The Impact of Digital Economy Development on Carbon Emissions: A Multi-dimensional Study Based on Threshold Effect

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Abstract. The digital economy has provided a strong traction role for China's pursuit of high-quality economic development and offers a significant chance for low-carbon transition. This research employs the threshold model to experimentally assess the association between the growth level of the digital economy and carbon emissions using panel data from 30 Chinese provinces collected between 2013 and 2020, and analyzes the possible threshold variables. The results show that the impact of development level of digital economy on carbon emissions is not linear. The level of industrial structure development will determine the relationship between the growth of the digital economy and carbon emissions, with industrial structure having a single threshold effect. Meanwhile, since digital economy is a multi-dimensional concept, different dimensions of digital economy have different impacts on carbon emissions. So its effect cannot be generalized. Specifically, the effect of digital economy in the dimension of digital industrialization on carbon emissions with the development of industrial structure presents an inverted U shape.

Keywords: digital economy · carbon emission · industrial structure · threshold effect · digital industry · entropy weight method

1 Introduction

At present, all countries in the world are paying close attention to resource and environmental issues and effectively reducing the carbon emission is an issue that all countries need to coordinate in the process of economic development. The EU has successively promulgated the "EU Climate Change Adaptation Strategy" and the "Fit for 55" plan, aiming to achieve carbon emission reduction by promote technological innovation, energy tax and reduce carbon quota. In September 2020, China has pledged to the world to implement the strategic goal of "dual carbon", which is to reach the carbon peak by 2030 and achieve carbon neutrality by 2060 [1]. China's efforts and contributions to carbon emission reduction in the past have been widely recognized by the world.

In order to achieve this meaningful policy goal of carbon emission reduction faster and better, further reasonable ways to control carbon emissions efficiently are always being explored. Digital technology has become a new engine and opportunity to promote

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green economic development and achieve the goal of "dual carbon" because of its strong permeability, such as improving the efficiency of resource allocation in the whole society and promoting the diversified development of low-carbon industrial structure. This means that while China continues to strengthen, improve and expand the digital economy, it should effectively guide the digital economy to play a positive role in enabling carbon emission reduction, promoting the green development and transformation of industries, and promoting the continuous high-quality and sustainable development of China's economic cause.

The current research on carbon emission reduction and digital economy mainly includes the following aspects: A separate study on the digital economy or carbon emissions, and study on the relationship between digital economy and carbon emissions. First, some research began to design and calculate the development index of the digital economy, and carry out the trend analysis of the development and evolution of digital economy (Tatyana et al., 2019) [2]. In addition, some scholars have paid attention to the impact of digital economy on economic activities, such as high-quality economic development (Ma et al., 2022) [3], industrial structure (Ren et al., 2023) [4], innovation (Xu et al., 2022) [5], urban-rural gap (Yu et al., 2021) [6]. Secondly, the research on carbon emissions mainly focuses on urbanization (Hong et al., 2022) [7], technological progress (Hewage et al., 2022) [8], economic growth (Zhang et al., 2014) [9].

With the vigorous development of digital economy and the prospect of the dual-carbon goal, some scholars have begun to pay attention to the relationship between digital economy and carbon dioxide-emissions. Gu et al. (2023) used the threshold effect model, empirically testing the influence mechanism of the digital economy development on regional CEI. This study found that the digital economy development in the BTH region can reduce regional CEI. And the impact strength of digital economy on CEI varies at different threshold intervals of the mechanism variable [10]. On the other hand, Zhang and Mu et al. (2022) adopted 2012–2019 panel data of 30 provinces in China and found that the development of China's digital economy has exacerbated carbon emissions. Energy efficiency serves as a threshold between the two. The impact of digital economy on carbon emissions has a significant double-threshold effect and presents an N-shaped trend [11]. Jin et. al (2022) used the econometric and mediating effect model to reveal the impact of digital economy on carbon emissions and its mechanism. Furthermore, optimizing the industrial structure and strengthening the introduction and control of foreign enterprises can also effectively promote the carbon emission reduction of enterprises [12]. However, this paper only measures the digital economy in two dimensions, and does not consider the digital industry and other aspects, which may not accurately reflect the level of digital economy, resulting in deviation of the final results. Li & Wang (2022) conducts nonlinear analysis with the panel threshold model (PTM). The results reveal that the affect of digital economy on carbon emissions is inverted U-shaped [13].This paper has limited dimensions to measure the digital economy, and does not deeply analyze the differences in the impact of digital economy in each dimension on carbon emissions and the specific mechanism of action for these two dimensions.

