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Measuring and Analyzing the Efficiency of Low-Carbon Technology Innovation in China

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Abstract: The economic growth realized under the rugged development mode has led to serious resource consumption and environmental pollution problems, and the traditional high energy consumption and low efficiency development mode is contrary to the international economic background that advocates the concept of green development nowadays, and this kind of economic development mode at the expense of natural resources and the environment makes China's high-quality development stagnate. And realizing China's economic development through technological innovation is a strategic tool that China has always used. Low-carbon technological innovation, as the key to achieving the dual-carbon goal, is of great significance for China to realize sustainable development. Based on this background, this paper takes low-carbon technological innovation and measures the efficiency of low-carbon technological innovation in China from 2011 to 2021 through the SBM-Malmquist model with unintended output, to measure the results based on the analysis of the current situation of low-carbon technological innovation in the country and the region, and found that despite the fluctuations in the average annual efficiency value, China's low-carbon technological innovation as a whole shows an upward trend, but there are large regional differences in China's low-carbon technological innovation.

The research results reflect the problems of low-carbon technological innovation in China, enrich the research results of low-carbon technological innovation, and provide some insights into the realization of sustainable development in China.

Keywords: Low-Carbon Technology Innovation Efficiency; SBM-Malmquist; Sustainable Development

1. Introduction

Since the reform and opening up, China's economy has developed vigorously and improved significantly in terms of scale and quality, but the economic growth brought about at the expense of the environment in the past has made the contradiction between economic development and environmental protection increasingly obvious. The environmental pollution brought about has hindered the process of sustainable development in China. Technological innovation is of key significance to China's economic development, but with the proposal of the dual-carbon goal, in the international context of advocating environmental awareness, traditional technological innovation can not support the sustainable development of the manufacturing industry, and low-carbon technological innovation compared to traditional technological innovation, pay more attention to the consumption of resources and environmental protection, the positive externality characteristics of low-carbon technology can effectively solve the contradiction between economic development and environmental protection, and low-carbon technology brought by the environmental pollution is increasingly obvious. Low-carbon technology has positive externalities, which can effectively solve the contradiction between economic development and environmental protection, and the positive environmental benefits brought by low-carbon technology can effectively reduce carbon emissions and resource consumption. Low-carbon technological innovation can not only make the production process detached from the previous excessive dependence on factors of production such as labor, capital and capital, but also alleviate the environmental pollution brought by the past rough development mode.

2. Materials and Methods

Existing literature on low-carbon technological innovation mainly focuses on the following three aspects: low-carbon technological innovation and environmental regulation, low-carbon technological innovation and carbon emissions, and low-carbon technological innovation and low-carbon city construction.

2.1 Low carbon technology innovation and environmental regulation

Bai Ke (2023) [1] empirically analyzes the transmission mechanism of environmental regulation affecting industrial green factor productivity and studies the threshold benefit of low-carbon technological innovation, which shows that environmental regulation not only has a direct impact on industrial green total factor productivity, but also indirectly promotes industrial green total factor productivity by improving the level of low-carbon technological innovation. Sun Jia (2023) [2]studied the impact of environmental regulation and new urbanization on low-carbon technological innovation, and used the spatial Durbin model to find that environmental regulation and new urbanization have a significant positive impact on technological innovation. Xiang Lu (2018) [3] applied Var model to explore the dynamic relationship between environmental regulation, low carbon technology innovation and coal consumption carbon emission reduction, the results show that China's environmental regulation and low carbon technology innovation to promote, coal consumption carbon emission reduction is a long process, in which the role of environmental regulation has a lag, the role of low carbon technology innovation is more significant.

2.2 Low-carbon technology innovation and carbon emissions

Based on the perspective of government regulation, Sun Zhenglin et al. (2021)[4] used an evolutionary game model to study the role of carbon tax policy and carbon trading in promoting corporate innovation, and simulated the interaction of carbon regulatory tool combinations, the effectiveness of the implementation of carbon trading policy is subject to a series of market variables, including the price dynamics of the carbon trading market, the tradable carbon credits derived from corporate technological innovation, and the scale of excess carbon emissions under the condition of lack of innovation. These include the dynamics of the carbon market price, the tradable carbon emission credits derived from technological innovation of enterprises, and the scale of excess carbon emissions under the condition of lack of innovation. Yin He et al. (2020) [5] empirically analyzed the intrinsic mechanism of low-carbon technological innovation on the reduction of carbon emissions with the help of dynamic panel modeling method, focusing on the Y02 low-carbon patent indicator. It is found that low-carbon technological progress significantly suppresses carbon emissions through two main paths, namely, by reducing the carbon content ratio in the energy system on the one hand, and by improving the efficiency of energy use on the other hand, in which the indirect emission reduction effect is more prominent compared to the direct effect. Luna et al. (2019) [6] used spatial panel data and dynamic spatial Durbin model to empirically study the direct impact and spatial spillover effect of breakthrough low-carbon technological innovations on carbon emissions, and found that breakthrough low-carbon technological innovations inhibit carbon emissions in the short term and the long term, but the long-term impact has not been strengthened, which indicates that China's existing technological system is insufficient to digest breakthrough low-carbon technological innovations.

