Influence of Agglomeration of Manufacturing and the Producer Service Sector on Energy Efficiency

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Abstract

Due to the gradual agglomeration of economic activities and the continuous reinforcement of spatial linkages in specific geographic locations, the geospatial factor should become an important starting point to understand the relationship between industrial restructuring and energy conservation and emission reduction. This paper first introduces a non-separable hybrid DEA model that considers undesirable output to measure the energy efficiencies of 285 prefecture or higher-level cities in China during 2003-2016; then, a dynamic spatial panel model is used to investigate the influence of different types of industrial agglomerations and agglomeration modes on energy efficiency. According to the obtained study results, for the investigation period, the overall energy efficiency of China with regard to pollutants remained at a low level and presented a “U-shaped” decreasing-increasing trend. To be specific, China’s energy efficiency distribution presented a trend of “high in the east and low in the west.” The energy efficiency of East China changed relatively gently, while the energy efficiencies of central China and western China changed dramatically. China’s energy efficiency also presented a significant spatial agglomeration effect, i.e., cities with close energy efficiencies are usually adjacent to each other. At the national level, agglomeration of the manufacturing sector significantly inhibited the increase of energy efficiency; the agglomeration of the producer service sector and the co-agglomeration of the manufacturing sector and the producer service sector both facilitated an increase of energy efficiency. The influence of industrial agglomeration on energy efficiency differed across different city scale grades. Based on these conclusions, the paper proposes the following policy implications: 1) make full use of the energy savings and emission reduction effect of agglomeration; 2) accelerate the optimization of industrial layout; 3) develop high-end service industry and productive service industry; and 4) create an agglomeration environment that encourages benign industrial competition.

Keywords: industrial agglomeration, energy efficiency, manufacturing sector, producer service sector, non-separable hybrid DEA

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Introduction

Energy efficiency (EE) measures are regarded by all relevant international organizations as a central means to realize greenhouse gas emission reductions and related co-benefits such as better air quality and potential job growth worldwide, especially as a short-term strategy. Compared to other decarburization options, efficiency measures are often quick to implement, cost-effective and already widely available today [1].

In order to achieve widespread implementation and to exploit the various advantages linked to energy efficiency improvements, the EU adopted several plans and laws on energy efficiency, particularly in the past decade. An important recent policy is the Energy Efficiency Directive (EED), which was enacted in 2012. In order to achieve the EU’s 20% primary energy savings target by 2020, all Member States are required to cut their final energy consumption by at least 1.5% per year from 2014 to 2020 and to notify indicative national energy efficiency targets to be achieved by 2020 [2]. The European Council set climate and energy targets for 2030 in October 2014. The decision included an indicative target of at least 27% for improving energy efficiency in the EU as a whole compared to baseline projections for future energy consumption [3]. The target might be scaled up to 30% by no later than 2020.

Since China’s reform and opening up, significant changes have taken place in the country’s economy. From being one of the poorest countries in the world, China has become the world’s second largest economy, with an average annual growth rate of up to 9.6%. After experiencing an “economic miracle” for more than three decades, China is currently facing the early emergence of both environmental and energy problems [4]. Similar problems have been encountered by all developed countries of the West during their stage of industrialization [5-6]. China’s traditional mode of economic development has enabled it to realize this quantitative economic growth by continuously turning resources into waste, which has ultimately resulted in the shortage and exhaustion of the country’s natural resources, and generated the consequences of serious environmental pollution. The increasing tension between energy supply and demand and the overdraw of environmental bearing capacity are making it difficult to sustain the extensive economic development pattern [7]. Characterized by high input, high energy consumption, high pollution, and high emission, this pattern has turned China into the world’s largest energy producer and consumer, as well as a major emitter of greenhouse gases and air pollutants [8-9]. Moreover, due to the price advantage of coal resources, China is not going to change its coal-dominated energy consumption pattern soon. This suggests that the space for realizing energy conservation and emission reduction through the further optimization of the energy structure is very limited, and the most realistic way of solving the problem lies in increasing energy efficiency [10].

Energy efficiency is an important step for reducing the amount of required energy for providing products and services. Since being developed by Charnes, Cooper and Rhodes, the CCR model has been applied to measure energy efficiency. After their efforts, many authors have applied data envelopment analysis to measure it. The literature related to this topic can be classified under three lines. The first is composed of studies that are focused directly on energy efficiency [11-14] and its determinants [15-17] from the perspective of cross-national levels. The second and third lines include studies that deal with the energy efficiency issue at the sub-national level and sectoral, industry or microeconomic levels [18-21].

However, it remains unclear how energy efficiency can be increased. Most relevant studies attempted to answer this question at the level of industrial structure [22-24]. The “structural bonus hypothesis” suggests that due to the significant differences between the industrial sector and the service sector with regard to their energy efficiency, the transfer of energy from a low-productivity sector to a high-productivity sector would increase the overall energy efficiency of an economy that comprises various sectors. Many scholars have empirically analyzed the influence of industrial restructuring on energy efficiency; however, their drawn conclusions are different. Some of them have suggested that industrial restructuring poses a significant positive influence on energy efficiency, and that decreasing the proportion of the secondary industry or by increasing the proportion of the tertiary industry would increase energy efficiency [25-26]; others argue that the influence of industrial restructuring on energy efficiency is restrained by many factors, and therefore such influence becomes insignificant or even negative [27-30]. However, these studies only investigated the influence of industrial restructuring on energy efficiency in the temporal dimension, while rarely exploring interactions between both in the spatial dimension.

Through further analysis, it is not hard to learn that industrial restructuring in China is not only embodied in changes in the structures of the secondary industry and the tertiary industry, but also expresses itself in a geospatial agglomeration of related industries. On the one hand, energy serves as an input factor, similar to capital and labor, and its rate of return is influenced by pecuniary externalities, technological externalities, and competitive externalities created by industrial agglomeration. On the other hand, industrial agglomeration inevitably influences industrial restructuring, closely linking it with a change in energy efficiency [31]. The path of economic development taken by China is unbalanced and due to the gradual agglomeration of economic activities and the continuous reinforcement of spatial linkages in specific geographical locations, the geospatial factor should become an important starting point for understanding
the relationship between industrial restructuring and energy efficiency.

When it comes to studies on agglomeration, independent of whether the theory of new economic geography or the theory of Marshallian externalities or Jacobs externalities are applied, the focus lies on whether agglomeration can promote economic efficiency. Furthermore, these theories assume that industrial agglomeration can facilitate regional economic growth and technological progress through the agglomeration effect (i.e., spillover of knowledge and technology, vertical linkage and horizontal competition of industry chain, increasing returns to scale, and the saving of related costs) [32-33]. However, they rarely deal with the issue of energy efficiency under environmental constraints from the perspective of the externalities of agglomeration. Few scholars have attempted to investigate environmental and energy problems of a country from the perspectives of agglomeration, trade, geography, and other spatial linkages [34-37]. Apparently, progress has been made in comparison to traditional “closed” studies, despite the inconsistencies in the analysis results of spatial channels. In fact, the efficiency of energy, which is one of the factor inputs, is inevitably influenced by the spatial structure (agglomeration or decentralization), and the spatial distribution of the market. Furthermore, most published studies have simply focused on the intergenerational externalities and environmental externalities created via agglomeration, while having failed to reach consistent conclusions. According to the first viewpoint, an expansion of production capacity and an increase of energy consumption demand that accompanies agglomeration induce excessive energy consumption and aggravate pollution status [38-39]. The second viewpoint suggests that industrial agglomeration is an intermediate organization between market and enterprises that benefits from the dual advantages of market and enterprises [40]. Industrial agglomeration not only employs price mechanisms and competition mechanisms to increase the efficiency of resources allocation, but can also accelerate environmental innovation [41], increase energy efficiency, and thus promote emission reduction [42-44]. The third viewpoint argues that industrial agglomeration would have an uncertain relationship with energy conservation and emission reduction, and that its influence on the environment and energy consumption is staged and alternates [45-47].

