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The Impact and Mechanism behind the Effect of a Digital Economy on Industrial Carbon Emission Reduction

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Abstract: Digital technologies hold significant potential for addressing environmental issues, such as air pollution and rising global temperatures. China is focusing on accelerating the dual transformation of industrial greening and digitization to accomplish the UN's 2030 Agenda for Sustainable Development and sustainable economic growth. By combining a two-way fixed effect model, a mediated effect model, and a panel threshold model, this research endeavors to explore the effect that the expansion of the digital economy has on the level of carbon emission intensity that is produced by industry. The research yielded the following primary conclusions. (1) The digital economy effectively reduces the industrial carbon intensity via three distinct mechanisms: enhancements to the technological and innovative capacities of China, improvements in energy efficiency, and enhancements to the country's overall industrial structure. (2) Regions where industrialization and digitization are highly integrated and developing, as well as the early pilot regions of the Comprehensive Big Data Pilot Zones, are particularly susceptible to this inhibitory effect. This research offers a theoretical backing for advancements in the digital economy; the achievement of energy-saving and carbon-reducing sustainable development objectives; and the establishment of green, ecologically friendly, and recycling development strategies.

Keywords: digital economy; carbon emission intensity; carbon sequestration; mediation effect; panel threshold modeling

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1. Introduction

Significant carbon emissions resulting from human activities are a primary contributor to global climate change. The climate issue has led humanity off course from progressing towards sustainable development. The United Nations Framework Convention on Climate Change (UNFCCC), established in May 1992, required industrialized countries to maintain their annual greenhouse gas emissions at 1990 levels by the end of the 1990s [1]. The Kyoto Protocol, established in Japan in 1997, seeks to reduce global warming by restricting greenhouse gas emissions in industrialized nations. Using particular environmental experimental results, Bryan and Michael (2002) tested the consistency of the Kyoto Protocol with changes in greenhouse gas (GHG) emissions. They showed that the agreement provides a necessary first step in addressing the dangerous disruptions affecting the process of sustainable human development [2]. The 2030 Agenda for Sustainable Development, which the United Nations General Assembly adopted during its seventieth session in 2015, advocates for international cooperation among nations in their endeavor to achieve the seventeen sustainable development objectives over fifteen years. In this context, the State Council declared the Action Program on Energy Conservation and Carbon Reduction for 2024–2025 on 29 May 2024. This program outlines China's commitment to gradually advancing energy conservation and carbon reduction through ten significant initiatives.

These initiatives encompass the reduction and substitution of fossil fuel usage, as well as the implementation of energy conservation and carbon reduction strategies in industries that are known for their high levels of pollution. China will collaborate with other nations to become a major global player in the transformation of energy development and the fight against global warming.

According to the report of the 20th Party Congress, China should advocate proactively and consistently for carbon neutrality and peak at that level while also implementing carbon peaking measures systematically and progressively. The China Carbon Accounting Databases (CEADs) contain accurate information that indicates that carbon dioxide production in China will reach 11 billion tons in the year 2022. This constitutes approximately 28.87% of the total carbon emissions that are generated nationwide. The industrial sector is responsible for 4.2 billion tons of carbon dioxide emissions, which accounts for 38.18% of the emissions of carbon dioxide in China. The power sector is the second largest contributor to carbon emissions, with 5.1 billion tons, or 46.37%, of the total. One of the most significant pillars of the economy and an essential component in the general strategy regarding the reduction in greenhouse gases in various nations is the industrial sector [3]. Efforts initiated by the entire country to realize the "dual-carbon target" and to pursue the harmonization of economic, social, and environmental benefits contain a decrease in emissions of carbon, along with the exploration of a long-term mechanism for improving the scale and efficiency of industrial production.

The growing assimilation of digital components into many economic domains has transformed the digital economy into a novel power engine capable of improving China's economic development quality and accomplishing environmentally friendly objectives. The digital economy showcases a nation's overall capability in the information technology age, contributing to significant transformations in production and lifestyle and serving as a crucial factor for the astonishing expansion of the national economy. From the micro standpoint, the profound integration of the digital sector, exemplified by e-commerce, with the physical economy has substantially increased enterprise information channels, transparency, and total factor productivity and decreased production and transaction costs [4]. The electronic transformation of the Chinese-style economy facilitates manufacturing sectors' upgrading and evolution into technology-intensive and capital-intensive industries, as well as services into productive services, at the meso level. The result has been crucial in restructuring and promoting the advancement of China's industrial framework [5]. The interpenetration of digital factors and conventional economic elements of production at the macro level facilitates the efficient allocation and unrestricted circulation of production factors, thereby substantially augmenting social productivity and optimizing resource utilization [6].

