Advances in Management & Applied Economics, Vol. 14, No. 6, 2024, 396-418
ISSN: 1792-7544 (print version), 1792-7552(online)
https://doi.org/10.47260/amae/14622
Scientific Press International Limited

Comparison and Analysis of the effects of Three Economic Transitions under the Dual-carbon Goal

Yongke Yuan[1], Xiao Qian[1], Zuliakhan Maitespal[1], Zhuoran Wang[2] and Yufan Chen[3]*

Abstract

By comparing and analyzing the carbon emission effects of different economic transitions, we can gain an in-depth understanding of the differences between different economic transitions to help achieve the dual carbon goals, and then provide theoretical guidance for each region to formulate more accurate measures to achieve the dual carbon goals. This paper empirically compares and analyzes the effects of three major economic transitions (Low-Carbon Economy Transition, Energy Economy Transition, and Digital Economy Transition) in reducing carbon emissions. The results show that: (1) Low-Carbon Economic Transition, Energy Economic Transition, and Digital Economic Transition all have significant effects on suppressing carbon emissions, but there are differences in the degree of the impact, among which the energy economy transition has the most significant inhibitory effect on carbon emissions, and the low-carbon economic transition has a weaker inhibitory effect on carbon emissions. (2) Heterogeneity analysis shows that the digital economy transition and energy economy transition in the central region, the digital economy transition and the low-carbon economy transition in the western region all have significant effects on suppressing regional carbon emissions, while the three major economic transformations in the eastern region do not have a significant effect on suppressing carbon emissions. (3) The digital economy transition in high economic development regions promotes carbon emissions, and the low-carbon economy transition suppresses carbon emissions. The digital economy transition and energy economy transition in low economic development regions significantly reduce carbon emissions.

Keywords: Digital Economy Transition, Energy Economy Transition, Low-Carbon Economy Transition.

[1] School of Economics and Management, Beijing University of Technology, Beijing 100124, China.
[2] Beijing-Dublin international college, Beijing University of Technology, Beijing 100124, China.
[3] School of the Gifted Young, University of Science and Technology of China. *Corresponding author.

Article Info: *Received:* August 30, 2024. *Revised*: September 25, 2024.
Published online: September 27, 2024.

1. Introduction

Between 2011 and 2020, China's carbon dioxide emissions increased from an initial 8.83 billion tons to 9.90 billion tons. China's industrial structure favors coal, energy consumption favors coal, energy efficiency is low, and the risk of oil and gas supply is high, the emission reduction situation is grim (Deng, 2022). Under the background of carbon neutrality and carbon peaking, various economic transformation strategies came into being. Low-carbon economy transition, energy economy transition, digital economy transition from different economic theories and economic reality to give the mechanism and direction of emissions reduction. Comparing and analyzing the impact of economic transformation on carbon emissions under the dual carbon target, and analyzing the emission reduction effects of various economic transformation will play positive roles in optimizing the measures of economic transformation, promoting the realization of sustainable development and realizing the dual carbon target.

2. Literature review

According to the summary of relevant academic networks such as CNKI, we find that there are three main kinds of economic transformation when realizing the dual-carbon goal: low-carbon economy transformation, energy economy transformation and digital economy transformation. The relevant literature is summarized below.

2.1 Study on the impact of low-carbon economic transition on carbon emissions

Low-carbon economic transformation aims to coordinate economic development and ecological environment, and achieve coordinated development through technological innovation, institutional innovation, industrial transformation and new energy development, which is an important strategy to reduce carbon emissions, address climate change and promote sustainable development (Zhou and Qin, 2020). Pan et al. (2010) put forward the characteristics of low-carbon economic transformation. The premise is to update the concept of low-carbon economic transformation. From national strategic policies to personal consciousness of citizens, low-carbon ideas need to be integrated. At the same time, comprehensive benefits should be pursued, economic growth at the cost of environmental damage should be abandoned, and a development model of low consumption and low pollution should be adopted to achieve a win-win situation between economy and environment (Yu Lan et al., 2022).The low-carbon economic transition is a dynamic evolution process guided by the core of industrial low-carbon, and a key path to accelerate the construction of a new development pattern and realize the strategic goal of "dual carbon" (Chen, 2022). The mode should establish strict control standards and institutional constraints, and cultivate the public's low-carbon consciousness. By improving energy efficiency and optimizing energy structure, energy consumption can be reduced and environmental protection and economic

growth can be achieved in harmony (Zhu and Zhang, 2022). Chen (2012) used the SBM-DDF-AAM theory to build a dynamic evaluation index of low-carbon economy, quantitatively measure the transformation of low-carbon economy, and analyze the transformation process of low-carbon economy in various regions (Bruce, 2006).

2.2 Research on the impact of energy economic transition on carbon emissions

Fossil energy sources such as coal, oil and natural gas, and renewable energy sources such as nuclear energy, hydropower and solar energy represent different transition stages. Lin and Li (2015) proposed that the transformation of energy structure is conducive to the reduction of carbon emissions and coal consumption, and that economic development and dual-carbon goals are not in conflict (Zeng et al. 2021). Energy transformation should be marked by the proportion of clean energy in the total energy consumption, promote the development of clean energy from the energy supply side, and stimulate the consumption demand of clean energy from the energy demand segment. Zhang et al. (2022) used the China-Global Energy Model (C-GEM) and other models to explore the path of China's energy economic transition in detail, and quantitatively analyzed the emissions reduction effects of various emissions reduction measures in different time periods and the required policy support. At the same time, they also carried out uncertainty analysis for key characteristic indicators in the process of energy economic transformation to reveal the risks and challenges of transformation in a more comprehensive way. Wang (2023) used DEA model to calculate the energy economic index and systematically evaluated the energy economic transformation of many provinces.

2.3 Research on the impact of digital economy transformation on carbon emissions

The environmental effects of digital economy transformation are still debated. With the help of digital technologies such as big data and cloud computing, enterprises can track and analyze pollutants in real time and formulate more accurate and efficient treatment plans, thus helping to improve the regional ecological environment (Kwon et al. 2014). Meng (2021) analyzed the role of digital economy transformation of Chinese Internet enterprises in promoting carbon neutrality of industrial chain and value chain. In the long run, increased investment in digital economy infrastructure can reduce regional carbon emissions (Bhujabal et al. 2021). Xie (2021) found that digital economy development inhibits carbon emissions and promotes the transformation and improvement of energy structure is an important mechanism and path for digital economy to curb carbon emissions, while Jin et al (2023) found that there is a "U-shaped" relationship between digital economy development and carbon emission intensity, indicating that digital economy does not inhibit carbon emissions from beginning to end, but will increase carbon emissions in the early stage of digital economy development. In the later stage, with

the upgrading of technology and equipment, the digital economy has the role of reducing carbon emissions. The impact of digital economy development on carbon emissions is heterogeneous, that is, the effect of digital economy on curbing carbon emissions is more obvious in the regions with higher carbon emissions in the central and western regions. The impact of digital economy transformation on carbon emissions has multiple mechanisms. Chen (2024) found that smart grid and energy storage schemes supported by digital technologies promote access to renewable energy and help reduce carbon emissions. Cao et al (2024) believes that digital economy has a significant impact on carbon emissions through technological innovation and industrial structure optimization. He constructed an evaluation system to evaluate the digital economy index to further explore the potential impact of its transformation effect on carbon emissions.

