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Impact of Digital Economy on Carbon Emissions and Its Mechanism: Evidence from China

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Abstract: Advancing the digital economy while curbing carbon emissions is essential for fostering high-quality economic growth. Based on China's provincial panel data from 2011 to 2021, this study adopts an empirical model to investigate the direct influence of digital economic development on carbon emissions and utilizes both a mediating effects model and a moderating effects model to explore the transmission mechanism of green technological innovation and the moderating effect of R&D investment. The research results indicate that the following: (1) The digital economy contributes to carbon emissions reduction. (2) The analysis of heterogeneity demonstrates that the impact of the digital economy on carbon emissions is pronounced in the eastern and central regions of China but is insignificant in the western provinces. Furthermore, the carbon mitigation effect of the digital economy is more potent in regions with high marketization compared to those with low marketization. (3) The mediation effect analysis shows that green technology innovation plays a transmitting role between the digital economy and carbon emissions reduction. (4) The moderating effect test reveals that R&D investment enhances the digital economy's ability to reduce carbon emissions. The conclusions highlight the need to optimize digital economy development and strengthen green technology innovation to achieve carbon emissions reduction.

Keywords: digital economy; carbon emissions; green technology innovation; R&D investment

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1. Introduction

The escalating climate crisis has created urgent demands for global carbon emissions reduction. Achieving carbon peak targets and carbon neutrality has become a consensus within the international community, emphasizing the need for green development. According to the International Energy Agency's statistical report, China's carbon emissions reached 12.6 billion tons of CO_2 in 2023 [1]. To address the environmental challenges posed by carbon emissions, the Chinese government has set clear targets: achieving carbon peak by 2030 and carbon neutrality by 2060. Consequently, finding ways for China to reach these ambitious goals and transition to a green economy has become a pressing issue.

According to the White Paper on Global Digital Economy (2024) issued by the China Academy of Information and Communications Technology (CAICT), the digital economy accounted for 60% of global GDP in 2023 [2]. The rapid development of the digital economy has transformed human life, influencing not only communication but also interaction with the environment. Digitalization has opened new avenues for innovation and efficiency, providing tangible benefits and new possibilities for individuals, organizations, and nations. However, concerns have arisen about the environmental impact of the digital economy, especially its link to carbon emissions.

The concept of digital economy was first defined as a new paradigm of economic and social operation supported by information and communications technology in the network intelligence age [3]. Additionally, the concept of digital economy is continually refined by international organizations, countries, and research institutions. The Organization for

Economic Cooperation and Development (OECD) describes DE as an economic activity that uses electronic ordering or electronic delivery methods to realize transactions [4]. The National Bureau of Statistics of China (NBSC) defines DE as "a series of economic activities that take data resources as a key factor of production, modern information networks as an important carrier, and the effective use of information and communication technologies as an important driving force for improving efficiency and optimizing economic structure" [5].

With the rapid development of the digital economy and increasing attention to climate change, many scholars have researched the impact of the digital economy on carbon emissions at both macro and micro levels. According to the research results, the literature can be classified into three categories.

The first category of findings indicates that the digital economy can contribute to reducing carbon emissions [6–13]. The research has shown that the digital economy can facilitate the reduction of carbon emissions through various factors, including energy consumption, environmental pollution, technological progress, digital infrastructure development, product innovation, high-quality foreign direct investment, and spatial spillover effects. Li et al. (2023) [14] also proved that the digital economy has reduced China's carbon emission intensity from 2013 to 2020. On an industrial scale, the existing literature has also revealed that the digital economy helps reduce carbon emissions, as the digital economy can promote virtual agglomeration in carbon reduction [15]. Some scholars have conducted research at the micro level, studying the impact of enterprises' digital transformation on carbon emissions under the digital economy. Haseeb et al. (2019) [16] found that the digital economy can reduce enterprise carbon emissions by combining advanced knowledge and human resources together. Goldfarb and Tucker (2019) [17] suggested that digital technology can help enterprises reduce carbon emissions. The carbon reduction effect of the digital economy has also been verified in China's listed manufacturing firms [18]. Although many studies have proved that the digital economy has an inhibitory effect on carbon emissions, notably, the second group of studies presents a different perspective. It finds that the digital economy might increase a country's total emissions by expanding digital demand and supply scales. Driven by expanding digital demand and supply scales, digital emissions increased from 210 to 418 Mt CO_2 between 2002 and 2007 [19]. Xie J. (2024) [20] found that digital economy significantly boosts emissions in the top twenty carbon-emitting nations. Based on China's provincial data, Zhang et al. (2022) [21] revealed that the development of the digital economy is neither conducive to improving energy efficiency nor helpful to reducing carbon emissions. Dong et al. (2022) [22] used country-level panel data from 2008 to 2018 and revealed that digital economy significantly reduces the carbon emission intensity but increases the per capita carbon emissions. The third category of literature suggests that the relationship between the digital economy and carbon emissions is nonlinear. The effect of digital economy on carbon emissions could also be an inverted U-shape [23,24] or an "N" shape [14].

