Frontiers in Business, Economics and Management
ISSN: 2766-824X | Vol. 14, No. 1, 2024

Impact Of Digital Economy On Carbon Emission Intensity

-- The Moderating Effect Of FDI

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Abstract: The rapid and widespread development of digital economy has given renewed impetus to efforts to peak and reduce carbon emissions, and has heralded significant changes in the energy sector. In this paper, panel data of 70 major countries from 2010 to 2019 are selected as samples, and an indicator system is constructed to measure the level of digital economy development in each country using the entropy weight method to study the development status of digital economy development and carbon emission intensity in each country. This research utilizes a regression model incorporating curve moderating effects to investigate how the carbon emission intensity is influenced by the digital economy, while also considering the moderating influence of foreign direct investment (FDI). The findings unequivocally confirm the presence of a noteworthy U-shaped relationship between the digital economy and carbon emissions. As the digital economy progresses, it moves from supporting to reducing carbon emissions. Improving FDI plays a critical part in regulating the digital economy's relationship to carbon intensity. The shape of the curve is flattened by the moderating effect of FDI. Based on the obtained conclusions, the paper puts forward targeted recommendations in order to curb carbon emissions and further improve the ecological environment.

Keywords: Digital economy, foreign direct investment, carbon intensity, mediating effect, inverted U-shaped relationship.

1. Introduction

As a transformative model for economic growth, the digital economy emerged in the 1990s.This collection of economic activities, geared towards optimizing efficiency and streamlining economic structures, has significantly disrupted traditional economic paradigms and introduced innovative prospects for societal advancement. Within the digital economy, digitization, networking, and intelligence are key drivers of economic development. Data has emerged as a new productive resource, the network has taken on the role of a new infrastructure, and artificial intelligence has become a powerful productive tool. Throughout this evolution, technological innovation drives upgrades in industry and consumption, while enhancing society's ability for effective governance. Essentially, the swiftly growing digital economy is progressively asserting itself as a pivotal catalyst for economic advancement.

Climate disruption presents one of the most serious dangers to sustainable development worldwide. Overwhelming evidence from extensive, long-term observations has firmly linked it to emissions of greenhouse gases. In recent years, nations around the world have embarked on a collective journey to combat climate change, setting their sights on carbon neutrality and peak carbon targets. China has made a significant pledge to peak carbon emissions by 2030 and to achieve carbon neutrality by 2060.To accomplish these ambitious objectives, China is actively advancing the expansion of clean energy and extending the adoption of renewable energy sources, accelerating the transformation of its energy infrastructure, improving energy efficiency, and strengthening the establishment of carbon trading markets. Meanwhile, the United States has also taken a significant step by announcing its intention to achieve carbon neutrality by 2050, accompanied by a robust commitment to reduce greenhouse gas emissions by 50%-52% by 2030. Similarly, the European Union has enshrined in law its mission to achieve carbon neutrality by 2050 and has laid out ambitious plans to reduce greenhouse gas emissions by 55% by 2030.The concerted efforts of nations around the world reflect their determination to address the complex conundrum of reconciling economic growth with environmental protection, as underscored by (Yu et al.,2022a)[1]. These initiatives have generated significant global momentum, with over 130 nations and regions worldwide working towards the attainment of "zero-carbon" or "carbon-neutral" climate targets(United Nations Climate Change, 2021)[2].

From the point of view of the history of economic development, carbon emissions have gradually expanded along with the industrial revolution, and with the extraction and application of fossil fuels such as oil and coal, a large amount of carbon dioxide has been emitted into the atmosphere, so the scale of carbon emissions is often highly correlated with the degree of industrialization. In the era of digital economy, what kind of relationship between carbon emission and economic form is still inconclusive. On the one hand, the digital economy provides opportunities for international low-carbon development. Several researchers have put forth both theoretical and practical evidence advocating the idea that digital economy has the ability to substantially decrease emission of carbon dioxide, concurrently curbing energy consumption through the process of digitalization. (Wu et al., 2021a, 2021b; Ishida, 2015)[3-5]. The digital economy can reduce transaction costs, minimize resource mismatch, and improve manufacturing productivity. Digital inputs in production and operation can promote technological progress and structural optimization, reduce resource and energy losses, help enterprises climb up the global value chain, and enhance green environmental performance. While effectively promoting high-quality economic development and improving innovation capacity, it demonstrates certain effects of carbon reduction and emission reduction and environmental improvement. On the other hand, it's crucial to recognize that certain experts hold an alternative viewpoint. They contend the swift development in the digital economy has indeed fueled economic development but has also heightened energy requirements, leading to a global upsurge in carbon intensity of the emissions (Azam et al., 2021; Ren et al., 2021) [6, 7]. The development of the digital economy may promote some emerging economic activities, such as digital manufacturing and Internet finance. These activities may bring new energy consumption and carbon emissions, and some studies have shown that the development of information technology, the infrastructure of the digital economy as a core component of the digital economy, will ultimately lead to an increase in carbon emissions by stimulating electricity consumption.