To sum up, the existing literature still has the following shortcomings: First, the mechanism of various economic transformation and carbon emissions still needs to be further studied. Second, there is a lack of comparison of the effects of various economic transitions on carbon emissions. Third, there are relatively few regional heterogeneity analyses of various economic transformation effects. Therefore, this paper analyzes and compares the impacts of low-carbon economy transformation, energy economy transformation and digital economy transformation on carbon emissions, and discusses the regional heterogeneity and economic level heterogeneity of economic transformation effects, and puts forward targeted suggestions to promote economic transformation.

3. Theoretical analysis and research hypothesis

Effectively promoting the transformation and development of low-carbon economy is a key step to implement the strategic plan of carbon peaking and carbon neutrality, as well as an important decision to actively respond to and solve the challenge of climate change (Shao, et al. 2022). The transformation of low-carbon economy pays attention to the whole process of economic activities, takes the promotion of environmental improvement and ecological restoration as the premise, emphasizes the coordination between the economy and the ecosystem, highlights scientific and technological progress and technological innovation, realizes green production, green circulation and green distribution, and achieves the purpose of transforming the economic development model and reducing the improvement of ecological environment quality. The main mechanism of low-carbon economic transformation to reduce carbon emissions and promote the dual-carbon goal is mainly manifested in the following aspects. First, by restructuring the industrial value chain and supply chain, the traditional industries with high energy consumption and high pollution are transformed into green industries with low energy consumption and low pollution, and the production mode is adjusted to promote low-carbon development and reduce carbon emissions in the production process. The second is to encourage enterprises to reduce carbon emissions through market mechanisms such as carbon emission trading. Enterprises can flexibly adjust emission reduction strategies

according to their actual conditions, buy or sell carbon emission rights, and achieve a win-win situation of economic and environmental benefits. In addition, the market mechanism can guide the flow of capital to low-carbon fields, promote the development and application of low-carbon technologies, which accelerates the pace of low-carbon economic transformation, reduces the carbon dioxide emissions in various production processes, and strongly promotes the realization of carbon peak and carbon neutrality.

Hypothesis 1: *Theoretically, low-carbon economy can effectively curb carbon emissions, but the implementation time of low-carbon transition is short, and the effect has not been fully demonstrated.*

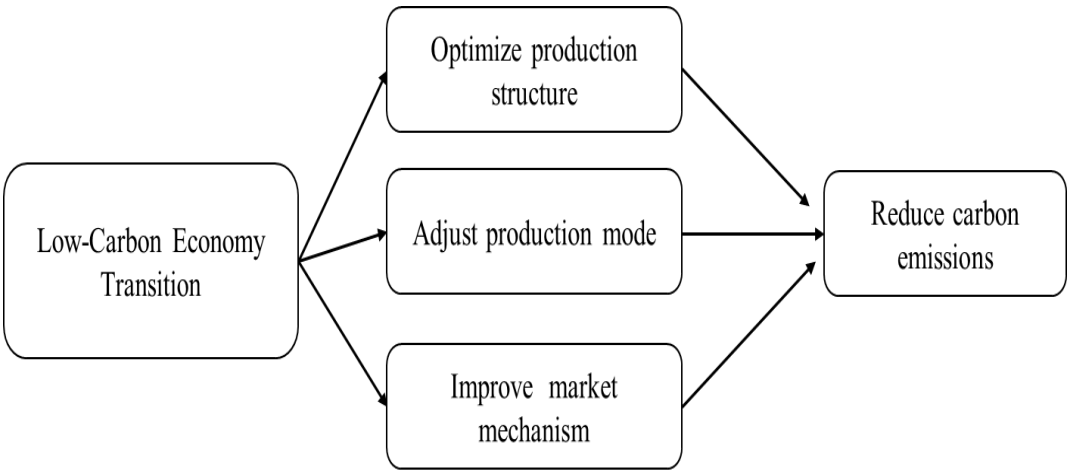

Figure 1: Mechanism of low-carbon economic transition on carbon emissions

Most carbon emissions come from the burning of fossil energy, and the energy economy transition focuses on solving the energy structure and global climate change. The influence mechanism of energy economy transition in reducing carbon emissions is manifested in the following two aspects. By optimizing the energy production structure and energy consumption structure, economic development will shift from high-carbon energy to low-carbon and carbon-free energy, and increase the proportion of clean energy in the energy production and energy consumption structure. This means reducing dependence on traditional fossil energy sources such as coal and oil, and increasing the use of renewable energy sources such as solar, wind and water. This transition directly reduces carbon emissions in the production and consumption of energy. Second, the transformation of energy economy has promoted the improvement of energy efficiency. Through technological innovation and industrial upgrading, the efficiency of energy use has been significantly improved, which means that energy consumption and carbon emissions can be reduced for the same output. The improvement of energy efficiency not only helps

to reduce carbon emissions, but also helps to reduce energy costs and promote sustainable economic development. Energy economic transformation plays a pivotal role in the era of pursuing the goal of "double carbon". China should establish a new energy economic development system led by green energy to promote the green transformation of energy economy (Fang and Zhang 2022).

