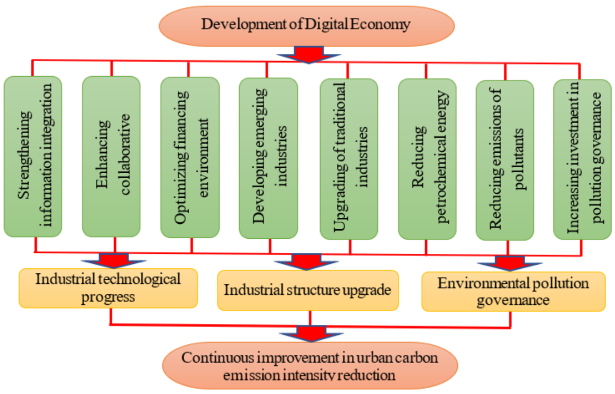
Global NEST Journal, Vol 26, No 2, 05660

Influence and its spatial verification of digital economy development on carbon emission intensity from urban energy consumption

Guangyu Ge[1], Shuhong Liu[2], Yibin Liu[2], Chuanwen Chen[2] and Xiuyan Han[2]*
[1]Jiangsu Second Normal University, School of Business, Nanjing Jiangsu, 211200, China
[2]Qufu Normal University - Rizhao Campus School of Economics, Rizhao Shandong 276826, China
Received: 15/12/2023, Accepted: 23/01/2024, Available online: 29/01/2024
*to whom all correspondence should be addressed: e-mail: hanxy2015@163.com
https://doi.org/10.30955/gnj.005660

Graphical abstract



Abstract

In order to explore the influence of digital economy development on carbon emission intensity from urban energy consumption, digital economy development is incorporated into the reduction framework of carbon emission intensity from urban energy consumption in this paper. With carbon emission intensity from urban energy consumption in China taken as the research object, empirical tests and dynamic effect analyses were carried out on the factors influencing carbon emission intensity from urban energy consumption, using urban panel data for the period of 2012–2022. It is found that digital economy has a significant inhibitory effect on carbon emission intensity from urban energy consumption in China, with a coefficient of -0.348. Among the five selected control variables, PCG, UR, and IS show a positive correlation with carbon emission intensity (CEI) from urban energy consumption, enhancing CEI with corresponding influence coefficients of 0.472, 0.135, and 0.331 respectively; EGRI and TRL show an inverse correlation with EI, inhibiting the growth of EI with corresponding influence coefficients of -0.556 and -0.201, respectively. Policy suggestions were put forward to minimize EI on the basis of the test results combined with the actual situation of China's urban economic development.

Keywords: Urban energy consumption; Carbon emission intensity; Spatial verification; Digital economic development

1. Introduction

Digital economy refers to the new economic era that utilizes internet platforms and fully utilizes data resources to promote comprehensive development of economic activities such as research and development, production, circulation, services, and consumption. At the technical level, it mainly includes emerging technologies such as big data, cloud computing, the Internet of Things, blockchain, artificial intelligence, and 5G communication; at the application level, it is a typical representative of new economic forms such as "new retail" and "new manufacturing". In 1994, Don Tapscott first proposed the concept of digital economy in his monograph "Digital Economy". And he is known as the "father of digital economy" (Tapscott, 1994). China's digital economy began in 2015, and on July 4 of the same year, the State Council issued the *Guiding Opinions on Actively Promoting "Internet +" Actions*, marking the beginning of research on the application of digital economy. In November 2016, the State Council released the *"13th Five-Year" National Strategic Emerging Industries Development Plan*, which added digital creative industries, marking the development of China's digital economy. In 2019, the "14th Five-Year" Plan of China included digital economy in the national strategy for the first time (Zhao *et al.*, 2023). In June 2021, the National Statistical Office issued Order 33 specifically for the concept and classification of digital economy. In May 2022, the country released the *"14th Five-Year" Digital Economy Development Plan*, and the 20th Congress of the CPC took the greening and low-carbon of social and economic development as an important link of high-quality development. In January 2023, the State Council released the White Paper on *"China's Green Development in the New Era"*, which identified the " dual-carbon " goals and green, low-carbon, and high-quality development as strategic tasks for China's future development. The development of the Chinese economy is based on the development of cities, and the development of digital economy also began in cities. On the one hand, the development of the urban economy is accompanied by the development of digital economy, and on the other hand, the development of the urban economy has caused a certain degree of environmental pollution. The development of digital economy in Chinese cities plays a role in replacing the development of manufacturing industry, and also plays a significant role in supervising and controlling urban production energy consumption. In order to examine the impact of China's digital economy development on carbon emission intensity from urban energy consumption, this article takes 285 cities in China as the research object, and based on statistical data from 2012 to 2022, empirically tests the impact of digital economy development on carbon emission intensity from urban energy consumption, and tests the spatial dynamic effect.