In summary, whether the digital economy promotes or inhibits carbon emissions remains inconclusive. As digital economic development continues, understanding how this economic paradigm affects carbon emissions warrants further investigation. This paper aims to explore the impact of the digital economy on carbon emissions at the provincial level in China and further examine the effecting mechanisms by using a mediating model and a moderating model, respectively. This study expands the theoretical mechanisms of how the digital economy affects carbon mitigation. Moreover, the findings not only offer new ideas for managing inter-regional carbon emissions in China but also serve as valuable references for other developing countries aiming to develop their digital economies and pursue low-carbon growth.

The contribution of this paper is threefold. (1) In terms of research content, based on the "theoretical–empirical analysis", this study integrates the digital economy, green technology innovation, R&D investment, and carbon emissions into a comprehensive framework, examining the digital economy's impact on carbon emissions and its underlying mechanisms. (2) Regarding research perspectives, this study examines the two key variables of R&D investment and green innovation as influencing mechanisms, effectively clarifying the transmission path between the digital economy and carbon emissions, which offers novel inspirations for related research. (3) From a multidimensional perspective, the paper explores the regional and marketization heterogeneity in the digital economy's impact on carbon emissions. This heterogeneity analysis enhances the specificity of the conclusions and recommendations. In particular, the findings on marketization heterogeneity provide new directions for reforms aimed at low-carbon development.

The remainder of this paper is organized as follows: Section 2 provides the theoretical mechanism and research hypotheses. Section 3 describes the models and explains the variables. Section 4 reports the main empirical results. Section 5 provides a discussion and concludes with policy implications.

2. Theoretical Mechanism and Hypothesis Development

2.1. The Direct Effect of Digital Economy on Carbon Emissions

The digital economy has directly altered human lifestyles, production methods, and carbon emissions.

First, the digital economy can help reduce carbon emissions through changing the lifestyle. The rise of the digital economy has increased the use of digital tools like telecommuting, online shopping, and virtual meetings. These tools reduce the need for transportation and travel, leading to lower carbon emissions from vehicles. Additionally, the digital economy can replace traditional physical activities, such as using digital documents instead of paper and streaming videos instead of DVDs, which reduces energy consumption and related carbon emissions.

Second, compared to traditional manufacturing, which is a major emitter, the digital industry is "greener". The digital economy inherently promotes energy conservation and carbon reduction. According to the NBSC, the digital economy consists of the digital industry and industrial digitization [25]. The digital industry primarily encompasses the manufacturing of communication equipment, information transmission, internet services, and software technology services. Industrial digitization refers to the use of digital technology in industries that already exist but have resulted in increased output and efficiency through the application of digital technology and data resources, integrating digital technology with the real economy.

Third, digital transformation in the era of the digital economy can enhance carbon mitigation. On one hand, big data can store information across the entire industry chain and accurately disclose significant amounts of environmental data, promoting "source control" of carbon emissions. This helps organizations quickly identify internal control issues, enabling targeted adjustments and improvements in carbon reduction. Furthermore, increased information transparency allows organizations to quickly track dynamic changes in carbon emission reductions and green product trends in the market [26].

Therefore, Hypothesis 1 is formulated as follows:

Hypothesis 1. *The digital economy reduces carbon emissions*.

2.2. Mediating Effect Analysis

The growth of the digital economy accelerates the dissemination of information. Through information sharing and expansion, the continuous accumulation of knowledge has accelerated technological progress. Furthermore, information sharing and telecommunications infrastructure, key components of the digital economy, can promote technological innovation, including green technology innovation [27].

According to Ecological Modernization Theory [28], technology innovation can mitigate the environmental impacts of economic growth by enhancing resource efficiency. Green technology innovation, a subset of technology innovation, refers to technological or product innovations that enhance environmental performance, emerging as a critical response to challenges such as ecological degradation, pollution, energy scarcity, and resource depletion [29]. The positive impact of green technology innovation on carbon mitigation has been confirmed by numerous studies [29–33].

The positive impact can be understood in two ways. On the one hand, through green technology innovation, the digital economy is integrated into carbon-intensive sectors like industrial production and distribution, reducing energy and resource consumption in traditional industries, controlling carbon growth, and lowering overall carbon levels, leading to energy conservation and emission reduction. On the other hand, the digital economy, as a driving force for green transformation, promotes digital, intelligent, and other green technologies to facilitate carbon reduction across various sectors.

Based on the above analysis, this article puts forth Hypothesis 2.