Studies devoted to investigating the influence of industrial agglomeration on energy efficiency have proven to be fruitful; however, there is still room for further improvement: first, since the inception of neoclassical economics to the rise of new economic geographies, studies on industry agglomeration have aroused widespread concern in academic circles. Industry agglomeration refers to the phenomenon whereby, in the process of industrial development, relevant enterprises or institutions in a particular field become closely linked with one other due to certain similarities and complementarities between them. This eventually forms a geographically concentrated group of industrial clusters in which the different bodies interconnect and support each other. Classical industry agglomeration theories have the common point of taking industry or manufacturing industry agglomeration as their object of study, without analyzing the situation of service industry agglomeration. With the increasing specialization of the social division of labor and the need for global economic transformation, service industries, especially producer services, have begun to separate out from the manufacturing industry in the form of outsourcing, forming a “service economy.” New national urbanization policies (2014-2010) highlight the need to adapt to the requirements of this transformation and upgrade the manufacturing industry, promoting the professionalization, marketization and socialization of producer services and guiding the latter towards aggregation in central cities and areas dense with manufacturing industries. The concept of industrial agglomeration synergy was first proposed by Ellison and Glaeser (1997) [48]. This focused on the internal relations between different industry agglomerations and deepened the theory of industry agglomeration under the current background of industrial interaction and integration development. Venables (1996) [49] analyzed the synergetic agglomeration occurring among correlative industries based on “demand correlation” and “cost correlation” by establishing a vertically associated industry agglomeration model. Since then, follow-up studies have mostly focused on analyzing the synergetic agglomeration between the internal industries of manufacturing industry, with very few studies having focused on the synergetic agglomeration of producer services and the manufacturing industry.

Existing studies largely emphasized the investigation of industrial agglomeration over its influence on energy efficiency at the manufacturing sector level, while neglecting the specificities of different types of industrial agglomeration; in particular, the influence of the agglomeration of the producer service sector and the co-agglomeration of the manufacturing sector and the producer service sector on energy efficiency have been neglected. In fact, compared to simply lowering the proportion of the manufacturing industry, strengthening benign inter-industry interactions may better inhibit environmental deterioration. Moreover, due to its knowledge-intensive characteristics, the producer service sector typically presents significant spatial agglomeration; at the initial stage of development, it may also adjoin the industrial agglomeration belts of the manufacturing sector because of the need of industrial interaction. For this reason, when analyzing the influence of the agglomeration of the manufacturing sector on both energy conservation and emission reduction, it is necessary to take the agglomeration of the producer service sector into account. Second, in terms of energy efficiency measurement, total factor energy
efficiency was introduced and proceeded to calculate energy efficiency under the total factor framework [50]. However, as far as energy efficiency measurements are concerned, most researchers have overlooked the pollutant emission generated by energy consumption and consequently failed to take the non-separability between energy input and undesirable output into consideration, meaning that, when technical level remains constant, the consumption of every unit of energy will inevitably generate a specific volume of environmental pollutants [51]. Due to these insufficiencies, exiting measurements cannot truthfully reflect the energy efficiency with regard to pollution emission. Fourth, when investigating the issue of energy efficiency, most scholars have not sufficiently considered the influence of the geospatial factor on energy efficiency. According to the theory of spatial econometrics, the economic characteristics of the spatial units of a region are not isolated; instead, they always form spatial linkages with identical economic characteristics of adjacent regions. Therefore, when analyzing regional energy efficiency, it is necessary to integrate the geospatial effect as a premise of analysis [52]. Finally, existing studies mostly selected provincial data of large spatial scale and significant internal differences, instead of urban data that might better be able to depict the characteristics of agglomeration and the real status of pollution. This may also mislead any interpretation of empirical results. The majority of studies agree that the influencing mechanisms of agglomeration on energy and environment stem from both the technological spillover effect and the spatial scale effect; however, existing investigations of the agglomeration effect of urban spatial dimensions and urban heterogeneity are not deep enough.

The research aim of this paper is to incorporate the dynamic externality and spatial dependence of industry agglomeration into the analytical framework of the influencing factors of energy efficiency from the perspective of new economic geographies, and to investigate the spatial association and overflow effect of energy efficiency. First, the industry agglomeration mode is subdivided into manufacturing industry agglomeration, producer services agglomeration, and the joint agglomeration of the manufacturing industry and producer services. This is followed by an investigation of the effect mechanism and influencing effect of different industry agglomerations on energy efficiency, and by an analysis of the influence of different industry agglomeration modes on energy efficiency under different agglomeration scales; the objective here is to help cities formulate rational industry agglomeration policies. Next, the paper examines whether China’s energy efficiency mode follows specific spatial distribution patterns, also assessing the extent to which there exists an interplay between the energy efficiency of different regions, and measuring and calculating the spatial spillover boundary of energy efficiency. This is designed to provide benchmarks for the purpose of optimizing the country’s industrial spatial layout.

Based on existing studies, this paper attempts to propose the following improvements: first, it classifies industrial agglomeration into agglomeration of the manufacturing sector, agglomeration of the producer service sector, and co-agglomeration of the manufacturing and producer service sectors and further discusses the influencing mechanism that different types of industrial agglomeration and agglomeration modes pose on energy efficiency; second, it introduces a non-separable hybrid data envelopment analysis (DEA) model, considering undesirable output to measure energy efficiency under pollution emission, besides fully considering the slackness of input-output, it also takes radial and non-radial perspectives into account, as well as the non-separability between energy input and undesirable output; third, based on data on 285 prefecture or higher-level cities in China, it uses a dynamic spatial panel model to analyze the influence industrial agglomeration poses on energy efficiency under different agglomeration scales in order to achieve more accurate and reliable model estimation results.

Materials and Methods

Energy Efficiency: Non-Separable Hybrid DEA Model Considering Pollutants

Data envelopment analysis (DEA) models have been extensively applied in the field of productivity measurement and evaluation. Slacks-based measure (SBM) was proposed, which considers the slackness of input-output [53-54], a hybrid DEA model that could not only deal with multiple desirable outputs but also take the non-separability of input-output into account. This model can be described as follows: the first assumption is that there are \( n \) similar decision-making units in a production system and that the input and output vectors of a decision-making unit in the production process are respectively \( X \in \mathbb{R}^{n \times 1} \) and \( Y \in \mathbb{R}^{m \times 1} \). Here, input-output matrices \( X \) and \( Y \) can be decomposed as follows:

\[
X = \begin{pmatrix} X^f \; X^b \end{pmatrix}, \quad Y = \begin{pmatrix} Y^F \; Y^B \end{pmatrix}
\]

(1)

...where \( X^f \in \mathbb{R}^{n \times 1} \) and \( X^b \in \mathbb{R}^{n \times 1} \) represent separable and non-separable input matrices, respectively; \( Y^F \in \mathbb{R}^{m \times 1} \), \( Y^B \in \mathbb{R}^{m \times 1} \), \( Y_{FG} \in \mathbb{R}^{m \times 1} \), and \( Y_{FB} \in \mathbb{R}^{m \times 1} \) represent separable desirable output, separable undesirable output, non-separable desirable output, and non-separable undesirable output, respectively. In this case, the production possibility set of constant returns to scale can be described as:
\[ P_{BF} = \left\{ (x'_F, y'_F, y''_F, y'_B, y''_B) \mid x'_F \geq x'_F \lambda, x''_F \geq x''_F \lambda, y'_F \leq Y'_F \lambda, y''_F \leq Y''_F \lambda, y'_B \geq Y'_B \lambda, y''_B \geq Y''_B \lambda \right\} \]

...where \( \lambda \) represents the weight vector.