Hypothesis 2: *The transformation of energy economy can effectively curb carbon emissions, but the western region is limited by the industrial structure, and the effect of energy economy transformation is not obvious.*

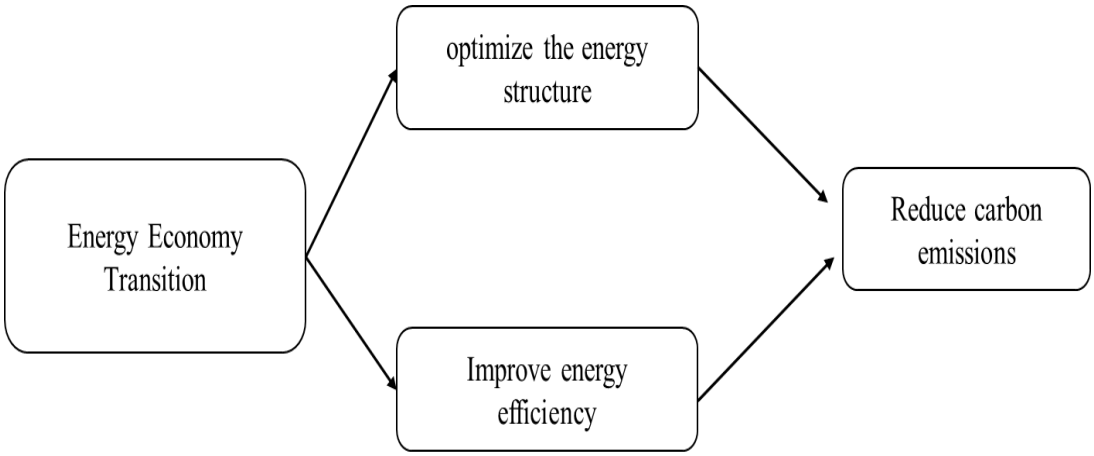

Figure 2: Mechanism of energy economy transition on carbon emissions

Digital economy transformation is a driving force and an important engine that can promote high-quality economic development. The mechanism of digital economy transformation to reduce carbon emissions and promote the dual-carbon goal is reflected in the following three aspects. First, the digital economy effectively helps reduce carbon emissions by promoting the digital upgrading of infrastructure, accelerating green transformation, and promoting intelligent upgrading. Second, the digital economy, to a certain extent, can improve information technology, resource utilization, social and economic development, and have a great role in promoting energy conservation and emission reduction. With the development of digital economy, the use of the Internet (Abdul, 2021) and the improvement of Internet penetration will significantly reduce carbon emissions in the long run (Hu and Zhang, 2023). Third, the digital economy can optimize the allocation of economic resources, improve efficiency, and thus reduce social carbon emissions. In the process of continuous development, the digital economy gradually and fully integrates with the society, deeply participates in all aspects of the social economy, and then improves the operation efficiency of all aspects of the whole process of economic operation, including production, distribution, circulation and

consumption. This convergence not only optimizes resource allocation, but also leads to significant reductions in carbon emissions.

Hypothesis 3: *Digital economy transformation can effectively inhibit carbon emissions. In regions with high economic development level, digital economy transformation can promote carbon emissions, while in regions with low economic development level, digital economy transformation can inhibit carbon emissions.*

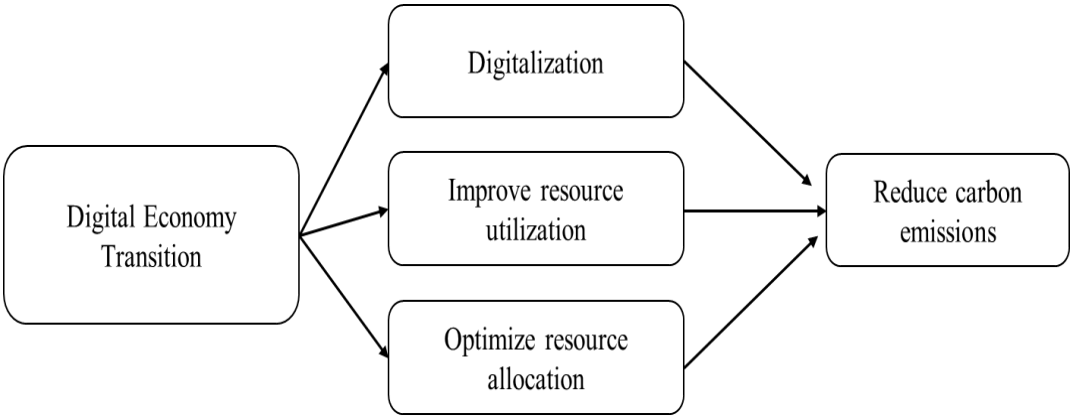

Figure 3: Mechanism of digital economic transition on carbon emissions

4. Research design

4.1 Model design

This paper mainly studies the impact of digital economy transformation, energy economy transformation and low-carbon economy transformation on carbon emissions under the dual-carbon goal, and compares the impact degree. In order to control the macroeconomic environment and the differences between individuals that do not change over time, the double fixed effects model is used for regression. Firstly, the fixed effect model of panel data is constructed referring to Hu and Zhang (2023).

$$CO2_{it} = \alpha_0 + \alpha_1 digital_{it} + \alpha_2 energy_{it} + \alpha_3 gtfp_{it} + \sum Z_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (1)$$

Where *i* represents the province and *t* represents the year; $CO2_{it}$ is the dependent variable, representing total carbon emission; $digital_{it}$, $energy_{it}$ and $gtfp_{it}$ are independent variables, representing digital economy index, energy economy index and green total factor productivity respectively. $\sum z_{it}$ is a series of control variables, including government intervention level (*gov*), economic development (*econ*), urbanization (*urb*), industrialization (*indu*), informatization (*intel*), opening to the outside world level (*fdi*) and population density **(***pop*). ε_{it} is a random interference term. λ_i and u_i denotes the intercept term for individual and time fixed effects.

4.2 Measurement and description of variables

4.2.1 Dependent variable

The dependent variable studied in this paper is the total amount of carbon emissions $(CO2)$, which is measured by the sum of all direct carbon emissions, energy-related indirect carbon emissions and other indirect carbon emissions within each province based on the measurement method of Cong et al (2014).

4.2.2 Independent variables

There are three independent variables in this paper, namely, low-carbon economy transition, energy economy transition and digital economy transition.

(1) Low-carbon economic transition: Based on the research of Zhu and Zhang (2022), this paper uses green Total factor productivity (GTFP) to measure low-carbon economic transition. Green total factor productivity (GTFP) is regarded as a key variable to measure the relationship between population, energy input and carbon emissions output. Considering the dual goals of economic growth and carbon emission reduction, this study chooses green total factor productivity (GTFP) as an indicator to measure the transition to low-carbon economy. GTFP index construction is divided into factor input and output variables, factor input index is divided into physical capital stock and labor input, labor input is expressed by the number of urban employment at the end of the year. The physical capital stock is measured by referring to Zhang et al. (2004). The specific calculation formula is shown in equation (2):

$$k_{it} = l_{it}k_{it-1}(1-\delta) \tag{2}$$

k_{it} is the physical capital stock, l_{it} is the total capital formation in the current year, and δ is the depreciation rate. Output indicators include expected output and unexpected output. Non-desired outputs include wastewater emissions, sulfur emissions, dust and soot emissions.