Digital economy first emerged in the United States, and this concept was first proposed by American economist Tapscott. Subsequently, he further studied the hopes and dangers of the era of network intelligence and proposed a systematic theory of digital economy (Tapscott, 1996). In May 1997, the Ministry of International Trade and Industry (MITI) of Japan defined digital economy as an economic form with four characteristics: physical movement without personnel, objects, and funds; contract signing, value transfer, and asset accumulation are completed using electronic means; the high speed of development of information technology as the basis of the economy; and the extensive expansion of e-commerce, with digitalization penetrating all aspects of human life. In June 1999, the US Department of Commerce released the Emerging Digital Economy Report, which divided e-commerce and the information technology industry that made e-commerce possible into two aspects of digital economy; In October of the same year, the United States Bureau of Statistics defined the specific scope of digital economy, including network and inter-network, e-commerce, e-business, and online transactions, and provided a specific definition of digital economy. Lilien and Rangaswamy (2000) studied the decision-making model of the digital network economy and believed that digital marketing is the main model of online marketing; Miller and Wilson (2001) argued that the electronic economy has entered all fields, and digital economy has promoted the sustainable development of e-commerce; Garifova (2015) studied the value of information in digital economy and the importance of information economics, believing that information is the core of digital economics; Watanabe *et al.* (2018) believed that the output value of digital economy has become a major part of GDP, and the role of digital economy in promoting socio-economic development will become increasingly significant. Glitman *et al.* (2019) believed that electric vehicles have a good decarbonization effect and are the main direction for future automotive development; Nguyen *et al.* (2020) argued that the G20 group of countries has identified information, communication technology, and innovation as important means of reducing carbon emissions and promoting economic development; Kovacikova *et al.* (2021) argued that digital economy plays an important role in promoting carbon emissions and strengthening environmental pollution control; Ozturk and Ullah (2022) argued that the inclusiveness of digital economy plays an important role in promoting economic growth of OBRI economies and sustainable development, and used empirical testing methods to test the degree of influence of the main driving factors; Khan *et al.* (2023) argued that the inclusiveness of digital economy can affect the CO_2 emissions of industries, and conducted empirical tests using data from 76 emerging markets and developing economies. It can be seen that research on digital economy started earlier in foreign countries. Early relevant research mainly focused on the influence of digital economy on economic development, and only in the middle and late stages did it begin to pay attention to the influence of digital economy on carbon emissions in economic development.

China's development of digital economy is basically consistent with that of developed countries. In 1998, Jiang Qiping, a reporter from Internet Weekly, gave a speech on "21st Century Digital Economy and the Future of Enterprises" at Intel's "Enterprises Winning Century Forum", marking the beginning of research on China's digital economy. From 1998 to 2000, many Chinese scholars were not optimistic about digital economy, believing it to be a "bubble economy" and "a foggy economy". In the early 21st century, some Chinese scholars began to recognize the role of digital economy, believing that it has broad development prospects (Jing, 2003; Xu and Zeng, 2009; Yang *et al.*, 2023). China's comprehensive research on the development of digital economy began with the *"Digital Economy Development Strategy Outline"* jointly released by the General Office of the Central Committee and the State Council in August 2018. Cao (2018) studied a new model to promote high-quality industrial development in China under the background of digital economy, and believed that the innovation ecosystem of the manufacturing industry is accelerating its formation, with new models such as intelligent manufacturing, networked collaborative manufacturing, personalized customization manufacturing, and service-oriented manufacturing constantly emerging; Lin and Shao (2019) studied the impact of blockchain on the high-quality development of digital economy and concluded that rational social cognition, breakthroughs in core technologies, new information infrastructure, application scenarios, policy guidance, and business environment are the key influencing factors of blockchain on the high-quality development of digital economy; Wei *et al.* (2023) used panel data from 286 cities from 2012 to 2018 to empirically test the impact of the digital economy on high-quality urban development, and found that the digital economy has a significant driving effect on high-quality urban development. At the meso level, it is achieved through industrial innovation effects, industrial correlation effects, and industrial integration effects to achieve industrial structure adjustment and transformation upgrading. At the macro level, it is achieved through enriching the sources of factors, improving factor allocation efficiency, and deepening capital effects; Bi *et al.* (2023) believed that high-quality development is a key factor in driving economic growth through digital economy. With the help of new technologies, formats, and models, digital economy adds new momentum to economic growth by reshaping China's new advantages in international cooperation and competition. Xu *et al.* (2022) studied the impact of digital economy on carbon emission intensity from urban energy consumption and its spatial effects. They found that there is significant spatial heterogeneity in the development of digital economy, which significantly improves carbon emission intensity from urban energy consumption pollution. The development of the digital industry, digital innovation capabilities, and digital inclusive finance are important driving factors for the improvement of energy consumption and carbon emissions pollution in digital economy; Kong *et al.* (2022) studied the impact of digital economy development on energy consumption and carbon emissions, and concluded that improving urban production efficiency and technological innovation level are the two basic paths for digital economy to significantly suppress carbon emission intensity from urban energy consumption; The inhibitory effect of digital economy on urban carbon emissions is also influenced by the degree of marketization and the level of urbanization, exhibiting a threshold effect, showing a "inverted U-shaped" and a "weak N-shaped" trend respectively; Li and Wang (2023) studied the impact of digital economic agglomeration on energy consumption and carbon emissions, and found that this impact exhibits a double-layer stochastic frontier. They conducted corresponding spatial decomposition and determined the specific degree of impact. It can be seen that although China's research on the influence of digital economy on carbon emission from urban energy consumption is slightly later than that of foreign developed countries, China's research began by combining the development of digital economy with the influence of carbon emission from urban energy consumption.