The quantity and quality of FDI has a profound impact on the digital economy and carbon emissions of host countries. This complex process shapes the relationship between the digital economy and carbon emissions in several ways. First, FDI is often accompanied by the introduction of technology and innovation, especially in the digital economy. This not only enhances local digitization, but also promotes more efficient production methods, which can help reduce carbon emissions. Second, FDI brings with it the application of international best practices in management and production. The digital economy plays a key role in this process, supporting reductions in carbon emissions by reducing waste of resources in the production process through intelligence and optimization of management. Third, the development of the digital economy may lead to the evolution of the local industrial structure in a cleaner, low-carbon direction. The influx of FDI accelerates this process, driving down carbon-intensive industries and allowing clean technology and digital industries to gradually dominate. In addition, FDI has the potential to transform global value chains, strengthening firms' linkages to global supply chains, enabling more efficient resource allocation and reducing carbon emissions globally.

In the current research literature, investigations into how carbon intensity is influenced by the digital economy have mainly focused on establishing linear linkages. However, increasing evidence suggests that the two are not simply linear inhibitory or promoting effects. Does the impact of the digital economy on carbon emissions vary depending on the amount of FDI funds? Is there a U-shaped connection between the digital economy and carbon emissions? If the digital economy affects carbon emissions, what is the relationship? In contrast to previous research, this article offers unique contributions in several key areas. (1) we examine the non-linear influence of the evolution of digital economy on the intensity of carbon emissions. We observe that as the digital economy advances, carbon intensity may initially increase, but beyond a certain threshold, further growth of the digital economy leads to a reduction in carbon intensity. (2)A moderating effects model is used for the analysis. The article investigates how the digital economy influences carbon emissions on varying degrees of FDI. The focus is on potential shifts and changes in the curve's shape.

Section 2 presents a literature review. Section 3 explains theoretical analysis and hypothesis. Section 4 introduces the methods and data. In Section 5, we presented the discussion and conclusions. Finally, our conclusions and policy recommendations are presented.

2. Literature Review

Tapscott first proposed the concept of the digital economy. Although the term has rich connotations, scholars and institutions have analyzed it from various dimensions. From a technical perspective, Neal proposed that the digital economy is essentially a fusion economy. It integrates digital technology with production and business activities to form an economic activity. Compared to traditional economic production methods, the digital economy places more emphasis on digital information technology, the digital technology industry, and its market-oriented applications. Since the turn of the 21st century, the world has witnessed a continuous advancement in information technology. A new generation of information and communication technology (ICT) is expected to drive the transformation of the traditional industrial economy into a new technology-based economy. The ICT-based digital economy has given rise to e-commerce, the sharing economy, the platform economy, and other data-driven businesses. Lamb defined the digital economy as goods or services traded through digital technology, including development, production, and sales processes. The digital economy is a new business model that has formed due to the continuous development of information technology and socio-economic activities generated by the popularization of the Internet and the large-scale application of information and communication technology.

Economics posits that economic development leads to externalities, including negative externalities such as environmental pollution. Certain academics suggest that the digital economy may also have detrimental impacts on the environment, prompting further research in this area. The green economy and the Internet have gained significant attention, owing to the multifaceted economic impacts of production technology upgrades and industrial restructuring due to the implementation of internet technology. These advancements can influence pollutant emissions via a range of pathways, including energy utilization, economic growth, and industrial restructuring (Kwon et al. 2014; Shin and Choi 2015; Hampton et al. 2013) [8-10]. In addition, the Internet influences pollutant emissions through efficient energy utilization, economic development, and industrial structural upgrades. (Dong et al., 2022a, 2022b) [11, 12]. The web decreases energy reliance of several sectors and helps to optimize their structure. (Ishida, 2015). The digital economy has contributed greatly to reducing industrial energy dependence, improving industrial structure, and fostering green finance and green investment, and will continue to offer more possibilities for energy conservation and emission abatement as Internet technology continues to develop and be applied.

Several studies have indicated potential negative environmental consequences resulting from the growth of the digital economy. While the agglomeration of ICT (Information and Communication Technology) may indirectly decrease carbon emissions through the mediation of technological innovation. Carbon emissions can also be positively affected by expanding economic scale. The widespread adoption of ICT has undoubtedly led to improvements in the efficiency of energy use(Wang et al, 2022)[13].However,the corresponding rise in energy demand in the non-metallic manufacturing industry has resulted in a surge of carbon emissions (Jin and Yu, 2022)[14]. Moreover, the evolution towards a digital economy hinges on the rapidly evolving technology of the Internet. The extensive deployment of internet infrastructure and the swift proliferation of the utilization of the Internet are bound to result in increased electricity and energy consumption in the area (Alam and Salahuddin, 2016)[15], which will increase in carbon emission intensity (Dong et al, 2021)[16]. Prior studies indicate that the Internet, ICT (Information and Communication Technology), and the ICT sector, central components of the digital economy, exert both beneficial and detrimental influences on the environment. These impacts originate from their effects on technological advancement, energy usage, industrial configuration, and infrastructure development.

Research has demonstrated that the digital economy's impact on spatial carbon emissions is non-linear. The impact has an inverted U-shaped effect on reducing local carbon emissions, first stimulating growth and then suppressing it (Li and Wang, 2022)[17]. In addition, under conditions of economic agglomeration, spatial spillover emissions also have a U-shaped reduction effect that initially inhibits growth and subsequently promotes growth.

In short, digital economy's impact on carbon emissions remains uncertain, rendering it unclear whether its impact is positive or negative.