The current academic research on the impact of digital economy on carbon emission is still in the early stage, and the existing research has not yet reached a relatively unified conclusion, and its impact mechanism also needs further study and test. Can the digital economy with great potential really promote carbon emission reduction? Which sectors of the digital economy can really and effectively drive carbon emission reduction? Answering the above questions is very urgent for solving a series of current environmental and resource problems. It has important academic value and practical significance.

In view of the above issues, this paper further standardizes the measurement index system of digital economy, the panel data of 30 provinces in China from 2013 to 2020 was constructed, they comprehensively and deeply explores the impact and mechanism of digital economy on carbon emissions at the provincial level, so as to provide a solid theoretical foundation for promoting and realizing digital carbon neutrality. The innovation and marginal contribution of this paper are as follows: First, a new digital economy index measurement system is selected, and the threshold model is used to analyze the relationship between the two, which passes the robustness test and endogeneity test. Second, we divide the development level of digital economy by dimensions, and find that the impact of digital economy on carbon emissions is different under different dimensions. Thirdly, we put industrial structure as a threshold variable in the same research framework as digital economy and carbon emissions to explore the different impacts of digital economy in different dimensions on carbon emissions due to different industrial structure development. The relationship and the specific mechanism of action increase the depth of research and enrich the research in related fields.

The rest of this paper is arranged as follows: The second part puts forward research assumptions, the third part points out the model method and data sources, the fourth part reports the empirical results and tests, and the fifth part summarizes the research conclusion and process of this paper.

2 Theoretical Analysis and Hypothesis Formulation

2.1 Digital Economy Level and Carbon Emissions

In the early stage of development of the digital economy, investment in the construction and application of digital equipment and infrastructure may directly increase the demand for energy. This will put enormous pressure on carbon emissions. However, When the digital economy reaches the mature stage, first, the digital economy can be widely used to enable new infrastructure. For example, investment in smart energy, smart transportation and other digital infrastructure can effectively reduce carbon emissions [14]. Second, Through the identification, screening, filtering, storage and utilization of big data, the platform composed of digital technology can realize the optimal allocation of resources and reduce carbon emissions per unit of resource use [15, 16]. Digital economy plays an important role in carbon emission source locking, data analysis, regulation and real-time monitoring [17].Third, relying on the strong coverage and significant efficiency of digital economy, it will not only improve the efficiency of energy research, enhance the proportion of renewable energy consumption, gradually reduce the dependence on fossil energy that causes a lot of environmental pollution, upgrading the energy consumption structure, and then form a low-carbon and sustainable energy structure. Moreover, (Zhao et al., 2021) agreeed that improving energy efficiency means reducing energy intensity, which helps to reduce carbon emissions [18]. Therefore, the digital economy will ultimately promote the overall improvement of the quality of national economic development, show its dividend effect, and gradually reduce carbon emissions while moving towards digital economy in an allround way. Based on above, this paper proposes following first hypothesis:

H1: The impact of digital economy on provincial carbon emissions may have a negative impact.