The production possibility set has the following characteristics:
- Non-separable input-output variables are radial, while separable input-output variables are non-radial.
- The decrease of non-separable undesirable output is accompanied by a proportional decrease of non-separable desirable output.

Under the production possibility set, the non-separable validity of the production unit DMU \( (x'_0, x''_0, y'_0, y''_0, \theta, \delta) \) is defined as:

For any \( 0 \leq \theta < 1 \), the production unit will be valid only if \((x'_0, \theta x'_0, y'_0, \theta y'_0, \delta) \) belongs to \( P_{BF} \) and if there is no \((x''_0, \theta x''_0, \theta y''_0, \delta) \) that allows any of the strict inequalities \( x''_0 \leq x'_0 \lambda \), \( y'_0 \leq Y'_0 \lambda \), \( y''_0 \leq Y''_0 \lambda \) and \( y'_B \geq y''_B \) to be established. In this case, \( \rho \) represents the energy efficiency value. The model proposed in this paper can be expressed as:

\[
\begin{align*}
\rho^* &= \text{Min} \\
&= \frac{1}{m} \left( \sum_{t=0}^{m-1} \frac{y'_t}{x'_t} - m(1-\theta) + \sum_{t=1}^m \frac{y''_t}{x''_t} \right) \\
&= \frac{1}{m} \left( \sum_{t=0}^{m-1} \frac{y'_t}{x'_t} - (1+\theta)(1-\theta) + \sum_{t=1}^m \frac{y''_t}{x''_t} \right) \\
\text{subject to} \\
&\chi'_t = x'_t \lambda + s' \\
&\theta x'_t = x'_t \lambda + s'_t \\
&y'_t = y'_t \lambda + s'_t \\
&\theta y'_t = y'_t \lambda + s'_t \\
&\sum_{t=1}^{m-1} y''_t = \sum_{t=1}^{m-1} y''_t + \sum_{t=1}^{m} y''_t - \sum_{t=1}^{m-1} y''_t \\
&m = m + m_t \\
&l = l + l + l \\
&s'' \geq 0, s'' \geq 0, s'' \geq 0, s'' \geq 0, s'' \geq 0, \lambda \geq 0, 0 \leq s' \leq 1 \\
\end{align*}
\]

...where \( S'F, S''F, S'G, S''G, S'B, S''B \) represent the slack variables of input-output, respectively (here, surplus variables are collectively referred to as slack variables); \( \theta \) represents the reduction coefficient; \( \delta \) represents the expansion coefficient of the separable desirable output; and \( \sum_{t=1}^{m-1} y''_t + \sum_{t=1}^{m} y''_t = \sum_{t=1}^{m} y''_t + \sum_{t=1}^{m} y''_t \) indicates that the quantity of the desirable output must remain constant.

When \( 0 \leq \rho^* < 1 \), this suggests that the decision-making unit is inefficient and that the input-output of the production process needs to be improved; \( \rho^* = 1 \) suggests that the decision-making unit is efficient and that it is at the production frontier.

The output indices energy efficiency (EE) include both desirable output and undesirable output. Desirable output selects the gross industrial output value index, adopts the producer price index as price adjustment basis of gross industrial output value, and utilizes 2003 as the base period of consumption price deflator. Considering the absence of statistics for the producer price index on the scale of prefecture-level cities, the producer price indices of provinces to which various cities belong are used instead. Undesirable output selects industrial pollution emission, which consists of industrial wastewater discharge, industrial SO2 emission, and industrial soot emission. The input indices adopt the annual average balance of net value of fixed assets, annual average of the employed and industrial energy consumption. To be specific, the conversion indices of fixed assets adopt the related indices of various provinces. The conversion of the annual average balance of net value of fixed assets uses the following formula:

\[
K_i(t) = K_i(t_0) + \sum_{t=1}^{m} \Delta K_i(t) / P_i(t), \text{ with } K_i(t) \text{ and } P_i(t)
\]

represent the annual average balance of net value of fixed assets and the price index of investment in fixed assets of the \( t^t \) city in the \( r^t \) year, respectively.

Considering both the lack of formal statistics on “the three industrial wastes” (i.e., waste gas, wastewater, and industrial residue) for Chinese cities prior to 2003 and the implementation of large-scale administrative division adjustments in many Chinese cities at around 2000, this paper begins its statistics with the year 2003. What needs to be pointed out is that, during 2011/2012, the State Council repealed Chaohu of Anhui Province, and established prefecture-level cities Bijie and Tongren in Guizhou Province and prefecture-level city Sansha in Hainan Province. After that, the number of prefectures or higher-level cities in China changed from 287 to 289. For the sake of consistency in the utilized statistics, this paper adopts panel data of 285 prefecture or higher-level cities in China in 2003-2016 (excluding Chaohu, Bijie, Tongren, Sansha, and Lhasa due to lack of data of previous years). The data are derived from the China Statistical Yearbook, China City Statistical Yearbook and the Comprehensive Statistical Data and Materials on 50 Years of New China over the years. The data for certain years was missing and was supplemented by estimating the average values of the data of their preceding and following years.

Dynamic Spatial Panel Regression Model

With regard to the relationship between industrial agglomeration and energy conservation and emission reduction, classical theories have not enabled any in-depth discussions. The influence of industrial agglomeration on energy conservation and emission reduction is not a simple case of “expanded scale, increased energy consumption, and deteriorated environment”; in fact, industrial agglomeration may
also create positive externalities, e.g., promoting inter-
industry or inter-enterprise cooperation in response to initiatives of energy conservation and emission reduction. This paper therefore constructs a model for the influence of different types of industrial agglomeration and agglomeration modes on energy efficiency (agglomeration of the manufacturing sector, agglomeration of the producer service sector, and co-
agglomeration of both the manufacturing and the producer service sectors). The developed model refers to Fisher-Vanden’s energy efficiency model and includes the factor of industrial agglomeration. Assuming that the production process of a city follows the Cobb-
Douglas cost function below:

\[ C(P_k, P_L, P_E, P_M, Q) = A \cdot e^\gamma P_k^{\rho} P_L^{\delta} P_E^{\eta} P_M^{\theta} Q \]

(4)

...where \( A \) represents the total factor productivity; \( Q \) represents the city output level; \( P_k, P_L, P_E, P_M \) represent the capital (K), labor (L), energy (E), and nominal prices of raw material (M), respectively; \( \gamma_j \) represents the output elasticity; and \( \theta \) represents the elasticity of the influence of industrial agglomeration on city production cost.

Worth noting is the fact that the above-mentioned studies have ignored the spatial relationships of a city with its hinterland and peripheral cities when it attracts industries and population via the agglomeration effect. Due to the specificities of the spatial positions of cities, peripheral cities inevitably influence industrial agglomeration and this also determines the spatial spillover effect of industrial agglomeration. Based on Formula (4), this paper takes the possible dynamic effect and spatial spillover effect of energy efficiency into account, incorporates the time-lag term and spatial-
lag term of energy efficiency, and uses statistical data of 285 prefecture or higher-level cities in China during 2003-2016 to investigate the influence that the agglomeration of the manufacturing sector (magg), the agglomeration of the producer service sector (psagg), and the co-agglomeration of the manufacturing sector and the producer service sector (coagg) pose on energy efficiency. The following dynamic spatial econometric model was established for the influencing factors of energy efficiency:

\[ LnEE_{it} = \tau LnEE_{it-1} + \rho \sum_{j=1}^{N} W_{ij} LnEE_{it} + \theta_1 Lnagg_{it} + \gamma_1 (Lnagg_{it})^2 + \theta_2 Lnsagg_{it} + \gamma_2 (Lnsagg_{it})^2 + \theta_3 Lncagg_{it} + \gamma_3 (Lncagg_{it})^2 + \delta \Delta LnX_{it} + \eta_i + \nu_i + \epsilon_{it} \]

