubbed as deepening energy supply side reform.

Second, changes in the energy structure should be handled progressively. Optimization and transition of the coal energy structure should be based on the premise of sustainable economic development and the safety and reliability of the economy and society and focus on phased completion of energy structure transition objectives and when to complete the target. Specifically, full consideration should be given to the regional resource distribution and the actual development of industrial structure, and the reform of the energy structure and system should be accelerated in areas with relatively good economic development and rich clean energy resources. There should be focus on supporting technological breakthroughs in pollutant recycling, wastewater reuse, and waste gas recovery, reducing coal consumption, optimizing the ecological environment, and improving ecological efficiency. In cities with poor economic development and that are dominated by traditional energy and resource endowment, the pressure of energy structure transition is greater. Therefore, the government can actively adopt economic subsidies and flexible policies, promote coal reduction and coal restriction in industries such as steel, non-ferrous metals, and building materials, strictly control the blind development of “two high and one low” projects, and carry out energy conservation and upgrading in key areas to improve ecological efficiency.

Third, the energy structure should be improved according to local conditions. Considering factors such as differences in economic development levels, industrial structure, and resource endowment conditions, we should coordinate the optimization of the regional energy supply, enhance economies of scale in the energy industry, and improve the overall efficiency of resource utilization. This is achievable by resource integration, merger and reorganization, and construction of energy industrial parks, as well as shutting down and cleaning up energy enterprises with small scale, low efficiency, and high pollution. These strategies will improve the development quality of the traditional energy industry. A regional coordination system should be established for energy structure transition to realize structural adjustment and efficiency improvement among regions on the basis of ensuring economic and social development. Furthermore, domestic capacity building for transmission and distribution, gas storage, and peak regulation should be strengthened. In addition, all regions are encouraged to optimize energy networks and subsidy programs according to the list of major energy consumers and gradually achieve energy conservation and consumption reduction.

Finally, a focus should be placed on regional cooperation and coordination. Self-promotion and positive spatial effect of high-value eco-efficiency cities should be consolidated and strengthened. Urban clusters with relatively mature development and a certain positive spatial spillover effect should further strengthen their ability to cultivate and apply high-quality production factors and enhance their agglomeration effect and economies of scale, so as to enhance their economic development level and spatial spillover ability, and finally broaden their radiation range to surrounding cities. This will enable the realization of the simultaneous improvement in economic quality and level in a wide range of regions.

Similarly, for unstable cities with positive spatial effects, cities and regions should gradually break down administrative barriers, strengthen cross-regional cooperation in environmental governance, and implement policies that are conducive to coordinated improvement of environmental quality. Establishment of cooperation should be actively promoted in such areas as environmental planning, investment in environmental governance, compensation for environmental pollution, emission trading, and ecological transfer payments, with urban clusters and metropolitan areas as units, and a joint construction pattern should be built with economic coordination as the main feature and policy and management coordination as the secondary feature.

7.3. Deficiencies and Prospects

In conclusion, this study evaluated the impact mechanism, measurement, and empirical research regarding energy structure and eco-efficiency and posits policy suggestions. The research conclusions align with theoretical expectations and practice; however, some limitations remain. First, the statistical measurement of energy structure per unit of city is complicated. Because of the limitation of statistical data, we conducted the energy structure measurement referring to the existing research. However, this approach still cannot accurately measure the coal consumption of each city, and there may be differences in coal consumption in different cities. Second, the mechanism of the influence of energy structure on ecological efficiency was theoretically discussed in this paper. It may not only reduce pollution emission, improve energy efficiency, and affect economic income and ecological efficiency through production costs and other forms mentioned here, but it may also change with economic development. Future research should explore and expand this influence path.

Author Contributions: Conceptualization, N.L.; methodology, N.L.; formal analysis, F.Z.; writing—original draft preparation, F.Z.; writing—review and editing, Y.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to the authors not having permission to share data.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Energy Structure, Ecological Efficiency, and Industrial Pollution Index of Major Cities in China

Table A1. Energy structure of major cities in China.

	2005	2010	2015	2020
Beijing	0.455	0.740	0.594	0.550
Tianjin	0.534	0.518	0.564	0.554
Shijiazhuang	0.865	0.891	0.768	0.768
Taiyuan	0.780	0.697	0.623	0.611
Huhehaote	0.885	0.768	0.784	0.775
Shenyang	0.686	0.761	0.618	0.486
Dalian	0.533	0.473	0.345	0.336
Changchun	0.519	0.449	0.426	0.337
Harbin	0.865	0.865	0.770	0.786
Shanghai	0.462	0.436	0.416	0.402

Table A1. *Cont.*

	2005	2010	2015	2020
Nanjing	0.150	0.243	0.559	0.546
Hangzhou	0.600	0.589	0.450	0.405
Ningbo	0.708	0.725	0.701	0.654
Hefei	0.748	0.721	0.697	0.659
Fuzhou	0.695	0.799	0.742	0.726
Xiamen	0.395	0.443	0.407	0.382
Nanchang	0.590	0.734	0.586	0.559
Jinan	0.781	0.793	0.802	0.748
Qingdao	0.797	0.811	0.807	0.798
Zhengzhou	0.788	0.715	0.562	0.561
Wuhan	0.710	0.762	0.762	0.754
Changsha	0.854	0.882	0.832	0.824
Guangzhou	0.611	0.619	0.559	0.549
Shenzhen	0.346	0.425	0.463	0.479
Zhuhai	0.343	0.318	0.265	0.277
Shantou	0.100	0.223	0.041	0.668
Nanning	0.676	0.747	0.734	0.683
Haikou	0.642	0.591	0.546	0.346
Chongqing	0.682	0.619	0.566	0.538
Chengdu	0.714	0.632	0.711	0.673
Guiyang	0.634	0.651	0.745	0.568
Kunming	0.5577	0.5909	0.6279	0.593
Xi’an	0.576	0.697	0.553	0.453
Lanzhou	0.417	0.648	0.655	0.718
Xining	0.712	0.728	0.731	0.692
Yinchuan	0.662	0.757	0.551	0.501
Urumqi	0.632	0.743	0.652	0.511

Source: authors’ calculation.