From the results of the literature review above, it is evident that China's research on the development of digital economy and carbon emission from energy consumption in China is slightly later than that of developed countries abroad. However, research on the impact of digital economy development on energy consumption and carbon emissions in China is basically the same as that of developed countries abroad. With the continuous deepening of research on digital economy, Chinese scholars have achieved more and more research results, and have made good improvements and breakthroughs in the quality of their papers and ideological concepts. The research results in this area have increasingly high reference value. There is a common phenomenon of outdated concepts and insufficient empirical testing in the research on the impact of digital economy development on urban energy consumption and carbon emissions. Therefore, in order to empirically test the driving factors of China's digital economy development on carbon emission intensity from urban energy consumption and analyze the spatiotemporal dynamic effects, this article introduces regression models and Durbin spatial panel models to empirically test the impact of digital economy and auxiliary variable combinations on the scale of carbon emission intensity from urban energy consumption. By analyzing the spatiotemporal dynamic effects of the driving factors of carbon emission intensity from urban energy consumption based on specific test results, we aim to explore effective ways to save energy and reduce emissions.

2. Materials and methods

2.1. Research objects and data sources

In order to examine the influence and its spatiotemporal dynamic effect of China's digital economy development on carbon emission intensity from urban energy consumption, in this paper, 285 cities were selected as the research object, including prefecture-level cities, sub-provincial cities and municipalities directly under the central government in China. To carry out the research statistical data were used from the *Statistical Yearbook*, *Energy Statistical Yearbook*, *Urban Statistical Yearbook* and *Ecological and Environmental Condition Bulletin* of the state, provinces, municipalities and autonomous regions, as well as cities. Since the publication of China's *Ecological and Environmental Condition Bulletin* began in 2012, considering the consistency of data information, basic data of 11 years were chosen as the data system during the period of 2012-2022. In the process of constructing the empirical testing model, the principle of variable selection is that the variables are correlated with each other but without collinearity, and the independent variables are selected which have a large effect on the dependent variable. Considering data availability of the selected variables, most initial data were obtained directly from the statistical yearbook, while initial data of individual variables were obtained through simple calculations.

2.2. Theoretical analysis and research hypothesis

With rapid development of China's digital economy, the size of China's digital economy had reached RMB 50.20 trillion by the end of 2022, accounting for 41.5 percent of GDP and ranking second in the world (Zhao, 2023). According to the experience, digital economy development has reduced energy consumption to a large extent, and has positively inhibited carbon emission intensity from urban energy consumption in China. Carbon emission intensity from urban energy consumption is generally expressed as the ratio of CO_2 emission scale from urban production and living energy consumption to the GDP of the same period, and reduction in the carbon emission intensity from energy consumption implies an improvement in the efficiency of carbon emission from energy consumption (Chang *et al.*, 2023). Factors connecting digital economy development and carbon emission intensity from urban energy consumption are multifaceted, and the mechanism of the influence of digital economy development on carbon emission intensity from urban energy consumption can be determined as three main aspects, namely, industrial technological progress, upgrading of industrial structure, and environmental pollution governance. These three aspects are not only the key factors influencing carbon emission from urban energy consumption, but also the objects that digital economic development directly acts on and changes.

By subdividing the key factors between digital economic development and the three main aspects, eight main factors are identified and used to construct the mechanism of digital economy development to inhibit carbon emission intensity from urban energy consumption, as shown in Figure 1.

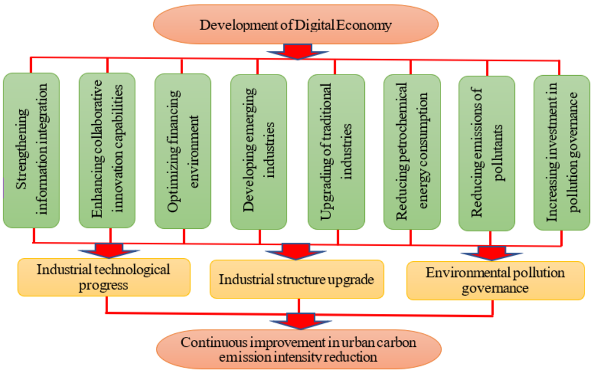


Figure 1. Mechanism of digital economy development to inhibit carbon emission intensity from urban energy consumption

(1) Digital economy development promotes the reduction of carbon emission intensity from urban energy consumption through technological progress. Information technology is of the core of digital economy, and disseminates technological progress, provides information resources for technological innovation and technological progress, supports technological innovation, and promotes technological progress. On the other hand, information technology promotes the control of energy consumption in production and requirements of technological innovation through disseminating production results and technological requirements. Consolidation of information technology and reduction of search costs promote synergies in information technology and promote technological innovation, which helps achieving technological progress, and eventually increasing the urban GDP (Shu *et al.*,2023). Technological progress is generally realized through technological innovation based on technological requirements, and therefore technological progress in turn promotes energy conservation and emission reduction in industrial processes, and contributes to the realization of the "dual carbon" goal. While digital economy is increasing the city's GDP, it is also promoting energy conservation and emission reduction, which ultimately suppressing the increase of the carbon emission intensity from urban energy consumption.

(2) Digital economy development promotes the reduction of carbon emission intensity from urban energy consumption through industrial structure upgrade. Digital economy has become an important industry, and China's digital economic output value has accounted for more than 40% of its GDP, which is an optimization and adjustment of the industrial structure in itself, promoting the upgrade of traditional industries. At the same time, digital economy has penetrated into other major industries, to a large extent, to promote the transformation of energy-consuming industries, energy conservation and emission reduction, and to promote the optimization and industrial structure upgrade (Pan *et al.*, 2023).On the other hand, information is an important resource, and digital economy promotes intelligence and digitalization of industrials through utilization of information technology, which promotes energy conservation and emission reduction, rapid growth of production and industrial structure upgrade, and ultimately contributes to the reduction of carbon emission intensity.