Hypothesis 2. *Green technology innovation acts as a mediator between the digital economy and carbon reduction.*

2.3. Moderating Effect Analysis

Investment in research and development (R&D) can support enterprises and research institutions in strengthening technological transformation and transitioning to a low-carbon economy. First, R&D investment allows digital economy infrastructure to more effectively support energy conservation and emission reduction efforts. Adequate R&D investment can better utilize digital economy infrastructure and technologies for carbon reduction activities. Secondly, increased R&D investment can boost research motivation and capabilities, finally helping low-carbon development. Especially given the public nature of carbon reduction, R&D investment from the governments can improve expected returns or decrease costs for organizations. Because carbon emission reduction has the characteristics of a public good, investors cannot fully monopolize its benefits. Emission reduction and green transformation require significant R&D investment and are long-term commitments, which may discourage organizations from participating. Lastly, government R&D investment can promote collaboration among governments, universities, and enterprises, accelerating synergies in carbon reduction efforts.

In summary, this study prompts the third hypothesis:

Hypothesis 3. *R&D investment strengthens the effect of the digital economy on carbon reduction.*

The mechanism analysis of this paper is shown in Figure 1.

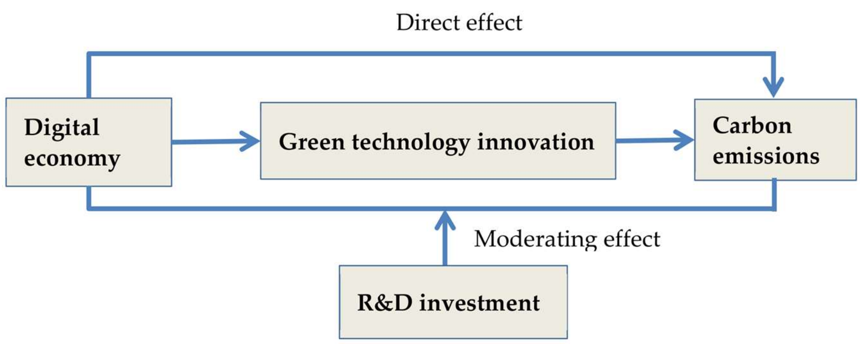

Figure 1. Mechanism analysis framework.

3. Variables and Methods

3.1. Variables

3.1.1. Carbon Emissions

The major carbon sources are energy consumption, so this study mainly estimates carbon emissions from energy consumption. Based on IPCC Guidelines [34], carbon emissions (CE) have been calculated by Equation (1).

$$CE = \sum_i Q_i NCV_i EF_i \quad (1)$$

In Equation (1), CE refers to carbon dioxide emissions; Q_i is the consumption of type i fuel; NCV_i represents the net calorific value of type i fuel, from the China Energy Statistical Yearbook [35]; and EF_i is CO_2 emission factors of type i fuel.

3.1.2. Digital Economy

Since no official method exists for measuring the digital economy, scholars mainly use various indicators to measure its development [22,36–41]. Based on different research objects, scholars choose specific indicators that are not the same. Considering the data availability and accurate descriptions of the characteristics of the digital economy, this paper, building on the research by Zhao et al. (2020) [38], employs a digital economy development index (DEI) to assess the development level of the digital economy. The DEI contains five secondary indexes: internet usage, number of employees in the internet industry concerned, gross internet-related product, mobile internet usage, and digital finance, as shown in Table 1. For the inclusive development of digital finance, this study adopts the Peking University Digital Financial Inclusion Index of China (PKU_DFIIC) [42]. This paper adopts an entropy evaluation method to calculate the weight of each index in DEI. Table 1 shows the indicator weights in the DEI measurement system employed in this study. Based on the DEI, the levels of digital economy development for China's provinces have been calculated.

Table 1. DEI measurement system.

Sub-Indices	Measurement	Indicator Weights	Data Source	Property
Internet usage	Internet users per 100 persons	0.077	NBSC	+
Number of employees in the internet industry concerned	The proportion of employees in the information transmission, software, and information technology service industries to all the local employees	0.315	NBSC	+
Gross internet-related product	The ratio of total telecommunications services product to permanent population	0.432	NBSC	+
Mobile internet usage	Number of mobile phones per 100 persons	0.085	NBSC	+
Digital finance	Digital Financial Inclusion Index of China	0.091	IDFPU	+

3.1.3. Mediator Variable

As aforementioned, this paper uses green technology innovation (GI) as a mechanism to enhance the impact of DE on CE. Due to variations in research subjects and statistical practices, scholars have employed various methods to measure GI. Some research [43,44] has utilized green patent citations as a proxy for GI, whereas a few studies [45–49] have employed a broader scope, including both green invention patents and green utility patents to represent green patents. Therefore, considering China's patent system [50] and data accessibility, this study measures a province's GI capability by employing the latter method.

