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Research on the Impact of Digital Economy on Ecological Efficiency

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Abstract: *As a key force driving economic and social development, studying whether the digital economy can improve ecological efficiency is of great practical significance. This article is based on existing research in the academic community, combined with theories such as endogenous growth and externalities, as well as the characteristics and laws of the digital economy, and proposes research hypotheses. Subsequently, panel data from 29 provinces and cities in China from 2011 to 2020 were selected for empirical research on research hypotheses. The entropy method and the unexpected super efficiency SBM model were used to calculate the digital economy and ecological efficiency, mainly analyzing the impact of the digital economy on the improvement of ecological efficiency. In terms of robustness testing, by replacing explanatory variables, excluding municipalities directly under the central government, and selecting instrumental variables, through empirical analysis, this article concludes that the digital economy has an improvement effect on ecological efficiency.*

Keywords: *Digital Economy, ecological efficiency, SBM model, Fixed effect model, "Dual carbon" targets, High quality development*

1. Introduction and Literature Review

In 2020, China achieved the goal of building a moderately prosperous society in all respects, and its economy entered a stage of high-quality development. China has become the second largest economy in the world. At the same time, China has established two major goals: "carbon peak" and "carbon neutrality". In this context, taking the path of green and sustainable development has become an inevitable choice for China. How to control this critical period and achieve the highest economic benefits and ecological efficiency with minimal energy consumption and ecological impact is of great significance for promoting China's establishment and improvement of an ecological economic system with industrial ecology and ecological industrialization as the main body. On the other hand, the digital economy has developed rapidly. From 2014 to 1010, the contribution rate of the digital economy to GDP growth has been increasing year by year, becoming a key driving force for China's economic development. In the future, with policy support and further improvement of infrastructure, the digital economy will play a greater role.In today's society, as the key to driving economic growth, the development of the digital economy can promote the improvement of ecological efficiency. This article attempts to explore feasible ways for China to achieve green transformation under the background of rapid development of the digital economy through empirical research.

The research and calculation of the digital economy in China started relatively late. In 2008, Kang Tiexiang, based on economic accounting, first calculated the total amount of China's digital economy by constructing a measurement framework from two perspectives to calculate added value; In 2020, Peng Gang and Zhao Lexin measured the total amount of the digital economy from two aspects: the basic functions of the digital economy and the combination with other applications. Jin Xingye and Fu Lin et al. (2020) redefined the digital economy, which relies on two elements: digital technology and digital information. They believe that the development of the digital economy is based on the digital infrastructure and services of the economic industry, thereby effectively improving production and organizational efficiency. The current difficulty in the research of the digital economy lies in the measurement of the digital part of the industry. The measurement of indicators has not yet reached a unified level, and scholars and institutions have different focuses. With the deepening understanding of the digital economy, the indicator system of the digital economy is also constantly updated. By drawing on international experience, domestic scholars have also begun to explore the construction and compilation of digital economy satellite accounts to calculate the digital economy. In 2018, scholars such as Xiang Shujian calculated the added value of China's main digital economy industries and their contribution to GDP based on the digital economy satellite account framework method. They ultimately concluded that the contribution rate of total transaction volume mediated by the digital economy to GDP increased by 10.97% between 2012 and 2017. In the early stages of the development of the digital economy, literature mainly focused on concept identification and calculation. Currently, most research mainly focuses on the socio-economic effects it brings[1-5].

The measurement of ecological efficiency is also a research hotspot in the field, and the mainstream measurement methods can be divided into three types: single ratio method, system indicator method, and model method. Effectively measuring ecological efficiency is not applicable to research on different levels and objects. Typical single indicators include the ratio of resource and environmental input to economic value output (Muller, 2001), and the GDP output per unit ecological footprint (Shi Dan and Wang Junjie, 2016). In addition, Aldieri (2019) used renewable energy and waste as a percentage of total energy to represent ecological efficiency. Scholar Ren Shenggang et al. (2016) used the indicator method to measure ecological efficiency with input factors such as land resources, water resources, energy, and human capital, with the three wastes as non expected outputs, and GDP as expected outputs. In 2017, scholars Peng Diyun and Li Sha used the entropy weight method to form cost based and benefit based indicators and studied the ecological efficiency of eastern provinces in China; Liang Xing and Zhuo Debo (2017) used provincial panel data to construct comprehensive indicators using entropy method to measure ecological efficiency; Gu Pinghua et al. (2017) analyzed industrial material flow based on material flow indicators, combined with industrial added value and regional area; Yan Xiaohe and Tu Jianjun (2021) used entropy method to construct an evaluation index system from four perspectives: natural resource input, economic factor input, ecological environment cost, and economic output, and measured the ecological efficiency of 37 resource-based cities in the Yellow River Basin.