(3) Digital economy development promotes the reduction of carbon emission intensity from urban energy consumption through environmental pollution governance. With rapid growth of China's digital economy, high-quality urban development has become an inevitable choice, and environmental pollution governance has become an important factor in promoting high-quality urban development. The influence of digital economy on the environmental pollution governance is multifaceted, and the main influence is to understand, manage and control environmental pollution and relevant investment data through information transfer. At the same time, digital economy promotes industrial energy conservation and emission reduction, and ultimately reducing carbon emission intensity from urban energy consumption by penetrating into the process of industrial environmental pollution governance.

It can be seen through the above analyses, that reduction of carbon emission intensity from urban energy consumption is mainly achieved through industrial technology progress, industrial structure upgrade, and industrial environmental pollution governance. Hypothesis H1 is proposed based on the above analysis:

H1: Digital economy reduces carbon emission intensity from urban energy consumption through three key factors.

The influence of digital economy on carbon emission intensity from urban energy consumption is the result of the long-term effect during urban economic development, and shows an increasing effect over time. In fact, digital economy development plays a positive role in promoting the reduction of carbon emission intensity from urban energy consumption through technological progress, industrial structure upgrade and environmental pollution governance. That is, digital economy development continues to promote the gradual reduction of carbon emission intensity from urban energy consumption through the continuous promotion of technological progress, industrial structure upgrade and the effect of environmental pollution governance (Zhang, 2023). From a spatial point of view, industrial technological progress, industrial structure upgrade and industrial environmental pollution governance all have different degrees of spatial spillover effects. That is, effects of industrial technological progress, industrial structure upgrade and environmental pollution governance of a city will affect the relevant effect of neighboring cities to different degrees. Spillover effects can be proved by a spatial verification, and spillover effects of technological progress, industrial structure upgrade and environmental pollution governance among cities is a general phenomenon verified by practice. Based on the above analysis, hypothesis H2 is proposed:

H2: Digital economy has a temporal reduction effect as well as a spatial spillover effect on reduction of carbon emission intensity from urban energy consumption.

2.3. Model construction and variable interpretation

In order to examine the influence of digital economy development on carbon emission intensity from urban energy consumption and its spatial spillover effects, regression panel model is used in this paper, and expressed as follows:

$$Y_{it}=\alpha_1 DEDI_{it}+\sum_{i=1}^{n}\beta_i X_{it}+\omega_{it}+\varphi_{it}+\mu_{it} \quad (1)$$

Where Y_{it} is the dependent variable, also known as the explained variable, $DEDL_{it}$ is the explanatory variable, X_{it} is the control variable, α_I,β_I are the coefficients of the test formula, ω_{it} is urban fixed effect, φ_{it} is time fixed effect, and μ_{it} is the random error term. Combined with the research objectives, the dependent variable was determined to be carbon emission intensity from urban energy consumption.

Using the formula: $E(CO_2)_t=\sum_{t=1}^{n}(EC_t\cdot SCC_t\cdot CEF_t)\times(44/12)$, EC_i is energy consumption *i*, SCC_i is the standard coal conversion coefficient of energy source I, CEF_i is the carbon emission coefficient of energy source *i*, and 44/12 is the ratio of CO_2 molecular weight to carbon molecular weight. Data of the parameters in the formula were derived from coal conversion coefficient in the various energy reference standards in the appendix of 2016 *China Energy Statistics Yearbook* and the carbon emission coefficient in *2016 IPCC National Greenhouse Gas Inventory Guidelines*. Carbon emission intensity (*CEI*) from urban energy consumption was calculated using the calculated CO_2 emissions and response caliber of each city, as well as the GDP during the period; explanatory variable *DEDI* measures development level of urban digital economy using four dimensions: digital economy infrastructure, digital economy practitioners, digital economy output, and digital inclusive finance; Considering the actual situation of the influence of China's urban digital economy development on carbon emissions, the following five control variables are selected based on comprehensive analysis: urban economic development level (*PCG*) expressed in terms of city GDP per capita; urbanization rate (*UR*) used the ratio of the non-agricultural population to the total population at the end of the period; ratio of investment in environmental pollution governance to GDP (*EGIR*) expressed in terms of the ratio of the investment size in urban environmental pollution governance at the end of the period to GDP of the same period; industrial structure (*IS*) expressed in terms of the ratio of urban industrial added value to GDP; technological progress level (*TPL*) expressed in terms of the ratio of city-wide industrial technology R&D investment to GDP. Based on the six selected control variables, Durbin Spatial Post-Panel model considering all the driving factors is constructed as following:

$$\begin{aligned}CEI_{it}=&\alpha_1 DEDI_{1t}+\beta_1 PCG_{it}+\beta_2 UR_{it}\\&+\beta_3 EGIR_{it}+\beta_4 IS_{it}+\beta_5 TPL_{it}+\mu_{it}\end{aligned} \quad (2)$$

In order to test the spillover effect of the influence of digital economy development on the carbon emission intensity from urban energy consumption, according to Durbin spatial panel model, combined with formula (2) to add the lag term of carbon emission intensity from urban energy consumption, Durbin spatial panel lag model is constructed as follows:

$$\begin{aligned}CEI_{it}=&\eta+\gamma W\cdot CEI_{it-1}+\alpha_1 W\cdot DEDI_{1t}+\beta_1 PCG_{it}+\\&\beta_2 UR_{it}+\beta_3 EGIR_{it}+\beta_4 IS_{it}+\beta_5 TPL_{it}+\mu_{it}\end{aligned} \quad (3)$$

3. Results and discussion

3.1. Results of regression tests

In order to use empirical testing models to test the extent of the impact of digital economy on carbon emission from urban energy consumption, it is necessary to first use the Hausman test to determine whether the variables follow a fixed effects model or a random effects model. The coefficient of the test is 19.362, The corresponding probability value is: P=0.029. Therefore, Therefore, based on the test results, the fixed effects model was chosen to test the influence of digital economy development on carbon emission from urban energy consumption. Model (1) shows the test results that only consider the effects of lagged terms and explanatory variables on the dependent variable. Models (2) to (7) show the combined equation test results after sequentially adding five control variables and PCG^2 terms. The specific test results are shown in Table 1.