3.1.4. Moderator Variable

Research has established that R&D investment (RD) is a key contributor to economic development and technological innovation [51,52]. Building on these studies, this paper investigates whether RD can moderate the digital economy's impact on carbon emissions.

3.1.5. Control Variables

Ehrlich et al. (1971) [53] introduced the IPAT equation to analyze environmental changes resulting from human activities such as population growth, economic development, and technological advancements. Yoichi Kaya (1990) [54] applied the IPAT equation to study carbon emissions and developed the KAYA equation, which represents CO_2 emissions as a product of population, per capita GDP, energy intensity, and carbon emission factors. Therefore, the factors determining carbon emissions include population, economic development, energy consumption, and technology. To control for other factors affecting the empirical results, several control variables are included in the econometric model, such as GDP, industrial structure (IS), energy structure (ES), population (PU), the level of foreign direct investment (FDI), and urbanization rate (UR). The share of the secondary industry output in regional GDP is used to measure IS, and the ratio of coal consumption to total energy consumption is adopted to calculate ES. This paper measures FDI by using the ratio of foreign direct investment to GDP.

3.2. Data Sources

This paper covers panel data of 30 Chinese provinces from 2011 to 2021. The data originate from the databases of the China Information and Communication Research Institute, China National Intellectual Property Administration, China Energy Statistics yearbooks, China statistical yearbooks, and the statistical yearbooks of each province. The missing part in the middle of each year is filled in to obtain the linear interpolation version of the data by using the linear trend of the data. To eliminate heteroskedasticity and ensure the smoothness of data, some variables are logarithmically processed, including the logarithm of CE (lnCE), population (lnPU), GDP (lnGDP), green technology innovation (lnGI), and R&D investment (lnRD), as listed in Table 2. To avoid interference from outliers, the data have been winsorized at the 1st and 99th percentiles.

Table 2. Descriptive statistics.

Variable Name	Symbol	Observations	Mean	Sd	Min	Max
Carbon emissions	lnCE	330	10.44	0.736	8.494	11.91
Digital economy	DE	330	0.216	0.153	0.00765	0.954
Population	lnPU	330	7.687	1.35	3.219	10.74
Gross Domestic Product	lnGDP	330	9.825	0.89	7.223	11.73
Industrial structure	IS	330	0.407	0.0805	0.16	0.62
Energy structure	ES	330	0.385	0.15	0.00594	0.692
Green technology innovation	lnGI	330	7.687	1.35	3.219	10.74
Rate of urbanization	UR	330	0.596	0.121	0.35	0.896
Foreign direct investment	FDI	330	0.187	0.018	0.000	0.121
R&D investment	lnRD	330	5.615	1.329	2.342	8.295

3.3. Methods

3.3.1. Benchmark Model

To investigate the effect of digital economy on carbon dioxide emissions, we consider the following two-way fixed effects model:

$$CE_{nt} = \beta_0 + \beta_1 DE_{nt} + \beta_2 control_{nt} + year_t + prov_n + \varepsilon_{nt} \quad (2)$$

CE_{nt} refers to carbon dioxide emissions; DE_{nt} is the level of the digital economy; $control_{nt}$ represents a set of control variables; β_0 is a constant term; and β_2 measures the direct effect of the digital economy on total factor carbon emission performance. $year_t$ is the year fixed effect, controlling for time-invariant provincial characteristics; $prov_n$ denotes province fixed effects, which control time-invariant province shocks; and ε_{nt} is a stochastic error term.

3.3.2. Mediating Effect Model

In order to investigate whether green technology innovation has transmission effects between DE and CE, this paper adopts a two-stage method. In the initial stage, this study tests the impact of the digital economy on green technology innovation, as shown in Equation (3). In the second stage, the influence of GI on CE is examined by using Equation (4).

$$GI_{nt} = \beta_0 + \beta_3 DE_{nt} + \beta_2 control_{nt} + year_t + prov_n + \varepsilon_{nt} \quad (3)$$

$$CE_{nt} = \beta_0 + \beta_4 GI_{nt} + \beta_2 control_{nt} + year_t + prov_n + \varepsilon_{nt} \quad (4)$$

where GI refers to the green technology innovation. If regression coefficients β_3 and β_4 are significant, the mediating effect exists.

3.3.3. Moderating Effect Model

Based on Equation (2), Equation (5) is constructed to investigate whether R&D investment can moderate the relationship between DE and CE.

$$CE_{nt} = \beta_0 + \beta_1 DE_{nt} + \gamma_1 RD_{nt} + \gamma_2 RD_{nt} \times DE_{nt} + \beta_2 control_{nt} + year_t + prov_n + \varepsilon_{nt} \quad (5)$$

In Equation (5), the RD denotes R&D investment. If regression coefficients γ_1 and γ_2 are significant, the moderating effect exists.