2. Theoretical analysis and research hypotheses

The development of the digital economy has enriched the types of green investment factors, which can effectively improve ecological efficiency. The rapid development of the digital economy has led economic participants to pay more and more attention to digital knowledge and information, supplementing and enriching the original elements of capital and labor in the growth function; At the same time, new elements centered on digital information can replace and supplement the high pollution and low output elements in traditional production, and are environmentally friendly resources compared to traditional industries. They have more efficient conversion efficiency, effectively reduce the negative impact of production, and ultimately achieve an improvement in ecological efficiency.

At the same time, the digital economy can optimize resource allocation efficiency and improve ecological efficiency. The digital economy effectively achieves timely and in-depth information communication between supply and demand through technologies such as the Internet and blockchain, improves work efficiency, reduces search costs (Xu Xianchun and Ren Xue et al., 2019), and shortens transaction time; And a more reasonable pricing mechanism has been formed, which has to some extent improved the efficiency of negotiation and decision-making (Jing Wenjun and Sun Baowen, 2019). The digital economy has rapidly spread information, efficiently linked resources, recombined various elements and improved speed, optimizing resource allocation efficiency[6-9].

Finally, the digital economy can spread the concept of green ecology, build an ecological friendly environmental protection feedback mechanism, and achieve the improvement of ecological efficiency. Firstly, the rapid development of the digital economy can continuously update the green concept of digital communication media, and improve the overall understanding of ecological and environmental protection construction in society. Secondly, the scope economy effect and long tail characteristics of the digital economy can not only meet the needs of different social consumer groups (Wang Weiling and Wang Jing, 2019); At the same time, the existing analysis foundation of consumer behavior theory has been expanded, and big data and algorithms have maximized the utility within the budget range. Consumers have expanded their consumption behavior (Chen Xiaohong and Li Yangyang et al., 2022). Therefore, by constructing green consumption platforms and producing green products, new types of green consumption have been achieved, improving ecological efficiency. Thirdly, the development of digital technology has promoted the improvement of government digital governance capabilities, improved effective interaction between the government, enterprises, and the public.

Based on the above analysis, hypothesis 1 is proposed: the digital economy can improve ecological efficiency.

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3. Research design

3.1 Econometrics model

The benchmark regression model used in this article is a fixed effects model:

$$EE_{it} = C_1 + \alpha_1 DE_{it} + \alpha_2 Control_{it} + \varepsilon_{it} \quad (1)$$

Among them, the dependent variable EE_{it} is the ecological efficiency value of province i in year t, the core explanatory variable DE_{it} is the level of digital economy development, and Control represents the control variable. Based on literature review, the control variables selected in this article are regional per capita gross domestic product (GDP), urbanization rate (ur), industrial structure (tp), and degree of openness to the outside world (op)[10-13].

3.2 Variable Selection

3.2.1 Explained variable: ecological efficiency

Through literature review, this article defines ecological efficiency as the ratio of resource consumption, environmental pollution, and economic benefits within a certain region. In terms of methodology, following the approach of Feng Ximing and Zhang Renjie (2021), an unexpected super efficiency SBM model was used to calculate the ecological efficiency of 29 provinces and cities in China (excluding Tibet, Xinjiang, and Hong Kong, Macao, and Taiwan regions) from 2011 to 2020. The model includes three parts: environmental input, unexpected output, and expected output. Table 1 shows the specific indicator system.

Table 1: Construction system of ecological efficiency indicators

Target layer	constitute	Indicator layer
input	Capital	Stock of fixed assets investment at the end of the year
	labor input	Number of employees
	energy input	total energy consumption
undesirable output	Industrial waste water	Industrial wastewater discharge
	industrial waste gas	Industrial sulfur dioxide emissions
	industrial solid waste	Generation of general industrial solid waste
Expected output	GDP	Actual Gross Domestic Product of the Region

Among them, the calculation of year-end investment stock in each province follows the perpetual inventory method proposed by Goldsmith. The estimation methods of scholars Shan Haojie (2008) and Zhang Jun (2004) for the determination of the base period capital stock and the selection of depreciation rates are widely recognized in the academic community. This article adopts Zhang Jun's method, dividing the fixed asset investment in the base period (2010) by 10% as the initial capital stock of the province and city, and setting the depreciation rate at 9.6%.

The non expected output super efficiency SBM model used is a combination of the super efficiency DEA model and the non expected output SBM model, which can be implemented through MaxDEA data software. The basic idea is to first use the SBM model to evaluate the effectiveness of decision units, appropriately handle non expected outputs, and then evaluate the effective decision units (DMUs) through the super efficiency SBM.