Most previous research has examined the link between climate change and digital economy, but most of it has been qualitative. There is a shortage of empirical studies utilizing real data, particularly on an international scale. This paper issues with past research and has two main findings. First, we found a U-shaped connection between the digital economy and the intensity of carbon use through both theory and testing. Secondly, we will explore how FDI moderates the relationship between two key variables, uncovering the digital economy's direct and indirect environmental impacts, and addressing gaps in current research.

3. Theoretical Assumptions

3.1. Impact of the digital economy on carbon emissions

Kuznets discovered that in countries where economic development is low, environmental degradation intensifies alongside economic growth. However, after reaching a specific threshold, economic development results in slower environmental pollution. In other words, there is an inverted "U" shape to the relation between economic expansion and environmental pollution. Consequently, we propose a similar link can be found between the intensity of carbon emissions and digital economy. This is primarily due to the early phases of digital economy development, where the establishment and utilization of infrastructure required significant energy support. This, in turn, stimulated the uptake of novel ICT devices, encouraged power-intensive consumption patterns, and increased dependency on energy consumption (Kim et al., 2021a,2021b;Kouton,2019)[18-20].By incentivizing electricity use and increasing energy consumption, the demand for energy has continued to rise, creating significant challenges for reducing carbon emission. Additionally, the growth of the digital economy offers the opportunity to stimulate new economic activities, including digital manufacturing and internet finance, which could result in increased energy usage and carbon emissions, ultimately contributing to a rise in carbon emissions.

In the mature stage of digital economy, researchers have discovered the integration of digitization and industrialization has improved industrial efficiency. The integration of digital technology into manufacturing, operations, and management removed obsolete facilities and led to a significant drop in energy use. Morever, the digital economy reduces transaction costs and addresses resource mismatch (Ishida, 2015). The digital economy can reduce transactional costs and address resource mismatches. Additionally, investing in digital production and operations can advance technology and streamline structures, resulting in less resource and energy usage. The digital economy plays a critical role in fostering innovation, driving the transformation of the economy, and promoting high-quality economic growth. Additionally, it exhibits a beneficial influence on reducing of dioxide emissions and enhancing environmental quality. The favorable environmental effects from digital economy are expected to grow, gradually mitigating the adverse consequences of carbon emission. Based on our theoretical analysis, this paper presents the following hypothesis:

H1: There exists an inverted U-shaped nonlinear correlation between the digital economy and carbon emission intensity.

3.2. Moderating effect of FDI in the digital economy and carbon intensity

Foreign direct investment (FDI) is often viewed as an effective way to introduce advanced technology and equipment, and to promote the optimization of industrial structure. High-quality FDI can channel capital and technology to high-tech industries and environmentally friendly enterprises, thereby significantly reducing the carbon footprint of the production process.

In cases where a host country attracts a significant amount of foreign direct investment (FDI), there are similarities in the impact of FDI and the digital economy on carbon emissions. This suggests a potential substitution between the two. This influence is primarily manifested in two ways. Foreign direct investment (FDI) can bring advanced technology and management experience to countries, improving production efficiency and reducing carbon emissions. This is because advanced technology can help companies implement more efficient and environmentally friendly production methods. On the other hand, FDI can promote the optimization of industrial structure and the green transformation of enterprises. The tertiary industry has higher added value than the primary and secondary industries, and all countries are vigorously promoting and developing the tertiary industry. Foreign investors are more inclined to invest their capital in high value-added industries, while the government constantly strengthens the guidance, so that a large amount of capital flows into the service industry, financial industry and other tertiary industries, which can alleviate the capital problem and reduce the cost of financing. And the introduction of management experience and ideas of environmental protection concepts helps to promote the transformation and improvement of host country enterprises to environmental protection, and further reduce the intensity of carbon emissions. Therefore, FDI contributes to the reduction of carbon emissions by improving the level of technology and promoting the optimization of industrial structure. This is similar to the path of the impact of the digital economy on carbon emission intensity.

In countries with low FDI inflows, foreign capital tends to prioritize investment in industries that already have a mature development base and profit potential in the host country. These industries are often dominated by carbon-intensive sectors such as heavy industry, energy extraction and processing. As these industries have a high carbon intensity, FDI can lead to further expansion of the initial scale of production and increased production efficiency. It is important to note that in the absence of effective environmental regulation and carbon emission control measures, these foreign funds may flow into highly polluting and carbon emitting industries, such as coal mining and fossil fuel production. In this case, FDI not only fails to promote sustainable development, but may also exacerbate the increase in carbon emissions and have a negative impact on global climate change.

In the case of low levels of FDI, government-led investment policies and environmental regulations have little influence on the intensity of carbon emissions. Additionally, the impact of the digital economy on carbon emissions remains unaffected by FDI, demonstrating a clear inverted U-shaped relationship. On the contrary, attracting a large amount of foreign direct investment can mitigate the relationship between the digital economy and carbon emissions, resulting in a gentler curve. This paper proposes the following hypotheses based on the above analysis:

H2: FDI is a significant moderator of the inverted U-shaped association between the intensity of carbon emissions and digital economy.

4. Theoretical Assumptions

4.1. Methodology and data

(1) Dependent variable.

In this research, we chose carbon emission intensity (cei) as our dependent variable. We derived our data from the World Development Indicators (WDI), focusing on carbon emissions and Gross Domestic Product (GDP). Specifically, we calculated cei by examining the sum of total carbon emissions as a percentage of GDP.

(2) Independent variables.