4. Results and Discussion

4.1. Baseline Regression

Based on Equation (2), this paper conducts a regression analysis, and the benchmark regression results are shown in Table 3.

Table 3. Baseline regression results.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	lnCE	lnCE	lnCE	lnCE	lnCE	lnCE	lnCE
DE	−0.719 ***	−0.863 ***	−0.834 ***	−0.963 ***	−0.933 ***	−0.923 ***	−0.921 ***
	(−2.95)	(−3.73)	(−3.54)	(−4.39)	(−4.13)	(−4.08)	(−4.06)
lnPU		0.181 ***	0.186 ***	0.138 ***	0.132 ***	0.123 ***	0.122 ***
		(6.11)	(6.03)	(4.67)	(4.23)	(3.73)	(3.72)
lnGDP			−0.052	0.063	0.052	0.025	0.032
			(−0.62)	(0.80)	(0.64)	(0.29)	(0.37)
ES				1.038 ***	1.052 ***	1.054 ***	1.058 ***
				(6.90)	(6.90)	(6.91)	(6.92)
UR					0.214	0.265	0.330
					(0.58)	(0.71)	(0.85)
IS						0.273	0.286
						(0.94)	(0.98)
FDI							−0.304
							(−0.60)
Constant	10.428 ***	9.214 ***	9.660 ***	8.445 ***	8.467 ***	8.631 ***	8.533 ***
	(433.04)	(46.06)	(12.95)	(11.83)	(11.83)	(11.71)	(11.29)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	330	330	330	330	330	330	330
R-squared	0.134	0.231	0.230	0.337	0.336	0.335	0.334
F	8.283	11.660	10.769	15.028	14.016	13.190	12.407

Note: *** $p < 0.01$; ( ) presents the t-values.

As shown in Column (1) of Table 3, the coefficient for DE is −0.719, indicating a significant negative relationship at the 1% significance level in the absence of control variables. When all control variables are incorporated, DE continues to exhibit a significant negative effect on CE at the 1% significance level, with a regression coefficient of −0.921 in Column (7). This result proves that the growth of DE contributes to carbon reduction, verifying Hypothesis 1. Furthermore, the results displayed in Columns (1–7) show that the coefficients for DE are all significantly negative, suggesting that the baseline regression outcomes exhibit a degree of robustness.

4.2. Robustness Test Results

Based on the existing literature, this paper tested the robustness of benchmark regression results in three ways.

4.2.1. Change the Sample Interval

China's digital economy has stabilized since 2013, and the coronavirus outbreak, which was a new engine for the development of digital economy, began in 2020. To minimize the impact of this external shock on the estimation results, this paper dropped the data in 2020 and beyond, substituting the sample range with the period from 2013 to 2019, and re-evaluated Equation (2). Column (1) of Table 3 reports the results following the adjustment of the sample period, which confirm the inhibitory impact of DE on CE. Consequently, with the adjusted sample interval, the estimated effect of the DE on CE maintains its robustness.

4.2.2. Lagged Effects Estimation

Considering the time lag inherent in the development of the digital economy, this study incorporated a lagged DE variable into the model and employed the system GMM to examine the impact of the digital economy on carbon emissions. The regression outcomes are presented in Column (2) of Table 4. As indicated in Column (2) of Table 3, the AR(1) coefficient is statistically significant, while the AR(2) coefficient is not. The Sargan test result is also insignificant, which endorses the appropriateness of the model specification. The coefficient for lnCE_1 is significant, indicating that changes in CE in the prior period influence current changes in CE. Moreover, the coefficient of DE remains strongly negative, signifying its inhibitory effect on CE.

Table 4. Robustness testing results.

	(1)	**(2)**	**(3)**	**(4)**
	lnCE	lnCE	first-stage	second-stage
lnCE_1		0.865 ***		
		−21.55		
DE_w	−0.696 **	−0.242 **		−2.942 ***
	(−2.56)	(−2.11)		(−2.52)
IV = ID_2			−0.0001 ***	
			(7.46)	
Control variables	Control	Control	Control	Control
Constant	8.923 ***		0.058 ***	10.57 ***
	(9.33)		−21.86	−155.01
Year FE	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes
Obs.	270	270	330	330
R-squared	0.224			
F	7.876		55.6	
AR(1)		−6.20 ***		
AR(2)		0.42		
Sargen test		219.13		
Wald F-statistic				36.35

Note: ( ) presents the *t*-values. *** $p < 0.01$ and ** $p < 0.05$, respectively.