3.2.2 Core explanatory variable: Digital Economy Index

At present, there is no unified standard for measuring and measuring the digital economy. Based on the availability of data, this article draws on the methods of Zhao Tao and Zhang Zhi et al. (2020) to measure the development level of the digital economy in 29 provinces and cities in China from 2011 to 2020. The indicators for the development of the digital economy are jointly constructed using the development level of digital inclusive finance and the development level of the internet, and are decomposed into five three-level indicators. The system is shown in Table 2.

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Table 2: Construction of Digital Economy Indicator System

<table>
<tr><th>Primary indicators</th><th>Secondary indicators</th><th>Third level indicators</th></tr>
<tr><td rowspan="5">Development level of digital economy</td><td>Development level of digital inclusive finance</td><td>Digital Inclusive Financial Development Index</td></tr>
<tr><td rowspan="4">Internet development level</td><td>Number of internet broadband access users per 100 people</td></tr>
<tr><td>Proportion of employees engaged in information transmission, software, and information technology services</td></tr>
<tr><td>Total telecommunications business per capita</td></tr>
<tr><td>Mobile phone penetration rate</td></tr>
</table>

3.2.3 Other variables

Gross Domestic Product (GDP) per capita: The actual GDP per capita reflects the level of economic development in a region, and due to its large absolute value, it is logarithmically processed during the measurement process.

Urbanization rate (ur): Urbanization will have a significant impact on industrial structure, production and lifestyle, ideological concepts, and other aspects, directly and indirectly affecting the ecological efficiency of the region. This article uses the ratio of urban population to total permanent population in each province to measure the level of urbanization.

Industrial Structure (TP): Ratio of the Second Industry to GDP

Opening up to the outside world (OP): The ratio of foreign investment to GDP.

3.2.4 Data sources and descriptive statistics

This article selects panel data from 29 provinces, cities, and autonomous regions in China (excluding Tibet, Xinjiang, and Hong Kong, Macao, and Taiwan) from 2011 to 2020 for analysis. The above data comes from the National Bureau of Statistics, China Energy Statistical Yearbook, China Environmental Statistical Yearbook, China Information Statistical Yearbook, and various provincial statistical yearbooks. The descriptive statistical results of the variables are presented in Table 3.

Table 3: Descriptive statistics of variables

Variable type	variable	Observations	mean value	standard deviation	minimum value	Maximum value
Explained Variable	ee	280	0.9651	0.7566	0.0307	4.8259
explanatory variable	de	280	0.3759	0.3044	0.1400	1.2602
control variable	gdp	280	56498.4	27978.2	16413	164889
	ur	280	4726.56	2789.6	568	12624
	tp	280	43.0573	8.8996	15.8	59
	op	280	0.0804	0.2984	0.0099	4.9617

4. Empirical analysis

4.1 Benchmark regression analysis

When selecting random effects and fixed effects models, the Hausman test is required, and the test results show that the P-value is 0.0004 (less than 0.01). Therefore, the original assumption of random effects is rejected, and the fixed effects model is chosen for regression. Meanwhile, Table 4 reports the results of regression using fixed effects model (Model 1), mixed OLS model (Model 2), and random effects model (Model 3), respectively. The fitting coefficient R2 of the fixed effects model is 0.582, which is the highest value among the three models. The fitting effect of the model is good.

Table 4: Model regression results

	Fixed effect (1)	Mixed effect (2)	random effect (3)
	ee	ee	ee
de	0.4791***	0.6533***	0.4791***
	(4.19)	(5.71)	(4.19)
gdp	-0.0042	0.0024***	-0.0300
	(-0.02)	(0.02)	(-1.23)
ur	0.0011***	0.0002***	0.0002***
	(15.07)	(9.87)	(9.08)
tp	-0.0298***	-0.0248***	-0.0387***
	(-11.20)	(-10.48)	(-10.40)
op	-0.0468	0.0315	-0.0387
	(-1.27)	(1.26)	(-0.82)
_cons	-3.9960***	-0.2601***	0.2657
	(-10.95)	(-0.97)	(1.29)
N	280	280	280
adj. R2	0.862	0.835	0.842
time	Yes		
ind	Yes		

Here, we mainly analyze the regression results of model (1) in Table 4, which is the fixed effects model, with a focus on the core explanatory variable digital economy and other control variables that have a significant impact on ecological efficiency.

