Research on the Impact of Digital Economy Development on Carbon Emissions

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ABSTRACT

In the context of digital transformation, conducting in-depth research on the relationship between the digital economy and carbon emissions is of significant importance for achieving green and high-quality development. This study, based on panel data from 30 provinces in China from 2013 to 2021, establishes a digital economy evaluation index system and uses the entropy method to calculate the level of digital economy development in each province. The study employs a double fixed-effects model to empirically analyze the carbon emission reduction effects of the digital economy. The results indicate: (1) There are significant regional differences in the level of digital economy development in China, with the eastern region having a higher level compared to the central and western regions. (2) The digital economy significantly reduces both carbon emissions and carbon emission intensity. (3) The impact of the digital economy on carbon emissions and carbon emission intensity shows regional heterogeneity, with the central region benefiting the most in terms of carbon emission reduction. Based on these findings, it is suggested to tailor digital economy development strategies to specific regional conditions, enhance regional cooperation, achieve the integration of digital economy and low-carbon economy development, and fully leverage the carbon emission reduction effects of the digital economy.

Keywords: *Digital economy, Carbon emissions, Carbon emission intensity, Carbon emission reduction effect.*

1. INTRODUCTION

With the increasingly pressing issue of global climate change, reducing carbon emissions has become a focal point of international concern. In this context, China has put forward the "dual carbon" strategy to promote low-carbon development into a consensus. Meanwhile, digital economy reflects the close integration of information and communication technology and economic activities, and is committed to realizing the optimization of resource allocation and the maximization of efficiency of economic activities through technological innovation. While driving economic growth, the impact of digital economy on the environment has attracted wide attention. Digital economy has natural advantages in optimizing resource allocation, improving energy efficiency and promoting industrial transformation, and theoretically has the potential to reduce carbon emissions.

Based on this, can digital economy effectively promote carbon emission reduction effect? If so, how can the digital economy impact carbon reduction? And is there regional heterogeneity in this promotion effect? The exploration of the above questions is of great significance for realizing the goal of "dual carbon", and provides theoretical basis and practical guidance for realizing the digital transformation of economy and sustainable development of the environment.

2. LITERATURE REVIEW AND THEORETICAL HYPOTHESES

In recent years, the rapid development of the digital economy has attracted increasing attention from researchers domestically and internationally regarding the relationship between the digital economy and carbon emissions. Existing studies suggest that some researchers believe the rapid development of the digital economy will increase electricity consumption, leading to an increase in carbon emissions[1]. Furthermore, as the digital economy progresses, the proportion of carbon emissions it generates relative to the total carbon emissions will also increase[2]. However, there are also opposing views among researchers who argue that the digital economy plays a significant positive role in curbing carbon emissions[3]. Based on analysis, the digital economy stimulates green innovation, enhances production efficiency, and resource utilization; it transforms production and consumption patterns, promotes the development of low-carbon industries, and it can monitor and analyze carbon emission data in real time, helping enterprises and governments formulate more effective emission reduction strategies and policies.

Based on this, the article proposes Hypothesis 1:

Hypothesis 1: The development of the digital economy contributes to promoting carbon emission reduction effects.

Empirical studies by Feng Langang et al.[4] suggest that the development of the digital economy significantly affects carbon emission reduction, with innovation capacity and energy intensity being two important influencing mechanisms. Wang Weiguo et al.[5] studied the mechanism of carbon emission reduction in the digital economy and found that the digital economy mainly suppresses carbon emissions by reducing energy intensity, optimizing industrial structure, promoting technological progress, and empowering digital infrastructure. Based on this analysis, first, The application of digital technology promotes the transformation of energy structure to clean energy, reduces energy waste, and helps reduce carbon emissions per unit of economic output. Second, the digital economy helps the intelligent transformation of traditional industries, enhances the synergistic effect between industries, and promotes the low-carbon upgrading of the industrial structure.

Based on this, the article proposes Hypothesis 2:

Hypothesis 2: The digital economy indirectly reduces carbon emissions and suppresses carbon emission intensity by improving the quality of economic development and promoting the optimization of industrial structure.