4.2.3. Instrumental Variable Test

Due to the possibility of unobservable variables, measurement errors, and reverse causality, the research model may encounter potential endogeneity problems. To mitigate the influence of the possible endogeneity issue, this paper uses an instrumental variable test of two-stage least squares (2SLS) to reassess the results. Most studies have used the historical data of post and telecommunication [10,37,55] or number of landlines telephones [56] in 1984 as the instrumental variables. However, this indicator still has disputes for reasons such as the adjustment in the administrative jurisdiction of Chinese provinces and the discontinuity of technology associated with the widespread adoption of the internet [11]. Drawing on the above considerations, this paper adopts the approach of Zhang et al. (2022) [21] by selecting the number of Internet broadband access users per unit of land area for each province in the two years following the study period, termed the Internet user density with a two-year latter (ID_2) as the instrumental variable. On the one hand, the expansion of DE is contingent upon communication technologies, and ID_2 can serve as an indicator of the current state of DE to some extent. Thus, the choice of ID_2 as the instrumental variable meets the relevance criterion. On the other hand, ID_2 is likely to influence CE in the concurrent year but is expected to have a minimal impact on CE from the two preceding years. Consequently, the instrumental variable ID_2 adheres to the exogeneity requirement.

The results are presented in Columns (3) and (4) of Table 4. In the first stage regression, the coefficient for IV is statistically significant at the 1% level, and the F-statistic value (55.6) significantly exceeds the critical value of 10 for the weak instrument test. In the second stage regression, the estimated coefficient for DE is −2.942 and is significant at the 1% level. Additionally, the Wald F-statistic is 36.35. These results suggest the robustness of the benchmark model.

4.3. Heterogeneity Analysis

Variations in regulations, economic development, and energy consumption across different regions may result in heterogeneity in how DE affects CE. Given China's vast territory, these differences among provinces need to be considered. In order to study the regional heterogeneity effects of DE on CE, this paper divides the data into eastern, central, and western regions. The analysis results presented in Columns (1–3) of Table 5 indicate that DE in eastern and central regions can reduce CE. However, the effect of DE on CE in western provinces is not significant. The reason may be that, compared with eastern and central regions, western regions have a relatively lower level of digital infrastructure and digital industries [57].

Table 5. Heterogeneity analysis results.

	(1)	(2)	(3)	(4)	(5)
	East regions	Central regions	West regions	Low-marketization regions	High-marketization regions
	lnCE	lnCE	lnCE	lnCE	lnCE
DE	−0.984 ***	−4.449 ***	−0.532	−0.008 *	−0.012 ***
	(−3.92)	(−4.41)	(−0.85)	(−1.80)	(−4.20)
lnPU	0.007	0.171 ***	0.040	0.079	0.075 *
	(0.20)	(2.73)	(0.63)	(1.57)	(1.74)
lnGDP	0.456 ***	0.284 *	0.195	0.097	−0.195
	(3.48)	(1.68)	(0.78)	(0.62)	(−1.16)
ES	−0.054	0.136	1.703 ***	0.012 ***	0.007 ***
	(−0.26)	(0.50)	(4.89)	(4.98)	(2.76)
UR	1.154 ***	1.124	−4.363 **	0.318	−0.144
	(2.80)	(0.77)	(−2.56)	(0.27)	(−0.29)
IS	0.252	−1.485 ***	−0.141	−0.000	0.005
	(0.52)	(−3.33)	(−0.18)	(−0.03)	(0.96)
FDI	−0.918 **	−0.067	5.125 *	−2.940	0.769
	(−2.15)	(−0.03)	(1.95)	(−1.65)	(1.38)

Table 5. *Cont.*

	(1)	(2)	(3)	(4)	(5)
_cons	5.265 ***	6.968 ***	9.275 ***	8.249 ***	11.551 ***
	(4.21)	(6.54)	(4.68)	(7.53)	(7.57)
Obs.	121	88	121	165	165
R-squared	0.510	0.424	0.448	0.366	0.181
F	8.925	5.178	7.328	7.391	3.962

Note: ( ) presents the t-values; *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$, respectively.

The level of marketization indicates how market-oriented a region's goods and production factors are at a given time, characterized by the free movement of goods and factors of production, less market intervention, and active competition mechanisms. The development of the digital economy is influenced by marketization, and previous studies [58,59] have examined the environmental impact of market factors. This article uses a marketization index to group samples and examines the DE's impact on CE with different levels of marketization. The marketization index is based on the "Marketization Index of China's Provinces" [60] and includes five components: government–market relations, the development of the non-state economy, product market maturity, factor market development, and intermediary organizations and the legal environment. Provinces with marketization scores above the median are classified as high-marketization regions, while those below the median are considered low-marketization regions. The results in Columns (4) and (5) of Table 5 show that DE reduces carbon emissions in both high and low-marketization regions. However, the effect of the DE on CE is stronger in high-marketization regions, with DE coefficients of −0.012 and −0.008, respectively. This suggests that more mature markets better support the regulatory impact of DE on CE.

