Pol. J. Environ. Stud. Vol. XX, No. X (XXXX), 1-13
DOI: 10.15244/pjoes/193384 ONLINE PUBLICATION DATE:

Original Research

Does the Digital Economy Matter for Carbon Emissions in China? Mechanism and Path

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Received: 28 July 2024
Accepted: 13 September 2024

Abstract

Currently, the rapid expansion of the digital economy is essential for advancing the healthy development of the economy. Utilizing China's provincial data for the years 2011–2020, this study examines the impact mechanism of the digital economy on carbon emissions by using a mediation model, a moderating model, and a threshold model. The results indicate that: (1) the digital economy significantly reduces carbon emissions, even with variations between different regions; (2) it also decreases carbon emissions through enhanced energy efficiency and innovations in technology. Enhancing industrial structure and optimizing the distribution of resources can bolster this reduction effect; (3) the degree of financial development and the reduction of carbon emissions are positively correlated and are subject to a dual threshold. Therefore, the government ought to seize opportunities for "new infrastructure" and "new digital technology" development to achieve "dual carbon".

Keywords: digital economy, environment pollution, dual carbon, carbon emission, intermediary effect

Introduction

The World Bank states that the digital economy contributes more than 15% to global GDP on average. In the past decade, China has emerged as the country with the fastest-growing digital economy in the world. According to "the China Internet Development Report (2021)", the proportion of China's GDP attributed to its digital economy was 38.6% and will increase in the future. In November 2021, the Chinese central government issued the "14th Five-Year Plan for the Development of the Big Data Industry", which listed "giving play to the characteristics and advantages of big data" as a key task [1]. It indicates that China intends to strengthen the prominence of the digital economy. It also shows that the government will devote itself to overall high-quality development through digital empowerment.

Rapid digital economy growth comes at a crucial time for global climate change action [2, 3]. Over the past decades, the economy of China has experienced significant expansion, albeit accompanied by a significant increase in carbon emissions [4, 5]. To deal with environmental concerns like air pollution and climate change, Chinese President Xi Jinping proposed that China aim to achieve a "carbon peak" by 2030 and "carbon neutrality" by 2060 through the implementation of effective strategies [6, 7]. In 2021, the "Carbon Peak Action Plan by 2030" was proposed to expedite the formation of eco-friendly industries and lifestyles and

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further promote integrated advancement in the related industrial field.

As an industrial revolution product, the digital economy is an inevitable trend that effectively empowers green transformation and industry upgrades. For one thing, it enhances the allocation of resources, improves the efficiency of technological innovation, and positively influences low-carbon transformation [8, 9]. For another, based on digital technologies like cloud services and digital networks, the advancement of regional industries and energy structures is propelled by the digital economy, which creates a good environment for urban low-carbon transformation [10, 11].

Nevertheless, the digital economy necessitates addressing the CO_2 emissions produced by its own energy consumption. Previous literature has shown that the impact is multifaceted. For one thing, the digital economy has been found to contribute to increased energy usage, thereby leading to an escalation in carbon emissions [12, 13]. For another, the changes in production and life brought about by it will reduce carbon emissions [14, 15]. Therefore, whether the digital economy promotes low-carbon development still needs more discussion. China is now at a new historical starting point for the second centenary goal, and it is also a crucial phase in low-carbon transformation. Therefore, conducting a systematic study of their relationship is quite necessary and important.

The subsequent sections are: The second section comprises the literature review; the third involves theoretical analysis and assumptions; the fourth and fifth sections are the research design and empirical results; and the last part is the conclusions and suggestions.

Literature Review

The background of "dual carbon" and the growth of the digital economy has made the task of reducing carbon emissions more important. Many researchers have examined this effect: The first category examines the correlation between the development of the digital economy and carbon emissions [16-18]. Some academics found that the digital economy had significantly inhibited carbon emissions. Hao et al. (2022) and Wang et al. (2022) [19, 20] believed it had spatial influence and also influenced carbon emissions in adjacent regions in China. Other scholars believed that the impact was nonlinear and had phase characteristics. Xu et al. (2023) [21] found that the digital economy reduced carbon emissions, but increased them in the early stages. Furthermore, Li et al. (2021) [22] discovered an inverted U-shaped relationship between them based on empirical evidence, and it is suggested that the government take some policies to offset the carbon emission effect in the early stages.