Table A2. Ecological efficiency of major cities in China.

	2005	2010	2015	2020
Beijing	0.707	1.037	1.073	1.073
Tianjin	0.568	0.689	1.026	1.020
Shijiazhuang	0.553	0.670	0.621	0.608
Taiyuan	0.525	0.590	0.611	0.596
Huhehaote	0.532	0.681	1.017	0.670
Shenyang	0.575	0.666	0.664	0.642
Dalian	0.582	0.641	0.671	0.612
Changchun	0.573	0.639	1.047	1.051
Harbin	0.554	0.643	0.703	0.680
Shanghai	0.581	1.022	1.021	1.058

Table A2. *Cont.*

	2005	2010	2015	2020
Nanjing	0.534	0.585	0.619	0.663
Hangzhou	0.558	0.575	0.617	0.635
Ningbo	0.607	0.610	0.707	0.668
Hefei	0.543	0.605	0.596	0.602
Fuzhou	0.561	0.647	0.712	0.697
Xiamen	0.544	0.604	0.600	0.642
Nanchang	0.549	0.573	0.602	0.593
Jinan	0.578	0.640	0.739	0.676
Qingdao	0.600	0.761	1.021	1.054
Zhengzhou	1.088	0.588	0.599	0.645
Wuhan	0.705	0.567	0.680	0.644
Changsha	0.585	0.629	0.789	0.724
Guangzhou	0.855	0.642	1.015	0.680
Shenzhen	0.658	1.049	1.104	1.082
Zhuhai	1.055	0.557	0.601	0.607
Shantou	0.536	0.592	0.642	0.601
Nanning	0.497	0.527	0.587	0.609
Haikou	0.715	1.052	0.706	1.025
Chongqing	0.536	0.573	0.592	0.595
Chengdu	0.512	0.598	0.651	0.644
Guiyang	0.620	0.546	0.593	0.570
Kunming	0.800	0.824	0.744	0.591
Xi'an	0.438	0.571	0.645	0.710
Lanzhou	0.439	0.568	0.591	0.594
Xining	0.336	0.503	0.552	0.529
Yinchuan	0.456	0.519	0.533	0.541
Urumqi	0.407	0.532	0.584	0.505

Source: authors' calculation.

Table A3. Industrial pollution index for major cities in China.

	2005	2010	2015	2020
Beijing	0.19255	0.16940	0.08367	0.11572
Tianjin	1.28407	1.35075	0.78253	0.82359
Shijiazhuang	1.04330	0.64560	0.70688	0.95091
Taiyuan	0.37284	0.35658	0.09073	0.05729
Huhehaote	0.39472	0.09695	0.09523	0.43430
Shenyang	0.19096	0.85804	0.25738	0.19084
Dalian	1.07077	0.62495	1.28314	1.36554
Changchun	0.24794	1.93706	0.08641	0.06805
Harbin	0.31270	0.22824	0.08172	0.09816
Shanghai	2.64373	1.67917	2.28399	2.49098

Table A3. *Cont.*

	2005	2010	2015	2020
Nanjing	1.49987	1.04506	0.70874	0.82118
Hangzhou	4.13948	4.02527	1.14154	1.31229
Ningbo	0.46036	0.50896	0.42923	0.52541
Hefei	0.03698	0.04105	0.08293	0.04891
Fuzhou	0.11644	0.12462	0.10380	0.29201
Xiamen	0.04804	0.03391	0.42929	0.48500
Nanchang	0.07155	0.08242	0.11140	0.20456
Jinan	0.09921	0.15376	0.17151	0.21379
Qingdao	0.20825	0.17996	0.17960	0.08463
Zhengzhou	1.41584	0.68183	0.57090	0.22013
Wuhan	0.62636	0.40698	0.32341	0.34993
Changsha	0.14008	0.17277	0.02891	0.03167
Guangzhou	0.39831	0.50110	0.36187	0.58008
Shenzhen	0.03894	0.05840	0.33730	0.17393
Zhuhai	0.01185	0.04895	0.04136	0.03196
Shantou	0.02214	0.03367	0.04039	0.06463
Nanning	0.24716	0.26287	0.06702	0.03144
Haikou	0.00009	0.00015	0.00052	0.00039
Chongqing	8.52802	6.94691	4.58626	3.73594
Chengdu	2.29472	0.30924	0.14756	0.16261
Guiyang	0.56265	0.11427	0.06721	0.15907
Kunming	0.08321	0.12090	0.11441	0.59916
Xi’an	0.31496	0.24130	0.05261	0.02571
Lanzhou	0.05874	0.07500	0.09041	0.05468
Xining	0.10216	0.16062	0.07816	0.40604
Yinchuan	0.00542	0.04094	0.09849	0.07291
Urumqi	0.17753	0.34601	0.08143	0.20048

Source: authors’ calculation.

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