4.4. Mediating Effect Test

Columns (1)–(4) in Table 6 display the mediating effect of GI on the relationship between DE and CE. In Column (2) of Table 6, at a 10% level, DE significantly contributes to lnGI. In Column (3), the coefficient of DE was −0.206, statistically significant at a 5% level, indicating that GI helps decrease carbon emissions. In Column (4), both DE and lnGI have negative impacts on lnCE with regression coefficients of −0.879 and −0.168, respectively. The findings suggest that the link between the DE and CE is mediated by GI, thus supporting Hypothesis 2.

Table 6. Results of mediating effect analysis.

	(1)	(2)	(3)	(4)
	lnCE	lnGI	lnCE	lnCE
DE	−0.921 ***	0.247 *		−0.879 ***
	(−4.06)	(1.75)		(−3.87)
lnGI			−0.206 **	−0.168 *
			(−2.12)	(−1.76)
lnPU	0.122 ***	0.996 ***	0.314 ***	0.289 ***
	(3.72)	(48.65)	(3.07)	(2.88)
lnGDP	0.032	−0.305 ***	−0.114	−0.019
	(0.37)	(−5.64)	(−1.27)	(−0.21)
ES	1.058 ***	0.071	1.047 ***	1.070 ***
	(6.92)	(0.74)	(6.71)	(7.02)
UR	0.330	0.515 **	0.776 **	0.417
	(0.85)	(2.14)	(2.01)	(1.07)
IS	0.286	0.944 ***	0.536 *	0.444
	(0.98)	(5.19)	(1.72)	(1.46)
FDI	−0.304	0.068	−0.325	−0.292
	(−0.60)	(0.22)	(−0.63)	(−0.58)

Table 6. *Cont.*

	(1)	(2)	(3)	(4)
Constant	8.533 ***	2.112 ***	9.585 ***	8.887 ***
	(11.29)	(4.49)	(12.34)	(11.40)
Year FE	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes
Obs.	330	330	330	330
R-squared	0.334	0.992	0.306	0.339
F	12.407	2536.301	11.241	11.977

Note: ( ) presents the t-values; *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$, respectively.

4.5. Moderating Effect Test

The moderating effect results based on model (4) are reported in Table 7. In Column (1) of Table 7, the coefficient of lnRD is not statistically significant. However, after incorporating their interaction terms between lnRD and DE, the interaction term coefficient in Column (2) is −0.120, statistically significant at the 1% level, and the coefficient of DE is -0.793. The sign of the interaction term is negative, with the same sign as the main explanatory variable, digital economy, which indicates that R&D investment strengthens the inhibitory effect of digital economy on carbon emissions. The absolute value of DE's coefficient in Column (1) 0.711 is smaller than 0.793, which reveals that RD has enhanced the impact of DE on CE. This suggests that the relationship between the DE and CE is positively moderated by R&D investment. Thus, Hypothesis 3 is proved.

Table 7. Results of moderating effect analysis.

	(1)	(2)
	lnCE	lnCE
DE	−0.711 ***	−0.793 ***
	(−2.87)	(−3.28)
lnRD	−0.007	0.001
	(−0.18)	(0.04)
c_DE c_lnRD		−0.120 ***
		(−4.20)
Control variables	Control	Control
Constant	10.271 ***	10.278 ***
	(238.07)	(244.81)
Year FE	Yes	Yes
Province FE	Yes	Yes
Obs.	330	330
R-squared	0.132	0.179
F	7.570	8.745

Note: ( ) presents the t-values; *** $p < 0.01$.

5. Discussion and Conclusions

5.1. Discussion

This study employs theoretical analysis and econometric models to conduct empirical analysis of the digital economy's effect on carbon emissions. The findings show that the growth of the digital economy significantly decreases carbon emissions at the provincial level in China. This result aligns with previous studies in the literature. Wang et al. (2022) [8] demonstrated that the digital economy contributes to a reduction in CO2 emissions based on Chinese provincial data from 2006 to 2017 and analyzed the mediating effects of economic scale, structural changes, and energy composition. Utilizing panel data from Chinese provinces spanning 2006 to 2017, Ma et al. (2022) [11] identified a bidirectional causal relationship between the digital economy and carbon emissions through cointegration tests and causal analysis. Several studies have explored this issue from the perspectives of industry, cities, and enterprises. As the government is the primary agent for policy implementation, provincial-level research can offer more actionable policy recommendations. Furthermore, the findings indicate that both green technology innovation and R&D investment enhance the carbon reduction benefits of the digital economy. The result of regional heterogeneity shows that the digital economy's effect on carbon emissions in western provinces is not as significant as that in eastern and central regions. Coincidentally, except for Shaanxi Province, which has a slightly higher average development level of digital economy than the national average, the development level of digital economy in other western provinces is lower than the national average, and most of them are far below the national average. Additionally, the digital economy's carbon mitigation effect is more pronounced in highly marketized regions. Therefore, to advance green development, provincial governments can make policies that foster green technology innovation, increase R&D investment, and enhance marketization levels.