The second category mainly focuses on the details of the influence mechanism and impact path. Ma et al. (2022) [23] emphasized that investment in technological advancements plays a regulating role in the digital economy, hence exerting an influence on total carbon emissions. Gu et al. (2023) [24] and Tan et al. (2023) [25] believed that the development of the digital economy reduced the intensity of carbon emissions by promoting the upgrading of industrial structures and improving the quality of green innovation. The study by Liu et al. [26] (2022) showed that the promotion of digital innovation reduces carbon emissions, but introducing technology is not an ideal approach. Moreover, as innovation capabilities improve, the impact becomes more significant. Yi et al. [27] (2022) found that the digital economy has significant spatial spillover effects on carbon emission reduction through the transformation of energy structures, and strengthening the construction of digital infrastructure can enhance regional environment governance.

Even though there are plenty of studies that investigate the impact of the digital economy on carbon emissions, most of them do not consider the mediating effects and moderating effects at the same time, as well as the non-linear effect of setting the thresholds. The present study examines the relationship and the influence mechanism of the digital economy on carbon emissions in-depth. In detail, it reveals the mediating role of energy utilization efficiency and technological innovation, and it further explores the moderating impact of industrial structure upgrading and resource allocation. Additionally, the study introduces the financial development threshold to delve deeper into the nonlinear relationship that plenty of studies have not yet carefully examined.

Compared to previous studies, this study first constructs the index system of the digital economy and then examines its impact. Second, this study clarifies and enriches the influencing mechanisms. That is, from the intermediary effects and the moderating effects. Third, this study examines the potential threshold effect by considering the financial development level as the threshold variable. Conducting this in-depth mechanism analysis is a further step toward the effect of the digital economy on carbon emissions, and it is vital for industrial upgrading and efficient resource allocation in China. Hence, this study provides new ideas to achieve the "double carbon" goal.

Theoretical Analysis and Assumptions

The Direct Impact

The digital economy has altered the production and living models of modern society. Besides, platform management has promoted the efficiency of carbon trading, providing new ideas for realizing carbon emissions. Specifically, the digital economy affects the transition of businesses to low-carbon practices, the digital administration of the government, and the green life of residents.

First, the profound incorporation of digital technology and industries with high carbon emissions can improve the production effectiveness of enterprises and facilitate structural optimization and industrial transformation [8, 28]. The digital economy may expedite the application of non-energy sources and then reduce carbon emissions. Second, it increased the capacity of the local government to monitor and manage carbon emissions. Relevant departments use digital technology to monitor carbon emissions in real-time and effectively improve their management capabilities [29]. Third, local residents are encouraged to establish low-carbon production techniques via the digital economy, which also changes their consumption concepts and demand preferences and leads to changes in consumption decisions. The application of green technologies has enhanced residents' green consumption and green life awareness [30-33]. The digital economy has been found to be an efficient means of mitigating carbon emissions by improving the government's carbon emission governance and guiding residents to live a greener life. Then, hypothesis H1 is proposed.

H1: The digital economy can significantly reduce carbon emissions.

The Indirect Impact

Energy Use Effect

Improvements in energy efficiency can significantly mitigate carbon emissions. Digital transformation can enhance corporate manufacturing techniques, thereby cutting expenses and conserving energy. Furthermore, digital technology helps companies and local governments manage carbon emissions, minimize energy usage, and improve energy efficiency in areas such as transportation, residential, and commercial buildings [34].

Technological Innovation Effect

Rapid change and faster technology diffusion are driving the digital economy's explosive growth. As a result, the characteristics of technical advancement and innovation are inherent to it. First of all, the digital penetration of innovation elements can transcend constraints related to physical time and location, realize the lower costs of information sharing, and enhance the efficiency of utilizing innovation resources [35]. Second, the digital economy enables the financial industry to experience digital transformation and provides financial assistance to companies for creative endeavors and the cultivation of innovative talents to stimulate innovation motivation. Last but not least, digital technology is essentially a technological innovation that enables a more accurate assessment of market supply and demand, making innovative products have more targeted characteristics, shorten the innovation cycle, and reduce innovation risks [36].

The Effect of Industrial Structure Upgrading

The essence of upgrading the industrial structure is gradually increasing the proportion of relatively advanced industries. For example, the ongoing convergence of the digital economy and the real economy has led to the emergence of new models and new industries. New industries represented by modern technologies gradually became the leading industries in China and then promoted the upgrading of industrial institutions. The digital economy can revolutionize and enhance established sectors. As the digital economy develops, emerging industries extend to other traditional industries, thereby transforming and upgrading traditional industries. In short, the digital economy facilitates the evolution of the industrial structure towards higher technology and a better environment [24].

Resource Allocation Effect

The contradiction between economics and the environment primarily depends on the mode of resource allocation and utilization efficiency. Research indicates that the digital economy offers effective information through the network and the alignment of supply and demand, thereby strengthening the effectiveness of resource allocation.