(5)

...where \( \tau \) represents the regression coefficient of the first-order lag term of energy efficiency (EE); \( \rho \) represents the spatial lag coefficient; \( \lambda \) represents the spatial error coefficient; \( W_{ij} \) represents the spatial weight matrix of geographical distances; and \( \epsilon_{it}, \eta_i, \nu_i \) represent random disturbance term, regional effect, and temporal effect, respectively. The key to constructing a spatial panel model lies in defining the spatial weight matrix \( W_{285-285} \). This paper adopts SASIML programming and uses the formula \( R \times \arccos(\cos(\alpha_i - \alpha_j) \cdot \cos(B_i \cdot \cos(B_j + \sin(B_i) \cdot \sin(B_j))) \) to calculate intercity distances (data source: National Fundamental Geographic Information System). \( \alpha_i \) and \( \alpha_j \) represent the longitudes of \( i \) and \( j \); \( \beta_i \) and \( \beta_j \) represent their latitudes; \( R \) is 6,378 km. The spatial lag (error) variables of this paper are all created within a distance of 100 km, and it has been found that the externalities of agglomeration suffer from geographical limitations, i.e., the spatial lag (error) variables within a distance of 100 km have the highest statistical significance. Thus, if the distance between two cities falls within 100 km, \( w_{ij} = w_{ji} = 1 \); otherwise, \( w_{ij} = w_{ji} = 0 \). According to the theory of new economic geography, the process of industrial spatial agglomeration is a result of the combined action of the agglomeration effect under a “centripetal force” and the congestion effect under a “centrifugal force”; consequently, industrial agglomeration exerts different influence effects on energy efficiency. At the same time, the quadratic terms of the agglomeration of the manufacturing sector, the agglomeration of the producer service sector, and the co-agglomeration of the manufacturing sector and the producer service sector are introduced into the model, respectively, to test whether a nonlinear relationship exists between both.

The core explanatory variables are: agglomeration of the manufacturing sector, agglomeration of the producer service sector, and co-agglomeration of the manufacturing sector and the producer service sector. The typically used methods for industrial agglomeration measurement include the location quotient index, Hoover’s index, the Gini coefficient, and the E-G index, etc. Given that the location quotient index can eliminate the factor of regional scale difference and thus truthfully reflect the spatial distribution of the factors of a city, this paper adopts the location quotient index to measure the agglomeration level. The following calculation formula was used:

\[ agg(t) = \left[ \frac{\sum_{j} e_{ij}(t)}{\sum_{j} e_{ij}(t)} \right] \left[ \frac{\sum_{i} e_{ij}(t)}{\sum_{i} e_{ij}(t)} \right] \]

(6)

...where \( agg(t) \) represents the location quotient index of industry \( j \) of city \( i \) during period \( t \); \( e_{ij}(t) \) represents the total employment of industry \( j \) of city \( i \) during period \( t \); \( \sum_{i} e_{ij}(t) \) represents the total employment of all industries of city \( i \) during period \( t \); \( \sum_{i} e_{ij}(t) \) represents the total employment of industry \( i \) of all cities during period \( t \); and \( \sum_{i} \sum_{j} e_{ij}(t) \) represents the total employment of all industries of all cities during period \( t \).
A higher location quotient index implies a higher degree of agglomeration, and vice versa. According to Formula (6), the location quotient of the manufacturing sector and that of the producer service sector can be obtained. The producer service sector consists mainly of five industries, i.e., information transmission, computer service; and software industry; financial industry; real estate industry; rental and commercial service industry; and scientific research, technical service, and geological survey industry. The specific algorithm for the agglomeration of the producer service sector is identical to that for the agglomeration of the manufacturing sector. The index of the co-agglomeration of the manufacturing sector and the producer service sector was constructed on this basis. The following calculation formula was used:

\[
coagg_i = 1 - \frac{|magg_i - psagg_i|}{magg_i + psagg_i},
\]

(7)

A higher co-agglomeration index implies a higher degree of synergistic agglomeration between the producer service sector and the manufacturing sector of a city.

Control variables include:
- Energy price (EP): An increasing energy price encourages enterprises to improve their management mode, upgrade production efficiency, and further increase energy efficiency; this paper adopts the purchasing price indexes of fuel and power to measure the energy price.
- Human capital (EDU): Increasing human capital facilitates R&D, popularization, and application of energy-saving technologies, enhances the awareness and consciousness of energy conservation and emission reduction, and thus increases energy efficiency; therefore, this paper adopts student enrollment in institutions of higher learning per 10,000 persons in cities as a measure of human capital.
- Infrastructure (INFRA): Improving infrastructure upgrades the allocation efficiency of the energy factor, effectively reduces transaction cost and transport cost, and thus increases energy efficiency; this paper therefore adopts per capita area of paved roads in cities as a measure of infrastructure.
- Technological innovation (INNO): Industrial agglomeration urges more enterprises in the industrial agglomeration belts to engage in technological innovation; technological innovation in turn directly drives technological progress, which further facilitates the transformation of the enterprise production mode and, consequently, the optimization of intra-regional industrial structure and reduces pollution emission at the level of technological innovation; this paper adopts the numbers of domestic patents applied and granted as a measure of technological innovation. The theoretical expectation of this study was that the above-mentioned control variables all exert a significant positive influence on energy efficiency.
- Government intervention (GOV): Excessive government intervention twists the dominant role of the market in resource allocation, and possibly also induces repeated construction, resources waste, over-investment, and excess capacity, which are all detrimental to the increase of energy efficiency; this study therefore adopted the proportion of government expenditure in GDP to cities as a measure of the degree of government intervention. This paper found that government intervention exerts a significant negative influence on energy efficiency.

\[
\text{Spatial Autocorrelation Test}
\]

First, the global Moran's I was adopted to test whether the energy efficiencies followed specific spatial distribution laws. The following calculation formula was used:

\[
\text{Moran's } I = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij} (Y_i - \bar{Y})(Y_j - \bar{Y})}{S^2 \sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij}}
\]

(8)

\[
S^2 = \frac{1}{n} \sum_{i=1}^{n} (Y_i - \bar{Y})^2
\]

where \( \bar{Y} = \frac{1}{n} \sum_{i=1}^{n} Y_i \). \( Y_i \) and \( Y_j \) represent the observed energy efficiency values of cities \( i \) and \( j \), respectively, and \( W_{ij} \) represents the spatial weight matrix.

The above data are all derived from the China City Statistical Yearbook, China Statistical Yearbook and the statistical yearbooks of various provinces (cities) during 2004-2017.

Regarding the purchasing price index of fuel and power, some cities in Zibo, Wuzhong, Tongliao, Yulin and Karamay are missing data, accounting for 1.7% of all sample cities. About the per capita area of paved roads in cities, some of the cities with Jixi and Chuzhou have missing data, accounting for 0.7% of all sample cities. So, the data of certain cities have been supplemented via interpolation.