3. RESEARCH DESIGN

3.1 Model Construction

To test the research hypotheses proposed in the theoretical analysis above, this study will empirically analyze the impact of digital economic development on carbon emissions using provincial-level balanced panel data in China. The following dual fixed-effects baseline regression model is set:

$$CE_{it} = a_0 + \alpha_1 DE_{it} + \alpha_2 X_{it} + \gamma_i + \delta_t + \varepsilon_{it} \qquad (1)$$

$$CI_{it} = \beta_0 + \beta_1 DE_{it} + \beta_2 X_{it} + \gamma_i + \delta_t + \varepsilon_{it} \qquad (2)$$

Where: i=1, 2…30 represents provinces, t=2013, 2014…2022 represents years; CE_{it} represents carbon emission intensity; CI_{it} represents carbon emission intensity; DE_{it} denotes the level of digital economic development; X_{it} represents a series of control variables; γ_i represents province fixed effects that do not vary over time; δ_t represents year fixed effects; represents the error term; a_0-α_2, β_0-β_2 are parameters to be estimated.

3.2 Data Description and Variable Selection

Excluding Tibet and the regions of Hong Kong, Macao, and Taiwan due to severe data missing, this article conducts empirical research using sample data from 30 provinces in China from 2013 to 2021. The data for each indicator mainly come from the annual "China Statistical Yearbook," the National Bureau of Statistics database, EPS database, and CEADS database, with some missing values supplemented and improved through interpolation. To mitigate the impact of heteroscedasticity, some variables used in the article are logarithmically transformed. The government attention to digital economy is computed using Python.

3.2.1 Dependent Variable

Carbon Emissions (CE) and Carbon Emission Intensity (CI), the data on carbon emissions come from the provincial carbon emission inventory of the Carbon Emission Accounts and Datasets, and the carbon emission intensity is measured by the proportion of carbon emissions to the gross domestic product of the province.

3.2.2 Core Explanatory Variables

Digital Economy (DE): The indicator system method provides a more comprehensive analytical framework that can reveal the diverse characteristics and imbalanced roots of digital economic development. Therefore, this study utilizes the indicator system method at the provincial level to measure the level of digital economic development. Based on the essence of the digital economy and referencing existing research[6-7], from the four dimensions of digital industrialization, industrial digitization, digital infrastructure, and industrial development environment of the digital economy, a comprehensive evaluation index system for provincial digital economic development is constructed. As shown in "Table 1", this index system covers 24 secondary indicators under four primary indicators. Among them, the government attention to digital economy in the development environment is constructed using Python to create a comprehensive dictionary of digital economy-related terminologies and calculate the results.

Table 1. Provincial digital economy development evaluation index system

Dimensionality	Index	Attribute
Digital industrialization	Software revenue	Positive
	Software product revenue	Positive
	Total volume of telecommunication service	Positive
	Digital TV subscribers	Positive
Industrial digitization	Rural broadband access users	Positive
	Proportion of administrative villages with postal services	Positive
	The number of mobile phones owned by rural residents per 100 households at the end of the year	Positive
	Number of computers used by enterprises per 100 people	Positive
	Number of websites per 100 companies	Positive
	Proportion of enterprises with e-commerce transaction activities	Positive
	E-commerce sales	Positive
	E-commerce purchases	Positive
Digital infrastructure	Domain number	Positive
	Optical cable line length	Positive
	Internet broadband access port	Positive
	Internet broadband access users	Positive
	Mobile phone penetration	Positive
Development environment	Number of domestic patent applications authorized	Positive
	Local government expenditure on science and technology	Positive
	Government attention to digital economy	Positive
	Average number of students enrolled in colleges and universities per 100,000 population	Positive
	R&D expenditure of industrial enterprises above designated size	Positive
Development environment	R&D expenditure of industrial enterprises above designated size	Positive
	Information transmission, software and information technology services employment in urban units	Positive

Due to the vast geographical expanse of China and the influence of different economic environments, there is a significant disparity in the level of digital economic development among different regions. Therefore, considering the geographical location and economic environment of China, the sample data is divided into three regions: East, Central, and West. The entropy value method formula is used to calculate the level of digital economic development in each province from 2013 to 2021, as shown in "Table 2". During the data processing, due to the presence of missing values in some variables, and their small proportion, this study employs the Random Forest interpolation method for handling the missing values.