(2) Energy economy transition: DEA model is generally used in existing studies to evaluate and analyze inter-provincial energy economy and calculate the energy economic index. The improvement of the energy economic index reflects the improvement of regional environmental level. The energy economy index of traditional industries such as coal is relatively low, while the energy economy index of renewable energy industries such as solar, wind and hydropower are usually high, which reflect the transformation of energy economy to some extent (Feng, et al. 2023). Based on the above research results, this paper uses the energy economic index to measure the energy economic transition.

(3) Digital economy transition: Referring to the algorithm of Zhao Tao et al (2021), the digital economy is quantified by Internet development and financial development of each province, and constitutes the digital economy development index, as shown in Table 1. The weighted entropy method is used to measure the digital economy development index of 30 provinces to measure the digital economy transformation.

Table 1: Digital economy index

Primary index	Secondary index	Tertiary index	Property
Digital economy index	Internet penetration	Internet users per 100 people	+
	Internet-related employees	Share of computer services and software workers in the total employed population	+
	Internet-related output	Total telecommunications services per capita	+
	mobile Internet users	mobile phone users per 100 people	+
	Inclusive development of digital finance	Digital Financial Inclusion Index	+

4.2.3 Control variables

In order to control other economic characteristic indicators that affect carbon dioxide emissions, this paper introduces a series of control variables by referring to the practice of existing literatures, as shown in Table 2.

Table 2: Control variables

Variable	Measurement
Government intervention (*gov*)	Proportion of fiscal expenditure in regional GDP
Economic development (*econ*）	GDP per capita
Urbanization level (*urb*)	The proportion of urban population in the total
Industrialization level (*indu*)	The ratio of industrial value added to GDP
Informatization level (*intel*)	Share of post and telecommunications business in
Opening level (*fdi*)	The proportion of actual utilized foreign capital in
Population density (*pop*)	The total population divided by the area

4.3 Data source

This paper selects the relevant data of 30 provinces from 2012 to 2022. The data comes from authoritative data sources such as China Statistical Yearbook, National Bureau of Statistics, and provincial statistical yearbooks. In this paper, some missing data were filled with linear interpolation method and some outliers were removed. The descriptive statistical results of variables are shown in Table 3.

Table 3: Descriptive statistics of variables

Variable	Obs	Mean	Std. dev.	Min	Max
CO_2	330	0.337	0.138	0.0649	0.642
digital	330	0.317	0.0793	0.101	0.523
energy	330	0.128	0.0819	0.0542	0.493
gtfp	330	1.132	0.515	0.400	3.974
gov	330	0.249	0.102	0.107	0.643
econ	330	0.966	0.475	-2.268	2.658
urb	330	0.588	0.123	0.229	0.896
indu	330	0.241	0.180	0.0491	1.000
intel	330	0.0708	0.146	0.0147	2.513
fdi	330	0.259	0.274	0.00757	1.441
pop	330	0.0691	0.111	0.000791	0.771
avco2	330	0.158	0.0643	0.0303	0.300

5. The impact of economic transformation on carbon emissions

5.1 Benchmark regression results

Table 4 shows the regression results of the impact of digital economy transformation, energy economy transformation and low-carbon economy transformation on carbon emissions. Column 2 is the estimation results obtained by using the least square method, column 3 is the estimation results by using the random effects model containing three explanatory variables and control variables, and column 4 is the estimation results of the impact of only three explanatory variables on carbon emissions after a fixed province and year. Column 5 shows the estimated results of the bidirectional fixed-effect model after adding some control variables. Column 6 shows the estimated results after adding all control variables and three explanatory variables. It is not difficult to see that the bidirectional fixed effect model has the best results and the highest goodness of fit.

The coefficient of digital economy transformation is -0.404, which is significantly negative at 1% level, indicating that digital economy transformation has a significant effect on inhibiting carbon emissions. The higher the degree of transformation of the digital economy, the higher the efficiency of resource utilization, which can promote the development of various industries in the direction of green and low-carbon, which is conducive to reducing carbon emissions. The transformation of digital economy has a "carbon reduction effect" (Chen, 2024), which plays an indispensable positive role on the way to achieving the dual-carbon goal.

The coefficient of energy economic transformation is -0.840, which is negative at 1% level, indicating that the deeper the degree of energy economic transformation, the stronger the effect of reducing carbon emissions. With the transformation of the

energy economy, the higher the efficiency of renewable energy and energy utilization, the dependence on traditional fossil energy is reduced. Improvements in energy efficiency, optimization of the energy mix and increased penetration of renewable energy can effectively reduce CO2 emissions, thereby helping the region achieve a lower emission level, and positively contribute to environmental protection and climate change response.

The regression coefficient of low-carbon economy transition is -0.0753, which is negative at 1% level, indicating that low-carbon economy transition can effectively reduce carbon dioxide emissions. With the promotion of low-carbon economic transformation, the industrial structure will also change, and more low-carbon and environmentally friendly industries and services will be shifted. This transition will not only help reduce greenhouse gas emissions, but also reduce the pressure on environmental pollution, while accelerating the pace of sustainable development and laying a solid foundation for long-term economic development.

Both the level of economic development and the degree of government intervention play a positive role in reducing carbon dioxide emissions. The reason for this may be that the government provides legal guarantees for emission reduction through the formulation and implementation of environment-related laws and regulations, and the use of economic incentives such as tax incentives and green credits. At the same time, financial subsidies are given to clean energy and energy-saving technologies, further promoting the research and development and application of these low-carbon technologies. Together, these measures have effectively curbed carbon emissions. Although economic development cannot be separated from industrialization and urbanization, carbon emissions may be increased to a certain extent. However, the higher the level of economic development, the stronger the social innovation ability, the more advanced clean energy technology can be developed, the industrial structure can be changed to improve energy efficiency and thus reduce carbon dioxide emissions. In the process of improving economic development, it is necessary to adhere to the realization of high-quality economic development and adhere to the new development concept of "innovation, coordination, green, open and sharing", which will have a positive impact on reducing carbon emissions.

