Scholar Publishing Group
International Journal of Social Sciences and Economic Management
https://doi.org/10.38007/IJSSEM.2023.040214
ISSN 2789-715X Vol. 4, Issue 2: 108-118

Research on the Efficiency Evaluation of Green Transformation of Resource-based Cities in China under the Goal of "Carbon Neutrality"

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Keywords: "Carbon Neutral" Goal, Resource-Based City, Green Transformation, Efficiency Evaluation

Abstract: Resource-based cities provide a large amount of natural resources for national economic construction, but they are faced with problems such as resource depletion and environmental pollution, so they must carry out green transformation and upgrading to achieve sustainable development. In this paper, the green transformation efficiency of typical resource-based cities in China is evaluated and studied in the context of "carbon neutrality". Firstly, this paper explains and determines the main influencing factors of green transformation of resource-based cities, constructs the evaluation index system of green transformation, and divides the transformation levels. Secondly, an evaluation model considering the non-expected output is established to conduct an empirical evaluation of the green transformation efficiency of 17 typical resource-based cities in China to test the scientificity and feasibility of the evaluation system constructed. The results show that the dual effects of low-carbon technology progress and environmental control policies can promote the green transformation of resource-based cities, and the superposition of the two effects makes the funds more inclined to the field of technological innovation and concentrate on green industries, which effectively promotes the growth of green economy of resource-based cities.

1. Introduction

Resource-based cities have been rich in natural resources, in the process of urban economic development to obtain the priority of development of the foundation, to provide a large number of natural resources for the national economic construction, to social development has made an important contribution [1]. However, as time goes by, resource-based cities also have a series of problems such as exhaustion of natural resources, serious environmental pollution, weak economic development, unreasonable industrial structure and low social welfare benefits due to excessive exploitation and demand of natural resources, which seriously affect the further development of regional economy [2-3]. With the concept of green economy, environmentally friendly city and environmentally friendly low-carbon technology attracting more and more attention and attention, the economic development direction of resource-based cities is gradually changing from relying on resource consumption to green environmental protection and energy saving [4]. Especially in the current situation where the concept of ecological society and green development is dominant, the green transformation of resource-based cities has become the focus of scholars [5-7].

About the transformation of resource-based cities, domestic and foreign scholars have conducted a lot of research, mainly involving the transformation of resource-based cities, transformation efficiency [8], transformation approach [9], transformation mechanism [10], transformation direction [11], transformation stage [12] and other issues [13-15]. These studies have obtained rich results and experience, which is of great significance for traditional resource-based cities to improve the level of existing industries, optimize the industrial structure, and accelerate the formation of new and efficient economic models. However, few studies have examined the effect of the transformation of resource-based cities from the perspective of green transformation, and few research results have established a multi-dimensional thinking framework of green transformation based on resource-based cities. Therefore, based on the goal of "Carbon neutrality", this paper evaluates the efficiency of green transformation of typical resource-based cities in China.

2. The Influencing Factors of Green Transformation of Resource-Based Cities

The influencing factors of green transformation of resource-based cities involve many levels, and this paper believes that the main influencing factors are reflected in the following aspects.

2.1. Resource Type

Constrained by the physical characteristics of resources and the existing processing technology, the difficulty and complexity of green transformation of different types of resources are different, and different technical characteristics have correspondingly derived differentiated leading industrial clusters and extended industrial chains in the field of urban economy. The difference of resource type affects the difficulty of urban green transformation to some extent, while the difference of vertical extension and horizontal expansion ability of the leading industrial chain caused by resource endowment has different impacts on the green transformation of resource-based cities.

2.2. Life Cycle of Resource Industry

Due to the non-renewable and exhaustible nature of natural resources such as coal and oil, the industries dominated by them will inevitably decline after experiencing the initial and mature stages due to touching the red line of resource stocks. Generally speaking, from the perspective of the life cycle of the resource industry, the closer to the recession period, the more resource-based cities need to bear higher costs and the greater the risk of green transformation.

2.3. Technological Innovation Level

On the one hand, technological innovation can improve the production efficiency and resource use efficiency, and promote the evolution of resource cities to the economic model of reduction and recycling. On the other hand, technological innovation can accelerate the research and development and commercial application of renewable energy, and reduce the dependence of resource-based cities on resources.