Table 2. Measurement results of digital economy development level in each province from 2013 to 2021

	Area	2013	2014	2015	2016	2017	2018	2019	2020	2021	Mean	Average annual growth rate/%
	Beijing	0.365	0.403	0.428	0.446	0.467	0.485	0.505	0.523	0.556	0.464	0.054
	Tianjin	0.222	0.232	0.237	0.247	0.249	0.247	0.254	0.266	0.283	0.249	0.031
	Hebei	0.217	0.236	0.258	0.286	0.303	0.327	0.343	0.360	0.366	0.300	0.068
	Shanghai	0.301	0.323	0.331	0.350	0.359	0.362	0.381	0.403	0.424	0.359	0.044
	Jiangsu	0.392	0.409	0.444	0.472	0.496	0.533	0.569	0.590	0.608	0.501	0.056
East	Zhejiang	0.349	0.361	0.396	0.414	0.427	0.458	0.494	0.509	0.522	0.437	0.052
	Fujian	0.240	0.261	0.284	0.306	0.330	0.340	0.357	0.337	0.358	0.313	0.051
	Shandong	0.307	0.333	0.355	0.399	0.413	0.453	0.463	0.488	0.533	0.416	0.071
	Guangdong	0.437	0.471	0.513	0.559	0.580	0.646	0.698	0.712	0.741	0.595	0.068
	Hainan	0.194	0.236	0.233	0.248	0.250	0.250	0.257	0.251	0.256	0.242	0.035
	Liaoning	0.217	0.236	0.251	0.273	0.279	0.285	0.293	0.302	0.329	0.274	0.053
	Mean	0.295	0.318	0.339	0.364	0.378	0.399	0.419	0.431	0.452	0.377	0.055
	Shanxi	0.176	0.192	0.197	0.209	0.215	0.225	0.229	0.242	0.266	0.217	0.053
	Anhui	0.212	0.234	0.259	0.286	0.304	0.344	0.374	0.373	0.400	0.310	0.083
	Jiangxi	0.182	0.203	0.236	0.234	0.259	0.289	0.310	0.326	0.346	0.265	0.084
	Henan	0.214	0.235	0.262	0.296	0.312	0.346	0.371	0.392	0.411	0.315	0.085
Central	Hubei	0.235	0.255	0.282	0.303	0.315	0.346	0.372	0.397	0.417	0.325	0.074
	Hunan	0.205	0.216	0.253	0.286	0.304	0.333	0.349	0.369	0.389	0.300	0.083
	Jilin	0.188	0.204	0.213	0.216	0.224	0.237	0.241	0.258	0.272	0.228	0.047
	Heilongjiang	0.179	0.201	0.203	0.217	0.225	0.238	0.252	0.265	0.271	0.228	0.053
	Mean	0.199	0.218	0.238	0.256	0.270	0.295	0.312	0.328	0.347	0.273	0.072
	Chongqing	0.181	0.204	0.219	0.230	0.255	0.288	0.301	0.313	0.317	0.256	0.073
	Sichuan	0.236	0.267	0.303	0.340	0.359	0.394	0.425	0.440	0.458	0.358	0.086
	Guizhou	0.135	0.170	0.199	0.233	0.249	0.266	0.285	0.296	0.310	0.238	0.110
	Yunnan	0.168	0.183	0.212	0.236	0.243	0.269	0.291	0.306	0.320	0.248	0.084
	Shanxi	0.224	0.241	0.265	0.293	0.306	0.314	0.330	0.342	0.357	0.297	0.060
	Gansu	0.158	0.173	0.201	0.221	0.226	0.247	0.255	0.258	0.277	0.224	0.073
West	Qinghai	0.076	0.131	0.181	0.202	0.208	0.211	0.212	0.217	0.229	0.185	0.148
	Inner Mongolia	0.157	0.184	0.193	0.172	0.223	0.223	0.228	0.238	0.254	0.208	0.062
	Guangxi	0.170	0.189	0.194	0.218	0.238	0.273	0.300	0.322	0.329	0.248	0.086
	Ningxia	0.165	0.194	0.211	0.205	0.226	0.232	0.229	0.236	0.242	0.216	0.049
	Xinjiang	0.147	0.155	0.154	0.163	0.164	0.192	0.205	0.217	0.228	0.181	0.056
	Mean	0.165	0.190	0.212	0.228	0.245	0.264	0.278	0.290	0.302	0.242	0.078
China	Mean	0.222	0.244	0.266	0.285	0.300	0.322	0.339	0.352	0.369	0.300	0.066

It can be observed that there is significant regional heterogeneity in the level of digital economic development. From 2013 to 2021, the average value of digital economic development in China increased from 0.222 to 0.300, with an annual growth rate of 0.066%. In 2021, the level of digital economic development in Guangdong (0.741) was 3.25 times that of Xinjiang (0.228), indicating significant inter-provincial differences in the level of digital economic development across the country. Significant differences in digital economic development levels also exist among provinces within the same region, such as in 2021, where in the eastern region, the level of digital economic development in Guangdong (0.741) was 2.89 times that of Hainan (0.256).