Table 1 Empirical test results of regression model

Variables	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)	Model (7)
DEDI	-0.406** (-1.96)	-0.397*** (-3.57)	-0.385*** (-3.28)	-0.378*** (-3.721)	-0.373*** (-3.672)	-0.356*** (-3.358)	-0.348 (-3.384)
PCG		0.442*** (5.382)	0.456*** (5.63)	0.459*** (5.72)	0.462*** (5.29)	0.468*** (5.52)	0.472*** (6.07)
PCG^2			0.118*** (3.925)	0.123*** (3.884)	0.127*** (3.819)	0.121*** (3.752)	0.135*** (3.683)
UR				0.227** (2.43)	0.236** (2.41)	0.241** (2.37)	0.247** (2.28)
EGRI					-0.562*** (4.56)	-0.559*** (4.14)	-0.556*** (3.85)
IS						0.327** (2.26)	0.331** (2.15)
TPL							-0.201** (-2.19)
Fixed city	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fixed time	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.51	0.54	0.55	0.56	0.58	0.58	0.59
F	216.02	236.27	221.38	218.27	207.28	210.35	208.32

It can be clearly seen from the above table that digital economy has a significant reducing effect on carbon emission intensity, and with the gradual addition of control scalars, and the inhibitory effect on carbon emission intensity from urban energy consumption under mixed effects becomes more and more obvious. The growth of GDP per capita is the main reason for the increase in carbon emission intensity from urban energy consumption, so energy conservation and emission reduction are the key to controlling carbon emission from urban energy consumption. PCG^2 is inversely correlated with carbon emission intensity from urban energy consumption, indicating that the growth of GDP per capita makes the growth of carbon emission intensity from urban energy consumption show a weak N trend. Urbanization has greatly promoted the improvement of carbon emission intensity from urban energy consumption, but the degree of improvement is limited; Investment in environmental pollution governance is a key factor in curbing carbon emission intensity from urban energy consumption, with a comprehensive reduction coefficient of -0.556; The improvement of industrialization level can promote the increase of carbon emission intensity from urban energy consumption. Therefore, controlling the speed of industrialization development is a long-term requirement for energy conservation and emission reduction; Technological progress can promote the reduction of carbon emission intensity from urban energy consumption, and its degree of reducing carbon emissions is limited in the short term. It needs to rely on long-term effects to gradually increase its impact.

3.2. Discussion of robustness tests

In order to improve the validity of empirical test results, it is necessary to conduct robustness tests on the equation and its variables to enhance the explanatory power of the test indicators and the validity of the test results. There are multiple methods for robustness testing, and this article chooses the alternative variable method and the control fixed effects method. Using energy consumption intensity instead of CO_2 emission intensity, the robustness of the empirical test model and its variables was evaluated by examining the impact of digital economy development on urban energy consumption intensity. The test results are shown in column 1 of Table 2; The China Urban Digital Economy Index calculated by Tencent Research Institute is used to replace the development level of China's urban digital economy calculated in this article. The test results are shown in column 2 of Table 2. At the same time, this article also use the method of controlling for fixed effects to conduct stability tests, mainly controlling for fixed effects in each province and the interaction effects between provinces and years. Specific test results are detailed in columns 3 and 4 in Table 2. The robustness test results of the two methods are shown in Table 2.

Table 2 Robustness test results

Variables	Substitution variable method		Controlled fixed effect method	
	Replace dependent variable	Replace independent variables	Control province effect	Control year effect
DEDI	-0.306* (-1.903)	-0.336** (-2.18)	-0.315*** (-3.16)	-0.348*** (-3.07)
Control variable	Yes	Yes	Yes	Yes
Province effect	No	No	Yes	Yes
Vintage effect	No	No	No	Yes
Fixed city	Yes	Yes	Yes	Yes
Fixed time	Yes	Yes	Yes	Yes
R^2	0.52	0.47	0.50	0.48

From the above test results, it can be seen that after replacing carbon emission intensity from urban energy consumption with urban energy consumption intensity, it is significantly negative at a 10% level; After replacing the development level of digital finance with the digital finance index, it is negative at a significant level of 5%. This indicates that China's digital economy has a suppressive effect on urban energy consumption intensity and carbon emission intensity, and also indicates that the test results have obvious robustness. Similarly, the test results of the controlled fixed effect method also exhibit significant robustness.