2.4. Environmental Regulation Intensity

Compared with other functional cities, resource-based cities generally have the lowest degree of resource utilization and environmental protection due to their easy and cheap access to resources, and environmental regulation can be a "driver" and "regulator" for the green transformation of resource-based cities. Strict environmental regulations will bring about low-carbon improvement of production technology and improvement of production management methods. The most direct manifestation is the increase in the number of waste reuse in the production process, the improvement of water quality and air quality around industrial production areas, and the gradual reduction of the impact on surrounding residents, and ultimately promote the transformation of the city from the original high pollution and high consumption to low pollution and low consumption.

3. Green Transformation Efficiency Evaluation System for Resource-Based Cities

3.1. Selection of Evaluation Indicators

Based on the influencing factors of the green transformation of resource-based cities, the green transformation evaluation of resource-based cities can be summarized into four dimensions: economic green transformation, social green transformation, environmental green transformation and policy green transformation, and the four dimensions are further subdivided into several measurement indicators, as shown in Table 1, to evaluate the efficiency of the transformation of resource-based cities into low-energy cities.

Table 1: Evaluation index system of green transformation efficiency of resource-based cities

Target layer	Dimension level	Index level
Efficiency evaluation index of green transformation of resource city	Economic green transformation	Per capita GDP
		Intensity of R&D expenditure
		The proportion of value-added of tertiary industry to GDP
		The contribution rate of high-tech industry to industry
		Energy consumption per unit of GDP
	Social green transformation	Surveyed urban unemployment rate
		Engel coefficient
		Proportion of green consumption expenditure
		Proportion of green buildings
	Environmental green transformation	The proportion of environmental protection input in GDP
		Air quality up to standard rate
		Water quality up to standard rate
		Comprehensive treatment rate of industrial solid waste
		Mine reclamation rate
	Policy green	Low carbon policy perfection

	transformation	Low carbon policy effectiveness
		Low carbon publicity and education popularization rate

3.2. Classification of Efficiency Levels

In order to more accurately describe the phased characteristics of green transformation of resource-based cities, it is also necessary to divide the efficiency of urban transformation into several stages. In this paper, the efficiency level of resource-based cities' green transformation is divided into five levels: Ⅰ, Ⅱ, Ⅲ, Ⅳ and Ⅴ. The comprehensive evaluation efficiency value of each level has a different value range, as shown in Table 2.

Table 2: Efficiency classification of green transformation in resource-based cities

Level	Efficiency value range	Stage
Ⅰ	[0, 0.5)	Low
Ⅱ	[0.5, 1.0]	Primary
Ⅲ	(1.0, 1.5]	Intermediate
Ⅳ	(1.5, 2.0]	Advanced
Ⅴ	(2.0, ∞)	Ideal

(1) Low stage. When the comprehensive evaluation efficiency value of green transformation of resource-based cities is less than 0.5, it indicates that the effect of green transformation of the city is not ideal and is in a low stage. At this stage, the city's economic and social resource system has not been reasonably low-carbon planning and distribution, the resource utilization efficiency is relatively low, and the ecological environment has not been significantly improved. At the same time, due to the insufficient use of resources, there may be negative problems such as large loss of energy consumption and carbon emissions.

(2) Primary stage. When the comprehensive evaluation efficiency of resource-based city's green transformation falls into the range of 0.5-1.0, it indicates that the city's green transformation has entered the primary stage. Although at this stage, the green development of the city has been improved to a certain extent, and some problems encountered in the process of green development have been solved to a certain extent, and the economic recession has been temporarily avoided. However, the contradiction between ecological environment and economic development is still prominent, mainly because there are still some behaviors in the pursuit of maximizing economic benefits at the cost of resource and environmental carrying capacity, resource utilization is not high, the city's energy consumption loss is still difficult to reduce, and carbon emissions need to be further regulated.