Results and Discussion

Energy Efficiency Measurement Results and Analysis

Based on the above panel data on input-output, this paper uses DEA solver pro5.0 software, which was developed by DEASolver to solve the model and to obtain the energy efficiency value of Chinese cities considering pollutants during 2003-2016. A division of East China, Central China, and West China is introduced and the mean values were calculated; see results presented in Table 1 and Fig. 1.
For the purpose of comparison, this paper also provides the energy efficiency measurement results without considering pollutants. According to the obtained results (irrespective of pollutants), the average energy efficiency of Chinese cities (0.723) was noticeably higher than the average energy efficiency obtained when considering pollutants (0.605), suggesting that measuring energy efficiency regardless of pollution would be biased. For the country as a whole, the average energy efficiency of China considering pollutants during 2013-2016 was only 0.605, and its energy efficiency loss reached as high as 0.395; therefore, its overall energy efficiency level during this period was relatively low. By investigating the distribution of energy efficiency across China’s three major regions, energy efficiency distribution presented a very obvious trend of “high in the east and low in the west,” and the annual average energy efficiency values of eastern, central, and western cities were 0.728, 0.456, and 0.469, respectively (see Chart 1). This indicates that the energy efficiency of eastern cities was higher than the energy efficiencies of central and western cities, which is consistent with the study results obtained by most scholars. By investigating the intra-regional distribution, it became apparent that the energy efficiencies of east China, central China, and west China all presented an obvious “U-shaped” decreasing-increasing trend; the energy efficiency of east China changed relatively gently and increased gradually after 2007 (excluding 2007, in which it declined significantly); however, given that it was already at a high level, its increasing velocity remained relatively low; the energy efficiencies of central and west China changed dramatically, especially during 2006-2008 (during which they experienced an abrupt drop). Furthermore, they did not begin to slowly pick up until after 2008; after 2014, the energy efficiency of Central China presented a “skipping” increase, while the energy efficiencies of East China and West China maintained a slow increase.

Due to space limitations, Chart 3 only shows the average energy efficiency of cities in the eastern regions over the years. Generally speaking, China’s eastern areas maintained high EE scores (almost greater than 0.6) over the entire sample period. The energy efficiency of cities in the eastern provinces is quite different. The efficiency values of the four provinces of Shanghai, Guangdong, Fujian and Liaoning are always the highest, far above the average. Analysis of its industrial structure shows that Shanghai’s financial, commercial and other

<table>
<thead>
<tr>
<th>Year</th>
<th>285 cities in China</th>
<th>115 cities in East China</th>
<th>110 cities in Central China</th>
<th>60 cities in West China</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Considering pollutants</td>
<td>Without considering pollutants</td>
<td>Considering pollutants</td>
<td>Without considering pollutants</td>
</tr>
<tr>
<td>2003</td>
<td>0.621</td>
<td>0.754</td>
<td>0.756</td>
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</tr>
<tr>
<td>2004</td>
<td>0.606</td>
<td>0.757</td>
<td>0.745</td>
<td>0.790</td>
</tr>
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<td>0.587</td>
<td>0.745</td>
<td>0.732</td>
<td>0.780</td>
</tr>
<tr>
<td>2006</td>
<td>0.580</td>
<td>0.724</td>
<td>0.730</td>
<td>0.767</td>
</tr>
<tr>
<td>2007</td>
<td>0.565</td>
<td>0.709</td>
<td>0.702</td>
<td>0.760</td>
</tr>
<tr>
<td>2008</td>
<td>0.568</td>
<td>0.678</td>
<td>0.711</td>
<td>0.770</td>
</tr>
<tr>
<td>2009</td>
<td>0.589</td>
<td>0.690</td>
<td>0.715</td>
<td>0.778</td>
</tr>
<tr>
<td>2010</td>
<td>0.598</td>
<td>0.712</td>
<td>0.724</td>
<td>0.795</td>
</tr>
<tr>
<td>2011</td>
<td>0.623</td>
<td>0.723</td>
<td>0.720</td>
<td>0.798</td>
</tr>
<tr>
<td>2012</td>
<td>0.631</td>
<td>0.730</td>
<td>0.728</td>
<td>0.812</td>
</tr>
<tr>
<td>2013</td>
<td>0.643</td>
<td>0.726</td>
<td>0.734</td>
<td>0.817</td>
</tr>
<tr>
<td>2014</td>
<td>0.641</td>
<td>0.734</td>
<td>0.730</td>
<td>0.823</td>
</tr>
<tr>
<td>2015</td>
<td>0.654</td>
<td>0.744</td>
<td>0.738</td>
<td>0.830</td>
</tr>
<tr>
<td>2016</td>
<td>0.666</td>
<td>0.750</td>
<td>0.738</td>
<td>0.833</td>
</tr>
<tr>
<td>Mean</td>
<td>0.605</td>
<td>0.723</td>
<td>0.728</td>
<td>0.805</td>
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</table>
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Chart 1. Mean values of energy efficiency across regions during 2003-2016.

Chart 2. Mean values of energy efficiency of eastern region during 2003-2016.

Chart 3. Energy efficiency trends in different cities.
tertiary industries are very developed, while the tertiary industry consumes less energy, so Shanghai’s energy efficiency is higher. In Guangdong Province and Fujian Province, low-energy-consuming industries such as electronics and clothing and tertiary industries are developed, so their energy consumption is low. Hainan’s tourism industry is developed, its main industry is agriculture, and its industry is relatively weak, so its energy consumption is low. The energy efficiency of Shandong Province and Hebei Province is relatively low, far below the average level, which is related to the industrial structure dominated by heavy industry.

This paper adopts the total population at the year-end in urban districts as a proxy variable at city scale. Considering the fact that many cities frequently change their administrative division of urban districts, this study used the city scale of 2016 as the criterion for classification. Based on the total population at the end of the year in urban districts, cities can be classified into three city scale grades:

1. Big cities, with a population above 2,000,000 (the largest city: Shanghai 24,197,000).
2. Medium-sized cities, with a population of 500,000-2,000,000.
3. Small cities, with a population below 500,000 (the smallest city is Shenlongjia, with 76,700).

Among all city samples, there are 45 big cities, 189 medium-sized cities, and 51 small cities.

According to Chart 3 (different from the regional analysis), urban energy efficiency of different scales has two turning points during the sample study period, namely 2005 and 2011. The energy efficiency of these two years is relatively low. Overall, big cities have the highest average energy efficiency, while medium and small cities have lower and similar energy efficiency.

### Spatial Econometrics Test and Analysis

GeoDa software developed by Luc Anselin was used to measure the global Moran I index and the test values of the energy efficiency of China during 2003-2016. According to the test, during the investigated period, the global Moran I statistics of the energy efficiencies of Chinese cities all remained positive and passed the significance test of 1%, thus rejecting the original hypothesis of the absence of spatial autocorrelation in the energy efficiencies of cities. This suggests that the spatial distributions of energy efficiencies of Chinese cities is not random, but rather that it shows an obvious characteristic of spatial agglomeration, i.e., cities of close energy efficiencies are usually adjacent to each other.

In China, the minimum “threshold distance” between cities is 306 km, i.e., it is possible for every city to have at least one geographically adjacent city only when the distance between cities is no less than 306 km. Consequently, this paper calculates both the Moran I index and statistical test values of the energy efficiency of China during 2003-2016 under a distance range of 350-1,100 km (see Table 2). As indicated by the obtained results, the spatial correlation of the energy efficiencies of Chinese cities weakened gradually with increasing geographical distance, and as the distance exceeded 1,110 km, the spatial correlation was no longer significant. This not only indicates that the spatial correlation of China’s energy efficiency conforms to