There are two distinct research perspectives regarding the connection between the dynamics of the digital economy and the actual growth of atmospheric carbon dioxide across diverse businesses. Several academics have concluded that the extensive implementation of digital production factors contributes to the increase in carbon emissions. According to one study by Belkhirh and Elmeligi (2018), the growth of the information and communication industry has resulted in a growing carbon imprint [7]. By integrating the input–output approach, Zhou et al. (2019) investigated the mechanism by which information and communication technology (ICT) contributes to carbon emissions from a sectoral perspective. On this basis, they identified the generating sectors, transfer pathways, and economic development drivers of carbon emissions, thereby revealing the principles of the formation and change in carbon emissions [8]. Scholars who have investigated the theoretical underpinnings of the current correlation between the degree of Internet-based economy development and carbon emissions have arrived at the finding that a steady trajectory of growth in the digital economy might culminate in resource conservation and decreasing emissions. As an illustration, Chen et al. (2023) examined the transmission mechanism and theoretical mechanism of the digital economy, an inevitable consequence of the new technological revolution, concerning the facilitation of carbon emission decrease at the levels of direct effect and spatial spillover effect. By utilizing provincial data, the researchers confirmed the finding that the digital economy possesses a substantial impact on reducing carbon intensity in specific regions [9]. Yu et al. (2022) looked at the efficacy of digital technology in decreasing emissions of carbon from both theoretical and empirical perspectives. This research was achieved through an evaluation of the digital economy's growth rate in 278 Chinese localities situated at or above the regional level [10]. Additionally, Tian et al. (2024) concluded that an enterprise's digital transformation may greatly lower the intensity of carbon production from the viewpoint of the carbon trading market based on their analysis of panel statistics of a-share listed businesses in Shanghai and Shenzhen [11].

Researchers have studied how technology developments in the digital economy, a relatively new industry, have influenced the decrease in carbon emissions from the industrial sector. Yang and Hu (2022) investigated how digital input levels affect the decrease in industrial carbon emissions by using Chinese industrial input–output panel data [12]. In their research, Jun et al. (2023) conducted an investigation that assessed Internet-based economies' implications regarding the ecological consequences of urban industrial greenhouse gas productivity. Additionally, they analyzed both the temporal and spatial effects and features of this productivity [13]. Integrating the digital production elements with the manufacturing-based conventional tangible economy prevents economic development from becoming disconnected from physical industries. The integration presents necessary support for the enhancement of digital productivity and speeds up the transformation of the economic operation mechanism. According to Ting et al. (2022), the degree to which the new economic model is integrated with different segments of the manufacturing industry will determine the amount to which it affects decreasing carbon emissions related to manufacturing [14].

Furthermore, certain research has revealed discrepancies in the influence of digital element inputs on manufacturing-related carbon footprints: domestic digital inputs significantly reduce carbon intensity, whereas imported digital inputs may raise carbon intensity [15].

Typically, within the realm of economics, the fixed effect model is widely utilized by researchers as a panel data model. Gao and He (2024) utilized a two-way fixed effect approach to explore the causal relationship between digital technology and urban carbon emissions. Furthermore, the researchers employed a mediated effect model, specifically the fixed effect model, to find out the mechanisms by which the digital economy aids in decreasing urban carbon footprints by effectively addressing the issue of land resource mismatch [16]. Li et al. (2024) conducted a study that not only analyzed carbon emissions but also investigated the relationships between the digital economy and the performance of low-carbon cities (LCCs). They used a fixed effect model for their paper. According to their research, the digital economy could greatly reduce both the quantity and carbon emission intensity while also improving the efficiency of LCCs. This study offers concrete evidence to substantiate the utilization of the digital economy's potential to encourage low-carbon urban construction [17].

In addition, researchers choose fixed-effect models to examine the regional spillover effects of the digital economy on carbon emissions, taking into account the specific characteristics of the data presented in the publication. In their study, Yuan et al. (2024) utilized a spatial Durbin model with dual fixed effects to investigate the influence of the digital economy on carbon emissions. The study found that there is strong spatial autocorrelation and that the digital economy has a negative spatial spillover impact on carbon emissions in neighboring provinces [18].