(3) Intermediate stage. When the comprehensive evaluation efficiency of green transformation of resource-based cities falls into the range of 1.0-1.5, it indicates that the green transformation of the city has entered the intermediate stage. Compared with the previous stage, in this stage, the economic development mode of the city tends to be benign, and people's ideas have changed, and they are no longer simply sacrificing the environment as the cost of development, they can consciously reduce pollution, actively find ways to improve resource utilization and improve production methods, and the carbon emission of the city has gradually decreased. However, this is far from enough. At this stage, the city's economic development is still highly dependent on resources, which restricts the city's further transformation into a low-energy city.

(4) Advanced stage. When the comprehensive evaluation efficiency of resource-based city's green transformation falls into the range of 1.5-2.0, it indicates that the green transformation of the city has entered an advanced stage, which is a necessary stage for the low-carbon development of

resource-based cities. In this stage, it means that after the accumulation of development experience in the previous stages, the green transformation of the city is basically completed, the economic development of the city is in overall coordination with the ecological environment, the allocation of resources is more reasonable, the dependence of economic development on resources is significantly reduced, and the energy consumption and carbon emissions are significantly reduced. Nevertheless, at this stage, there is still room for improvement in the economic structure and low-carbon development of cities, and there is also room for better coordination of urban economic, social and environmental systems.

(5) Ideal stage. When the comprehensive evaluation efficiency of resource-based city's green transformation falls into the range greater than 2.0, it is the ideal stage of the city's green transformation. In this stage, the city has basically achieved the goal of low-energy transformation, and the consumption of resources and carbon emissions have been reduced to a greater extent compared with the advanced stage, which has well solved the contradiction between the urban economy and resources and environment and other systems, basically got rid of the resource-dominated economic development mode, and economic operation is no longer dependent on the input of large amounts of resources. It is a healthy and harmonious city with lower energy consumption and less carbon emissions.

3.3. Efficiency Evaluation Model Based on Undesired Output

This paper combined SBM model with Malmquist-Luenberger index (ML index) to measure the green transformation efficiency of resource-based cities. In order to better and more intuitively reflect the effect of the green transformation of resource-based cities, the data to be measured in the evaluation include the ML index value and the optimal efficiency value. For the construction of the production technology frontier, resource-based cities are taken as the decision-making unit, assuming that the current number of resource-based cities is *K*, the economic production activities for each city have the equivalent of *M* kinds of inputs, and can obtain *P* kinds of undesirable output and *D* kinds of expected output.

Formula (1) represents the definition of the directional distance function based on the above assumptions. Where: β is the value of the directional distance function; g^t is the direction vector. β can be used to represent not only the negative fluctuation of undesired output, but also the positive fluctuation of expected output.

$$\overline{D}_0^t\left(x^t, y^t, u^t, g^t\right) = \sup\left\{\beta \middle| \left(y^t, u^t\right) + \beta \times g' \in T^t(x)\right\} \tag{1}$$

When $g^t = \left(g_y^t, -g_u^t\right)$, the undesirable output will gradually decrease in the direction of $-g_u^t$, but the increase in the desired output will affect it, causing it to increase. Formula (2) shows the final function definition of the directional distance function in the *t* period:

$$\overline{D}_0^t\left(x^t, y^t, u^t, g_y^t, -g_u^t\right) = \sup\left\{\beta \middle| y^t + \beta \times g_y^t, u^t \times g_u^t \in T^t(x)\right\} \tag{2}$$

Set $g^t = \left(y^t, -u^t\right)$, take the expected and unexpected outputs as the observed values, and the actual observed values are the direction vector, then the mixed direction distance function between the *t* period and the *t*+1 period is shown in Formula (3) :

$$\max \beta$$
$$s.t.\begin{cases} \sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t y_{kd}^t \geq (1+\beta) y_{kd}^{t+1}, \quad d=1,2,\Lambda\ ,D \\ \sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t u_{kp}^t = (1-\beta) u_{kp}^{t+1}, \quad p=1,2,\Lambda\ ,P \\ \sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t x_{kn}^t \leq x_{kn}^{t+1}, \quad n=1,2,\Lambda\ ,N \\ z_k^t \geq 0, \quad k=1,2,\Lambda\ ,K \end{cases} \tag{3}$$

The value of the direction vector is defined as the actual observed data in each resource-based city, and Formula (4) is used to represent the specific productivity index from the period t to t+1. In order to study the needs of the problem, the ML index is decomposed into two parts, namely, the technical progress index (TCML) and the technical efficiency index (ECML), respectively, see Formula (5) and Formula (6), ML=TCML×ECML, and the precondition of decomposition is that the return to scale remains unchanged.