2.3 Low-carbon technology innovation and low-carbon city construction

Song Shiyun (2023)[7] explored the impact of low-carbon city construction on inclusive low-carbon growth, and studied the low-carbon technology innovation, the role of the mechanism between the two relationships, the study shows that low-carbon city construction can significantly promote inclusive low-carbon growth, low-carbon technology innovation has a mediating effect in the promotion of the role, the level of marketization plays a moderating effect in the role. Wang Weidong (2023)[8] verifies the impact of domestic low-carbon city pilot policies on low-carbon technological knowledge flow and its mechanism based on the perspective of low-carbon technological knowledge flow, and finds that low-carbon city pilot policies can effectively promote low-carbon technological knowledge flow in general, and its promotional effect is mainly manifested in accelerating the inflow of low-carbon knowledge, whereas the pilot policy's promotional effect on the spillover of low-carbon technological knowledge does not have any obvious performance. Guo Feng (2023)[9] to low-carbon city pilot policy quasi-natural experiment to assess the impact of low-carbon city construction on urban low-carbon technological innovation and the role of the mechanism, the experimental results show that the construction of low-carbon cities through the increase of scientific and technological personnel and alleviate the financing constraints significantly enhance the level of urban low-carbon technological innovation, but the construction of low-carbon cities in the low level of green technological innovation, the city, as well as resource cities, failed to form the above effective positive promotion relationship.

3. Results and Discussion

3.1 Model Selection and Measurement Methods

Some researchers have paid attention to and explored the low-carbon technological innovation capacity of different regions in China. Some of them have pointed out that the evaluation system of low-carbon technological innovation can be structured from the dimensions of the input of innovation resources and the output of innovation results, which is specifically manifested in the measurement of the efficiency of low-carbon technological innovation as well as the actual output of low-carbon innovation products.

Based on these theoretical foundations, some scholars have used the data envelopment analysis (DEA) model to quantify the efficiency performance of low-carbon technological innovation. This paper follows this research path, while taking into account the core element of carbon emissions, selects carbon dioxide emissions as the negative output indicator, and adopts the modified SBM model (with the addition of non-expected output considerations) to measure the effectiveness of low-carbon technological innovation in China's provincial-level regions, so as to characterize the overall strength of low-carbon technological innovation in each region.

3.2 Selection of indicators and data description

This study analyzes the effectiveness of low-carbon technological innovations from 2011 to 2021 at the provincial level in mainland China, covering thirty provinces except Tibet Autonomous Region, Hong Kong, Macao and Taiwan. The data are mainly obtained from four authoritative statistical literature: China Environmental Statistical Yearbook, China Energy Statistical Yearbook, China Science and Technology Statistical Yearbook, and China Statistical Yearbook.

According to the meaning of low-carbon technological innovation, this paper refers to the methods used by Yao Jiong and Shen Neng, Lin Shanshan and Cui Xiaolei[10], and many other scholars to measure the efficiency of low-carbon technological innovation, with the labor input measured by the full-time equivalents of R&D personnel in high-tech industries, the capital input quantified by the internal expenditure, and the energy input reflected in the form of the overall energy consumption. These three elements constitute the complete set of input variables. As for the expected measurement of outputs, a two-pronged approach is adopted, taking into account the comprehensive economic indicator of regional gross output value on the one hand, and incorporating the number of patent applications of high-tech industries on the other hand, both of which together build up a framework for the measurement of expected outputs.