We selected the degree of development in the digital economy as the principal explanatory factor. Due to the absence of a standardized, official methodology for measuring the extent of digital economy, it is difficult to directly calculate. Based on available data and an accurate description of the characteristics of the digital economy, and with reference to the systems of indicators that have been defined in earlier studies and the digital economy indicators issued by the World Economic Forum, the International Telecommunication Union and other international organizations, this article selects 15 indicators, with the development of the Internet as the core measurement approach and combined with data availability, using the personal usage rate of the Internet, mobile cellular subscription rate, fixed phone subscription rate, fixed broadband subscription rate, service industry employment rate, high-tech product export rate,the export rate of ICT services, the export rate of information and communication technology products, government expenditure on education, the labor force ratio with higher education, the percentage of households with computers, the percentage of households with the Internet, the enrollment rate of higher education, the per capita ownership of scientific and technological journal articles, and the subscription rate of active mobile broadband are 15 indicators. In Table 1, we created an assessment framework to gauge the digital economy's development across three dimensions national digital competitiveness, digital economy innovation environment and digital economy infrastructure.

Table 1. Evaluation system of the country's digitalization level.

Prime Index	Secondary indicators	Weights of indicators	Source of data
Digital economy infrastructure	Individuals using the internet (% of population)	2.727%	WDI
	Mobile cellular subscriptions	1.84%	WDI
	Fixed telephone subscriptions	6.301%	WDI
	Fixed broadband subscriptions	7.933%	WDI
	Households with a computer	4.121%	ITU
	Households with Internet access at home	3.993%	ITU
	Active mobile-broadband subscriptions	6.33%	ITU
Digital economy innovation environment	Employment in services (% of total employment)	1.715%	WDI
	Workforce with tertiary education	1.232%	WDI
	Government expenditure on education, total (% of GDP)	2.903%	WDI
	Tertiary Education Enrollment	4.072%	WDI
	Scientific and technical journal article ownership	14.604%	WDI
National digital competitiveness	High-tech products export	10.22%	WDI
	ICT service exports of total service export	10.324%	WDI
	ICT goods exports of total goods export	21.685%	WDI

To ensure objectivity and eliminate human bias, we employed the entropy value methodology to calculate the information entropy of indicators. This approach doesn't require any specific data distribution, preserving all information within the dataset. After standardizing the data, we calculated the level of development in the digital economy for each country within our sample.

(4) Moderating variables.

FDI is measured by calculating the present value of net FDI inflows in dollars, denoted as lnfdi, from the World Bank database.

(5) Control variables.

We employed the urbanization level (urd), which is computed as the percentage of the total population that is urban, to assess the extent of urbanization. The liberalization and opening of the financial sector is the fundamental factor in reducing carbon emissions. (Tamazian et al., 2008)[21]. Economic development (pgdp) is measured through the per capital GDP of each country. By examining percentage of renewable energy use relative to primary energy use, energy structure (es) was quantified. Improving industrial structure should contribute to reducing carbon emissions (Sun et al., 2020)[22]. The manufacturing industry is a significant source of pollution, hindering to decrease carbon emissions. However, carbon emissions can be effectively reduced by rationalizing and developing the industrial structure(Wang et al., 2019)[23]. We gauge industrial structure upgrade (ind) by assessing the proportion of the production of the third sector to that of the second sector. Government intervention (gov) level is determined by calculating general government consumption expenditure as a percentage of GDP. Population (pop) is defined by the country or region's year-end population. External openness (trd) is measured by the ratio of imports and exports of goods and services to GDP.

We primarily sourced data for the mentioned variables from databases such as the World Bank, SWIID, ITU, and others. Interpolation was employed to fill in missing values where necessary. Descriptive statistics of the variables are presented in Table 2.

Table 2. Descriptive statistics of variables.

Variable	Obs	Mean	Std. Dev.	Min	Max
cei	700	0.415	0.295	0.06	1.468
dig	700	0.342	0.114	0.109	0.592
lnfdi	654	22.407	1.956	17.328	26.960
lnpgdp	700	9.488	1.13	6.663	11.542
fd	700	0.490	0.233	0.084	0.955
trd	700	95.516	50.394	22.772	379.099
urd	700	68.6	16.595	20.294	100
es	700	22.585	16.916	0	81.07
gov	700	17.198	4.531	4.807	31.839
ind	700	2.515	0.95	0.924	7.603
lnpop	700	16.486	1.681	12.67	21.065

4.2. Model selection

4.2.1. Fixed effect model

In this research, we tested the previously mentioned hypotheses by creating a regression model linking carbon emission intensity (cei) and the digital economy development level (dig). Recognize the possibility that the digital economy will have both a positive and a negative impact on carbon emissions, potentially exhibiting a non-linear connection. As an independent factor, we introduced the quadratic expression of the level of development of the digital economy.

$$\mathrm{Cei}_{it} = \beta_0 + \beta_1 \mathrm{dig}_{it} + \beta_2 \mathrm{dig}_{it}^2 + \beta_3 \mathrm{lnfdi} + \beta_4 \mathrm{fd}_{it} + \beta_5 \mathrm{ind}_{it} + \beta_6 \mathrm{urd}_{it} + \beta_7 \mathrm{es}_{it} + \beta_8 \mathrm{lnpgdp}_{it} + \beta_9 \mathrm{gov}_{it} + \beta_{10} \mathrm{lnpop}_{it} + \beta_{11} \mathrm{trd}_{it} + \alpha_i + \gamma_t + \varepsilon_{it} \quad (1)$$

In model (1) $\beta_1 \sim \beta_{11}$ represents the coefficients of different variables. β_0 represents a constant term. Individual and time fixed effects are denoted by α_i and γ_t, respectively. The random error term is denoted by ε.