### Table 2. The change of Moran I index of energy efficiency with geographic distance in China.

<table>
<thead>
<tr>
<th>Year</th>
<th>(0-350) km</th>
<th>(0-500) km</th>
<th>(0-650) km</th>
<th>(0-800) km</th>
<th>(0-950) km</th>
<th>(0-1100) km</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>0.165***</td>
<td>0.118***</td>
<td>0.065***</td>
<td>0.027***</td>
<td>0.007**</td>
<td>-0.023</td>
</tr>
<tr>
<td>2004</td>
<td>0.177***</td>
<td>0.147***</td>
<td>0.088***</td>
<td>0.046***</td>
<td>0.014***</td>
<td>-0.005</td>
</tr>
<tr>
<td>2005</td>
<td>0.190***</td>
<td>0.157***</td>
<td>0.101***</td>
<td>0.064***</td>
<td>0.016***</td>
<td>-0.035</td>
</tr>
<tr>
<td>2006</td>
<td>0.197***</td>
<td>0.154***</td>
<td>0.121***</td>
<td>0.087***</td>
<td>0.034**</td>
<td>-0.035</td>
</tr>
<tr>
<td>2007</td>
<td>0.202***</td>
<td>0.158***</td>
<td>0.080***</td>
<td>0.065***</td>
<td>0.067**</td>
<td>-0.004</td>
</tr>
<tr>
<td>2008</td>
<td>0.217***</td>
<td>0.158***</td>
<td>0.077***</td>
<td>0.065***</td>
<td>0.054**</td>
<td>-0.007</td>
</tr>
<tr>
<td>2009</td>
<td>0.219***</td>
<td>0.157***</td>
<td>0.067***</td>
<td>0.045***</td>
<td>0.065**</td>
<td>-0.025</td>
</tr>
<tr>
<td>2010</td>
<td>0.225***</td>
<td>0.164***</td>
<td>0.101***</td>
<td>0.076***</td>
<td>0.087**</td>
<td>-0.018</td>
</tr>
<tr>
<td>2011</td>
<td>0.230***</td>
<td>0.187***</td>
<td>0.105***</td>
<td>0.064***</td>
<td>0.098**</td>
<td>-0.006</td>
</tr>
<tr>
<td>2012</td>
<td>0.241***</td>
<td>0.201***</td>
<td>0.157***</td>
<td>0.123***</td>
<td>0.108***</td>
<td>-0.014</td>
</tr>
<tr>
<td>2013</td>
<td>0.265***</td>
<td>0.213***</td>
<td>0.165***</td>
<td>0.132***</td>
<td>0.095***</td>
<td>-0.008</td>
</tr>
<tr>
<td>2014</td>
<td>0.254***</td>
<td>0.232***</td>
<td>0.203***</td>
<td>0.165***</td>
<td>0.123**</td>
<td>-0.010</td>
</tr>
<tr>
<td>2015</td>
<td>0.234***</td>
<td>0.201***</td>
<td>0.185***</td>
<td>0.134***</td>
<td>0.103**</td>
<td>-0.003</td>
</tr>
<tr>
<td>2016</td>
<td>0.265***</td>
<td>0.221***</td>
<td>0.212***</td>
<td>0.176***</td>
<td>0.123**</td>
<td>-0.001</td>
</tr>
</tbody>
</table>

Note: *, **, *** represent significance levels of 10%, 5%, and 1% respectively.
The Moran scatter diagram further demonstrates that the “H-H” type provinces in the first quadrant were mostly located on the eastern coast of China and in other economically developed areas. These areas benefit from favorable locations, abundant labor resources, stronger economies and advanced levels of technology, meaning that their levels of energy efficiency are relatively high. Meanwhile, through the spatial spillover effect, they had a knock-on effect on the surrounding regions, thus driving the growth of energy efficiency in the latter. For example, in the diagram, Shanghai, Jiangsu and Zhejiang lie in the first quadrant. Their energy efficiency levels can be seen to be high, as are those of their neighboring regions, Anhui, Fujian and Jiangxi. In contrast, the “L-L” type provinces in the third quadrant are mostly located in the central and western regions. These areas have less advanced technological levels, weaker economies, scarce labor resources and other disadvantages, meaning that their levels of energy efficiency are not high. Moreover, the energy efficiency levels of their neighboring provinces are also low. For example, Shaanxi and Gansu lie in the third quadrant. Their energy efficiency levels are lower, as is the energy efficiency of their neighboring provinces, Qinghai and Ningxia.

With regard to the “L-H” type provinces in the second quadrant, their energy efficiency is at a lower level, while the energy efficiency of their neighboring provinces is at a higher level. For example, the energy efficiency of Shandong is at a lower level, while that of its surrounding provinces, Jiangsu and Anhui, is at a higher level. Similarly, the energy efficiency of Guangxi is at a lower level, while that of its surrounding provinces, Guangdong and Hunan, is at a higher level. In terms of the “H-L” type provinces in the fourth quadrant, their energy efficiency is at a higher level, while the energy efficiency of their neighboring provinces is at a lower level. For example, the energy efficiency of Heilongjiang is at a higher level, while that of its neighboring region, Inner Mongolia, is at a lower level.

Sample Regression on a National Scale

This paper determines whether spatial econometrics should adopt the spatial lag model (SLM) or the spatial error model (SEM) by comparing Lagrange multipliers and their robustness. According to the obtained test results, the SLM-LM value was 154.54 (p-value = 0.000), which is larger than the SEM-LM value of 78.34; correspondingly, the SLM-RLM value was 77.33, which is also larger than the SEM-RLM value; furthermore, the Robust-LMLAG was significant while the Robust-LMERR was not significant; therefore, a more reasonable approach is to adopt the SLM model. Moreover, the model selects a fixed effect. Furthermore,
In particular, in circumstances where the policy effect local energy policies can reduce decision-making cost. of adjacent cities as benchmarks for the formulation of efficiency; on the other hand, adopting energy policies energy policies strengthens the convergence of energy the energy factor, and the inter-governmental game over local governments must impose strategic control over for the expansion of trade or for the attraction of funds, reason for this can, on the one hand, be found because the spatial spillover effect of energy efficiency [55]. The passed the significance test at 1%, thus verifying the lag regression coefficient $\rho$ was positive, which also activities of this stage or several lag stages. The spatial capital, and other factors, and will act on the economic and accumulation will doubtlessly be manifested through technological level, economic development, human and dynamic economic system, preliminary preparation suggests that, as far as the energy system is a continuous temporal dynamic effect of energy efficiency. This also estimation to conduct all parameter estimation.

As listed in Table 3, the regression coefficient $\tau$ of the first-order lag term of energy efficiency was positive and passed the significance test at 1%, thus verifying the temporal dynamic effect of energy efficiency. This also suggests that, as far as the energy system is a continuous and dynamic economic system, preliminary preparation and accumulation will doubtlessly be manifested through technological level, economic development, human capital, and other factors, and will act on the economic activities of this stage or several lag stages. The spatial lag regression coefficient $\rho$ was positive, which also passed the significance test at 1%, thus verifying the spatial spillover effect of energy efficiency [55]. The reason for this can, on the one hand, be found because for the expansion of trade or for the attraction of funds, local governments must impose strategic control over the energy factor, and the inter-governmental game over energy policies strengthens the convergence of energy efficiency; on the other hand, adopting energy policies of adjacent cities as benchmarks for the formulation of local energy policies can reduce decision-making cost. In particular, in circumstances where the policy effect is not yet clear, mutual imitation of energy policies by various cities usually results in the convergence of technical standards on energy [56]. In this scenario, no investigation about the influencing factors of energy efficiency can afford to neglect the influence of either dynamic effect or spatial spillover effect.

The coefficient of the agglomeration of the manufacturing sector was significantly negative, while its quadratic term coefficient was not significant, suggesting that the agglomeration of the manufacturing sector significantly reduced the energy efficiencies of cities [57-58]. The likely explanation as given by this paper is as follows: First, in China, the agglomeration of the manufacturing sector is in many cases a governmentally induced industrial agglomeration, which can hardly induce a spatial spillover of knowledge or technology in the strict sense; instead, intense homogeneous competition among manufacturing enterprises in the same region frequently induces repeated construction, blind investment, energy waste, and excess capacity, thus making it impossible to introduce or even inhibit the positive influence of the agglomeration of the manufacturing sector on energy efficiency. Second, faced by the intense homogenous

Table 3. Regression estimation results on a national scale.