2.2 Digital Economy Level, Industrial Structure and Carbon Emissions

The influence of digital economy on industrial structure adjustment is mainly manifested in industrial structure optimization and industrial transformation and upgrading (Zhu et al. 2020) [19]. By improving the productivity of sectors and rapidly developing digital technology, digital economy has promoted the transformation of industrial structure from factor-driven to innovation-driven [20], and strengthened the market competition mechanism. Digital economy is constantly improving the production and development of the industries, improving their production efficiency in terms of production technology and management mode [10]. This can break the existing industrial pattern, promote the coordinated industries development, eliminate backward production capacity and accelerate the process of industrial integration. Also, Ranta et al. (2021) found that digital technology promotes the innovation of business models [21]. That is, digital economy can cultivate more emerging industries that are more in line with the needs of today's development pattern, providing strong support for the upgrading of industrial structure. At the same time, the optimization of the industrial chain brought about by it makes the connection between the industrial sectors more coordinated, integrates the resources of the whole industrial chain, and enables the efficient and rational allocation of resource factors. As indicated by the relevant theory of the "structural dividend hypothesis", labor power, capital and other production factors tend to flow into the sectors with higher production efficiency. This means under such a reasonable structure, digital economy can more effectively reduce energy consumption, improve the efficiency of resource utilization, and finally achieve the positive effect of accelerating the transformation of industrial structure to input-output decarbonization, reducing carbon emissions and increasing economic benefits. Based on these studies, this paper proposes the following second hypothesis:

H2: The adjustment of industrial structure helps digital economy play a role in carbon emission reduction.

3 Estimation Model and Data

3.1 Model Setting

In order to empirically test the hypothesis above, the four threshold regression model as follows are built:

$$\begin{aligned}\mathrm{lncarbon_{it}} = &\theta_0 + \theta_1 \mathrm{lnscore2_{it}} \mathrm{I}(\mathrm{T_{it}} < \delta_1) + \theta_2 \mathrm{lnscore2_{it}} \mathrm{I}(\delta_1 \le \mathrm{T_{it}} < \delta_2) \\ &+ \theta_3 \mathrm{lnscore2_{it}} \mathrm{I}(\mathrm{T_{it}} \ge \delta_2) + \beta \mathrm{control}_{it} + \mu_{it} + \lambda_{it} + \varepsilon_{it}\end{aligned} \tag{1}$$

This paper uses Model (1) to explore the different impacts of digital industrialization on carbon emissions due to different industrial structures. Similarly, Models (2)-(4) respectively explore different impacts of the different dimension of the digital economy on carbon emissions with different industrial structures. Where i represents province, t represents year, $lncarbon_{it}$ represents the total carbon emissions in the province i in year t. $lnscore2_{it}$, $lnscore1_{it}$, $lnscore3_{it}$, $lnscore_{it}$ represents the development level of digital economy in the dimension of digital industrialization, industrial digitalizationin, industrial digitalization and the overall digital economy development level the province i in year t respectivel. $control_{it}$ is a series of other control variables that affect carbon emissions. α_0 is the constant term, μ_{it} is the region fixed effect, λ_{it} is the time fixed effect, ε_{it} is the random disturbance term. T is the threshold variable, δ is the threshold value, and $\delta 1 < \delta 2$, I(·) is an exponential function, if the condition is met, I = 1, otherwise I = 0.

3.2 Variable Definitions

In this paper, according to the method of Wang et al. (2013) and Li et. al (2012), the energy balance table is used to process energy consumption data. On this basis, the types of energy are added, and the measurement method is referred [22] to determine the primary and secondary energy used for combustion with 14 kinds of energy (2013–2020), so as to finally obtain a more accurate estimate of carbon dioxide emissions. The "Method 1" in IPCC (2006) [23] was used to estimate the data of 30 provinces (excluding Tibet) from 2013 to 2020. In order to comprehensively measure the development level of the digital economy, based on the relatively comprehensive digital economy indicator system of Wang Jun, Zhu Jie and Luo Qian (2021) [24] and considering the availability of data, three dimensions of digital economy development carrier, digital industrialization and industrial digitalization are finally selected. The measurement index system of digital economy development level is shown in the following table. Considering that the entropy method is relatively objective in making index table evaluation [25], In this paper, the entropy value method is used to measure the digital economy level. In particular, all the indicators selected in the TOPSIS in this paper have a positive effect on the measurement of digital economy.