$$\mathrm{ML}_t^{t+1} = \sqrt{\frac{1+\overline{D}_0^t\left(x^t, y^t, u^t, g^t\right)}{1+\overline{D}_0^t\left(x^{t+1}, y^{t+1}, u^{t+1}, g^{t+1}\right)} \times \frac{1+\overline{D}_0^{t+1}\left(x^t, y^t, u^t, g^t\right)}{1+\overline{D}_0^{t+1}\left(x^{t+1}, y^{t+1}, u^{t+1}, g^{t+1}\right)}} \tag{4}$$

$$\mathrm{TCML}_t^{t+1} = \sqrt{\frac{1+\overline{D}_0^{t+1}\left(x^t, y^t, u^t, g^t\right)}{1+\overline{D}_0^t\left(x^t, y^t, u^t, g^t\right)} \times \frac{1+\overline{D}_0^{t+1}\left(x^{t+1}, y^{t+1}, u^{t+1}, g^{t+1}\right)}{1+\overline{D}_0^t\left(x^{t+1}, y^{t+1}, u^{t+1}, g^{t+1}\right)}} \tag{5}$$

$$\mathrm{ECML}_t^{t+1} = \frac{1+\overline{D}_0^t\left(x^t, y^t, u^t, g^t\right)}{1+\overline{D}_0^{t+!}\left(x^{t+1}, y^{t+1}, u^{t+1}, g^{t+1}\right)} \tag{6}$$

In addition, the change degree of Total factor productivity (TFP) in DMU from t stage to t+1 stage can be measured by ML index. When ML index is greater than 1, TFP increases in the constructed model. When the ML index is equal to 1, TFP has not changed. Similarly, when the ML index is less than 1, TFP is reduced. In the adjacent period, the data produced by the ECML measure of each DMU will be approximated by the leading edge. When the ECML index value is greater than 1, it means that the production front is closer to a certain DMU in the t+1 period, indicating that the efficiency is constantly improving. The displacement generated by each production front surface between two time points is measured by TCML index. When the TCML index is greater than 1, it means that technological progress can simultaneously promote the positive change of expected output and the negative change of non-expected output.

4. Case Study

4.1. Data Source and Preprocessing

China is a developing resource country with numerous resource-based cities. In order to simplify the research, this paper selects 17 typical resource-based cities as the research objects based on the 118 resource-based cities that have been identified in China. The basic information of these resource-based cities is shown in Table 3. The basic data of all indicators are derived from China Urban Statistical Yearbook and China Regional Statistical Yearbook from 2014 to 2021. In the process of data preprocessing, indexes with small differences between evaluation units were excluded, and indexes with more than 90% information repetition in the same standard layer were excluded.

Table 3: Typical resource cities and their resource type

City	Type	City	Type
Fuxin	Coal mining	Dongying	Oil exploitation
Fushun	Coal mining	Puyang	Oil exploitation
Jixi	Coal mining	Zibo	Oil exploitation
Liaoyuan	Coal mining	Daqing	Oil exploitation and processing
Datong	Coal mining	Panjin	Oil exploitation and processing
Jincheng	Coal mining	Huangshi	Metal processing
Yangchuan	Coal mining	Baotou	Ferrous metal processing
Shuozhou	Coal mining	Anshan	Ferrous metal processing
Wuhai	Coal mining		

4.2. Evaluation Process and Results

Based on the data from 2013 to 2020, the ML index and the variation interval of efficiency value of each typical resource city are calculated. Then, on the basis of ML index, the TCML index and ECML index are decomposed and measured. The ML index, TCML index and ECML index values of typical resource cities during 2013-2020 are shown in Table 4, and the fluctuation changes of ML index, TCML index and ECML index are shown in Figure 1.