4.2.2. Moderating effect model

We use the following equation to examine the impact of FDI on the relationship between digital economy and carbon intensity:

$$\mathrm{cei}_{it} = \beta_0 + \beta_1 \mathrm{dig}_{it} + \beta_2 \mathrm{dig}_{it}^2 + \beta_3 \mathrm{dig}_{it} \times \mathrm{lnfdi}_{it} + \beta_4 \mathrm{dig}_{it}^2 \times \mathrm{lnfdi}_{it} + \beta_5 \mathrm{lnfdi}_{it} + \beta_6 \mathrm{fd}_{it} + \beta_7 \mathrm{ind}_{it} + \beta_8 \mathrm{urd}_{it} + \beta_9 \mathrm{es}_{it} + \beta_{10} \mathrm{lnpgdp}_{it} + \beta_{11} \mathrm{gov}_{it} + \beta_{12} \mathrm{lnpop}_{it} + \beta_{13} \mathrm{trd}_{it} + \alpha_i + \gamma_t + \varepsilon_{it} (2)$$

In Model (2), we incorporate interaction terms, specifically the product of foreign direct investment (lnfdi) and digital economy (dig), denoted as $dig_{it} \times lnfdi_{it}$, as well as the product of the square of foreign direct investment (lnfdi) and digital economy(dig[2]) represented as $dig_{it}^2 \times lnfdi_{it}$.

5. Empirical Results

5.1. Digital economy development level

Building upon the previously defined indicator system for the level of development of the national digital economy, we proceeded to compute the level of digital economy development in 70 nations. We determined the weights for each indicator using the entropy method and present the outcomes in Figure 1.

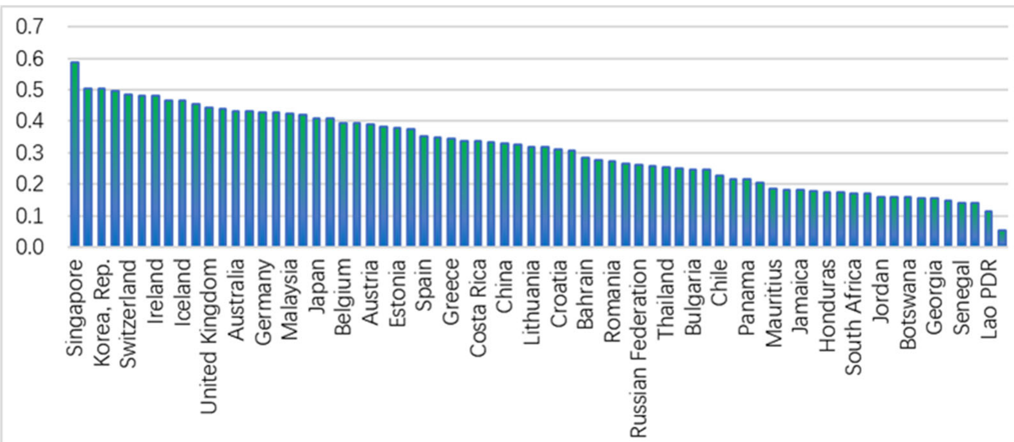

Figure 1. Average digital economy level of each country

Among the selected sample countries, Singapore is the country with the highest level of digital economy. In addition, the digital economy is more advanced in South Korea, the United States, and Western European countries. Lower level of digital economy in developing nations in comparison to developed nations, and the gap between nations with weak network connectivity and those with strong digital connections is increasingly evident worldwide.

5.2. Direct effect analysis

Table 3. Fixed effect model regression results

	(1) cei	(2) cei	(3) cei
dig	3.672***		2.932***
	(1.239)		(0.998)
dig^2	-5.177***		-3.999***
	(1.768)		(1.434)
lnfdi		0.001	0.003
		(0.003)	(0.003)
fd		-0.112	-0.264
		(0.238)	(0.244)
lnpgdp		-0.296***	-0.313***
		(0.089)	(0.073)
ind		-0.062***	-0.057**
		(0.021)	(0.023)
trd		0.052	0.012
		(0.041)	(0.046)
urd		-0.005	-0.005
		(0.009)	(0.008)
es		-0.017***	-0.013***
		(0.005)	(0.004)
gov		0.011	0.007
		(0.008)	(0.006)
lnpop		0.021	-0.030
		(0.158)	(0.201)
_cons	-0.109	3.510	4.102
	(0.207)	(2.960)	(3.650)
N	700.000	654.000	654.000
R^2	0.238	0.424	0.488
Adj R-squared	0.226	0.408	0.472
F	8.878	7.024	9.660

Robust standard errors in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 3 shows the direct impact of digitalization on carbon emissions. The level of development of the digital economy has a positive and significant effect on carbon emission intensity at a significance level of 1%, without considering other variables. Conversely, the negative effect of the quadratic term of the digital economy on carbon emission intensity is also significant at the 1% level. The results of model (3), after the introduction of control variables, indicate that the level of digital economy development and its square term remain significant factors that affect carbon emission intensity. Although the coefficients differ slightly, the overall direction is consistent with the findings of model (1). This fragment highlights the existence of an inverted U-shaped relationship between the development of the digital economy and carbon emission intensity. This relationship is characterized by an initial increase followed by a decrease. When the development of the digital economy is below a certain point, electricity consumption rises significantly due to the intensification of digital infrastructure investment and Internet use. At the same time, the widespread use of ICTs can promote energy efficiency, but it can also lead to higher energy consumption and carbon emissions. After the digital economy reaches the inflection point, the necessary digital infrastructure for its development is largely complete. By moving high-carbon-emission industries and channels online and utilizing information technology to improve the efficiency of information exchange and online transactions, carbon emissions can be gradually reduced.