This paper uses the natural logarithm of per capita GDP ratio to measure the variable of economic development level (lnpergdp) [26] In this paper, the natural logarithm of total energy consumption divided by GDP is used as the data to measure energy intensity, so as to reflect the efficiency of energy consumption. For urbanization (lnurban), this paper compares the urban population with the total population and takes its natural logarithm to measure. The urban-rural gap (lngap) is measured by taking the natural logarithm of the ratio of urban residents' per capita disposable income to rural residents' per capita disposable income. Financial development (lnfinance) is measured by natural logarithm after calculating the ratio of financial industry added value to GDP. Governance (lngovern), this paper divides the data of governance investment by GDP and makes its natural logarithm to measure the level of government investment. This paper measures the level of foreign direct investment (lnfdi) as a control variable by the natural logarithm of the ratio of foreign direct investment to GDP and the exchange rate treatment [27]. Import and export indicators are included into the range of control variables to reduce their interference on carbon emissions [28].Import trade (lnimport) takes the total import

Table 1. The measurement index system of digital economy development level

First-level indicators	Secondary indicators	Variables
Carrier of digital economy development	Traditional infrastructure	Internet broadband access ports (ten thousand)
		Internet broadband access users (10,000 Households)
		Number of internet domain names (ten thousand)
	New digital infrastructure	Number of ipv4 addresses
Digital industrialization	Industry scale	Revenue from software products (ten thousand)
		Output of integrated circuits (ten thousand)
		Output of microcomputers (ten thousand)
		Production of mobile communication handsets (ten thousand)
Industry digitalization	Industrial digitization	E-commerce sales (100 million yuan)
	Digitalization of services	Level of online mobile payments
		Degree of digitization of financial inclusion
		Depth of use of digital finance
		The coverage breadth of digital finance

of the place where the business unit is located divided by the GDP and makes the exchange rate treatment, and takes its natural logarithm as the final use data. Export trade (lnexport) uses the natural logarithm of the ratio of total export to GDP in the place where the business unit is located after the exchange rate is processed to measure this index.

In order to verify hypothesis 2, this paper selects industrial structure (lnindustry) as the threshold variable. Since the secondary industry accounts for the majority of China's energy use, the greater the proportion of the secondary industry is, the more likely the carbon emissions are. Therefore, this paper adopts the data of the added value of the secondary industry, calculates its ratio to GDP and takes the natural logarithm as the final measurement data.

3.3 Data Sources

According to the availability of data and the consistency of time, this paper adopts panel data of 30 Chinese provinces (excluding Tibet, Hong Kong, Macau and Taiwan) from 2013–2020 for the study. The sample data are mainly obtained from the official website

Table 2. Descriptive statistics of the variables

Variable	N	Mean	SD	Min	Max
carbon	240	36000	25000	3453	110000
score	240	0.0790	0.0840	0	0.409
pergdp	240	58000	28000	22000	160000
urban	240	0.603	0.116	0.379	0.896
energy	240	0.783	0.558	0.154	2.720
fdi	240	0.00600	0.0220	0	0.340
export	240	0.132	0.126	0.00400	0.631
import	240	0.127	0.168	0.00400	1.072
industry	240	0.398	0.0770	0.160	0.558
gap	240	2.554	0.362	1.845	3.556
govern	240	12.16	13.20	0.0860	110.3
finance	240	0.0760	0.0300	0.0320	0.196

of the National Bureau of Statistics of China, China Information Industry Yearbook etc. This paper takes logarithm of the non-ratio indicators. The descriptive statistics are shown in the following table.

4 Analysis of Empirical Results

4.1 Threshold Effect

This paper conducts threshold tests on models (1), (2), (3), (4). In the dimension of digital industrialization, it is found that the optimization of industrial structure helps the digital economy to play a greater role in reducing carbon emissions. Some of the more important test results are listed below.