3.3 Measurement of low-carbon technological innovation efficiency

Based on the sample data of 30 provincial administrative regions covered from 2011 to 2021, the low-carbon technology innovation efficiency is measured by the progressive Malmquist analysis method in the DEA model, aiming to quantitatively assess the low-carbon technology innovation effectiveness of each region. The results are summarized in the attached table. An index greater than 1 indicates an increase in efficiency, equal to 1 the efficiency remains unchanged, and less than 1 the efficiency decreases. The measurement results are shown in Table 1:

Table 1. Measurement results of low-carbon technology innovation efficiency of 30 provincial-level administrative regions in China, 2011-2021

Province	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2011-2021
Beijing	1.18	1.08	1.03	1.1	1.24	1.09	1.34	0.84	1	1.1	1.27	1.12
Tianjin	1	0.85	1.11	0.97	1.05	0.97	1.36	1	1.04	0.97	1.14	1.04
Hebei	0.42	0.99	1.46	1.35	0.5	1.03	1.51	1.34	0.52	0.98	1.11	1.02
Shanghai	1.19	1.07	0.8	1.07	1.37	0.82	1.12	1.06	1.31	1.2	0.85	1.08
Jiangsu	0.56	1.68	0.68	1.56	0.77	0.89	1.33	1.37	0.63	1.81	0.73	1.09
Zhejiang	1.06	1	0.92	1.03	1.28	1.07	0.95	1.08	0.89	1.17	1.02	1.04
Fujian	1.12	1	1.05	1.08	1.22	1.16	1.11	0.95	1.05	1	1	1.07
Shandong	0.56	2.18	0.79	1.04	0.7	1.37	1.18	1.08	0.74	1.96	0.77	1.12
Guangdong	1.11	0.98	0.83	1.31	1.16	1.15	1.1	0.81	1.23	1	1.14	1.08
Hainan	0.66	0.94	1.18	1.13	1.07	0.72	1.39	1.23	0.83	1.04	1.04	1.02

East	0.89	1.18	0.99	1.16	1.04	1.03	1.24	1.08	0.92	1.22	1.01	1.07
Shanxi	1.33	1.01	0.75	1.02	1.48	0.66	1.21	1	1.37	1.03	0.8	1.06
Anhui	1.02	0.92	0.96	1.01	1.32	1.2	0.87	1.08	0.94	1.06	0.98	1.03
Jiangxi	0.66	1.81	0.67	1.51	0.58	0.76	1.59	1.17	0.71	1.42	0.94	1.08
Henan	0.42	1.01	1.51	1.36	0.53	1.04	1.53	1.6	0.49	0.9	1.42	1.07
Hubei	0.53	1.19	1.31	1.32	0.66	1.09	1.54	1.36	0.62	1.13	1.13	1.08
Hunan	0.5	1.87	0.85	1.25	0.64	1.01	1.41	1.29	0.66	1.79	0.84	1.1
Central	0.74	1.30	1.01	1.25	0.87	0.96	1.36	1.25	0.80	1.22	1.02	1.08
Inner Mongolia	0.6	1.4	0.71	1.46	0.66	0.9	1.52	1.69	0.67	1.37	1.02	1.09
Guangxi	1.16	1	1.09	1.1	1.27	1.2	0.94	0.89	0.99	1.12	1.06	1.07
Chongqing	1.1	0.99	0.98	1	1.12	1.09	1.09	1.04	1.04	1.02	1.07	1.05
Sichuan	0.79	1.01	1.43	1.03	0.85	1.07	1.35	1.17	0.76	0.94	1.48	1.08
Guizhou	1.25	1.05	1.09	1.09	1.14	1.08	0.94	0.85	1.12	1.02	1.02	1.06
Yunnan	1.06	1.04	1	1.02	0.93	1.1	0.87	1.02	0.98	1.13	1.01	1.02
Shanxi	1.4	1.08	0.84	1.05	1.33	0.67	1.34	1.02	1.21	1.07	0.88	1.08
Gansu	1.34	1	1.07	0.98	1.05	1.04	1.09	0.93	1.07	1.07	1.03	1.06
Qinghai	0.87	1.5	0.9	1.08	1.26	1.03	0.91	1.31	0.83	1.78	0.7	1.11
Ningxia	0.8	1.58	0.81	0.98	0.96	1.07	1.12	0.98	0.78	1.45	0.83	1.03
Xinjiang	1.04	1.03	0.99	1.05	1.03	1.08	1.04	1.06	1.26	1.19	0.68	1.04
West	1.04	1.15	0.99	1.08	1.05	1.03	1.11	1.09	0.97	1.20	0.98	1.06
Liaoning	0.71	1.59	0.74	1.32	0.85	0.83	1.44	1.27	0.67	1.42	0.87	1.07
Jilin	0.73	1.49	0.76	1.34	0.73	0.81	1.62	1.5	0.67	1.52	0.85	1.09
Heilongjiang	0.54	1.07	1.49	1.4	0.64	1.12	1.5	1.62	0.45	1.02	1.51	1.12
Northeast	0.66	1.38	1.00	1.35	0.74	0.92	1.52	1.46	0.60	1.32	1.08	1.09
Nationwide	0.89	1.21	0.99	1.17	0.98	1.01	1.24	1.15	0.88	1.22	1.01	1.07

3.4 Characteristics of low-carbon technological innovation efficiency

This part explores the characteristics of low-carbon technological innovation from two dimensions: time and space.