Regarding the control variables, it is important to note that economic growth, industrial structure, and energy structure have a significant negative impact on carbon emission intensity at the 1% significance level. As economic growth and industrial structure improve, the use of renewable energy increases, and the level of economic development rises, carbon emissions continue to decrease. Increasing the proportion of tertiary industry relative to secondary industry can effectively reduce carbon emissions in the production process. No significant effect on carbon emission intensity was found for other control variables.

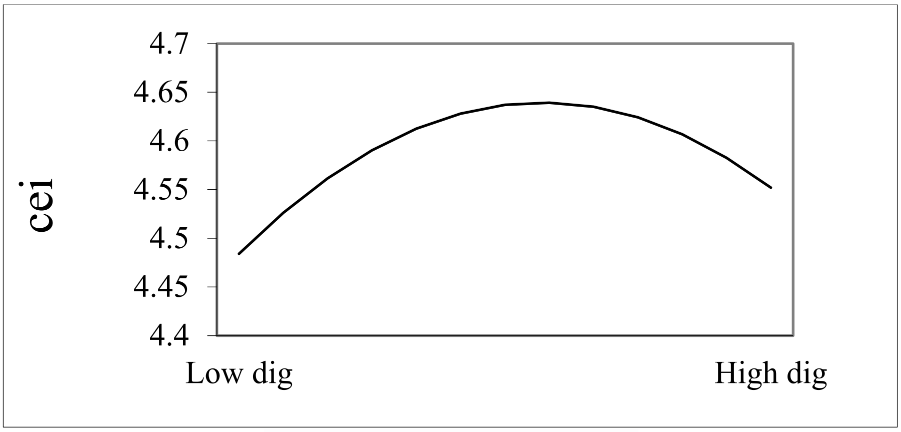

Figure 2. Quadratic effect diagram

To enhance the credibility of the earlier discussed study on the inverted U-shaped relationship, we conducted a targeted test referring to Lind J T, Mehlum H, Sasabuchi S. et al. The results indicated the highest value at the level of 0.370. To validate the findings, we conducted a U-shaped relationship test, which confirmed the existence of an inverted U-shaped relationship.

Analytical procedures from previous works by Aiken and West (1991), Dawson (2014), and Dawson and Richter (2006) were employed to visually capture the relationship between the two core variables. The relationship was visualized by plotting the inverted U-shaped correlation between the two core variables.

Data analysis and visualization tools reveal a correlation: a low level of digital economy (0.370 or below) leads to an increase in carbon emission intensity. This suggests that underdeveloped digital economies may be associated with higher carbon emissions. However, when the digital economy surpasses the critical threshold of 0.370, it has a dampening effect on carbon emission intensity, leading to a decrease in carbon emissions. This threshold highlights the intricate relationship between the digital economy and carbon emissions. In the early stages, the growth of the digital economy may lead to an increase in energy-intensive industries, resulting in a rise in carbon emissions. However, as digital technologies are applied and digital transformation deepens, enterprises and society may focus more on energy efficiency and carbon reduction, thereby realizing the inhibitory effect of the digital economy on carbon emissions.

5.3. Moderating effect analysis

Table 4. Regression results of the moderating effect model

	(1)	(2)
	cei	cei
dig	2.932***	23.527***
	(0.998)	(6.988)
dig^2	-3.999***	-32.302***
	(1.434)	(9.427)
dig*lnfdi		-0.960***
		(0.301)
dig^2*lnfdi		1.315***
		(0.401)
lnfdi	0.003	0.168***
	(0.003)	(0.056)
fd	-0.264	-0.267
	(0.244)	(0.211)
lnpgdp	-0.313***	-0.357***
	(0.073)	(0.066)
ind	-0.057**	-0.044**
	(0.023)	(0.022)
trd	0.012	0.015
	(0.046)	(0.040)
urd	-0.005	-0.004
	(0.008)	(0.007)
es	-0.013***	-0.013***
	(0.004)	(0.003)
gov	0.007	0.006
	(0.006)	(0.005)
lnpop	-0.030	-0.060
	(0.201)	(0.202)
_cons	4.102	1.374
	(3.650)	(3.709)
N	654.000	654.000
R^2	0.488	0.528
Adj R-squared	0.472	0.512
F	9.660	9.762

Robust standard errors in parentheses
$^{*} p < 0.1$, $^{**} p < 0.05$, $^{***} p < 0.01$

Regression result (2) in Table 4 presents the results of the moderating effect test on the level of FDI. From the regression results, after introducing the interaction terms of digital economy with FDI and digital economy squared with FDI, the indices of the interaction terms of FDI, FDI with digital economy and digital economy squared are all significant at the 1% level. This suggests that FDI plays a significant moderating role in the impact of the digital economy on carbon emission intensity.