According to the (1) of the digital economy results in the table above, there is a double threshold effect in the influence of industrial structure on the relationship between the level of digital economy and carbon emissions under the dimension of digital industry. The two threshold values of industrial structure have passed the significance test at the level of 10%, and the threshold values are −1.7780 and −0.7312 respectively. Therefore, when the industrial structure is used as the threshold variable, the impact of digital economy on carbon emissions under the dimension of digital industrialization can be divided into three stages. When lnindustry is less than −1.7780, the regression coefficient of digital economy on carbon emissions under the development level of digital economy is significantly positive at the level of 1%, indicating that the impact of digital economy on carbon emissions is increased. When lnindustry is between the two threshold values (−1.7780 and −0.7312), the regression coefficient of digital economy on carbon emissions is not significant. As a result, the digital economy no longer affects carbon emissions. However, when lnindustry further develops to a value greater than the second

Table 3. Results of threshold regression effect

	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
lnpergdp	0.918***	0.897***	0.918***	0.899***	0._cat#c.lnscore2	0.087***			
	(0.059)	(0.061)	(0.059)	(0.061)		(0.021)			
lnfdi	0.005	0.007	0.005	0.004	1._cat#c.lnscore2	0.002			
	(0.009)	(0.010)	(0.009)	(0.009)		(0.003)			
lnexport	0.023*	0.018	0.023*	0.024**	2._cat#c.lnscore2	−0.015***			
	(0.012)	(0.012)	(0.012)	(0.012)		(0.005)			
lnimport	−0.009	−0.012	−0.009	−0.007	0._cat#c.lnscore1		0.055***		
	(0.014)	(0.015)	(0.014)	(0.014)			(0.014)		
lnenergy	0.857***	0.830***	0.857***	0.837***	1._cat#c.lnscore1		−0.001		
	(0.043)	(0.044)	(0.043)	(0.045)			(0.003)		
lnurban	0.469***	0.434***	0.469***	0.401***	2._cat#c.lnscore1		−0.013***		
	(0.125)	(0.126)	(0.125)	(0.134)			(0.005)		
lngap	0.578***	0.566***	0.578***	0.575***	0._cat#c.lnscore3			−0.015	
	(0.164)	(0.170)	(0.164)	(0.164)				(0.015)	
lngovern	0.008	0.007	0.008	0.007	1._cat#c.lnscore3			−0.004	
	(0.006)	(0.006)	(0.006)	(0.006)				(0.010)	
lnfinance	−0.066**	−0.081**	−0.066**	−0.072**	2._cat#c.lnscore3			−0.018*	
	(0.033)	(0.035)	(0.033)	(0.033)				(0.011)	
					0._cat#c.lnscore				0.118***
									(0.027)
					1._cat#c.lnscore				0.014
									(0.011)
					2._cat#c.lnscore				−0.004
									(0.012)
					_cons	0.243	0.396	0.890	0.430
						(0.734)	(0.764)	(0.780)	(0.755)
N	240.000	240.000	240.000	240.000	r2	0.779	0.762	0.756	0.780

Standard errors in parentheses * p < 0.1, ** p < 0.05, *** p < 0.01.

Table 4. Results of threshold effect under the dimension of digital industry

Variables	Threshold type	F-score	P-value	Critical value			Threshold value	Confidence intervals
				10%	5%	1%		
lnindustry	Dual Threshold	24.42	0.07	21.5912	26.3539	39.7251	−1.7780	[−1.7991, −1.7571]
		20.33	0.09	18.9736	24.2735	37.7888	−0.7312	[−0.7402, −0.7257]

threshold −0.7312, that is, the industrial structure is [2.0776, + ∞], the regression coefficient of the impact of digital economy on carbon emissions is significantly negative at the level of 5%, indicating a decrease in carbon emissions. This implies that the development of the digital economy will significantly contribute to the reduction of carbon emissions when the industrial structure enters a mature stage of optimization.