The time-varying characteristics of low-carbon technology innovation are analyzed below.By measuring the average value of low-carbon technological innovation of 30 copies in China from 2011 to 2021, the current status of low-carbon technological innovation in the country during the study period is obtained, as shown in Figure 2:

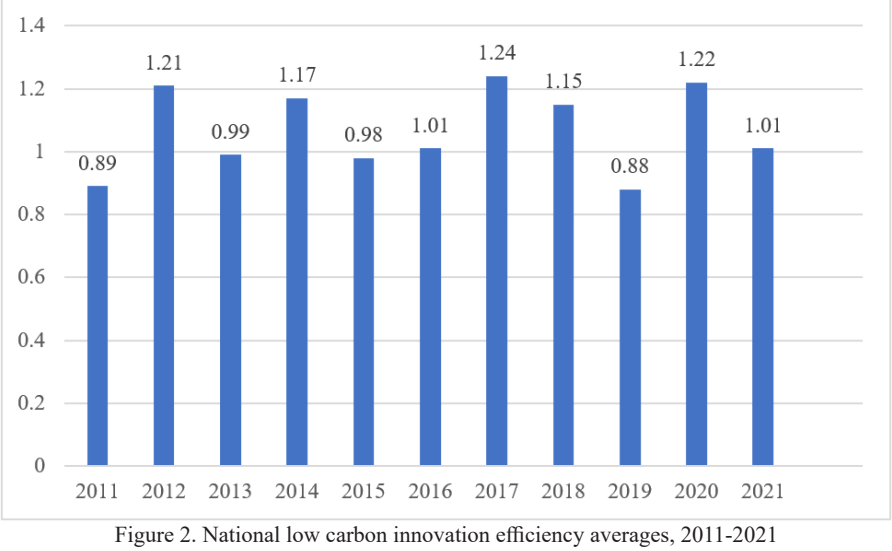

Figure 2. National low carbon innovation efficiency averages, 2011-2021

In the time interval analyzed, for the evolution of low-carbon technological innovation covering 30 provinces, it can be divided into four distinct phases. First, 2011 is the decline stage. In this phase, the efficiency of low-carbon technology innovation dropped to 0.89, with the 2008 Beijing Olympics and the 2010 Shanghai World Expo playing a key role. These two events drove the implementation of a series of environmental protection initiatives across the country, significantly optimizing the state of the ecological environment in each region, and at the same time had a significant boosting effect on regional economic growth. However, as the heat of the Olympics and the World Expo waned, the environmental policies implemented across the country began to slacken, and the ecological status of each region declined. Second, the transition period from 2012 to 2016 was entered, which was characterized by ups and downs in growth. The efficiency of low-carbon technological innovation has gone through the fluctuating changes of increasing and decreasing cycles during this period, with occasional downturns. This reflects the deficiencies and weaknesses of China's low-carbon economic system, especially the heavy industry and coal industry still dominate the industrial structure and energy structure pattern, and have not realized the deep-seated changes. This is reflected in the lack of investment in energy-saving and emission reduction facilities, a single source of funding and other prominent problems, which together lead to a cyclical decline in the efficiency of low-carbon technological innovation in this period. Furthermore, it enters the stage of steady improvement from 2016 to 2018. With the continuous promotion of ecological civilization construction work, low-carbon technology innovation efficiency maintains a stable upward trajectory. Finally, from 2019 to 2021, it enters the innovation re-construction stage. In 2019, under the influence of the epidemic, the national low-carbon technological innovation situation declines significantly, and the low-carbon technological innovation activities are hindered, at the same time, the epidemic also consumes more factors of production in the country. And then, as the epidemic situation improved, the efficiency of low-carbon technological innovation in China rose again.

The following is an analysis of the characteristics of regional changes in low-carbon technology innovation.In order to explore the regional change characteristics of low-carbon technological innovation efficiency, the mean values of low-carbon technological innovation efficiency in eastern, central, western and northeastern China from 2011 to 2021 are calculated on the basis of Table 1, as shown in Figure 3.