3.3. Results of spatial spillover effects

In order to test the spillover effect of digital economy on carbon emission intensity from urban energy consumption, a spatial Durbin lag model was constructed based on formula (3) to test the spatial weight matrix. This article selects three forms: spatial geographic weight, economic weight, and economic geographic weight. Spatial geographic weight (W_1) reflects the degree of correlation between two neighboring cities, which reflects the common boundary between city *i* and city *j*, then $w_{ij}=1$, otherwise $w_{ij}=0$; economic weight (W_2) It is the reciprocal of the difference in GDP per capita between two cities, using PGDP to represent GDP per capita. The economic weights of city *i* and city *j* can be expressed as: $W_2 = (PGDP_i - PGDP_j)^{-1}$; Economic geographical weight is the strengthened average of spatial geographical weight and economic weight. If ξ represents the weighting coefficient, then $W_3 = \xi W_1+(1-\xi)W_2$. In order to conduct spatial spillover testing, Moran's I is introduced, which is a spatial correlation testing method proposed by the Australian statistician Patrick Alfred Pierce Moran in the 1950s. Moran's I $\in$[-1.1] , When Moran's I > 0, this indicates spatial positive correlation; when Moran's I < 0, this indicates spatial negative correlation; and when Moran's I = 0, this indicates spatial randomness. The calculation formula is as follows:

$$I=\frac{n\sum_{i=1}^{n}\sum_{j=1}^{n}w_{ij}\left(x_i-\bar{x}\right)\left(x_j-\bar{x}\right)}{\sum_{i=1}^{n}\left(x_j-\bar{x}\right)^2\sum_{i=1}^{n}\sum_{j=1}^{n}w_{ij}} \tag{4}$$

In order to improve the testing effect of digital economy on the spatial impact of carbon emission intensity from urban energy consumption, the significance level of Moran's I is tested using the Z-value, which is called the standard statistic of Moran's I. According to statistical testing theory, the formula for calculating the Z-value is as follows:

$$Z=\frac{I-E(I)}{\sqrt{E[I^2]-E[I]^2}} \tag{5}$$

In order to empirically test the status of the influence of digital economy development on carbon emission intensity from urban energy consumption, based on the above formula and MATLAB software, the results of Moran's I for the entire domain of digital economy and urban energy consumption and carbon emission intensity are: Moran's I=0.314 and Moran's I=0.356, respectively. There are $0<Moran's\,I<1, z\geq 2.542,\ P\geq 0.03,$ indicating that both have passed the 1% random distribution significance test. After the LR test, Wald test and Hausman test, it is found that the spatial Durbin model cannot be simplified into a spatial lag model and a spatial error model, and must be tested using a fixed effects model. Therefore, using formula (3) and the determined three types of spatial relative weights, the lag term of carbon emission intensity from urban energy consumption and the impact of digital economy development level on carbon emission intensity from urban energy consumption were mainly tested. The test results are shown in Table 3.

Table 3 The test results of spatial spillover effects in digital economy

Variable	W_1	W_2	W_3
η	0.197^{***}(3.275)	0.228^{***}(3.215)	0.206^{***}(3.17)
CEI_{t-1}	0.1826^{**}(2.356)	0.203^{***}(2.287)	0.193^{**}(2.178)
DEDI	-0.4193^{***}(-4.275)	-0.4527^{***}(-4.183)	-0.436^{***}(-3.865)
$W\gamma$	0.064^{**}(2.363)	0.086^{***}(3.282)	0.073^{**}(2.255)
direct effect	-0.237^{***}(-3.351)	-0.256^{***}(-3.284)	-0.248^{***}(-3.163)
indirect effect	-0.189^{**}(-2.385)	-0.187^{**}(-2.294)	-0.188^{**}(-2.165)
Total effect	-0.426^{**}(-2.284)	-0.443^{***}(-3.263)	-0.436^{***}(-3.151)
Control variables	Yes	Yes	Yes
R^2	0.54	0.58	0.56
Log-L	768.32	862.37	896.25

Table 4 Test results of the mechanism of the effect of digital economy on carbon emission intensity from urban energy consumption

Items	Technological progress		Industrial structure upgrade		Environmental pollution governance	
	(1)	(2)	(3)	(4)	(5)	(6)
DEDI	0.087^{**}(2.265)		0.126^{***}(3.274)		0.148^{***}(3.286)	
λ_{DT}		0.091^{**}(2.316)				
λ_{DS}				0.095^{***}(3.325)		
λ_{DE}						0.087^{***}(3.217)
control variable	Yes	Yes	Yes	Yes	Yes	Yes
Fixed city	Yes	Yes	Yes	Yes	Yes	Yes
Fixed time	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.432	0.441	0.474	0.476	0.485	0.487
F	273.25	283.17	292.35	294.38	302．36	311.41

Based on the above test results, it can be clearly seen that the spatial autoregressive coefficient (η) of carbon emission intensity, the lagged term of carbon emission intensity from urban energy consumption (CEI_{t-1}), and the spatial mutual coefficient ($W\gamma$) of digital economy are all significantly positive. This indicates that there is not only an interactive effect of energy consumption and carbon emission intensity among cities in China, but also a significant spatial spillover effect. In other words, the status of carbon emission intensity from urban energy consumption in a city and the impact of data economy on carbon emission intensity from urban energy consumption have a significant impact on the corresponding matters of surrounding cities. This is mainly due to the implementation of basically the same policies in Chinese cities, and the dissemination of information makes each city have characteristics of correlation and permeability. At the same time, from the test results in Table 3, it can also be seen that digital economy development has a significant negative effect on carbon emission intensity from urban energy consumption. The important manifestation of this inhibition is that the direct effect is significantly greater than the indirect effect; that is, the development of digital economy has a significant inhibitory effect on the intensity of carbon emission intensity from urban energy consumption.