The scholarly scientific investigations on Internet-based economy and carbon dioxide emissions offer relevant theoretical backing for this paper. Currently, research within an area primarily focuses on national or provincial carbon emissions, whereas this paper undertakes a theoretical and empirical investigation into carbon emissions at the industry level. Given this, the following are this article's primary contributions: (1) This article develops an evaluation index system for China's inter-provincial industrial digital economy and uses the entropy approach to assess the progress of each province; it uses a two-way fixed effect model, a mediated effect model, and a threshold panel model to measure the link between digital economy growth and industrial carbon emission intensity in Chinese provinces. (2) This research examines the diversity of effects that digital policies have on different aspects, such as the level of integration between informatization and industrialization development. Additionally, it theoretically analyzes how digitization affects industrial carbon emissions and the mechanisms behind this impact.

2. Theoretical Exposition and Hypothesis

Digital transformation is a powerful force that enhances collaboration and improves resource allocation in the industrial and supply chains. It is an excellent method for promoting environmentally friendly, low-carbon, and sustainable development in the industry. Nevertheless, scholars must address the specific mechanisms via which the Internet-based economy impacts industrial carbon intensity. This section examines how the digital economy impacts the decrease in industrial carbon production. It explores the direct impact, mediating impact, and threshold effect of the digital economy on carbon footprint reduction. Ultimately, this section formulates rational research hypotheses to set objectives and provide direction for the research subject of this dissertation.

2.1. Direct Effects of the Digital Economy on Industrial Carbon Emission Reduction

The profound integration of digital resources and industry has the potential to facilitate a decrease in carbon emissions through the improvement of industrial manufacturing procedures and environmental detection and management. The digital economy could improve industrial production by simplifying processes, improving efficiency, and intelligently controlling production equipment to optimize operational efficiency, enhance quality, increase efficiency, and decrease energy consumption and hazardous emissions. Industrial equipment is a significant contributor to energy consumption during manufacturing and emits substantial quantities of greenhouse gases during operation. The digital economy can decrease enterprises' production energy utilization by enhancing equipment operational effectiveness. Utilizing advanced production processes and equipment like the circular economy and clean production technology can effectively lower industrial carbon emissions [19]. Digital governance theory proposes that advancements in digital technology offer new opportunities for strengthening and enhancing the methods and effectiveness of government administration [20].

Furthermore, technologies like intelligent manufacturing and big data (computing) can systematically and effectively monitor environmentally relevant information and data such as air quality and carbon emissions, offering additional insights for decision-making in industrial eco-friendly initiatives. The government is enhancing its regulatory capacity over resources and the environment. The digital economy and industry are being closely integrated to support policies aimed at reducing industrial carbon emissions, particularly in high energy-consuming sectors like nonferrous metals, building materials, electric power, iron and steel, and the chemical industry [21]. As a result, this research formulates Hypothesis 1.

Hypothesis 1. *The intensity of carbon emissions from industrial sources in the provinces may decrease as the digital economy grows.*

2.2. The Mediating Effect of the Digital Economy on Industrial Carbon Emission Reduction

From the macro viewpoint, the focus of economic development might be shifted from high-carbon to low-carbon industries by the digital economy, which would enable the industrial structure to be upgraded overall through industrialization and the commercial use of digital technology. At the micro level, digital technology can enhance energy efficiency and facilitate energy conversion, resulting in decreased energy wastage in manufacturing and trading operations and mitigating environmental pollution. Furthermore, the digital economy is essential for navigating the latest technological revolution, and science, technology, and innovation can achieve low-carbon objectives by reducing carbon at the source and during the production process. Therefore, this research will analyze the influence mechanisms through three channels: industrial structure effect, energy utilization effect, and technical innovation effect.

2.2.1. Mediating Effects of Industrial Structure

Upgrading the industrial structure involves the dynamic stage of development in which production factors circulate in low-efficiency and high-efficiency sectors, facilitating the economy's entry into a virtuous circle. The digital economy's advancement integrates data into various production factors, permeating multiple economic sectors. This optimization not only enhances the conventional industrial structure but also facilitates the merging of diverse industrial sectors, leading to the appearance of novel business models [5]. From the standpoint of digital industrialization, information industries such as the Internet, software, and telecommunications sectors, along with the electronic information manufacturing sector, have continued to grow in size within the industrial system due to increased labor productivity. The result has generated novel possibilities for digital dividends, elevated emerging sectors to the forefront of the social economy, and established a crucial basis for a stable economic cycle. Concerning the degree of industrial digitization, the permeability of the information-based production factors incorporating digital technology allows it to interact with and enhance other industries, leveraging each other's strengths and integrating deeply. The process of integration aids traditional enterprises in consolidating essential resources, boosting the quality and efficiency of industries, driving the transition from an industrial structure centered on industry to one that is service-oriented, and serving as a new catalyst for the transition and upgrade of traditional sectors.