The level of urbanization, industrialization, informatization, opening-up and population density will all increase carbon dioxide emissions. On the one hand, with the acceleration of urbanization, urban construction and housing construction increase, that is, the amount of energy consumption increases. On the other hand, with the acceleration of urbanization, the use of transportation vehicles shows a rapid growth trend, which leads to the increase of carbon dioxide emissions. The improvement of industrialization level has also significantly increased carbon emissions, mainly because the current energy structure of our country still relies on fossil energy to inevitably produce a large number of greenhouse gases such as carbon dioxide. The development of industrialization, while consuming a large amount of energy, is inevitably accompanied by an increase in carbon emissions (Hamdi et al. 2014). The improvement of information technology will lead to the

increase of carbon dioxide emissions. Some studies point out that the rapid development of information and communication technologies and industries has led to a sharp increase in electricity consumption and thus contributed to the upward trend of carbon emissions (Liu et al. 2022; Mi et al. 2024) Information technology equipment such as computers, servers, communication network equipment, etc., need a lot of power during operation, data center cooling system and backup power system of large energy consumption, rapid growth of energy consumption is also an important factor to increase carbon dioxide. Population density is also a key factor in increasing carbon emissions. With a large population and frequent economic activities, energy consumption and transportation needs will increase accordingly. This can lead to more energy consumption and higher carbon emissions.

Table 4: Benchmark regression results

	(1)	(2)	(3)	(4)	(5)
Variable	CO_2	CO_2	CO_2	CO_2	CO_2
digital	0.00158	-0.0755	0.00158	-0.350***	-0.404***
	(0.0837)	(0.0493)	(0.0837)	(0.0841)	(0.0816)
energy	0.741***	0.165	0.741***	0.371***	-0.840***
	(0.0811)	(0.137)	(0.0811)	(0.0953)	(0.215)
gtfp	-0.0731***	-0.0100	-0.0731***	-0.0764***	-0.0753***
	(0.0126)	(0.0101)	(0.0126)	(0.0115)	(0.0113)
gov		0.142**		-0.601***	-0.552***
		(0.0654)		(0.0686)	(0.0652)
enco		0.00220		-0.00967	-0.0162
		(0.00371)		(0.0123)	(0.0116)
urb		0.448***		0.0720	0.0410
		(0.0400)		(0.0621)	(0.0641)
indu		0.0465			0.387***
		(0.0479)			(0.0969)
intel		0.00474			0.0277
		(0.0107)			(0.0371)
fdi		-0.0927***			0.123***
		(0.0240)			(0.0463)
pop		0.0389**			0.171***
		(0.0178)			(0.0579)
Cons	0.325***	0.0606	0.325***	0.604***	0.648***
	(0.0360)	(0.0477)	(0.0360)	(0.0569)	(0.0559)
Observations	330	330	330	330	330
R-squared	0.293		0.293	0.446	0.518
Regional Fe	Yes	Yes	Yes	Yes	Yes
Year Fe	Yes	Yes	Yes	Yes	Yes

***** p<0.01, ** p<0.05, * p<0.1.**

5.2 Comparison of the impact of economic transformation on carbon emissions

Model 5 shows the impact of digital economy transformation, energy economy transformation and low-carbon economy transformation on carbon emissions. From the regression results, it is found that the regression coefficients of digital economy transformation, energy economy transformation and low-carbon economy transformation are -0.404, -0.840 and -0.0753, respectively, which are all negative significant at the level of 1%. By comparing the absolute values of the coefficients, it can be found that although the three economic transitions have significant effects on carbon emissions, the degree of inhibition is different. The transformation of energy economy has the most significant effect on curbing carbon emissions. The second is the inhibition effect of digital economy transformation on carbon emissions, and the last is the inhibition effect of low-carbon economy transformation on carbon emissions.

In theory, the inhibition effect of low-carbon economic transformation on carbon emissions should be more obvious than that of the other two economic transformations. The reason for this phenomenon may be that green total factor productivity data from 2012 to 2022 are used to study the impact of low-carbon economy transition on carbon emissions. The time span is relatively short, and low-carbon economy includes the overall transformation process of the entire economy and society to low-carbon development mode, involving energy conservation, emission reduction and green development of various economic fields and industries. Including but not limited to energy, industry, construction, transportation and other sectors, the transition to a low-carbon economy may take a long time and be relatively slow to transition. Compared with the radical transformation of the energy structure and the deep penetration of the digital economy, the improvement of the transformation of the low-carbon economy focuses more on the reform of policy guidance, market mechanism construction and technology promotion, etc. Although these measures are conducive to creating a low-carbon development environment, it may be difficult to bring the same substantial carbon emission reduction as the previous two in the short term. Therefore, the effect of low-carbon economy transformation on reducing carbon emissions is second to the effect of energy economy transformation and digital economy transformation. In short, in order to deeply understand its effects, future studies need to study the impact of low-carbon economic transition on carbon emissions from a longer perspective and more effective strategies.

China's energy structure has undergone significant changes in recent years. This is mainly manifested in the transition from a traditional energy system highly dependent on fossil fuels to a new renewable energy system dominated by renewable energy (such as solar, wind, hydropower, etc.), nuclear energy and low-carbon fossil energy (such as natural gas), which has a direct and significant impact on carbon emissions. With the development of energy economy and the transformation of energy economy, China can fundamentally reduce carbon dioxide

emissions from burning fossil fuels by replacing high-carbon energy with clean energy, adopting zero-carbon or low-carbon energy on a large scale, applying green energy technology, and improving the effective utilization of energy. This is the most direct and effective way to reduce emissions, so the energy economy transformation has the most significant effect on reducing carbon emissions.

The development of digital economy is also an important way to reduce carbon emissions. Through the application of intelligent technology, improve the operating efficiency of all walks of life, reduce unnecessary material consumption and energy waste. However, the carbon emission reduction effect of the digital economy is mostly achieved through the auxiliary energy system and the transformation of the energy economy. Therefore, the effect of digital economy transformation to curb carbon emissions is second to the energy economy transformation.

5.3 Robustness test

In order to further test the reliability of the model and the conclusion of the regression results, this paper uses the method of replacing the dependent variable (in the original model, the dependent variable is measured by total carbon emissions, and in the robustness test, the dependent variable is measured by per capita carbon emissions) to test the robustness of the bidirectional fixed effect model of the impact of digital economy transformation, energy economy transformation and low-carbon economy transformation on carbon emissions. The test results are shown in Table 5. The regression coefficients of digital economy transformation, energy economy transformation and low-carbon economy transformation are -0.189, -0.393 and -0.0352 respectively, all of which are significantly negative at the level of 1% and have significant carbon emission inhibition. The test results have been consistent with the regression results adopted in this paper, which proves the stability and reliability of the conclusions of this study.