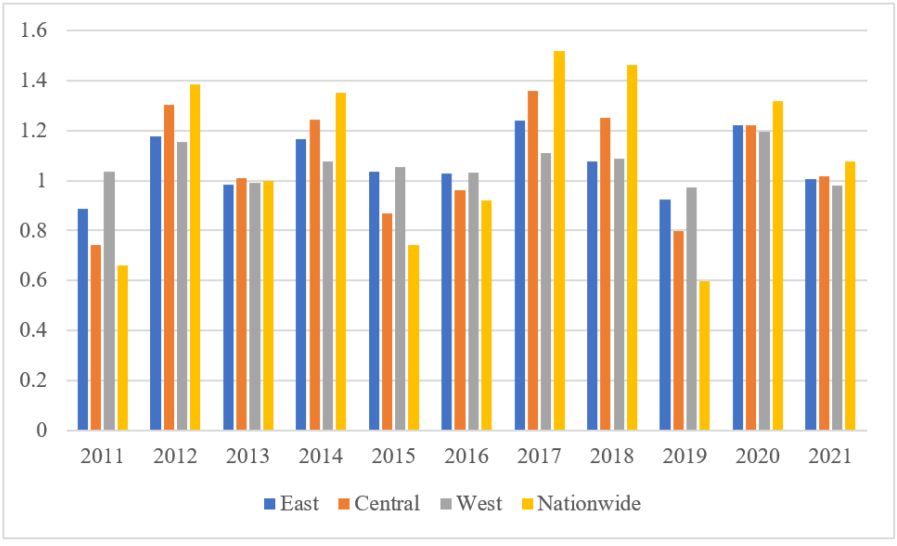

Figure 3. Low-carbon technology innovation efficiency in eastern, central, western and northeastern China, 2011-2021

The reason why the Northeast region can maintain the highest low-carbon technological innovation efficiency can be explained from the following three aspects: 1. Historical deposits and industrial foundation, the Northeast region is China's traditional heavy industrial base. In the face of the pressure of low-carbon transformation, these industrial foundations and existing technological advantages provide favorable conditions for its low-carbon technological innovation. 2. Policy orientation and resource allocation. In the process of economic restructuring and upgrading of the Northeast region, the policy level may pay more attention to the research and development and application of low-carbon technologies, and accelerate the process of low-carbon technological innovation through special support and financial subsidies, etc. 3. Educational resources and scientific research strength, the Northeast region has a number of high-level scientific and technological universities and research institutes, which provide an adequate reserve of talents and scientific research support for low-carbon technological innova-

tion.

The efficiency of low-carbon technology innovation in the central region follows closely: in the process of economic development and industrial transformation, the central region has benefited from the national strategy for the rise of central China, and has obtained more policy support and resource agglomeration.

The efficiency of low-carbon technology innovation in the eastern region is relatively low: although the eastern region has a developed economy and a strong scientific and technological innovation capacity, the difficulties and challenges faced by low-carbon transformation are more complicated due to the early start of industrialization, diversified and relatively mature industrial structure, and a large base of traditional high-energy-consuming industries.

The efficiency of low-carbon technological innovation efficiency in the western region lags behind other regions: the western region has relatively weak low-carbon technological innovation capacity due to geographic conditions, resource distribution, economic development level and other factors.

In general, the efficiency of low-carbon technological innovation in different regions of China shows large differences due to the combined effects of various factors such as historical accumulation, industrial structure, policy support, educational resources, and geographical characteristics of each region.

4. Conclusion

1. According to the results of low-carbon technology innovation efficiency measurement, on a national scale, China's low-carbon technology innovation efficiency shows an upward trend from 2011 to 2021, and on a regional scale, the technological innovation efficiency in the eastern region is slightly higher than that in the west, central and northeastern regions, and subdivided into the regions, in the eastern region, the low-carbon technological innovation efficiency of Beijing and Shandong is higher in the study period, while that of Henan and Tianjin is on the low side. In the central region, Hubei, Hunan and Jiangxi have higher low-carbon technological innovation efficiency than Shaanxi and Anhui, and in the western region, Inner Mongolia and Qinghai have higher low-carbon technological innovation, while Xinjiang and Ningxia have lower low-carbon technological innovation, and in the northeastern region, the low-carbon technological innovation in Heilongjiang is slightly higher than that in Jilin and Liaoning.

2. Through the analysis of low carbon technology innovation, time change characteristics, can be divided into four stages of China's low carbon technology innovation in the study period, 2001 for the decline stage, 2012 to 2016 for the transition period, from 2016 to 2018 is a period of steady enhancement, 2019 to 2021 is the innovation, in the construction stage but as a whole, China's low carbon technology innovation development is not obvious Although some results have been achieved, China's low-carbon technology innovation has a long way to go.

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