China's three primary industries consume varying amounts of different types of energy and produce differing levels of carbon emissions. The primary sector, encompassing animal farming, forestry, agriculture, and fisheries, and the tertiary sector, primarily consisting of the service industry, demands lower energy use and produces fewer carbon dioxide emissions. Industry dominates the secondary sector, consuming significant amounts of energy inefficiently and generating high levels of greenhouse gases. Hence, regulating carbon emissions in this sector is necessary for the effectiveness of China's "dual-carbon" program. The swift advancement of digital productivity in China can optimize the state of resource allocation among industries and facilitate the shift in the national economic emphasis from the primary to tertiary industry. The proper allocation of industrial weights can control the ratio of high-energy-consuming industries. Integrated development among various industrial sectors can facilitate the movement of resources, synchronize high and low-energy-consuming industries, and ultimately lead to an overall emission reduction.

2.2.2. Mediating Effects of Energy Utilization

Industry must prioritize energy efficiency improvements to establish a new paradigm of sustainable economic growth. The digital economy possesses the capacity to reduce industrial fossil energy usage and carbon emissions by improving several processes of industrial energy production, consumption, and storage. The advent of digital technologies such as the Sharing Economy, Blockchain, Internet of Things Engineering, and New Industrial Retail has led to increased intelligence, efficiency, and environmental friendliness in energy production and development. The digital economy speeds up clean energy advancement; enhances energy extraction efficiency enables continuous tracking and evaluation of energy storage, transmission, and distribution; reduces unnecessary energy losses; and enhances energy utilization efficiency. IoT, big data, artificial intelligence, and other technologies can assist energy managers in monitoring energy system operations and consumption. The digital economy helps develop more environmentally friendly and scientifically informed management strategies, enhance industrial energy system efficiency, and lower carbon emission levels. For instance, digital technology in smart grid construction enables precise monitoring and control of energy use, enhances energy usage efficiency, prevents the wastage of resource endowments, and reduces carbon-rich gas emissions.

Enhancements in the industrial resource utilization ratio reduce the amount of industrial energy utilized per unit of GDP, and the less energy used, the fewer greenhouse gases are generated for the identical output [22]. The swift growth of the digital economy has used effective ways to enhance energy structures, which in turn has led to a rise in the proportion of high-efficiency energy used and a decrease in carbon production.

2.2.3. Mediating Effects of Science, Technology, and Innovation

The digital economy is a major motor for the present revolution in productivity and the modernization and enhancement of sectors, offering fresh momentum for advancing global scientific and technical innovation and restructuring the global competition landscape. The emerging economy has the potential to decrease time and transaction costs in scientific and technological innovation for industrial enterprises; accelerate the learning effect; enhance innovation capacity; improve innovation levels; and integrate digitalization into innovation development, acting as a catalyst for innovation-led development [23]. Technologies like "Internet Plus", IOT, and the Industrial Internet have significantly improved the exchange of information elements among enterprises, reduced information asymmetry, and expanded opportunities for scientific and technological innovation and collaboration.

Furthermore, STI's impact on reducing industrial carbon emissions is seen in both conventional and sustainable energy sources. The implementation of scientific and technological advancements in conventional sectors has substantially enhanced the efficacy of conventional energy utilization and facilitated the adoption of renewable energy by industrial enterprises [24]. The Industrial Internet can utilize 5G high-speed networks to efficiently connect all elements of industrial manufacturing, the entire industrial chain, and information. This optimization can improve production and management processes, enhance production and management efficiency, reduce unnecessary loss of traditional resources, and increase energy efficiency. Scientific and technological innovation, driven by energy and digital transformation, enables the advancement of clean energy technology, particularly renewable energy. The exploitation and utilization of clean resources are crucial for industrial enterprises to achieve green development. Consequently, the present study posits Hypothesis 2.