To explore the reason, the industrial structure is the ratio of the value added of the secondary sector to the GDP. In the initial stage of industrial structure development, when the proportion of industry and manufacturing is relatively low, and the industries such as agriculture and service industry are more developed while the development of digital technology, it will attract a large number of labor and manufacturers from all over the country. With the development of digital economy and technology, it will not only bring production resources, but also increase the consumption of energy resources such as residential life. The value chain of related information and communication technology industry will also aggravate carbon emissions and environmental pollution. In addition, due to financial and technological limitations, the penetration rate of digital technology in traditional industries is still not high [29] (Qian et al., 2022). The construction of intelligent control of energy consumption and enterprise digital transformation have not played an effective role [30] (Dong et al., 2020), which eventually leads to an increase in carbon emissions.

However, when industry and manufacturing develop to a certain level, that is, when the proportion is relatively high, the consumption of resources required to maintain production and life is far less than the improvement of scale efficiency of digital economy and the expansion of dividend effect. Those old industries that consume a lot of energy and produce a lot of carbon emissions and cause environmental pollution are gradually eliminated by the industrial pattern. Also, the production technology and management level of the remaining industries have been improved, which promotes the optimization and upgrading of the industrial structure. At the same time, the close combination of digitalization and high-tech technology may not only produce new industrial models, but also promote the green and low-carbon transformation of existing industries, reflecting the beneficial impact of digital economy on the industrial structure supported by Internet technology [30]. Therefore, the digital economy can effectively promote the promotion of carbon emission reduction. The dimension of digital industrialization is the core dimension to describe the development level of digital economy, which reflects the accuracy of the results. The regression results of control variables show that economic development level, energy intensity, urban-rural gap, urbanization and export trade are significantly positively correlated with carbon emissions, and their regression coefficients are 0.918, 0.857, 0.578, 0.469 and 0.023, respectively. Financial development is significantly negatively correlated with carbon emissions and the figure of its regression coefficient is −0.066. However, regression coefficients of foreign direct investment, government governance and import trade on carbon emissions did not pass the significance test, and the relationship between them needs further investigation.

According to the (2), under the carrier dimension of digital economy development, the two threshold values of industrial structure fail to pass the significance test, which means that the impact of digital economy development level in this dimension on carbon emissions does not have the impact of industrial structure threshold effect. The reason is that the carrier dimension of digital economy development mainly includes the level of traditional infrastructure or new construction of digital economy. Compared with other dimensions, this dimension has a one-sided measurement of the development level of

Table 5. Results of threshold effect under the carrier dimension of digital economy development

Variables	Threshold type	F-score	P-value	Critical value			Threshold value	Confidence intervals
				10%	5%	1%		
lnindustry	Dual Threshold	17.06	0.23	22.0505	26.5189	35.1541	−1.7780	[−1.7991, −1.7571]
		9.74	0.38	20.7268	24.9782	38.3904	−0.7312	[−0.7595, −0.7257]

digital economy and cannot accurately show and measure the current development situation and level of digital economy. Thus, this dimension interferes with the relationship between the overall level of digital economy development and carbon emissions to a certain extent. In addition, the regression results of control variables show that economic development level, energy intensity, urban-rural gap and urbanization are significantly positively correlated with carbon emissions, and their regression coefficients are 0.897, 0.830, 0.566 and 0.434. Financial development is significantly negatively correlated with carbon emissions. The regression coefficient is −0.081. However, the relationship between foreign direct investment, government governance, and import, export trade on carbon emissions needs further investigation.

According to the (3), in this dimension, the industrial structure has passed the single threshold test, and the threshold value is − 0.7312. When lnindustry≧−0.7312, that is, when industrial structure $\in [2.0776, +\infty]$, the regression coefficient of digital economy level on carbon emissions passed the significance test at the level of 10%. The regression coefficient of −0.018 was significantly negative, indicating that when the industrial structure is optimized and develo ped, The digital economy under the dimension of industrial digitalization has a significantly negative impact on carbon emissions, that is, the digital economy can play a role in reducing carbon emissions.