3.4. The impact mechanism of digital economy on carbon emission intensity from energy consumption

According to the mechanism diagram of the suppression of carbon emission intensity from urban energy consumption by digital economy, the impact of digital economy on carbon emission intensity from urban energy consumption is mainly achieved through three aspects: technological progress, upgrading of industrial institutions, and environmental pollution control. According to the research design, the impact of these three aspects is mainly achieved through five control variables: PCG, UR, EGIR, IS, and TPL. The test results of the mechanism of the effect of digital economy on urban energy consumption and carbon emission intensity are shown in Table 4.

The results of the tests in the table can be clearly seen: columns (1) and (2) of the table test the impact of digital economy on technological progress. The coefficient of the impact of digital economy development on technological progress is 0.087, which has passed the significance test with a confidence level of 5%. The coefficient of the interactive impact of technological progress on digital economy is 0.091, which has also passed the significance test with a confidence level of 5%; The coefficient of impact of digital economy development on industrial structure upgrading is 0.126, which has passed the significance test with a confidence level of 1%. The coefficient of interactive impact of industrial structure upgrading on digital economy is 0.095, which has also passed the significance test with a confidence level of 1%; The impact coefficient of digital economy on environmental pollution control is 0.148, which has passed the significance test with a confidence level of 1%. The interaction coefficient of environmental pollution control on the development of digital economy is 0.087, which has also passed the significance test with a confidence level of 1%.

4. Conclusions and recommendations

In order to examine the impact of digital economy development on carbon emission intensity from urban energy consumption and its spatial spillover effects, this article selects 285 cities in China and uses statistical data from 2012 to 2022. Through literature review, theoretical analysis, and empirical design, the article empirically tests the impact of digital economy development on carbon emission intensity from urban energy consumption in China and its spatial spillover effects. Research has found that digital economy has a significant inhibitory effect on carbon emission intensity from urban energy consumption of Chinese cities, with an impact coefficient of -0.348; Among the five selected control variables, PCG, UR, and IS show a positive correlation with carbon emission intensity from urban energy consumption, indicating that these factors enhance CEI, with corresponding impact coefficients of 0.472, 0.135, and 0.331, respectively; EGRI and TRL exhibit an inverse correlation with CEI, indicating that these two factors inhibit the growth of CEI, with corresponding impact coefficients of -0.556 and -0.201, respectively. On this basis, this article proposes the following policy recommendations based on the test results and the actual situation of Chinese cities:

(1) Vigorous development of digital economy is an important means to inhibit carbon emission intensity from urban energy consumption. According to the results of the empirical test, digital economy has a strong inhibitory effect on carbon emission intensity from urban energy consumption and has a positive effect on reducing carbon emission intensity from urban energy consumption. Every 1 percent growth in digital economy can contribute to a 1 percent reduction in carbon emission intensity from urban energy consumption, and digital economy has the leverage to reduce carbon emission intensity from urban energy consumption. Therefore, digital economy development would be minimizing carbon emission intensity from urban energy consumption.

(2) Digital economy minimizes carbon emission intensity through technological progress, industrial structure upgrade, and environmental pollution governance. According to the empirical test results, digital economy has an interactive role with technological progress, industrial structure upgrade, and environmental pollution governance. It is demonstrated by both theory and practice that the inhibitory effect of digital economy development on carbon emission intensity from urban energy consumption is mainly realized through these three aspects. Therefore, it has a multiplier effect making full use of technological progress, industrial structure upgrade, and environmental pollution governance to control carbon emission intensity from urban energy consumption.

(3) Give full play to the positive effect of control variables on the control of carbon emission intensity from urban energy consumption. According to the empirical test results, among the five control variables, PCG, UR, and IR have an enhancing effect on CEI and should be controlled further; EGRI and TPL show an inverse correlation to CEI, which has the effect of inhibiting carbon emission intensity from urban energy consumption; and should be actively exerted to reduce carbon emission intensity from urban energy consumption so as to realize urban energy conservation and emission reduction in China.

Acknowledgments:

This paper is a phased research achievement of the key project of the Rizhao Social Science Fund, "Research on the Implementation Path of the New Pattern of Green and High-Quality Development Empowered by the Green and Low Carbon Transformation in Rizhao City", project number 2023002. The authors thank the Rizhao Social Science Federation for providing funding, and also thank the editor in chief and reviewers for their contributions to the review of this paper.

References

Bi D.T., Huang W.X., Wang L. and Shan B.A. (2023). How Does City Digital Economy Development Affect the Enterprise ESG Performance? —A New Path of Green and High-quality City-Enterprise Collaboration, Studies in Science of Science, on line: DOI: 10.16192/j.cnki.1003-2053.20230404.002.

Cao Z.Y. (2018). Research on the New Manufacturing Model to Promote High-Quality Development of China's Industry under the Background of Digital Economy, Theoretical Investigation, (2), 99–104, DOI: 10.16354/j.cnki.23-1013/d.2018.02.016.

Chang H., Ding Q.Y., Zhao W.Z., Hou N. and Liu W.W. (2023). Digital economy, industrial structure upgrade, and carbon emission intensity: empirical evidence from China's provinces, Energy Strategy Reviews, **50**, 101218, https://doi.org/10.1016/j.esr.2023.101218.

Garifova L.F. (2015). Infonomics and the Value of Information in digital economy, Procedia Economics and Finance, **23**, 738–743. https://doi.org/10.1016/S2212-5671(15)00423-2.

Glitman K., Farnsworth D. and Hildermeie J. (2019). The role of electric vehicles in a decarbonized economy: Supporting a reliable, affordable and efficient electric system, The Electricity Journal, **32(7)**, 106623, https://doi.org/10.1016/j.tej.2019.106623.