From the annual average of the national digital economy development level, the eastern region has the best digital economy development level, the central region is second, and the western region is last. Although the current level of digital economy development in the central and western regions is lower than that in the eastern region, the annual average DE growth rate in the western region is the fastest under the guidance of China's western development policy. Through a series of measures, such as strengthening the construction of digital infrastructure and promoting policy dividends, the central region has formed a new driving force for the development of digital economy; In addition, the large population scale in central China also brings market potential to the central region, thus bringing the demand and space for the development of digital economy.[8]. Hence, the annual growth rates of DE in the central and western regions are higher than the national average DE growth rate.

In conclusion, due to the differences in location conditions and resource endowments, there exists regional heterogeneity in the level of digital economic development across the country.

3.2.3 Control Variables

To avoid the bias caused by the omission of important explanatory variables in empirical testing, referencing relevant studies [9], the article introduces the following control variables in the model:

- Population Size, selected using the total population at the end of the year (POP).
- Economic Development Level, represented by the per capita regional gross domestic product (PGDP).
- Urban Greening, characterized by the coverage rate of greenery in built-up areas (UG).
- Infrastructure, represented by the urban road area (INF).
- Level of Openness, chosen to represent the total import and export volume of enterprises in the operating unit's location (LEOP).
- Industrial Structure, measured by the ratio of value added in the tertiary industry to that in the secondary industry (INDS).

Descriptive statistical results of the variables are presented in “Table 3”.

Table 3. Results of descriptive statistics of variables

Variable	Obs	Mean	Std. dev.	Min	Max
ln(DE)	270	-1.264	0.342	-2.579	-0.299
ln(CE)	270	5.665	0.807	3.721	7.650
ln(CI)	270	-4.244	0.852	-6.418	-2.053
ln(POP)	270	8.212	0.741	6.347	9.448
ln(PGDP)	270	10.909	0.423	10.003	12.142
INDS	270	1.410	0.745	0.665	5.244
UG	270	40.078	3.426	29.800	49.800
ln(LEOP)	270	17.766	1.582	12.715	20.970
ln(INF)	270	2.764	0.356	1.413	3.288

4. EMPIRICAL ANALYSIS

4.1 Impact of the Digital Economy on Carbon Emissions

Based on the model constructed earlier, this study examines the impact of the digital economy on provincial carbon emissions and carbon intensity. To enhance the robustness of the regression results, a time-space double fixed-effects model is employed. Additionally, both regressions models without control variables and with control variables are compared for baseline analysis. The benchmark analysis results are presented in “Table 4”.

It is worth noting that this study attempts to include the quadratic term of the level of digital economic development in the regression. The results, consistent with the sign of the linear term, indicate that within the scope of this study, no nonlinear relationship between the digital economy and carbon emissions or carbon intensity is found. Moreover, the inclusion of the quadratic term affects the significance of the linear term results; hence, the quadratic term of the level of digital economic development is not used as a reference in this study.

In models (4) and (8) in “Table 4”, the estimated coefficients of DE are -0.442 and -0.438, respectively, both significantly negative at the 1%

level. This demonstrates that the development of the digital economy reduces both carbon emissions and carbon intensity. Regarding the control variables, the coefficient of the level of economic development is negative. The higher level of digital economy development in a region will usually improve energy efficiency and transform industries into information services, which will help reduce carbon emissions. The coefficient of population size is positive, and an increase in population size often leads to an increase in energy consumption, which in turn increases carbon emissions. The coefficient of urban greening is negative, and urban vegetation can absorb CO2 in the air and indirectly reduce carbon emissions in the city. The coefficient of infrastructure is negative, and an increase in urban road area can improve traffic efficiency and reduce carbon emissions per kilometer traveled. The coefficient on the level of openness to the outside world is positive, and open economies tend to involve more product import and export and international transport activities, while sea and air transport using fossil fuels increase carbon emissions. The coefficient of industrial structure is negative, and the proportion of manufacturing and construction in the industrial structure is relatively small, which will reduce the use of high-carbon energy and reduce regional carbon emissions.