Table 5: Robustness test results

Variable	(6)	(7)
	CO_2	PCO_2
digital	-0.404***	-0.189***
	(0.0816)	(0.0381)
energy	-0.840***	-0.393***
	(0.215)	(0.101)
gtfp	-0.0753***	-0.0352***
	(0.0113)	(0.00529)
gov	-0.552***	-0.258***
	(0.0652)	(0.0304)
econ	-0.0162	-0.00759
	(0.0116)	(0.00544)
urb	0.0410	0.0192
	(0.0641)	(0.0300)
indu	0.387***	0.181***
	(0.0969)	(0.0453)
intel	0.0277	0.0129
	(0.0371)	(0.0173)
fdi	0.123***	0.0577***
	(0.0463)	(0.0216)
pop	0.171***	0.0800***
	(0.0579)	(0.0271)
Constant	0.648***	0.303***
	(0.0559)	(0.0261)
Observations	330	330
R-squared	0.518	0.518
Regional Fe	Yes	Yes
Year Fe	Yes	Yes

5.4 Heterogeneity analysis

First, considering regional heterogeneity, the sample is divided into eastern, central and western regions. The regression results are shown in Table 6. According to the results of regression analysis, it can be seen that the regression coefficients of digital economy transformation, energy economy transformation and low-carbon economy transformation in the eastern region are all negative, indicating that these three economic transformations have inhibited carbon emissions to a certain extent, but the impact is not significant. The reasons may be: compared with the central and western regions, the eastern region has a higher level of development, the level of economic transformation and industrialization has been relatively complete, and the tertiary industry occupies a larger proportion in the industrial structure of the eastern region. Based on these background factors, carbon emissions from energy economic activities and industrial production processes in the eastern region were originally at a low level. The transformation of low-carbon economy, energy structure and

digital economy to a large extent achieve the purpose of reducing carbon dioxide by optimizing industrial structure, optimizing energy structure and optimizing resource allocation rate. Therefore, the role of digital economy transformation, energy economy transformation and low-carbon economy transformation in reducing regional carbon emissions is not so obvious.

The regression coefficients of the impact of digital economy transformation and energy economy transformation on carbon emissions in the central region are -0.325 and -2.435 respectively, both at the level of 1%, indicating that the transformation and development of digital economy and energy economy in the central region have shown a significant positive role in reducing carbon emissions. The transformation of low-carbon economy also has a certain inhibitory effect on carbon emissions, but the effect is not significant. The regression coefficients of the impact of energy economy transformation and low-carbon economy transformation on carbon emissions in western China are -4.526 and -0.0472 respectively, both of which are significant at the level of 1%. It can be seen that the energy economy transformation and low-carbon economy transformation in western China have significant inhibiting effects on carbon emissions.

The economic transformation of the central and western regions has significant inhibitory effects on carbon emissions. The reason for this situation may be that there are many heavy industry enterprises in the central region, and their main focus is obviously inclined to the secondary industry such as mining and manufacturing, which makes the secondary industry occupy a significantly high proportion in the overall industrial structure. Moreover, some provinces, such as Shanxi, are more prominent in the field of energy exploitation, and their industrial development focuses more on heavy industry. The western region is also rich in energy, and industrialization is focused on energy extraction. With the development of economy and the promotion of low-carbon transformation, the economic structure of the central and western regions has been gradually transformed, the energy structure has been transformed to clean energy such as wind and solar energy, and the renewable energy sector has adjusted and optimized the structure, diversified the energy structure, and greatly improved the energy utilization rate. Although the level of digital economy is relatively weak in the western region, with the development of the economy, the digital economy has promoted the pace of innovation in the field of green energy technology in the energy system. The innovation and extensive use of digital technologies drive the transformation of industrial structure to low-carbon industries, and these transformation measures play important roles in reducing regional carbon emissions, making the economic transformation in the central and western regions more significant on reducing carbon emissions.

Table 6: Results of regional heterogeneity

Variable	Eastern region	Central region	Western region
	CO_2	CO_2	CO_2
digital	-0.0631	-0.325***	-0.134
	(0.0837)	(0.106)	(0.209)
energy	-0.116	-2.435***	-4.526***
	(0.164)	(0.632)	(0.573)
gtfp	-0.0225	-0.0222	-0.0472***
	(0.0352)	(0.0358)	(0.0157)
gov	0.396	0.680	-0.406***
	(0.394)	(0.448)	(0.113)
econ	0.00813	0.0344	-0.0479**
	(0.0137)	(0.0207)	(0.0216)
urb	-0.228**	0.875***	-0.0806
	(0.0872)	(0.242)	(0.116)
indu	0.125	-1.396***	0.498**
	(0.107)	(0.228)	(0.200)
intel	0.719***	-0.000432	0.169
	(0.158)	(0.0242)	(0.149)
fdi	0.0457	-0.0418	0.376**
	(0.0460)	(0.246)	(0.167)
pop	0.205***	-0.0411	0.249*
	(0.0629)	(0.0767)	(0.133)
Constant	0.256*	-0.419**	0.825***
	(0.151)	(0.175)	(0.108)
Observations	121	88	121
R-squared	0.487	0.572	0.633
Regional Fe	Yes	Yes	Yes
Year Fe	Yes	Yes	Yes

Secondly, considering the differences of economic development levels in different regions, this paper further examines the heterogeneity of economic development levels affected by economic transformation on carbon emissions. The level of economic development was measured by the per capita GDP of each province. According to the average per capita GDP of the whole country from 2012 to 2022, the sample was divided into high and low groups, and the two-way fixed effect model was continued for regression analysis. Table 7 shows that in regions with relatively high level of economic development, the digital economy transformation is positive and significant, and the digital economy transformation leads to an increase in carbon emissions. This is the same as that held by some scholars (Salahuddin and Alam,2015). In the regions with low economic development level, the coefficient of digital economy transformation is -0.488, with a significant

negative trend, and the digital economy transformation has the effect of reducing carbon emissions.

The transformation of low-carbon economy in high economic development areas is negative significantly. This is because the tertiary industry in areas with high economic development is more developed, and the regional industrial added value is improved through low-carbon economy such as service industry. The level of low-carbon economy is high, and the transformation of low-carbon economy is more obvious. Therefore, the transformation of low-carbon economy in high economic development areas has an obvious inhibitory effect on carbon emissions. The transformation of low-carbon economy in less developed areas also has an inhibitory effect on carbon emissions, but it is not obvious. This may be due to the low level of regional economic development. In order to promote economic development quickly and effectively, these regions may choose industries with regional advantages, such as heavy industry, to increase regional GDP. At the same time, the green total factor productivity (low-carbon economic transformation) in the less developed regions is low, and the level of low-carbon economic transformation in the regions is also low, so the impact of low-carbon economic transformation on regional carbon emissions is not obvious.