For one thing, digital technology enables enterprises to maximize production efficiency processes and improve energy structures. It can also use digital technologies to adjust its production and marketing plans according to market changes. It helps to make better use of resources and lower the emission intensity of carbon dioxide [37]. For another, the collaborative division of labor and information sharing is conducive to breaking the blockade caused by regional administrative monopolies under the traditional economy, promoting the integration of the market, and forming a free flow mechanism for resource elements. Finally, innovative resources such as knowledge, talents, and funds can be recombined, and resource elements will continue to be transferred to high-innovation, low-energy, and low-pollution enterprises and industries to achieve optimal allocation, thereby reducing resource consumption and CO_2 emissions [38]. Hence, this study posits hypothesis H2:

H2a: The digital economy facilitates the reduction of carbon emissions through the improvement of energy efficiency.

H2b: The digital economy facilitates the decrease of carbon emissions through the promotion of technical innovation.

H2c: The impact of the digital economy on carbon emissions reduction can be effectively moderated by upgrading industrial structures.

H2d: The impact of the digital economy on carbon emissions reduction can be effectively moderated by optimizing resource allocation.

Threshold Effect Test

The integration of the digital economy and financial institutions is a crucial method for attaining sustainable economic development. First, with the development of digital finance, the institutions can use digital technologies to supervise, manage, and control company financing on the platform, identify "green companies", and supervise the flow of green credit. Second, financial institutions use big data technology to monitor the transaction data, production data, and behavior data of enterprises on the platform in real-time and then accurately identify enterprise environmental information and improve their green efficiency. Third, financial institutions can use digital platforms to screen companies, eliminate high-energy and high-polluting companies, and guide financial resources to flow to environmentally friendly companies. As financial development advances, the impact becomes more obvious. Thus, this paper posits hypothesis H3:

H3: The influence of the digital economy on carbon emissions is subject to a threshold effect.

Research Design

Model Setting

Benchmark Model

In this study, a two-way fixed-effects model is constructed to examine the impact and the detailed mechanism of the digital economy on carbon emissions. To eliminate the effects of multicollinearity and heteroscedasticity, logarithmic processing is performed in Equation (1).

$$\ln ca_{it}=\alpha_0+\alpha_1 \ln dig_{it}+\gamma control_{it}+\mu_i+\theta_t+\varepsilon_{it} \tag{1}$$

Here, *i* represents the province, and *t* denotes the time. The degree of the digital economy serves as the explanatory variable, while the level of carbon emissions serves as the explained variable. $Control_{it}$ includes variables such as the degree of marketization (mar), the extent of foreign investment (fdi), the upgrading level of industrial structure (stru), the amount spent by the government on science and technology (gov), and the level of economic development (pgdp). μ_i, θ_t denotes province and time fixed effects. ε_{it} is the error term.

Mediating Effect Model

Since the digital economy may affect carbon emissions through intermediaries, such as energy efficiency and technological innovation, this study set up a mediation effect model, as shown in Equations (2) and (3).

$$M_{it}=\beta_0+\beta_1 \ln dig_{it}+\gamma control_{it}+\mu_i+\theta_t+\varepsilon_{it} \tag{2}$$

$$\ln ca_{it}=\theta_0+\theta_1 \ln dig_{it}+\rho M_{it}+\gamma control_{it}+\mu_i+\theta_t+\varepsilon_{it} \tag{3}$$

Here, M represents the intermediary variables, including energy efficiency (lnenergy) and technological innovation (lnrd). Besides, $Control_{it}$ are control variables, θ_1 and ρ are the coefficients of the digital economy and intermediary variables. If θ_1 in Equation (1) is significant, then test the Equations (2) and (3) in turn. If β_1 is significant, it means that the digital economy exerts a substantial influence on the mediator variable, and then Equation (3) is tested. If θ_1 and ρ in Equation (3) are significant, it shows that the mediator variable plays a part of the mediation effect (partial mediating effect). However, if θ_1 not significant and ρ is significant, it suggests that the mediating variable assumes a complete mediating function.