<table>
<thead>
<tr>
<th>Variable</th>
<th>model (1)</th>
<th>model (2)</th>
<th>model (3)</th>
<th>model (4)</th>
<th>model (5)</th>
<th>model (6)</th>
<th>model (7)</th>
</tr>
</thead>
<tbody>
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<td>$\tau$</td>
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<td>0.154***</td>
<td>0.160***</td>
<td>0.164***</td>
<td>0.158***</td>
<td>0.167***</td>
<td>0.155***</td>
</tr>
<tr>
<td></td>
<td>[3.898]</td>
<td>[4.143]</td>
<td>[4.190]</td>
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<td>[4.322]</td>
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<td>[5.031]</td>
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<tr>
<td>$\ln\text{magg}$</td>
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<td>-0.038***</td>
<td>-0.030***</td>
<td>-0.030***</td>
<td>-0.030***</td>
<td>-0.030***</td>
<td>-0.030***</td>
</tr>
<tr>
<td>$\ln\text{paagg}$</td>
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<td>-0.012</td>
<td>-0.012</td>
<td>-0.008</td>
<td>-0.008</td>
<td>-0.008</td>
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<td>[-0.054]</td>
<td>[-0.054]</td>
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<td>[-0.046]</td>
<td>[-0.046]</td>
<td>[-0.046]</td>
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<tr>
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<td>0.016*</td>
<td>0.016*</td>
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<td>0.019*</td>
<td>0.019*</td>
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<td>[1.870]</td>
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<td>[1.777]</td>
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<tr>
<td>$\ln\text{coaagg}$</td>
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<td>-0.032</td>
<td>-0.032</td>
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<td>-0.026</td>
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<td>0.032***</td>
<td>0.032***</td>
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<td>0.028</td>
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<td>[0.103]</td>
<td>[0.098]</td>
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<tr>
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<td>0.015***</td>
<td>0.014***</td>
<td>0.017***</td>
<td>0.019***</td>
<td>0.017***</td>
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<tr>
<td></td>
<td>[5.045]</td>
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<td>[3.909]</td>
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<tr>
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<td>0.018***</td>
<td>0.015***</td>
<td>0.018***</td>
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<td>-0.087***</td>
<td>-0.078***</td>
<td>-0.069***</td>
<td>-0.058***</td>
<td>-0.062***</td>
<td>-0.053***</td>
</tr>
<tr>
<td>$\rho$</td>
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<td>0.123***</td>
<td>0.126***</td>
<td>0.135***</td>
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<td>[4.782]</td>
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<td>$\log L$</td>
<td>2545.66</td>
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<td>2450.12</td>
<td>2428.26</td>
</tr>
</tbody>
</table>

Note: *, **, *** represent significance levels of 10%, 5% and 1%, respectively; the square brackets are $t$-statistics.
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competition, manufacturing enterprises in industrial agglomeration belts typically resort to a development pattern characterized by low technical content, high energy consumption, and high pollution emission, which not only consumes considerable amounts of energy and causes environmental pollution, but also results in low added value and profit rate of products, thus further decreasing energy efficiency.

The coefficient of the agglomeration of the producer service sector was significantly positive; however, its quadratic term coefficient was not significant, suggesting that the agglomeration of the producer service sector significantly increased the energy efficiencies of cities [59]. The results showed that producer services agglomeration Jacobs externalities not only contribute significantly to enhance energy efficiency in the region, but also obvious spatial spillover effect on the surrounding area, and producer services agglomeration MAR externalities only enhance energy efficiency in the region. The reason for this is that the development of the agglomeration of the service sector, especially that of the producer service sector, can effectively reduce energy consumption, energy redundancy, and pollutant emission of high-energy consuming and high-pollution emitting industries of the secondary industrial sector, suggesting that industrial restructuring ("reducing the secondary industry, while promoting the tertiary industry") or inter-industry substitution effect (substituting the service sector for the manufacturing sector) helped to increase energy efficiency.

The coefficient of the co-agglomeration of the manufacturing sector and the producer service sector was significantly positive, while its quadratic term coefficient was not significant, suggesting that such co-agglomeration facilitated the increase of energy efficiencies of cities. This is because in cities with a relatively high co-agglomeration degree, the agglomeration of the manufacturing sector effectively drives the rapid development of the producer service sector through producer service demands. In turn, the agglomeration of the producer service sector has promoted the transformation and upgrading of the manufacturing sector via technical R&D, specialized division of labor, and technological spillover. As a result, the achieved coordinated development of both manufacturing sector and the producer service sector further promotes the increase of energy efficiency. The influence coefficient of co-agglomeration was higher than that of the agglomeration of the producer service sector, suggesting that, although "reducing the secondary industry, while promoting the tertiary industry" represents the future developmental trend of industrial restructuring, close attention should still be focused on the synergism between the agglomeration of the manufacturing sector and the agglomeration of the producer service sector over the course of industrial restructuring.

From the perspective of control variables, human capital, infrastructure, and technological innovation all facilitated an increase of energy efficiency [60], which is consistent with the theoretical expectation of this paper. Government intervention exerted a significantly negative influence on energy efficiency, indicating that government interference with economic activities may twist the dominant role of the market in resource allocation and make it impossible for the energy factor to exert its maximum utility [61-62]. The influence of the energy price on energy efficiency was not significant, which is inconsistent with the theoretical expectation. A likely explanation is that excessive government interference with the energy price results in both a low level and inflexibility of the energy price, which hinders the reasonable allocation and effective utilization of the energy factor.

Sample Regression on Different City Scales

In order to conduct a study of the spatial distribution characteristics of the urban system, this paper used the spatial statistical analysis toolbox in ArcGIS 9.3 software developed by Environmental Systems Research Institute to calculate and obtain R statistics of all the cities, and cities of different scales, in 2003, 2005, 2010 and 2016, at a significance level of 0.05. Table 4 shows that during 2003-2016, these Chinese cities displayed an overall trend of agglomeration distribution, with an increasing degree of agglomeration. At the same time, very large gaps can be observed between the scales of the different cities, alongside major differences in the intensity and scope of the impact of all cities, in turn generating significant differences in the spatial distribution of cities of different scales. Large cities can be seen to contain the mode of random distribution, while medium-sized and small cities clearly present an agglomeration distribution mode. Moreover, the cities’ agglomeration intensity is seen to decrease with the increase of urban size given that, with an increase in urban size, the repulsive

**Table 4. Spatial distribution pattern and R index of urban China from 2003 to 2016.**

<table>
<thead>
<tr>
<th>Year</th>
<th>Large cities</th>
<th>Medium cities</th>
<th>Small cities</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>0.9565 (random)</td>
<td>0.7434 (agglomeration)</td>
<td>0.7240 (agglomeration)</td>
</tr>
<tr>
<td>2005</td>
<td>0.9432 (random)</td>
<td>0.6653 (agglomeration)</td>
<td>0.6986 (agglomeration)</td>
</tr>
<tr>
<td>2010</td>
<td>0.9113 (random)</td>
<td>0.6434 (agglomeration)</td>
<td>0.6454 (agglomeration)</td>
</tr>
<tr>
<td>2016</td>
<td>0.7545 (agglomeration)</td>
<td>0.6375 (agglomeration)</td>
<td>0.6365 (agglomeration)</td>
</tr>
</tbody>
</table>
Table 5. Regression estimation results on different city scales.