As for whether there are other thresholds in the industrial structure, and the impact of digital economy on carbon emissions in other ranges is not significant, the reasons are as follows: firstly, due to the availability and convenience of data, the number of data selected in this paper is insufficient and some indicators are limited to a certain extent, which will affect the results of the threshold effect; Secondly, the selected industrial digitalization dimension lacks certain accuracy when describing the development level of

Table 6. Results of threshold effect under the dimension of industrial digitalization

Variables	Threshold type	F-score	P-value	Critical value			Threshold value	Confidence intervals
				10%	5%	1%		
lnindustry	Dual Threshold	20.25	0.180	25.2539	29.9779	39.5291	−1.4230	[−1.7780, −1.3742]
		22.78	0.080	21.4722	29.5920	39.0304	−0.7312	[−0.7402, −0.7257]

Table 7. Results of threshold effect under the dimension of overall level of digital economy development

Variables	Threshold type	F-score	P-value	Critical value			Threshold value	Confidence intervals
				10%	5%	1%		
lnindustry	Dual Threshold	21.90	0.15	23.1617	25.6592	38.1049	−1.7780	[−1.8162, −1.5901]
		20.03	0.06	18.6280	23.5172	35.0474	−0.7312	[−0.7402, −0.7257]

digital economy and the development carrier dimension of digital economy, which makes the effect of digital economy cannot be displayed correctly and objectively, resulting in insignificant results. This will also interfere with the relationship between the overall level of digital economy development and carbon emissions. In addition, the regression results of control variables show that economic development level, energy intensity, urban-rural gap, urbanization, export trade and government governance are significantly positively cor related with carbon emissions, and their regression coefficients are 0.868, 0.855, 0.521, 0.625, 0.022 and 0.010, respectively. Financial development is significantly negatively correlated with carbon emissions, and its regression coefficient is - 0.066. However, the regression coefficients of foreign direct investment and import trade on carbon emissions did not pass the significance test, and the relationship between them needs further investigation.

According to the (4), in this research result, the industrial structure passes the single threshold test at the level of 10%, and the threshold value is −0.7312. However, in the interval divided by this threshold, the regression coefficients of the impact of digital economy development level on carbon emissions have not passed the significance test. This means that there may be other influencing factors that interfere with the relationship between the two.

4.2 Endogeneity Test and Robustness Test

In this paper, the development of digital economy, the core explanatory variable, and the threshold variable industrial structure are lagged by one period, and the threshold effect is used to test the empirical results again. The results show that under the dimension of digital industrialization (lnscore2), there is a single threshold effect of industrial structure, and the threshold value is significant at the level of 10% and the threshold value is −0.7513. When lnindustry > −0.7513, the regression coefficient of digital economy on carbon emissions is significantly negative, that is, digital economy can significantly inhibit carbon emissions. In the dimension of digital economy development carrier (lnscore1) and industrial digitalization (lnscore3), the threshold value fails to pass the test, and it is believed that there is no threshold effect in this dimension. Therefore, under the overall digital economy dimension (lnscore), the threshold value of industrial structure also fails to pass the significant test. This result is almost consistent with the results and mechanism obtained in this paper, which indicates that there is no endogeneity in the results.

At the same time, because we adjust the core explanatory variables and threshold variables to the level of digital economy and industrial structure of each dimension lagged by one period, it means that under the influence of industrial structure in the previous year, digital economy has a significant impact on the carbon emissions of the current period. This also indicates that the impact of digital economy on carbon emissions is real and significant.