Moderating Effect Model

As noted, it is preliminary determined that the level of resource allocation (lntfp) and the upgrading of industrial structure (lnins) are the potential moderating variables. These moderating variables may enlarge or reduce the effect of the digital economy on carbon emission reduction. Then, this study constructs the following Equation (4) to examine the moderating effects based on Equation (1). Here, δ_3 presents the moderating effect.

$$\ln ca_{it}=\delta_0+\delta_1 \ln dig_{it}+\delta_2 mod_{it}+\delta_3 \ln dig_{it}\times mod_{it}+\gamma control_{it}+\mu_i+\theta_t+\varepsilon_{it} \tag{4}$$

Variables

Explained Variable

Considering the data availability, this study selects the provincial-level data of energy consumption from 2011 to 2020. First, it calculates the aggregate carbon emissions for provinces through the 2006 carbon accounting approach of the IPCC. Then, the calculation of carbon emission intensity (lnca) involves the computation of the relationship between the gross regional product and the aggregate carbon dioxide emissions. Finally, carbon emission intensity is expressed as its logarithm.

Core Explanatory Variable

To comprehensively evaluate and consider data availability, this study constructs an indicator system

Table 1. Index System of the Level of Digital Economy.

Level 1	Level 2	Level 3	Data source	Properties
The level of the digital economy	Digital economy infrastructure	The line length of Long-distance optical cable (10,000 kilometers)	China Statistical Yearbook	+
		Mobile cellular users per 100 people	China Statistical Yearbook	+
		Internet broadband ports (10,000)	China Statistical Yearbook	+
	Digital industrialization	Software business income (10,000 Yuan)	Data on the electronic information industry	+
		Total telecom business (100 million Yuan)	Data on the electronic information industry	+
		The added value of the transportation, warehousing, and postal industry (100 million Yuan)	China Statistical Yearbook	+
	Industrial digitization	E-commerce sales (100 million Yuan)	China Statistical Yearbook	+
		Digital Financial Inclusion Index	The Peking University Digital Financial Inclusion Index of China	+
		Technology market contract transaction volume (100 million Yuan)	China Statistical Yearbook	+
	Digital innovation level	Ratio of R&D internal expenditure to GDP	China Statistical Yearbook	+
		Number of inventions, utility patent, and design patents granted (pieces)	China Statistical Yearbook	+
		Expenditures for new product development in high-tech industries (10,000 yuan)	Statistical yearbook of China's high-tech industry	+

as noted in Table 1. An entropy approach is utilized to allocate weights to each index, leading to the determination of the level of growth of the digital economy (lndig).

Mediating Variables

Increasing the effectiveness of energy utilization and minimizing energy consumption may effectively reduce carbon emissions. Therefore, enhancing energy efficiency is a crucial method to attain sustainable development. In this study, energy efficiency is measured using the energy intensity index, that is, per unit of GDP energy consumption. The traditional STIRPAT model regards the level of technological innovation (lnrd) as the main factor affecting carbon emissions. It can increase the effectiveness of energy consumption and decrease emissions of carbon dioxide. This paper uses the R&D investment of regional industrial businesses that exceed a certain size as an indicator.

Moderating Variables

The level of resource allocation presents the effectiveness of resource allocation in all aspects of a region. The higher the level of resource allocation, the higher the efficiency of resource allocation. That is, an efficient allocation of resources will facilitate the overall improvement of the industrial framework and realize carbon emission reduction. In this study, total factor productivity (TFP) quantifies the efficiency of resource allocation.

This study uses indicators such as non-agricultural proportion, industrial structure level, and high-tech industry proportion as a measure of the extent to which the industrial structure has undergone upgrading. Since the upgrading of industrial structure (lnins) is vital to achieve carbon emission reduction, it is used as a moderating variable, and the formula is:

$$\ln ins = \sum_{i=1}^{3} q_i \times i = q_1 \times 1 + q_2 \times 2 + q_3 \times 3 \tag{5}$$

Table 2. Descriptive statistics of the main variables.

Indicator	Name	Mean	Std	Min	Max
Level of the digital economy	lndig	-2.449	0.835	-4.89	-0.165
Level of carbon emissions	lnca	0.588	0.68	-1.774	2.115
Level of marketization	mar	7.941	1.892	3.359	11.934
Level of foreign investment	fdi	0.019	0.018	0.001	0.121
The upgrading level of the industrial structure	stru	1.219	0.696	0.518	5.297
The level of government expenditure on science and technology	gov	0.021	0.015	0.004	0.068
Level of economic development	pgdp	12692.78	7975.23	5125.47	47118.40

Control Variables

Refer to the "Marketization Index Report by Province in China". The marketization index is used to quantify the extent of marketization in each region (mar). This study used the ratio between "the production value of the tertiary industry" and "the output value of the secondary industry" as a metric of the extent to which the industrial structure has been upgraded (stru). According to usual practice, this study uses the degree of foreign capital utilization assessed by calculating the ratio between the actual quantity of foreign capital utilized and the regional GDP (fdi). During the computation procedure, the real utilization of foreign capital will be transformed in accordance with the yearly mean exchange rate between the Chinese currency (RMB) and the US dollar. The extent of government expenditure on scientific research and technological development (gov) is quantified by the percentage of science and technology spending in the general budget of local governments. Besides, the local economic progress is reflected by the per capita GDP (pgdp), and it is after deflating based on the year 2011.