The core explanatory variable is the digital economy, with a coefficient of 0.4791, which is significant at the 1% significance level. The empirical results indicate that once the hypothesis is established, the digital economy has a significant positive impact on promoting ecological efficiency improvement. The positive impact of the digital economy may come from the ability of digital technology brought about by the digital economy to handle massive amounts of data. As an emerging industrial element, data can create higher value in the era of big data and replace and supplement traditional high energy consumption and high pollution elements; All scale effects of the digital economy can reduce marginal and average costs; The technology brought by the digital economy has improved the speed of information transmission, reduced time costs, and optimized resource allocation efficiency. The continuous deepening development of the digital economy can provide impetus for China to achieve ecological efficiency improvement, comprehensive green transformation, and high-quality development[14-16].

The coefficient of regional economic development indicators is negative, indicating that China's industrial structure transformation still needs to be developed, and the current situation of high resource consumption and heavy environmental pollution has not changed. In the new era, in the context of the dual carbon goals, there is great potential to continuously improve ecological efficiency.

Meanwhile, in the control variables, the promotion of urbanization has a significant positive impact on the improvement of ecological efficiency at a significance level of 1%. Urbanization is the process of a society dominated by agriculture turning towards a society dominated by non agricultural industries. While urbanization develops, it affects the industrial structure of the region, promotes industrial agglomeration, and improves the efficiency of resource utilization and pollution control. At the same time, liberating the labor force, improving the quality level of the working population, and meeting the demand for labor in high-quality development society will also have a significant impact on the ideological concepts of the entire society, making green, low-carbon, efficient and energy-saving development gradually become a consensus.

The estimated coefficient of industrial structure is significantly negative at the significance level of 1%, which has an inhibitory effect on ecological efficiency, indicating that the secondary industry still has high resource consumption and high pollution emissions.

4.2 Robustness analysis

In order to further examine the impact of the digital economy on ecological efficiency, this article conducts a robustness analysis through four methods: replacing the dependent variable, explanatory variable, excluding municipalities, and selecting instrumental variables.

Firstly, change the sample size. Excluding extreme values, the carbon emission data was subjected to

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a 1% tailing process. The regression results are shown in column (1) of Table 5. The coefficient of the digital economy is significantly positive, proving the validity of hypothesis 1 in this article.

Secondly, exclude municipalities directly under the central government. Considering the significant differences in economic resources, society, and human capital between municipalities directly under the central government and ordinary prefecture level cities, as well as the differences in infrastructure construction, which may have an impact on the regression results, the sample of municipalities directly under the central government was removed. Column (2) in Table 3 indicates that the research conclusion of this article is reliable.

Fourthly, considering that the empirical results of the digital economy on ecological efficiency may have endogeneity, which affects the robustness of the conclusions in this article, a two-stage least squares method is used for endogeneity testing. The selected instrumental variable is the first-order lag of the digital economy, and the regression results are shown in column 3 of Table 3. The regression results are the same as the benchmark regression results, and the conclusion of this article is still valid.

Table 5: Robustness test results

	(1)	(2)	(3)
variable	Replace the dependent variable	Excluding municipalities directly under the central government	Instrumental variable
de	0.2510**	1.1515***	0.6896**
	(-2.45)	(3.08)	(2.24)
N	280	280	280
R2	0.8950	0.133	0.757
time	Yes	Yes	Yes
ind	Yes	Yes	Yes

5. Conclusion

In today's rapidly developing digital economy, the impact of the digital economy is beyond doubt. Building a digital China has been included in the national "14th Five Year Plan" and has become one of China's long-term goals for 2035, which has important guiding significance for China's economic and social development. Ecological efficiency is a unified standard for measuring economic benefits, resource conservation, and pollution prevention. Improving ecological efficiency is the goal for China to further achieve comprehensive green transformation and high-quality development. This article is based on panel data from 29 provinces, cities, and autonomous prefectures in China from 2011 to 2020, and empirically studies the impact of the digital economy on ecological efficiency. Using a fixed effects model for overall benchmark regression, it is concluded that the digital economy can significantly improve provincial ecological efficiency. After conducting robustness tests, this conclusion is still valid and has stability.

Based on the above research conclusions, the following three policy recommendations are proposed:

Make good use of the digital economy and fully leverage its role in improving ecological efficiency. The government should further improve the infrastructure construction of the digital economy, create a more favorable environment for the development of the digital economy, promote industrial structure adjustment and transformation, cultivate and develop new formats and models, guide enterprises to pay attention to the development of the digital industry, fully utilize the dividends brought by the digital economy, leverage the positive externalities, scale effects, and efficient resource allocation of the digital economy, improve resource utilization efficiency, and reduce production inputs and costs; Actively promote industrial integration, promote the transformation of traditional industries, and gradually improve or replace traditional high energy consumption and high pollution factors; At the same time, we will fully leverage the guidance, education, feedback, and supervision roles of digital media and digital governance platforms for enterprises and the general public, and promote the formation of a green development synergy throughout society.

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