Table 7: Results of heterogeneity in economic development

Variables	Developed regions	Developing regions
digital	0.238*	-0.488***
	(0.137)	(0.113)
energy	0.404	-2.775***
	(0.267)	(0.507)
gtfp	-0.0836***	-0.0277
	(0.0129)	(0.0387)
gov	0.0244	-0.592***
	(0.218)	(0.0870)
econ	0.0137	-0.0176
	(0.0243)	(0.0135)
urb	-0.285***	0.137
	(0.101)	(0.0914)
indu	0.0839	0.389**
	(0.113)	(0.151)
intel	0.891***	-0.000527
	(0.183)	(0.0392)
fdi	0.00938	0.177
	(0.0456)	(0.142)
pop	0.257***	0.0709
	(0.0614)	(0.0874)
Constant	0.422***	0.757***

Variables	Developed regions	Developing regions
	(0.106)	(0.0861)
Observations	121	209
R-squared	0.741	0.391
Regional Fe	Yes	Yes
Year Fe	Yes	Yes

6. Conclusions and Suggestions

This paper selects the panel data of 30 provinces in China from 2012 to 2022, adopts the two-way fixed effect model according to the results of Hausmann test, conducts regression analysis on the impact of three economic transitions on carbon emissions, and compares the impact of three economic transitions on carbon emissions. This paper also analyzes the regional heterogeneity of the impact of economic transformation on carbon emissions in eastern, central and western regions, and analyzes the heterogeneity of economic development level according to per capita GDP. The conclusion of this paper is as follows:

(1) The transformation of low-carbon economy, energy economy and digital economy all significantly inhibit the increase of carbon emissions, but the three economic transformations have different degrees of inhibition on carbon emissions, in which the transformation of energy economy has the most significant effect on carbon emissions, the transformation of digital economy has the second degree of inhibition on carbon emissions, and the last is the inhibition effect of low-carbon economy on carbon emissions.

(2) The heterogeneity analysis find that the transformation of energy economy and low-carbon economy in the western region significantly reduced regional carbon emissions, the transformation of digital economy and energy economy in the central region significantly reduced regional carbon emissions, and the three economic transformations in the eastern region also inhibited carbon emissions to a certain extent, but the impact was not significant.

(3) Heterogeneity analysis of per capita GDP shows that digital economy transformation in high economic development areas increases regional carbon emissions, energy economy transformation has no obvious effect on carbon emissions, and low-carbon economy transformation significantly inhibits carbon emissions. The transformation of digital economy and energy economy in low economic development areas can significantly inhibit carbon emissions, and the transformation of low carbon economy can also inhibit carbon emissions, but it is not significant.

According to the research results, this paper puts forward targeted optimization suggestions for low-carbon economy transformation, energy economy transformation and digital economy transformation respectively, and gives relevant targeted suggestions based on the heterogeneity analysis results and per capita GDP heterogeneity analysis results of eastern, central and western regions. Here are the suggestions from this article:

(1) Strengthen the role of low-carbon economic transition in curbing carbon emissions. We will strengthen research and development of low-carbon technologies and improve infrastructure. Set up special funds to support low-carbon projects and reduce financial pressure during the transition. Advocate green living and consumption patterns, and promote the public to choose low-carbon products and services through policy guidance and market mechanisms. At the same time, establish and improve carbon pricing mechanisms, such as carbon tax and carbon trading, so as to internalize the cost of carbon emissions and guide economic decision-making to transition to low-carbon. Adopt comprehensive policies to build an economic system with low energy consumption, low emissions and high efficiency, strengthen the role of low-carbon economic transition in emission reduction, and promote sustainable development.

(2) We need to optimize the energy mix and ensure security of energy supply. On the one hand, optimize the energy structure to determine the goal of renewable energy, and actively promote the large-scale development and application of clean energy such as solar energy, wind energy, water energy and biomass energy, and increase its proportion in the energy structure. Gradually shut down coal-fired power plants and other fossil fuel facilities with high pollution, high energy consumption and low efficiency, implement strict environmental standards and energy efficiency thresholds, and guide enterprises to carry out technological upgrading or transformation. On the other hand, increase the capital investment in the research and development of energy technology, in view of the problem that some key core technology and equipment of energy are subject to people, we should increase the investment in research and development, and promote the independent research and development and industrialization of related technologies and products. Encourage enterprises to increase technological innovation, promote energy science and technology innovation, so as to improve energy efficiency.

(3) Strengthen the role of digital economy transformation in promoting industrial transformation and upgrading, and transform from traditional high-carbon emission industries to low-carbon and green industries. The application of digital technology can help enterprises achieve the fine management of the production process and the efficient use of resources, so it is necessary to narrow the differences in the development level of the digital economy between regions, further strengthen the participation of digital technology in traditional industries, expand its coverage, deepen its application, and promote the balanced development of the digital economy to achieve the goal of global sustainable development. Accelerate the development of the digital economy while promoting the use of energy-efficient hardware equipment, reduce the carbon dioxide emissions brought by the digital economy itself.

(4) Take full account of the differences in resource endowments and industrial structures among the eastern, central and western regions, and give play to the roles of various economic transformations in reducing carbon emissions and promoting green development. Therefore, for the central region, emphasis should be placed on promoting the transformation of digital economy and energy economy, vigorously

cultivating technical talents, researching and developing related technologies, and widely applying digital technologies to the transformation of energy structure, so as to reduce the proportion of relevant heavy industries with coal as the main energy structure, so as to achieve the purpose of reducing regional carbon emissions. For the western region, considering the relatively lagging economic development in the western region, the state can promote the transformation of the low-carbon economy in the western region by increasing financial support, improving low-carbon related infrastructure, and improving relevant low-carbon economic policies. At the same time, digital technology is used in the transformation of industrial structure to promote the transformation of digital economy in the western region. This is not only conducive to reducing the development gap between regions, but also conducive to reducing regional greenhouse gas emissions and promoting the realization of the dual-carbon goal.

ACKNOWLEDGEMENTS

This work was financially supported by the National Natural Science Foundation of China (72140001).

AUTHORS CONTRIBUTIONS

Xiao Qian: Writing - Original Draft, Writing - Review & Editing, Formal analysis, Data Curation, Investigation, Visualization; **Yongke Yuan:** Writing - Review & Editing, Conceptualization, Methodology, Supervision, Resources; **Zuliakhan Maitespal:** Writing - Review & Editing, Formal analysis, Data Curation, software; **Zhuoran Wang:** Writing - Review & Editing, Formal analysis, Supervision, Validation; **Yunfan Chen(Corresponding author):** Writing-Review & Editing, Methodology, Supervision, Conceptualization, Resources.

References

[1] Deng Dejun (2022). Research on the impact of China's low-carbon economic transition on financial stability[J]. Hubei Social Sciences, (02): 75-82.