Table 4: Overall productivity index of typical resource cities from 2013 to 2020

Year	ML	TCML	ECML
2013-2014	0.919	0.948	0.969
2014-2015	0.952	0.978	0.973
2015-2016	1.018	1.012	1.006
2016-2017	1.060	1.063	0.997
2017-2018	1.005	0.994	1.011
2018-2019	1.037	1.024	1.013
2019-2020	1.183	1.163	1.017
Average value	1.024	1.026	0.998

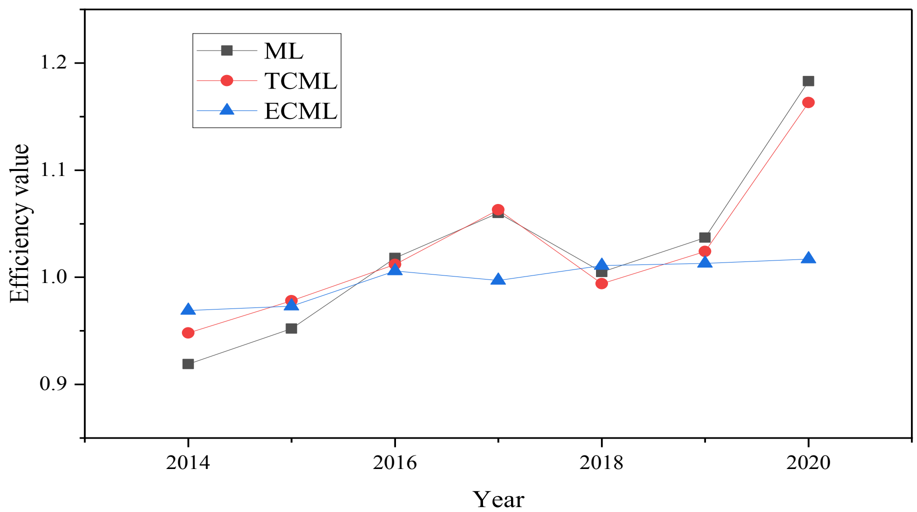

Figure 1: Overall productivity index trend of typical resource cities from 2013 to 2020

The statistical results show that under the premise of considering the non-expected output, the average annual growth rate of TFP represented by the ML index of typical resource cities from 2013 to 2020 is 2.4%, indicating that the overall green total factor productivity of these cities shows a benign development trend, that is, the green transformation has made some progress. Among them, technological progress is the main driving force of TFP improvement, TFP index increased by 2.6% on average, and the decrease of technical efficiency has a negative impact on TFP. As can be seen from Figure 1, ML index is positively correlated with TCML index, while ECML index is not significantly correlated with TCML index, which indicates that low-carbon technology progress has a relatively significant effect on the green transformation of typical resource cities, while the improvement of urban green management level has not attracted enough attention from the government, and the value has not been significantly improved.

In the period of 2015-2020, the TFP index is greater than 1, but the leading factors of its growth are different, among which the progress of low-carbon technology is the leading factor of TFP growth in 2015-2017 and 2018-2020. In 2017-2018, management efficiency improvements were the dominant factor in TFP growth. In 2019-2020, both technological progress and improved management efficiency have a positive effect on TFP, with technological progress playing a more significant role. It can be seen that TFP growth is the result of technological progress and management efficiency improvement, but its leading factors are in dynamic change. When the dominant factor is TCML, the low-carbon innovation of related industry technologies is more active, while when the dominant factor is ECML, the government is more active in the low-carbon management and leadership of related industries.

As shown in Table 5, from the perspective of spatial heterogeneity, only five typical resource cities, Jixi, Wuhai, Zibo, Panjin and Huangshi, had ML index values less than 1 from 2013 to 2020. In particular, the average increase of TFP in Daqing, Puyang, Fuxin and Jincheng is more than 7%, the increase of TFP in Datong and Yangquan is more than 5%, and the decrease of TFP in Huangshi is as high as 7%. From the perspective of the driving factors of TFP growth, the ECML index value of all cities did not increase significantly, indicating that the change of technical efficiency was not obvious, and except Jixi, Wuhai, Zibo, Panjin and Huangshi, the TCML index of most cities exceeded 1, indicating that low-carbon technology progress is the main power source of urban transformation. At the same time, it also shows that the application of low-carbon technology is the key control factor of urban decarbonization development. From the perspective of overall analysis, the vast majority of typical resource cities have seen technological progress and efficiency improvement during 2013-2020. From the perspective of urban subdivision, there are great differences in the degree of improvement among cities.