Data Source

Data for the digital financial inclusion index comes from "the Peking University Digital Financial Inclusion Index of China". Besides, other data mostly comes from "the China Statistical Yearbook, the Provincial Statistical Yearbooks, the China Environmental Statistical Yearbook, and the China Energy Statistics Yearbook". Table 2 displays the primary variables.

Empirical Results

The previous section introduces the research design of this study, which introduces the related models and the variables for the analysis as well as the data source. Based on the constructed models, this study conducts a comprehensive empirical analysis, which is listed in the following section. The following section is the results of empirical analysis in this study, which includes the baseline regression, mediating effect, moderating effect, heterogeneity analysis, robustness checks, and threshold regression analysis. All these contribute to the final conclusion and the policy recommendations at the end of this paper.

Baseline Regression

Before the baseline regression, this study demonstrated the need to employ the fixed effect model. The coefficient of lndig (without controls) is -0.698 and significant, as in Column (1) of Table 3. Columns (2)-(6) show the results of introducing controls sequentially, and all the coefficients of the outcome variable are negative and significant. Therefore, the digital economy has an impact on reducing carbon emissions, thereby supporting H1.

Regarding control variables, the coefficient of gov is negative and significant, which indicates there exists an inverse correlation between government spending on scientific research and technological advancements (gov) and carbon emissions. This may be because the government invests more in reducing carbon emissions. Besides, the coefficient of pgdp is significant and negative, implying that as the level of regional economic development increases, the higher the possibility that the area adopts energy-saving technologies.

Table 3. Results of baseline regression.

	(1)	(2)	(3)	(4)	(5)	(6)
lndig	-0.698***	-0.691***	-0.651***	-0.685***	-0.576***	-0.463***
	(0.122)	(0.123)	(0.129)	(0.141)	(0.138)	(0.118)
mar		-0.006	0.001	-0.009	-0.014	-0.002
		(0.019)	(0.020)	(0.021)	(0.020)	(0.016)
fdi			-1.171	-1.078	-0.496	2.037***
			(0.869)	(0.870)	(0.855)	(0.705)
stru				-0.122	-0.183*	-0.047
				(0.107)	(0.107)	(0.063)
gov					-7.613***	-4.081**
					(2.197)	(1.791)
pgdp						-7.91e-05***
						(9.05e-06)
Province fixed	YES	YES	YES	YES	YES	YES
Year fixed	YES	YES	YES	YES	YES	YES
Constant	-1.785***	-1.722***	-1.659***	-1.189**	-0.338**	2.256***
	(0.247)	(0.315)	(0.314)	(0.462)	(0.584)	(0.613)
Obs.	300	300	300	300	300	300
R-squared	0.965	0.965	0.965	0.966	0.968	0.980

Note: The values in bracket are robust standard errors. ***, **, * indicate that the significance level at 1%, 5% and 10% respectively (same as below).

Mediating Effect Test

This study, according to Equations (5) and (6), investigates the presence of the mediation effect. Columns (1) and (2) of Table 4 show the mediating impact of energy efficiency. The coefficient of lndig is significant at 1%, which shows that the digital economy reduces unit energy consumption. The coefficient of lnenergy is positive, signifying that as the energy usage per unit increases, the greater the carbon emissions. Moreover, the coefficient of lndig in column (2) is negative and significant, which aligns with that in column (1). Overall, carbon emissions can be reduced through the enhancement of energy efficiency.

The columns (3) and (4) show the effect of technological innovation. The coefficient is positive and significant in column (3), indicating that the digital economy fosters technological innovation. While the coefficients of technological innovation (lnrd) and the digital economy are both negative and significant in column (4), which demonstrates that technological innovation can reduce carbon emissions.

Besides, this research used the bootstrapping test (1000 times) to evaluate the robustness of the intermediary variables. The result is in Table 5. Specifically, energy efficiency plays an essential role since the 95% confidence interval of the indirect and direct effects of energy efficiency does not contain 0. Likewise, technology innovation plays a role in enabling the digital economy to decrease carbon emissions. Then, H2a and H2b were supported.