In order to test whether the existing fitting results are stable, we carried out the following work: Replace the explained variable and Eliminate or add explanatory variables. In this paper, the logarithm of per capita inter-provincial carbon dioxide emissions (lnpercarbon) is used to replace the original explained variable, the natural logarithm of total carbon dioxide emissions (lncarbon). The results show that in the dimension of digital industrialization (lnscore2), there is a double threshold effect of industrial structure, and the two threshold values (-1.7780, -0.7257) are significant at the level of 5% and 10% respectively. When lnindustry < -1.7780, the regression coefficient of digital economy on carbon emissions is significantly positive, indicating that digital economy will promote the increase of carbon emissions. When lnindustry > -0.7257, the regression coefficient is significantly negative, indicating that digital economy can significantly reduce carbon emissions at this time. In the dimension of digital as the carrier of economic development (lnscore1), there is still no threshold effect. In the dimension of industrial digitalization (lnscore3), there is a single threshold of industrial structure, and the threshold value (-1.4230) is significant at the level of 5%, but the regression coefficient of industrial digitalization on carbon emissions is not significant. Under the overall digital economy dimension (lnscore), there is a double threshold effect of industrial structure, and the two threshold values -1.4230 and -0.7275 are significant at the level of 5%. However, the regression coefficients of digital economy on carbon emissions in the three influence relationships divided according to the threshold did not pass the significance test, which needs further investigation. It can be seen that when the explanatory variables are replaced, the results of this paper are almost consistent with the previous results and the mechanism, indicating that the results of this paper are relatively robust.

In this paper, the explanatory variable foreign direct investment (lnfdi) is removed and the threshold regression is conducted again to examine whether the existing results are stable. Through comparison, it can be seen that the results are very close to the original threshold regression results, thus verifying the robustness of the results in this paper. Based on the above two test methods and results, it can be concluded that the existing results and conclusions obtained in this paper are robust.

5 Conclusion

Using the panel data of 30 provinces in China from 2013 to 2020, this paper empirically explores the impact of digital economy on carbon emissions. From the perspective of industrial structure, we used the threshold effect model to study the nonlinear relationship between digital economy and carbon emissions under different industrial structures and its influencing mechanism, and passes a series of tests. Specific conclusions are drawn through a series of tests: (1) It is found that the relationship between the development level of digital economy and carbon emissions cannot be generalized because the results of different measurement dimensions of digital economy are different. (2) The impact of digital economy development level on carbon emissions will be affected by the development of industrial structure, which is as the threshold variable. The adjustment of industrial structure helps to play the role of digital economy in carbon emission reduction. Developing a digital economy can improve departmental productivity, incorporate optimal allocation of industry chain resources, facilitates the optimisation of industrial structure, accelerates industrial transformation and upgrading and then has an effect on carbon emissions, which is embodied in the single threshold effect concretely, and the threshold value is -0.7312, indicating that the impact of digital economy on carbon emissions is nonlinear, but the impact of various development directions of digital economy on carbon emissions needs further investigation. (3) The results of the impact of digital economy on carbon emissions under different dimensions are different. The digital economy can effectively reduce carbon emissions in the dimension of digital industrialization, the fundamental dimension for describing the level of development of the digital economy. Specifically, there is double threshold effect in industrial structure. In the development progress of industry, the influence of digital economy on carbon emissions shows an inverted U-shaped influence relationship. However, under the carrier dimension of digital economy development, there is no threshold effect on industrial structure. In the dimension of industrial digitalization, there is a single threshold effect. At this time, the regression coefficient is significantly negative, indicating that digital economy can reduce carbon emissions. To sum up, this paper holds that in the dimension of digital economy development carrier and industrial digitalization, due to the problems of data availability and some indicators that cannot fully measure the development level of digital economy, the influence relationship between the two cannot be accurately reflected, which may further interferes the relationship between overall level of digital economy development and carbon emissions. Finally, after integrating the influence relationship of the three dimensions, the industrial structure shows a single threshold effect under the total digital economy dimension.

In addition, due to the limitations of data availability, there are still some problems and deficiencies in this paper, which are expected to be actively improved in the future research. Due to the limitation of data availability and the lack of relevant data, more comprehensive data should be sought to explore more significant results. The future research should continue to follow up and investigate to test the accuracy of the results and conclusions of this paper.

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