Table 5: Average productivity index of typical resource cities from 2013 to 2020 and its decomposition

City	ML	TCML	ECML
Fuxin	1.072	1.072	1.000
Fushun	1.035	1.032	1.002
Jixi	0.967	0.967	1.000
Liaoyuan	1.045	1.045	1.000
Datong	1.064	1.064	1.000
Jincheng	1.072	1.072	1.000
Yangquan	1.051	1.051	1.000
Shuozhou	1.023	1.035	0.994
Wuhai	0.962	0.962	1.000

Dongying	1.035	1.035	1.000
Puyang	1.079	1.079	1.000
Zibo	0.983	0.983	1.000
Daqing	1.084	1.076	1.003
Panjin	0.966	0.966	1.000
Huangshi	0.930	0.954	0.975
Baotou	1.027	1.027	1.000
Anshan	1.022	1.022	1.000
Average value	1.024	1.026	0.998

Based on the analysis of the changes in the initial TFP efficiency value of the green transformation of typical resource cities from 2013 to 2020, from the perspective of overall efficiency, it can be considered that these cities have steadily transited from the low stage of green transformation to the middle stage in the past eight years. Judging from the fluctuation of efficiency value, the efficiency of most cities deserves to be greatly improved, only Jixi, Zibo and Huangshi have relatively low overall efficiency value. In particular, it should be pointed out that the change characteristics of efficiency values of most typical resource cities are small range floating, rather than increasing year by year. For example, the efficiency values of Fushun and Fuxin decreased in 2015 and 2016 respectively, and Anshan showed a significant decline in 2019. The main reason is that resource-based cities need to take a series of mandatory measures in the process of low-carbon technology application and urban low-carbon regulation implementation, and these measures may have short-term adverse effects. Another example is Anshan's efficiency value growth tended to be stable before 2016. During this period, the government took relatively moderate measures on the low-carbon decoupling of the resource industry, mainly promoting the low-carbon governance of the industry from the aspects of urging enterprises to reduce pollution emissions, improving the utilization efficiency of non-renewable resources, and increasing the proportion of renewable energy use. In 2017, Anshan decided to dismantle the high-pollution and high-emission cement enterprises as a whole, and in 2019, it closed all the iron and steel soil roasting kiln enterprises as a whole, which made its efficiency value drop significantly in these two years.

5. Conclusions

In this paper, some typical resource-based cities in China are selected as research objects, and panel data is used to explore the spatio-temporal heterogeneity of their green transformation. In the case of non-expected output, the DEA-SBM model is adopted to measure the total factor productivity of resource-based cities in green transformation, and the TFP measurement model and efficiency value are used to measure and evaluate the transformation effect evaluation stage. The results show that:

On the whole, during the study period, the green TFP of typical resource cities showed a benign development trend, and the main source of TFP increase was technological progress, that is, the adoption of low-carbon technology, the renewal of machinery and equipment and other technological innovation means can effectively promote the growth of low-carbon economy. However, a small decline in technical efficiency determined by the level of factor allocation has a negative effect on TFP growth, indicating that cities are still lacking in low-carbon governance and emission reduction measures. From the perspective of spatial heterogeneity, resource-based cities show different changes in TFP and efficiency values in both vertical and horizontal dimensions, which is mainly due to the dual effects of low-carbon technology progress and environmental regulation policies. That is, on the one hand, funds are more inclined to the field of technological innovation and more concentrated in low-carbon industries, thus promoting TFP growth. On the other hand, due to short-term adverse governance, the economic capacity of the city will be temporarily reduced. However, from an overall perspective, compared with the beginning, the TFP growth and efficiency value of all resource-based cities in the later period are significantly improved, which indicates that reducing pollution emissions, actively developing green and sustainable energy alternatives, promoting low-carbon technology innovation and improving energy utilization efficiency have a long-term positive impact on the green transformation of resource-based cities and their total factor productivity growth.

Funding

This work is supported by the Humanities and Social Science Research Project of Hebei Education Department, China (Project No. SQ2022012).

Data Availability

Data sharing is not applicable to this article as no new data were created or analysed in this study.

Conflict of Interest

The author states that this article has no conflict of interest.

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