[2] Zhou Chaobo and Qin Yun(2020). The Impact of a Carbon Trading Pilot Policy on the Low-Carbon Economic Transformation in China——An Empirical Analysis Based on a DID Model[J]. Soft Science, 34 (10): 36-42+55.

[3] Pan Jiahua, Zhuang Guiyang, Zheng Yan, et al. (2010). Clarification of the Concept of Low-Carbon Economy and Analysis of its Core Elements[J]. International Economic Review, (04): 88-101+5.

[4] Yu Lan, Zhang Bingbing and Yan Zhijun (2022). How does Environmental Legislation Drive Urban Low-carbon Transition[J]? Journal of Finance and Economics,48 (09):18-31.

[5] Chen Shiyi (2022). Low-carbon Economy[J]. Economic Research Journal, 57 (06): 12-18.

[6] Zhu Yue and Zhang Juntao (2022). The Impact of digital Finance Development on green and low-carbon transformation of urban economy [J]. Urban Problems, (10): 64-71+81.
[7] Chen Shiyi (2012). Evaluation of Low Carbon Transformation Process for Chinese Provinces[J]. Economic Research Journal,47 (08): 32-44.
[8] Bruce Podobnik (2006). Global Energy Shifts: Fostering Sustainability in a Turbulent Age[J]. 2006, p240.
[9] Lin Boqiang and Li Jianglong (2015). Transformation of China's Energy Structure under Environmental Governance Constraints: A Peak Value Analysis of Coal and Carbon Dioxide[J]. Social Sciences in China, (09): 84-107+205.
[10] Zeng Shihong, Li Gen, Weng Zhixiong, et al. (2021). Research on China's Energy Transition Path Towards the Goals of Carbon Peak and Carbon Neutrality[J]. Environmental Protection,49 (16): 26-29.
[11] Zhang Xiliang, Huang Xiaodan, Zhang Da, et al. (2022). Research on the Pathway and Policies for China's Energy and Economy Transformation toward Carbon Neutrality[J]. Journal of Management World, 38 (01): 35-66.
[12] Wang Ying (2023). Based on the analysis of China's energy economic index and influencing factors under the background of green economy[J]. Journal of Inner Mongolia University of Finance and Economics, 21 (01): 77-82.
[13] Kwon O., Lee N. and Shin B. (2014). Data quality management, data usage experience and acquisition intention of big data analytics [J]. International Journal of Information Management, 34 (3): 387-394.
[14] Meng Qingli (2021). Analysis on the development of digital economy industry under the goal of carbon neutrality[J]. Information and Communications Technology and Policy, (11): 55-59.
[15] Bhujabal P., Sethi N. and Padhan C. P. (2021). ICT, Foreign direct investment and environmental pollution in major Asia Pacific countries [J]. Environmental Science and Pollution Research, 28 (31): 1-21.
[16] Xie Yunfei (2021). The Effect and Mechanism of Digital Economy on Regional Carbon Emission Intensity[J]. Contemporary Economic Management, 44 (02): 68-78.
[17] Jin Dianchen, Chen Xin and Liu Shuai (2023). How does the digital economy contribute to the "dual carbon" goal: An empirical test based on 275 prefecture-level cities[J]. Guizhou Social Sciences (09): 134-143.
[18] Chen Y. (2024). How the Digital Economy Affects Urban Carbon Emissions Reduction—Research based on Panel Data of 263 Cities [J]. Journal of Global Economy, Business and Finance, 6 (3).
[19] Cao Jianfei, Han Yanling and Liu Huilong (2024). Can the Development of the Digital Economy Affect Carbon Emissions: An Empirical Evidence from 288 Prefecture-Level Cities in China[J]. Ecological Economy, 40 (02): 39-51.

[20] Shao Shuai, Fan Meiting and Yang Lili (2022). Economic Restructuring, Green Technical Progress, and Low-Carbon Transition Development in China: An Empirical Investigation Based on the Overall Technology Frontier and Spatial Spillover Effect[J]. Journal of Management World, 38 (02): 46-69+4-10.
[21] Fang Shijiao and Zhang Ke (2022). Study on the impact of urban sprawl on energy carbon emissions in the Yangtze River Economic Belt: Empirical evidence from night lights [J].Study and Practice(10): 30-39.
[22] Abdul O.S. (2021). Decomposing the Persistent and Transitory Effect of Information and Communication Technology on Environmental Impacts Assessment in Africa: Evidence from Mundlak Specification [J]. Sustainability, 13 (9): 4683-4683.
[23] Hu Jinyan and Zhang Xiaofan (2023). Carbon Emission Reduction Effect of FinTech and the Moderation Effect of Green Policyunder the Background of Carbon Peaking and Carbon Neutrality Goals[J]. Modern Finance and Economics Journal, 43 (01): 3-16.
[24] Cong Jianhui, Liu Xuemin and Zhao Xueru (2014). Demarcation Problems and the Corresponding Measurement Methods of the Urban Carbon Accounting [J]. China Population, Resources and Environment, 24 (04): 19-26.
[25] Zhang Jun, Wu Guiying and Zhang Jipeng (2004). The Estimation of China's provincial capital stock: 1952-2000 [J]. Economic Research Journal (10): 35-44.
[26] Zhao Tao, Zhang Zhi and Liang Shangkun (2021). Digital Economy, Entrepreneurship, and High-Quality Economic Development: Empirical Evidence from Urban China[J]. Journal of Management World, 36 (10): 65-76.
[27] Feng Ziyang, Song Donglin and Xie Wenshuai (2023). Digital Economy Helps Realize the "Double Carbon" Goal: Basic Approaches, Internal Mechanisms and Action Strategies[J]. Journal of Beijing Normal University (Social Sciences) (01): 52-61.
[28] Hamdi H, Sbia R and Shahbaz M. (2014). The nexus between electricity consumption and economic growth in Bahrain [J]. Economic Modelling, 2014, 38 227-237.
[29] Liu Kang, Yuan Min and Shen Shefang (2022). Measurement of Regional Carbon Emission Efficiency and Analysis of Regional Differences in China-Based on a three-stage Super-SBM-DEA model [J]. Journal of Lanzhou University of Finance and Economics,38 (02): 44-59.
[30] Mi Guofang, Lv Miaoxin and Sun Kunrong (2024). Carbon Emission Reduction Effect of Integrating Digital Econom with Real Economy-Empirical Evidence from China's Provinces[J]. Journal of Statistics, 2024, 5 (02): 12-26.
[31] Salahuddin M. and Alam K. (2015). Internet usage, electricity consumption and economic growth in Australia: A time series evidence [J]. Telematics and Informatics, 32 (4): 862-878.