$$Y = \beta_0 + \beta_1 dig + \beta_2 dig^2 + \beta_3 dig \times lnfdi + \beta_4 dig^2 \times lnfdi + \beta_5 lnfdi$$

$$= \beta_0 + (\beta_1 + \beta_3 lnfdi)dig + (\beta_2 + \beta_4 lnfdi)dig^2 + \beta_5 lnfdi \quad (3)$$

$$C = \frac{d^2Y}{d(dig)^2} = 2(\beta_2 + \beta_4 lnfdi) \quad (4)$$

$$\frac{\partial C}{\partial lnfdi} = 2\beta_4 \quad (5)$$

$$IF = \frac{\beta_1 + \beta_3\ fd}{2(\beta_2 + \beta_4\ fd)} \quad (6)$$

$$\frac{\partial IF}{\partial lnfdi} = \frac{\beta_1\beta_4 - \beta_2\beta_3}{2(\beta_2 + \beta_4 lnfdi)^2} \quad (7)$$

The paper analyzes the effect of FDI on the shape of the curve. The research model is a quadratic function that examines the level of digital economic development. Equation (3) models the moderating effect of the inverted U-shaped curve regression after omitting control variables. The curvature of the vertex determines whether the quadratic function curve is smooth or steep. The vertex curvature, denoted by C, is equal to the second-order derivative of the quadratic function (see equation 4). If the curve is inverted U-shaped, C is less than 0. The smaller the value of C, the steeper the curve, and the larger the value of C, the smoother the curve. To determine the effect of FDI on the curve's shape, calculate the partial derivative of C with respect to lnfdi, as shown in equation (5). After deriving the formula, it is evident that the impact of FDI on the curve's shape is mainly determined by the positivity or negativity of β4. Model 2 indicates that the coefficient of the interaction term between the square of the digital economy and FDI is positive, resulting in a significant positive impact on the curvature of the apex C. This effect leads to a gentler curve shape.

Consider the impact of foreign direct investment (FDI) on the inflection point of the quadratic function curve expressed in formula (6). By taking the partial derivative with respect to lnfdi, you can analyze the effect of FDI on the curve's inflection point, as shown in formula (7). If the denominator of Formula (7) is greater than 0, the impact of FDI on the inflection point depends mainly on the molecule $\beta_1\beta_4 - \beta_2\beta_3$. Regression 4 shows that β_1、β_2、β_3、β_4 are all significant. By substituting the coefficient size to calculate the value of $\beta_1\beta_4 - \beta_2\beta_3$, we get -0.0719. Since $\beta_1\beta_4 - \beta_2\beta_3$ is less than 0, it indicates that FDI will shift the inflection point of the digital economy in relation to the carbon intensity to the left.

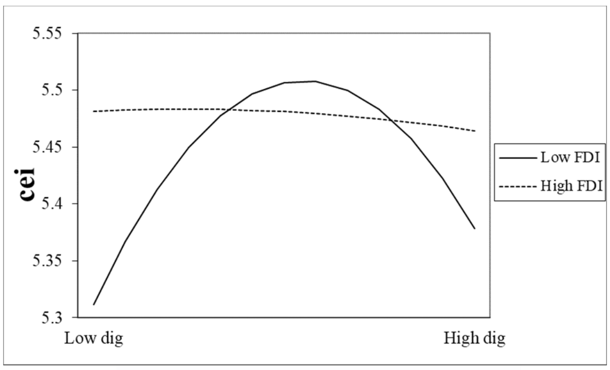

Figure 3. The moderating role of FDI

Figure 3 was plotted to visualize the moderating effect of FDI based on the regression results. The figure shows that in countries with high FDI, the inverted U-shaped curves are flatter and the inflection point is shifted to the left compared to countries and regions with low FDI. This observation further validates the important role of FDI in enhancing carbon reduction capacity. Foreign Direct Investment (FDI) facilitates the improvement and optimization of digital infrastructure by providing the necessary financial and technical support for the development of the digital economy. This accelerates the widespread application of digital technologies and the digital transformation of high-carbon emitting industries. This process improves energy efficiency and productivity, enabling the inflection point to be achieved early in the development of the digital economy by optimizing resource allocation.

In the case of limited FDI, the effect of the level of digital economy on carbon emission intensity shows a clear inverted U-shape. Carbon emission intensity increases at the beginning of the digital economy's development and then decreases as it progresses. However, when FDI inflows surge, the relationship between carbon emission intensity and the digital economy becomes less pronounced, and the inflection point of the inverted U-shaped curve appears earlier. This indicates that the link between the two core variables of this paper weakens with the increase of FDI inflow, and the increase of FDI will dilute the impact of the digital economy on carbon intensity, and can stimulate the digital economy to play its role in suppressing carbon emission intensity. It is clear that FDI plays a crucial role in the development of digital economy infrastructure. Investments in key areas such as telecommunication networks, data centers, and cloud computing provide financial support for related projects and promote the rapid development of the digital economy. As digital infrastructures become more sophisticated, their positive impact on energy conservation and emission reduction is increasingly evident. Efficient telecommunication networks, advanced data centers, and cloud computing services provide convenient and efficient digital solutions for various industries, reducing energy consumption and emissions under traditional business models. The construction and upgrading of infrastructure has promoted technological innovation and industrial upgrading, injecting new vitality into the digital economy and enabling it to play a more active role in promoting global sustainable development. Foreign Direct Investment (FDI) supports the construction of digital economy infrastructure and global efforts to reduce emissions. Such investments not only promote the rapid development of the digital economy but also lay a solid foundation for realizing a green, low-carbon future.