Moderating Effect Test

Table 6 demonstrates the moderating influence of resource allocation and industrial structure upgrading. The coefficient of lndig in column (1) is negative, which indicates the effects of reducing carbon emissions. In column (2), the coefficient of lndig* lntfp is negative and significant, showing that the resource allocation level strengthens the carbon emission reduction. In other words, the provinces characterized by higher levels of resource allocation strengthen the inhibition effect. It may be that provinces with a greater amount of resource allocation can promote industrial upgrading through the enhancement of resource utilization efficiency, thus facilitating the reduction, which proves the hypothesis H2c.

The coefficient of lndig* lnins in column (4) is negatively and significantly correlated, suggesting that the improvement of industrial structure strengthens the impact of the digital economy in promoting the reduction of carbon emissions. Provinces with a more reasonable level of industrial structure can strengthen the

Table 4. Results of the Mediating Effect.

Variables	(1) lnenergy	(2) lnca	(3) lnrd	(4) lnca
lndig	-0.194***	-0.276***	0.718***	-0.350***
	(0.074)	(0.075)	(0.109)	(0.119)
lnenergy		0.965***		
		(0.045)		
lnrd				-0.157***
				(0.055)
Controls	YES	YES	YES	YES
Province fixed	YES	YES	YES	YES
Year fixed	YES	YES	YES	YES
Constant	1.252***	1.049**	15.02***	4.609***
	(0.349)	(0.486)	(0.364)	(1.014)
Obs.	300	300	300	300
R-squared	0.978	0.992	0.993	0.981

Table 5. Bootstrap test of mediating effect.

Variables	Type of effect	Coefficient	Std.	95% Intervals
Energy efficiency	Indirect	-0.113**	0.048	[-0.223, -0.030]
	Direct	-0.350***	0.131	[-0.654, -0.126]
Technological innovation	Indirect	-0.186**	0.078	[-0.365, -0.058]
	Direct	-0.276***	0.080	[-0.445, -0.125]

suppressive impact on carbon emissions, thus proving H2d. It could be ascribed to the closure of polluting companies and the reformation and modernization of industrial frameworks aimed at facilitating the decrease in carbon emissions and realizing the objective of „double carbon".

Heterogeneity Analysis

Given the diversity of the decrease effect, this study classifies the 30 provinces (except Tibet due to data availability) into three categories. The lndig coefficient is negative and small in column (2) of Table 7, but not statistically significant. The digital economy is largely responsible for the decrease in carbon emissions in the eastern area, which has crossed a key node. Therefore, the impact is not obvious.

In column (3), the coefficient of lndig is positive while lacking statistical significance. One explanation is that the central region's digital economy is in the early stages of promoting carbon emission reduction. At present, it has not crossed the key nodes, and the impact has not yet been able to offset the carbon emissions accumulated by high energy-consuming industries. The lndig coefficient in column (4) is negative and significant. Currently, there is a relatively greater magnitude of carbon reduction impacts in the western area. Over the past years, the enhancement of digital economy infrastructure in the western region has resulted in a decrease in carbon emissions. In the past decade, due to the heavy carbon emission reduction burden from the government, plenty of heavy factories and manufacturing firms (for example, Hon Hai Technology Group) have moved to the central and western provinces with low environmental protection pressure and sufficient cheap labor force, such as Henan and Guizhou provinces. Therefore, the rapid development of digital economy infrastructure can easily improve their condition of carbon emissions.

Robustness Checks

Endogeneity Test

The increase in the digital economy has a significant impact on the geographical distribution of carbon emissions. Regions where the intensity of carbon emissions is high may be forced to facilitate the digital transformation of conventional sectors under public pressure. Thus, to address the issue of endogeneity, the study selected the one-period lagged digital economy

Table 6. Results of Moderating effect test.

Variables	(1) lnca	(2) lnca	(3) lnca	(4) lnca
lndig	-0.463***	-0.489***	-0.463***	-0.541***
	(0.118)	(0.114)	(0.118)	(0.124)
lntfp		-0.036*		
		(0.023)		
lndig* lntfp		-0.030**		
		(0.015)		
lnins				-1.395*
				(0.797)
lndig* lnins				-0.790**
				(0.327)
Controls	YES	YES	YES	YES
Province fixed	YES	YES	YES	YES
Year fixed	YES	YES	YES	YES
Constant	2.256***	2.171***	2.256***	3.164***
	(0.613)	(0.589)	(0.613)	(0.914)
Obs.	300	300	300	300
R-squared	0.980	0.980	0.980	0.981

Table 7. The results of regional heterogeneity analysis.