This paper expands the theoretical framework of low-carbon development by incorporating green technology innovation as a mediating factor and R&D investment as a moderating factor, offering a holistic analytical viewpoint. However, this study has certain limitations. First, the study's time frame is limited to 2011 to 2021 due to the unavailability of recent data, potentially limiting the generalizability of the results. Second, given that the digital economy in China is growing, a more comprehensive indicator system is necessary to assess its development level. Third, this study may not have encompassed all potential variables in examining the factors that influence the impact of the digital economy on carbon emissions. Future studies could address these limitations by developing a more rigorous indicator system for the digital economy and incorporating additional factors, such as environmental taxes and policies.

5.2. Research Conclusions

Promoting the digital economy is key for China to meet its "dual carbon" goals and to ensure high-quality development. Using panel data from 30 provincial samples, this paper employs empirical models to examine digital economy's effects on carbon emissions. Green technology innovation and R&D investment are incorporated as mediating and moderating variables, respectively, to examine the mechanisms by which digital economic development impacts carbon emissions. The specific findings are as follows:

First, the growth of the digital economy in China directly reduces carbon emissions. This conclusion stays valid after robustness tests, including adjusting the sample interval, applying lagged effects estimation, and conducting appropriate instrumental variable tests.

Second, the influence of the digital economy on carbon emissions differs across regions. Heterogeneity analysis reveals that digital economy development significantly reduces carbon emissions in China's eastern and central regions but is insignificant in the western region. This difference can be attributed to region-specific factors such as economic structure, technological level, environmental awareness, and local policies. Higher living standards have made people more likely to seek a greener environment, amplifying the impact of the digital economy. Furthermore, marketization heterogeneity analysis indicates that the digital economy in high-marketization regions facilitates stronger influence than that in low-marketization regions, consequently leading to a more pronounced effect on increasing carbon emissions.

Third, the digital economy indirectly affects carbon emissions through green technology innovation, which acts as a partial mediator. Enhancing green technology innovation helps reduce carbon emissions by developing technologies like clean production, carbon capture, and carbon sequestration. The growth of the digital economy fosters green technology innovation, thereby indirectly reducing carbon emissions.

Finally, R&D investment amplifies the digital economy's ability to reduce carbon emissions. In other words, regions with higher R&D investment are more likely to achieve carbon reduction through the development of the digital economy.

5.3. Policy Implications

The above conclusions offer insights for policymakers, particularly regarding strategic green technology innovation and increasing R&D investment.

First, actively advance the digital economy to strengthen its role in supporting carbon reduction. Specifically, efforts should focus on two areas: digital industrialization and industrial digitization. The government should prioritize the development of core digital technologies such as 5G, integrated circuits, operating systems, and artificial intelligence, as they are the foundation and core drivers of digital progress. Additionally, enhancing data infrastructure is essential for promoting the growth of digital industries. For industrial digitization, the government should develop and refine policies that facilitate digital transformation, such as offering financial support, tax incentives, and easier market access.

Second, differentiated carbon reduction policies should be formulated to account for regional and marketization heterogeneity in China. Since the digital economy's positive impact on carbon reduction in the western region requires further strengthening, dynamic and region-specific strategies should be implemented. This will enable the digital economy to act as the "hardware" supporting efforts to reduce regional imbalances in low-carbon development. Additionally, the government can reinforce the digital economy's capacity for emission reduction by fostering market-oriented development, especially improving the functionality of factor markets. Provinces can carry out regional market integration construction, establish regional cooperation mechanisms, and promote the construction of environmental factor markets.

Third, the government should incentivize green technology innovation through effective institutional arrangements. On the one hand, the government should strengthen policy support for green technology innovation, guiding and assisting organizations through measures like fiscal subsidies, tax cuts, and a green technology trading system. On the other hand, from a consumer perspective, the government can guide green consumption behavior through differentiated tax policies, lower costs for environmentally friendly and low-carbon products, and help these products gain market share. Additionally, the government should increase its procurement of green technologies and products.

Lastly, the government should further increase overall R&D investment in green technologies. First, the government should boost investment in green technology and innovation, providing essential laboratories and technical equipment for green technology innovation, particularly in areas like clean production, carbon capture, and storage. Second, adopt various measures to diversify investment forms, including technical support, tax deductions, and other incentives. Third, local governments can create a subsidy platform for green innovation to attract various types of social funds, continuously injecting new momentum into green innovation.

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