6. Empirical Results

6.1. Conclusion

This paper examines the impact of the digital economy on carbon emission intensity and explores the moderating role of FDI in digital economy and carbon emissions. The study selects a sample of 70 major countries worldwide and uses panel data from 2010 to 2019. The entropy value method is applied to construct the digital economy development from three dimensions: digital economy infrastructure, digital economy innovation environment, and national digital competitiveness. The study analyzed the evaluation index system and the level of digital economy development in sample countries. It calculated the overall digital economy development level of each country. The study confirmed the existence of an 'inverted U-shaped' effect of the digital economy on carbon intensity. Additionally, it investigated the moderating effect of foreign over direct investment on the association between the two core variables. The main findings are as follows:

First, the findings indicate that that the digital economy has been growing globally, but there are notable disparities between developed countries with advanced technology and developing countries with underdeveloped industrial structures, leading to a significant digital divide.

Second, through an in-depth analysis of an extensive dataset covering 70 countries and regions, we have discovered a significant nonlinear, inverted U-shaped relationship between two core variables. This finding provides a new perspective on understanding the interaction between the digital economy and carbon emissions.In regions with an underdeveloped digital economy, the rapid expansion of digital technologies, particularly in the early stages of development, may lead to increased energy consumption and a rise in carbon intensity due to the lack of necessary infrastructure, technical support, and effective regulatory frameworks. However, as the digital economy matures, this situation begins to change significantly. Once the digital economy reaches a certain level of maturity, its efficiency gains and innovations begin to outpace its energy consumption, resulting in a reduction in carbon emissions.

Final, upon analyzing the moderating effect of FDI, significant differences in the impact of FDI on the relationship between the digital economy and carbon emission intensity were found at different levels of FDI inflows and in different country or regional contexts. In countries and regions with low FDI inflows, the impact of FDI on the relationship between the digital economy and carbon intensity is not apparent. In countries and regions with high FDI inflows, the impact of FDI on the relationship between the digital economy and carbon emission intensity is significant. The impact of the digital economy on carbon intensity is weakened and the relationship between the two flattens out due to the large amounts of foreign funding moderating it. In addition, it has been found that in countries and regions with higher FDI inflows, the level of digital economy development can reach the turning point of cutting carbon emissions more quickly. The early arrival of this turning point means that these countries and regions are able to achieve their carbon emission reduction targets more quickly and are thus better equipped to meet the challenge of global climate change.

6.2. Policy recommendations

First, Governments should invest more in digital infrastructure to increase the penetration of digital tools. The widespread use of digital technologies can be facilitated by strengthening infrastructure such as network coverage and building data centers and cloud computing platforms. This can not only improve productivity and reduce energy consumption, but also help promote the low-carbon transformation of the economy. Through digital transformation, enterprises can realize the intelligence and automation of the production process, improve the efficiency of resource utilization, and reduce energy consumption and carbon emissions. At the same time, the government can introduce relevant policies to provide tax breaks, loan support and other incentives to encourage enterprises to carry out digital upgrading. In addition, the government should also pay attention to the development of renewable energy and use digital technology to improve the utilization efficiency of renewable energy. Through smart grids, energy storage technologies and other means, the optimal allocation and efficient use of energy can be achieved, reducing reliance on fossil energy and further reducing carbon emissions. In promoting digital transformation, the government must also strengthen cooperation with the international community to jointly address the challenge of climate change. By sharing experiences and exchanging technologies, the application of digitalization in reducing carbon emissions can be accelerated and the greening of the global economy can be promoted. In summary, the development of the digital economy can be accelerated and its potential for green emission reduction can be realized through measures such as strengthening infrastructure development, encouraging enterprises to digitalize, developing renewable energy, and promoting digital literacy. This will help decouple economic growth from energy consumption, promote the transformation to a low-carbon economy, and make a positive contribution to the global response to climate change.

Second, measures are recommended to channel FDI flows into green investments to support the development of a low-carbon economy. FDI in green investments can be attracted by providing tax incentives and reducing regulatory barriers, and administrative procedures can be simplified to reduce cumbersome formalities and approvals and lower operating costs for foreign investors. Governments can formulate investment promotion policies related to renewable energy, clean technology and environmental protection sectors to encourage foreign investors to invest in these areas. Through these policies, more FDI can be attracted to flow into green industries and promote the low-carbon transformation of the economy. It is emphasized that a clear framework of environmental protection regulations and policies should be established to ensure that FDI is environmentally friendly. These regulations should cover issues such as carbon emissions, waste disposal and resource management, and require investors to take effective measures to minimize negative environmental impacts. Monitoring and reporting mechanisms should also be established to track the impact of FDI on the digital economy and the environment, so that timely action can be taken to correct inappropriate behavior. In conclusion, through a combination of measures such as tax incentives, regulatory reforms, investment promotion policies and environmental protection regulations, more FDI can be attracted to areas such as renewable energy, clean technology and environmental protection industries. This will help promote the low-carbon transformation of the economy and achieve a balanced development between economic growth and environmental protection.

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