Variables	(1) Whole	(2) Eastern	(3) Central	(4) Western
lndig	-0.463***	-0.060	0.211	-0.974***
	(0.118)	(0.097)	(0.546)	(0.252)
Controls	YES	YES	YES	YES
Province fixed	YES	YES	YES	YES
Year fixed	YES	YES	YES	YES
Constant	2.256***	2.285**	4.080**	-2.956**
	(0.613)	(0.929)	(1.662)	(1.123)
Obs.	300	90	30	50
R-squared	0.980	0.981	0.981	0.993

(lndig) as the instrument variable (IV) to investigate the real effect. The coefficient of L.lndig in column (1) is negative, which aligns with the baseline regression.

Replace the Explained Variable

Considering the diversity of economic development, the utilization of carbon emissions per GDP unit was used to measure the intensity. However, there are still huge differences in population size among regions. This paper uses per capita carbon emissions as the explained variable to perform a rigorous test of validity. The coefficient of lndig is still negative and significant, which aligns with the findings shown in Table 3. It demonstrates the decrease in carbon emissions by fostering the growth of the digital economy.

Removing Extreme Values

Considering that individual extreme values may bias the empirical results, they should be excluded. In this study, Beijing (the highest) and Qinghai Province (the lowest) are eliminated, and then benchmark regression analysis is carried out again. As indicated in column (3) of Table 8, the impact is constantly negative and considerable.

Table 8. Result of the robustness test.

Variables	(1) One-period lagged	(2) Replace the explained variable	(3) Removing extreme values	(4) Adjusted sample period
lndig		-2.870**	-0.515***	-0.423**
		(1.391)	(0.120)	(0.166)
L.lndig	-0.405***			
	(0.118)			
Controls	YES	YES	YES	YES
Province fixed	YES	YES	YES	YES
Year fixed	YES	YES	YES	YES
Constant	2.399***	23.17***	0.714	2.897***
	(0.676)	(6.258)	(0.516)	(0.833)
Obs.	270	300	280	180
R-squared	0.993	0.960	0.992	0.992

Adjusted Sample Period

This study also adopts the method of shortening the sample interval for robustness checks. Taking into consideration the rapid growth of the regional economy after 2015, this study retains the data from 2015 to 2022 for analysis. The coefficient of lndig in column (4) of Table 8 remains negative, aligning with the results in Table 3, and the results are further strengthened in terms of their dependability. Furthermore, the coefficient of lndig is larger than that of the whole sample, indicating that the digital economy has demonstrated greater efficacy in facilitating the reduction of carbon emissions.

Threshold Regression Analysis

The regression findings from the benchmark analysis show a substantial influence on the decrease of carbon emissions, but various factors influence this impact. Therefore, it is necessary to examine whether a nonlinear characteristic exists. This shows the periodical effect on carbon emission reduction. To answer this question, this study constructs the subsequent threshold regression model:

$$Y_{it} = \alpha_0 + \alpha_1 \text{lndig} \times I\left(Z \leq \beta_1\right) + \alpha_2 \text{lndig} \times I\left(\beta_1 < Z \leq \beta_2\right) + \ldots + \alpha_n \text{lndig} \times I\left(\beta_{n-1} < Z \leq \beta_n\right) + X_{it} + \mu_i + \theta_t + \varepsilon_{it} \quad (6)$$

Here, Z represents the threshold variable, I represents the index function, and β_n represents the threshold value. The measure of financial development level is the ratio of total deposits and loans of financial institutions to GDP. The bootstrapping method is used to sample the data repeatedly, 1000 times. The results indicate that the single and double thresholds of financial development level are significant, but the triple threshold is not. It indicates that there is a double threshold, with values of 1.001 and 1.258, respectively.

Subsequently, this paper conducts threshold analysis, and the results are in Table 9. The digital economy significantly influences carbon emissions, displaying a clear and noticeable double-threshold effect. This effect shows a non-linear relationship that continuously affects carbon emissions. When the financial development level falls below the first threshold (1.001), there is a notable and adverse effect. That is a 1% increase in the digital economy will lead to a 0.378% decrease in carbon emissions. When the financial development ranges from 1.001 to 1.258, the coefficient is -0.420, showing a continuous suppression phenomenon. When the financial development level exceeds the second threshold (1.258),

Table 9. Results of threshold regression.