Based on the regression results, the impact of the level of digital economic development on carbon emissions and carbon intensity is significantly negative. Therefore, hypothesis 1 is confirmed, indicating that the development of the digital economy is conducive to carbon reduction.

Table 4. Results of benchmark regression of digital economy on CO_2 emissions and CO_2 emission intensity

Variable	(1) ln(CE)	(2) ln(CE)	(3) ln(CE)	(4) ln(CE)	(5) ln(CI)	(6) ln(CI)	(7) ln(CI)	(8) ln(CI)
DE	0.420***	-0.985***	-1.056***	-0.442***	-1.663***	-0.980***	-1.048***	-0.438***
	(0.142)	(0.233)	(0.251)	(0.099)	(0.114)	(0.233)	(0.251)	(0.100)
PGDP		0.801***	0.756***	-0.472***		-0.205	-0.246	-1.475***
		(0.196)	(0.226)	(0.179)		(0.195)	(0.225)	(0.180)
POP		0.844***	0.826***	1.586***		-0.160	-0.178	0.579*
		(0.110)	(0.117)	(0.306)		(0.110)	(0.116)	(0.307)
UG		0.005	0.006	-0.011*		0.005	0.007	-0.011*
		(0.014)	(0.015)	(0.007)		(0.014)	(0.015)	(0.007)
INF		0.527***	0.516***	0.083		0.526***	0.516***	0.086
		(0.132)	(0.138)	(0.078)		(0.132)	(0.138)	(0.078)
LEOP		-0.058	-0.034	0.070**		-0.056	-0.034	0.071**
		(0.052)	(0.065)	(0.030)		(0.052)	(0.065)	(0.030)
INDS		-0.228***	-0.238***	-0.228***		-0.229***	-0.239***	-0.232***
		(0.073)	(0.075)	(0.057)		(0.073)	(0.075)	(0.057)
Year_dummy	NO	NO	YES	YES	NO	NO	YES	YES
Pro_dummy	NO	NO	NO	YES	NO	NO	NO	YES
R^2	0.028	0.529	0.516	0.986	0.442	0.578	0.567	0.987
N	270	270	270	270	270	270	270	270

a Note: The values in parentheses are robust standard errors; ***, **, and * indicate statistical significance at the 1%, 5%, and 10% confidence levels, respectively.

4.2 Robustness Test

4.2.1 Replacement of Dependent Variables

The previous analysis examined the inhibitory effect of the digital economy on carbon emissions and carbon intensity. To further verify its effectiveness, this study replaced the dependent variable with the carbon emissions per capita produced in each unit area for regression. As shown in Model (4) in "Table 5", the estimated coefficient for the digital economy is -0.442, and it passes the 1% significance test, indicating a significant inhibitory effect of the digital economy's development on per capita CO_2 emissions.

Table 5. Replacement of Dependent Variables

Variable	(1) ln(PCE)	(2) ln(PCE)	(3) ln(PCE)	(4) ln(PCE)
DE	-0.763***	-0.985***	-1.056***	-0.442***
	(0.114)	(0.233)	(0.251)	(0.099)
PGDP		0.801***	0.756***	-0.472***
		(0.196)	(0.226)	(0.179)
POP		-0.156	-0.174	0.586*
		(0.110)	(0.117)	(0.306)
UG		0.005	0.006	-0.011*
		(0.014)	(0.015)	(0.007)
INF		0.527***	0.516***	0.083
		(0.132)	(0.138)	(0.078)
LEOP		-0.058	-0.034	0.070**
		(0.052)	(0.065)	(0.030)
INDS		-0.228***	-0.238***	-0.228***
		(0.073)	(0.075)	(0.057)
Year_dummy	NO	NO	YES	YES
Pro_dummy	NO	NO	NO	YES
R^2	0.140	0.353	0.336	0.981
N	270	270	270	270

a Note: The values in parentheses are robust standard errors; ***, **, and * indicate statistical significance at the 1%, 5%, and 10% confidence levels, respectively.