<table>
<thead>
<tr>
<th>Variable</th>
<th>big cities</th>
<th>medium-sized cities</th>
<th>small cities</th>
</tr>
</thead>
<tbody>
<tr>
<td>t</td>
<td>0.143***</td>
<td>0.148***</td>
<td>0.150***</td>
</tr>
<tr>
<td></td>
<td>[4.809]</td>
<td>[4.058]</td>
<td>[4.651]</td>
</tr>
<tr>
<td>Lnmagg</td>
<td>0.035***</td>
<td>0.033***</td>
<td>-0.024**</td>
</tr>
<tr>
<td></td>
<td>[4.656]</td>
<td>[4.908]</td>
<td>[-2.157]</td>
</tr>
<tr>
<td>(Lnmagg)^2</td>
<td>0.008***</td>
<td>0.007***</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>[4.232]</td>
<td>[4.127]</td>
<td>[-0.243]</td>
</tr>
<tr>
<td>Lnnaagg</td>
<td>0.026***</td>
<td>0.022***</td>
<td>0.016</td>
</tr>
<tr>
<td></td>
<td>[5.656]</td>
<td>[5.109]</td>
<td>[-0.003]</td>
</tr>
<tr>
<td>(Lnnaagg)^2</td>
<td>-0.003</td>
<td>-0.003</td>
<td>0.016</td>
</tr>
<tr>
<td></td>
<td>[-0.098]</td>
<td>[-0.065]</td>
<td>[-0.098]</td>
</tr>
<tr>
<td>LnEDU</td>
<td>0.009***</td>
<td>0.010***</td>
<td>0.008**</td>
</tr>
<tr>
<td></td>
<td>[4.445]</td>
<td>[4.431]</td>
<td>[3.889]</td>
</tr>
<tr>
<td>LnINFRO</td>
<td>0.012***</td>
<td>0.009***</td>
<td>0.011***</td>
</tr>
<tr>
<td></td>
<td>[4.898]</td>
<td>[3.875]</td>
<td>[4.666]</td>
</tr>
<tr>
<td>LnINNO</td>
<td>0.134***</td>
<td>0.139***</td>
<td>0.133***</td>
</tr>
<tr>
<td></td>
<td>[5.113]</td>
<td>[5.213]</td>
<td>[4.709]</td>
</tr>
<tr>
<td>LnGOV</td>
<td>-0.056***</td>
<td>-0.065***</td>
<td>-0.054**</td>
</tr>
<tr>
<td>ρ</td>
<td>0.134***</td>
<td>0.143***</td>
<td>0.133***</td>
</tr>
<tr>
<td></td>
<td>[4.165]</td>
<td>[4.321]</td>
<td>[4.197]</td>
</tr>
<tr>
<td>logL</td>
<td>2655.32</td>
<td>2587.03</td>
<td>25766.54</td>
</tr>
</tbody>
</table>

Note: *, **, *** represent significance levels of 10%, 5% and 1%, respectively; the square brackets are t statistics.
interaction between cities also keeps increasing. The
decrease of agglomeration intensity is conducive to
obtaining sufficient population resources and various
environmental resources, guaranteeing the city’s relative
stability and dominant position.

The test results of the spatial econometrics model
support the selection of the SLM model and the fixed
effect (Table 5).

Comparing different city scale grades with regard
to the regression coefficient τ of the first-order lag
term of energy efficiency shows that the τ of big
cities was higher than that of both small and medium-
sized cities. This is mainly because, in comparison to
small and medium-sized cities, big cities have a higher
economic development level, technical level, and human
capital level; furthermore, the development of these
economic factors requires preliminary preparation and
accumulation as a basis, and as a result, the increase
of energy efficiencies of big cities relies heavily on
preliminary related factors.

Different city scale grades showed significant
differences in their regression results of industrial
agglomeration. For big cities, the linear term
coefficient of the manufacturing sector agglomeration
was significantly positive, while its quadratic term
coefficient was significantly negative, suggesting that
the agglomeration of the manufacturing sector created a
congestion effect in big cities; furthermore, the influence
of the agglomeration of the manufacturing sector on
energy efficiency presented a threshold value for big
cities. According to the obtained regression results, the
number of cities above such a “threshold value” was
32, which accounted for 71% of the sample volume,
indicating that a considerable portion of big cities
completed their transition of the agglomeration of the
manufacturing sector from the agglomeration effect to
the congestion effect, and thus energy efficiency would
be more significantly inhibited. The agglomerations
of the producer service sector and co-agglomeration
both exerted positive influences on energy efficiency;
however, the influence coefficient of co-agglomeration
was larger than that of the agglomeration of the producer
service sector. This is consistent with the conclusion
drawn with regard to nationwide samples. This
indicates that the industrial development of big cities
should follow a coordinated development between the
manufacturing sector and the producer service sector.

For medium-sized cities, agglomeration of the
manufacturing sector significantly inhibited the increase
of energy efficiency without creating a congestion effect.
This is closely related to the emphasis on
resource-intensive manufacturing industries and the low
technical level and intense homogeneous completion of
the manufacturing sector of medium-sized cities. Both
the agglomeration of the producer service sector and the
co-agglomeration exerted a negative influence on energy
efficiency in medium-sized cities; however, they failed
to pass the significance test. Combined with the analysis
of the preceding part of this paper, the development
of the producer service sector is relatively extensive
in medium-sized cities and dominated by low-end
producer service industries; furthermore, medium-sized
cities are different from large-sized cities in this regard,
because the latter have shifted to a development pattern
dominated by high-end producer service industries. This
indicates that the industrial development of medium-
sized cities should focus on high-end producer service
industries and, consequently, efforts should be made
to introduce their role in increasing energy efficiency
based on promoting the transformation and upgrading of
the manufacturing industry.

For small cities, the agglomeration of the
manufacturing sector significantly increased energy
efficiency, mainly because the development of the
secondary industry was still in its growth stage in
small cities. Furthermore, industrial agglomeration
increased the efficiency of energy resources allocation
via knowledge spillover, resource recycling, and
environmental facility resource sharing. Both the
agglomeration of the producer service sector and co-
agglomeration exerted a positive influence on energy
efficiency in small cities, mainly because small cities
were dominated by the manufacturing sector and had
higher demand for the producer service sector. As a
result, this agglomeration of the producer service sector
significantly promoted an increase of energy efficiency.
Thus, as far as small cities are concerned, and based on
the preferential development of the manufacturing sector
(especially labor-intensive manufacturing industries),
efforts should be made toward gradually driving the
development of the producer service sector.

Conclusions

This paper first introduces a non-separable hybrid
DEA model that considers undesirable output to measure
the energy efficiencies of 285 prefecture or higher-level
cities in China during 2003-2016. Then a dynamic
spatial panel model is used to investigate the influence
of different types of industrial agglomerations and
agglomeration modes on energy efficiency. According to
the obtained study results, for the investigation period
the overall energy efficiency of China with regard to
pollutants remained at a low level and presented a
“U-shaped” decreasing-increasing trend. To be specific,
China’s energy efficiency distribution presented a trend
of “high in the east and low in the west.” The energy
efficiency of east China changed relatively gently, while
the energy efficiencies of central China and west China
changed dramatically. China’s energy efficiency also
presented a significant spatial agglomeration effect, i.e.,
cities with close energy efficiencies are usually adjacent
to each other. At the national level, agglomeration
of the manufacturing sector significantly inhibited
the increase of energy efficiency; the agglomeration
of the producer service sector and the co-agglomeration
of the manufacturing sector and the producer service
sector both facilitated an increase of energy efficiency. The influence of industrial agglomeration on energy efficiency differed across different city scale grades. For big cities, the agglomeration of the manufacturing sector created a congestion effect; the agglomerations of the producer service sector and co-agglomeration both exerted positive influences on energy efficiency; however, the influence coefficient of co-agglomeration was larger than that of the agglomeration of the producer service sector. For medium-sized cities, agglomeration of the manufacturing sector significantly inhibited the increase of energy efficiency without creating a congestion effect. Both the agglomeration of the producer service sector and the co-agglomeration exerted a negative influence on energy efficiency in medium-sized cities; however, they failed to pass the significance test. For small cities, the agglomeration of the manufacturing sector significantly increased energy efficiency. Both the agglomeration of the producer service sector and co-agglomeration exerted a positive influence on the energy efficiency in small cities. Based on these conclusions, the paper proposes the following policy implications:

1) Make full use of the energy saving and emission reduction effect of agglomeration.
2) Accelerate the optimization of industrial layout.
3) Develop a high-end service industry and a productive service industry.
4) Create an agglomeration environment that encourages benign industrial competition.

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Conflict of Interest

The authors declare no conflict of interest.

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