Variables	(1) Estimation coefficient	(2) T value
Finance<1.001	-0.378***	-10.93
	(0.035)	(0.035)
1.0018<Finance<1.258	-0.420***	-11.82
	(0.036)	(0.036)
Finance>1.258	-0.472***	-12.72
	(0.037)	(0.037)
Controls	YES	YES
Province fixed	YES	YES
Year fixed	YES	YES
Constant	0.424*	1.92*
	(0.221)	(0.221)
Obs.	300	300

the coefficient of the digital economy is -0.472. The result provides further evidence that, as the degree of financial development advances, the inhibitory influence grows. This may be related to the green credit policy launched by the government. In recent years, Chinese financial institutions have launched „green loans", linking the amount of carbon emissions from enterprises to the interest rates on loans. Put simply, the lower the carbon emission intensity or the greater the reduction, the lower the loan interest rate. Besides, financial institutions are more inclined to provide loan support to enterprises conducting green infrastructure upgrades. As a result, the industries implemented measures, which are critical in helping to reduce carbon emissions.

Conclusions and Suggestions

Conclusion

The digital economy of China has transitioned into a new phase and offers novel solutions to reduce carbon emissions. Utilizing provincial data, this study investigates the impact and mechanism by using the moderating, mediating, and threshold models. Employing these models for in-depth analysis can help us achieve a more efficient carbon emission reduction goal. It draws the following conclusions: First, carbon emissions can be considerably reduced through the digital economy, and this result passes several robustness checks. Second, the results of intermediary effect analysis indicate that it can facilitate the reduction by improving energy efficiency and fostering technical innovation. The results of the moderating effect analysis show that optimizing the allocation of resources and promoting the upgrading of industrial structures can influence the effect. Third, heterogeneity analysis revealed a significant drop in carbon emissions in the western area, while not significant in other regions. Fourth, the threshold effect analysis reveals that the reduction impact is influenced by the degree of financial development, and there are double thresholds. The findings in this study can provide insightful thoughts for the government in their future policy implementation, especially in the innovation of digital technology and financial tools [39].

Policy Suggestions

This study provides the following suggestions: Firstly, develop the digital economy and enhance urban digitalization. The empirical analysis indicates that the digital economy facilitates the shift towards low-carbon behaviors, and it can also generate economic advantages as well as environmental benefits. Local governments should improve the market mechanism and expedite the development of information infrastructure. Simultaneously, emphasizing the cultivation of digital talents is also necessary. Leveraging its technological and scale advantages and strengthening its contribution to reduce carbon emissions [18].

Second, strengthen technological innovation and form a specific mechanism for carbon emission reduction. Relying on the diverse innovation platforms provided by digital technology will increase the intensity of technological innovation [40]. For example, Jiangsu province has published clear plans for the 14th Five Year Plan in digital innovation platforms. Furthermore, the government can improve the energy consumption assessment system by guiding the development of the digital economy in a low-carbon orientation and improving energy utilization efficiency. The local government can also guide the healthy development of novel business models, promote the establishment of innovative industrial systems, and transform traditional industries with high-tech.

Third, the implementation of diverse governance methods that take into account variations in regional development. Given the differences in regional endowments, it is necessary to adjust the pace of digital economy development. Simultaneously, it is imperative to enhance the synergies of digital economic governance in different areas [41]. Regions with an established digital economy should lead the way and rationally export digital resources to backward regions, while regions characterized by a low level should expedite the process of constructing new infrastructure and realize the late-comer advantages.

Fourth, it must fully integrate the digital economy and financial institutions and reduce carbon emissions. The government can boost the incorporation of financial services with modern digital technologies, which is crucial to addressing carbon emissions. Simultaneously, it is important to improve the usability of various financial products, provide a diversified portfolio of financial products for related manufacturing firms in their environmentally friendly transformation, and reduce the risks they face. Besides, financial institutions should vigorously develop green credit to provide low-carbon environmental protection enterprises with credit support or low interest rates. It is imperative for the financial market to proactively direct the allocation of money towards regional green development. Furthermore, the government should consider its regional heterogeneity and formulate policies that are consistent with local environmental protection and financial development levels; for example, the policy can be relatively strict in the eastern instead of the western.

Research Limitations and Future Outlook

Even though this study conducts a thoughtful empirical analysis and investigates the in-depth mechanism analysis of the digital economy on carbon emission reduction in China, there also exist some limitations the researcher can consider solving in the future. First, this study only analyzes the provincial level. The researchers can check whether the analysis can be applied to the city level, even though there might be tough tasks in the data availability, especially for the western cities. Second, this study does not conduct a spatial analysis, and therefore the spillover effects are not examined. The researchers can probably conduct the spatial analysis to examine the spillover effect of the digital economy. There are also some other research limitations not listed here, which the researchers can try to solve in the future.

Conflicts of Interest

The authors declare no conflict of interest.

Funding

This research received support from the National Social Science Fund of China (22BJY036) and the Research Start-up Fund Project by Jiangsu Ocean University (KQ19060).

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