Jing G.F. (2003). Preliminarily Economic Analysis on Digital City Construction of China, Geography and Geo-Information Science, **19(4)**, 12–17.

Khan K., Luo T.Y., Ullah S., Rasheed H.M.W. and Li P.H. (2023). Does digital financial inclusion affect CO_2 emissions? Evidence from 76 emerging markets and developing economies (EMDE's), Journal of Cleaner Production,420:138313, https://doi.org/10.1016/j.jclepro.2023.138313.

Kong L.Y., Dong Y.T. and Zhao X. (2022). The Influence of Digital Economy Development on Carbon Emission: Based on the Test of Intermediary Effect and Threshold Effect, Urban Development Studies, **29(9)**, 42–49+55

Kovacikova M., Janoskova P. and Kovacikova K. (2021). The Influence of Emissions on the Environment within digital economy, Transportation Research Procedia, **55**, 1090–1097, https://doi.org/10.1016/j.trpro. 2021.07.080.

Li Z.G. and Wang J. (2023). How Does the Digital Economy Affect Spatial Carbon Emissions under Economic Agglomeration? Journal of Xi'an Jiaotong University (Social Sciences), **42(5)**, 87–97.

Lilien G.L. and Rangaswamy A. (2000). Modeled to bits: Decision models for the digital, networked economy, International Journal of Research in Marketing, **17(2–3)**, 227–235, https://doi.org/10.1016/S0167-8116(00)00021-5.

Lin H.W. and Shao P.J. (2019). Research on the Factors Influencing the High-Quality Development of Digital Economy by Blockchain, Guizhou Social Sciences, **360(12)**, 112–121, DOI: 10.13713/j.cnki.cssci. 2019.12.017

Miller P. and Wilsdon J. (2001). Digital Futures—An Agenda for a Sustainable Digital Economy, Corporate Environmental Strategy, **8(3)**, 275–280, https://doi.org/10.1016/S1066-7938(01)00116-6.

Nguyen T.T., Pham T.A.T. and Tram H.T.X. (2020). Role of information and communication technologies and innovation in driving carbon emissions and economic growth in selected G-20 countries, Journal of Environmental Management, **261**, 110162.

Ozturk I. and Ullah S. (2022).Does digital financial inclusion matter for economic growth and environmental sustainability in OBRI economies? An empirical analysis, Resources, Conservation and Recycling, **185**, 106489.

Pan X.F., Wang M.Y. and Li M.N. (2023). Low-carbon policy and industrial structure upgrade: Based on the perspective of strategic interaction among local governments, Energy Policy**,** **183**, 113794, https://doi.org/10. 1016/j.enpol.2023.113794

Shu W., Chen Y. and Chen X.J. (2023). Information technology empowerment and corporate budget control: Evidence from China, Pacific-Basin Finance Journal, **82**, 102131, https://doi.org/10.1016/j.pacfin.2023.102131.

Tapscott D. (1994). Digital economy: Promise and Peril in the Age of Networked Intelligence, New York: Mc Graw-Hill.

Tapscott D. (1996). Digital economy: promise and peril in the age of networked intelligence, New York: McGraw-Hill.

Wang L.L. and Chen L.Y. (2023). Influences of digital economy agglomeration on carbon emission: A two-tier stochastic frontier and spatial decomposition analysis of China, Sustainable Cities and Society, **95**, 104624, https://doi. org/10.1016/j.scs.2023.104624.

Watanabe C., Naveed K., Tou Y. and Neittaanmäki P. (2018). Measuring GDP in digital economy: Increasing dependence on uncaptured GDP, Technological Forecasting and Social Change, **137**, 226–240. https://doi.org/10.1016/j, techfore.2018.07.053.

Wei D.M., Xu Y. and Gu N.H. (2023). Digital economy promotes the high-quality economic development, Science Research Management, **44(9)**, 10–19.

Xu W.X., Zhou J.P. and Liu C.J. (2022). The influence of digital economy on urban carbon emissions: Based on the analysis of spatial effects, Geographical Research, **41(1)**, 111–129, DOI: 10.11821/dlyj020210459.

Xu X.S. and Zeng F.T. (2009). A Study on Economies of Scope and Profitability Strategy of Digital Products, Science & Technology Progress and Policy, **26(10)**, 72–74.

Yang G.Q., Wang H.S., Fan H.S. and Yue ZY. (2023). Carbon Reduction Effect of Digital Economy: Theoretical Analysis and Empirical Evidence, China Industrial Economics, **(5)**, 80–98.

Zhang Y. (2023). Digital Economy, Temporal-Spatial Dynamic Effect and Urban Carbon Emission Efficiency, Journal of Hebei University of Economics and Business, **44(6)**, 87–98, DOI: 10.14178/j.cnki.issn1007-2101. 20231108.010.

Zhao L., Yuan Z.X. and Wei H. (2023). The Internal Logic and Realization Path of Implementing “New Finance and Economics” Strategy under the Background of Digital Economy, Finance & Economics, **(10)**, 61–71.

Zhao Y.R. (2023). 50.2 trillion yuan! The development momentum of China's digital economy is strong, CHINA BUSINESS HERALD, DOI: 10.38304/n.cnki.nzgsb.2023.001615.

Zuo P.F. and Chen J. (2021). Digital Economy and Economic Growth from the Perspective of High-Quality Development, Research on Financial and Economic Issues, **(9)**, 19–27, DOI:10. 19654 /j. cnki. cjwtyj. 2021. 09. 003.