4.2.2 Exclusion of Direct-Controlled Municipalities in Regression Analysis

Direct-controlled municipalities have a higher level of economic development, and various policies related to the digital economy are implemented first, leading to potentially significant differences compared to other provinces. This could affect the research results. Therefore, Beijing, Tianjin, Shanghai, and Chongqing, the four direct-controlled municipalities, were excluded from the sample for a new regression analysis. As shown in Models (4) and (8) in “Table 6”, the estimated coefficients for the digital economy are both -0.514 and pass the 1% significance test, indicating a significant decrease in carbon emissions and carbon intensity due to the development of the digital economy.

Table 6. Regression after excluding direct-controlled municipalities

Variable	(1) ln(CE)	(2) ln(CE)	(3) ln(CE)	(4) ln(CE)	(5) ln(CI)	(6) ln(CI)	(7) ln(CI)	(8) ln(CI)
DE	0.702***	-1.050***	-1.313***	-0.514***	-1.498***	-1.047***	-1.308***	-0.514***
	(0.140)	(0.256)	(0.269)	(0.099)	(0.113)	(0.256)	(0.268)	(0.099)
PGDP		0.720***	0.327	-0.216		-0.284	-0.672**	-1.212***
		(0.235)	(0.272)	(0.189)		(0.234)	(0.272)	(0.189)
POP		0.725***	0.551***	1.546***		-0.279**	-0.451***	0.538*
		(0.119)	(0.132)	(0.299)		(0.119)	(0.131)	(0.300)
UG		-0.003	-0.014	-0.017**		-0.003	-0.013	-0.017**
		(0.017)	(0.018)	(0.007)		(0.017)	(0.018)	(0.007)
INF		0.798***	0.801***	-0.006		0.798***	0.801***	-0.007
		(0.202)	(0.202)	(0.084)		(0.202)	(0.202)	(0.084)
LEOP		0.006	0.171**	0.042		0.007	0.171**	0.042
		(0.058)	(0.078)	(0.030)		(0.058)	(0.078)	(0.030)
INDS		-0.424***	-0.658***	-0.168**		-0.426***	-0.658***	-0.168**
		(0.120)	(0.141)	(0.067)		(0.119)	(0.141)	(0.067)

Variable	(1) ln(CE)	(2) ln(CE)	(3) ln(CE)	(4) ln(CE)	(5) ln(CI)	(6) ln(CI)	(7) ln(CI)	(8) ln(CI)
Year_dummy	NO	NO	YES	YES	NO	NO	YES	YES
Pro_dummy	NO	NO	NO	YES	NO	NO	NO	YES
R^2	0.094	0.486	0.492	0.986	0.430	0.502	0.508	0.987
N	234	234	234	234	234	234	234	234

a Note: The values in parentheses are robust standard errors; ***, **, and * indicate statistical significance at the 1%, 5%, and 10% confidence levels, respectively.

4.2.3 *Winsorization Trimming*

To mitigate the potential impact of outliers on regression results, this study employs Winsorization trimming by applying a two-sided 1% trim to all variables. As shown in Models (4) and (8) in "Table 7", the estimated coefficients for the digital economy are -0.234 and -0.307, with the former passing the 10% significance test and the latter passing the 5% significance test. Therefore, the carbon emission reduction effect of the digital economy is highly robust.

Table 7. Winsorization trimming

Variable	(1) ln(CE)	(2) ln(CE)	(3) ln(CE)	(4) ln(CE)	(5) ln(CI)	(6) ln(CI)	(7) ln(CI)	(8) ln(CI)
DE	0.419***	-0.950***	-0.977***	-0.234*	-1.655***	-0.950***	-0.903***	-0.307**
	(0.144)	(0.239)	(0.255)	(0.124)	(0.110)	(0.240)	(0.255)	(0.138)
PGDP		0.917***	0.927***	-0.519***		-0.037	0.085	-1.110***
		(0.189)	(0.222)	(0.172)		(0.189)	(0.222)	(0.191)
POP		0.863***	0.861***	1.258***		-0.133	-0.093	-0.004
		(0.099)	(0.108)	(0.307)		(0.099)	(0.108)	(0.342)
UG		-0.011	-0.010	-0.017**		0.000	0.001	-0.020***
		(0.013)	(0.013)	(0.007)		(0.013)	(0.013)	(0.007)
INF		0.737***	0.749***	0.111		0.585***	0.639***	0.031
		(0.129)	(0.138)	(0.075)		(0.129)	(0.138)	(0.084)
LEOP		-0.108**	-0.104	-0.007		-0.127**	-0.169**	-0.010
		(0.051)	(0.068)	(0.035)		(0.051)	(0.068)	(0.039)
INDS		-0.321***	-0.323***	-0.252***		-0.246***	-0.209**	-0.165***
		(0.093)	(0.102)	(0.056)		(0.093)	(0.102)	(0.063)
Year_dummy	NO	NO	YES	YES	NO	NO	YES	YES
Pro_dummy	NO	NO	NO	YES	NO	NO	NO	YES
R^2	0.027	0.569	0.557	0.986	0.458	0.587	0.577	0.983
N	270	270	270	270	270	270	270	270

a Note: The values in parentheses are robust standard errors; ***, **, and * indicate statistical significance at the 1%, 5%, and 10% confidence levels, respectively.

4.3 *Heterogeneity Analysis*

Governments adopt different policies according to local conditions among regions, so there is regional heterogeneity in the impact of digital economy on carbon emissions. As shown in "Table 8", the inhibitory effect of digital economic development on carbon emissions is particularly prominent in the central region, followed by the eastern region, with the western region showing the least impact. For every 1% increase in the level of digital economic development in the central region, the total carbon dioxide emissions decrease by 1.328%, and the carbon emission intensity decreases by 1.339%.

Under the implementation of the strategy to promote the rise of central China, the central region has achieved high-quality development, with steady regional economic growth, significant improvement in infrastructure, significant enhancement of scientific and educational strength, and all-round development of social undertakings, which have played an important supporting role in the country's economic and social development[10].The central region has significant room for digital economic development, promoting the transformation of traditional energy industries towards intelligent and green development, significantly enhancing production efficiency and energy utilization efficiency. Consequently, the carbon emission reduction effect of the digital economy is more significant in the central region compared to the eastern region. In comparison to the western region, the central region holds certain advantages in economic scale, population density, education level, communication facilities, and transportation convenience, which contribute to the carbon emission reduction effect of digital economic development.

Table 8. Results of regional heterogeneity analysis

Area	Variable	(4) In(CE)	(8) In(CI)
East	DE	-0.435**	-0.435**
		(0.191)	(0.192)
Central	DE	-1.328***	-1.339***
		(0.230)	(0.232)
West	DE	-0.384**	-0.383**
		(0.176)	(0.176)
Control Variable		YES	YES
Year_dummy		YES	YES
Pro_dummy		YES	YES

a Note: The values in parentheses are robust standard errors; ***, **, and * indicate statistical significance at the 1%, 5%, and 10% confidence levels, respectively.

5. CONCLUSION

Based on provincial panel data from 2013 to 2021, this study evaluates the level of digital economic development using the entropy method. It constructs a dual fixed-effects model to empirically analyze the relationship between digital economy and carbon emissions and carbon emission intensity. The following conclusions are drawn: 1. There are inter-provincial and regional differences in the level of digital economic development, with the eastern region having the highest level, followed by the central region and the western region at the lowest level. 2. The digital economy has significantly reduced carbon emissions. For every 1% increase in the digital economy, the total amount and intensity of carbon emissions decrease by 0.491% and 0.966% respectively. 3. There is regional heterogeneity in the relationship between the digital economy and carbon emissions. The digital economy is more effective in carbon emission reduction in the central region.

Based on the above research conclusions, in order to further utilize the potential of digital economy, promote economic transformation and achieve energy conservation and emission reduction, the following three policy implications are proposed.

- (1)To promote high-quality development of the digital economy, first, increase investment to provide infrastructure support for the development of the digital economy; Second, strengthen technological innovation and research and development, improve the overall level of digitalization, and give full play to the role of digital economy in carbon emission reduction.
- (2)It is useful to use the indirect impact of the digital economy to promote carbon emission reduction to advance low-carbon development. First, develop smart city projects and use the Internet of Things and big data to efficiently manage urban environmental quality. Second, promote the adjustment of industrial structure, encourage the digital transformation of traditional industries, and promote low-carbon urban construction.
- (3)It is necessary to formulate digital economy development strategies according to local conditions. The central region will strengthen the deep integration of digital technology and traditional industries to further improve the level of industrial digitalization. The eastern region should

focus on improving innovation capacity in the development of digital economy, enhance the research and development and application of green technology, and improve the utilization rate of new energy. The western region should give full play to the advantages of digital economy in environmental monitoring and optimal allocation of resources to further enhance the role of digital economy in carbon emission reduction.

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