Hypothesis 2. *China's digital economy development decreases industrial carbon emissions in each province by upgrading the industrial structure, enhancing industrial energy utilization efficiency, and enhancing scientific and technological innovation.*

Figure 1 illustrates the impact of the digital economy on industrial carbon intensity. This picture supplies a succinct explanation of the theoretical mechanism explaining how the Internet-based economy decreases industrial carbon-rich gas emissions using three channels: the technical innovation effect, the energy consumption effect, and the industrial structure effect.

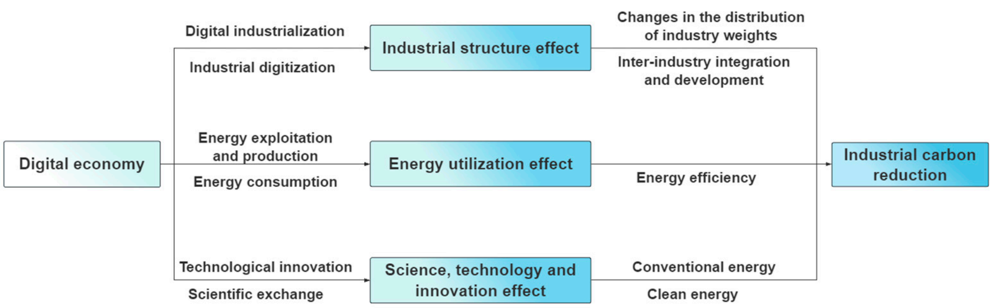

Figure 1. Mechanisms of the digital economy affecting industrial carbon emissions.

2.3. Threshold Effects of the Digital Economy on Industrial Carbon Emission Reduction

The swift progress of digital techniques, including the DC (data center) and industries like software, resulted in the extensive utilization of informational production factors in several businesses. Integrating digital technologies with the real economy might greatly decrease industrial carbon emissions. However, economic phenomena, such as "high-carbon lock-in", in the industrial economy might make sense of the swift expansion of the digital economy, including big data and the industrial Internet, on the industry's carbon production reduction exhibiting nonlinear features. The rapid growth of digital infrastructure could lead to a "Jevons paradox": the rapid progress of digital technology has led to more usage of natural resources, causing decreased pricing for subsequent items, hence boosting demand and consumption of natural resources. Similarly, the digital transformation of industries might result in an "energy rebound effect". The digital economy's advancement enhances equipment operation efficiency and empowers industrial enterprises to boost quality and productivity. Additionally, it leads to the heightened usage of energy and expanded industrial production scale, thereby undermining the future growth prospects of the digital economy and reducing manufacturing carbon-rich gas production [25]. Consequently, this present research posits Hypothesis 3.

Hypothesis 3. *The rapid expansion of the digital economy has a nonlinear impact on diminishing industrial carbon emissions.*

3. Model Construction and Variable Selection

Scientific models are necessary to provide support for rational research assumptions. Thus, this section presents a logical economic model to empirically examine the study assumptions mentioned before. Furthermore, this section provides a comprehensive explanation of the precise definitions of the variables, including the dependent variables, the explanatory variables and the control variables. This step could help other researchers gain a deeper understanding of the dissertation study's subject matter. Additionally, this section offers data sources that are scientifically solid.

3.1. Model Building

3.1.1. Two-Way Fixed Effect Model

Based on the Hausman test *p*-value of less than 0.01, this research rejects the random effect model hypothesis. Hence, drawing from the analysis mentioned above, this paper discusses the research conducted by Chen and Tang (2023) [26] and establishes a two-way fixed effect model to investigate how the expansion of the digital economy affects industrial carbon emission intensity:

$$\mathrm{CE_{it}} = \alpha_0 + \alpha_1 \mathrm{Dige_{it}} + \mathrm{X_{it}} + \mathrm{u_i} + \mathrm{v_t} + \varepsilon_{\mathrm{it}} \quad (1)$$

$\mathrm{CE_{it}}$ represents the industrial carbon intensity, with i representing the province and t representing the year. $\mathrm{Dige_{it}}$ represents the status of digital economy development in the ith province (region, city) during the tth year. $\mathrm{X_{it}}$ is each control variable, and $\mathrm{u_i}$, $\mathrm{v_t}$ and $\varepsilon_{\mathrm{it}}$ represent the province-fixed effects, time-fixed effects, and random error terms, respectively. α_0 is the intercept term. α_1 represents the digital economy regression coefficient, which is the key estimated coefficient in this paper.

3.1.2. Mediation Effect Model

This research constructs a mediating effect model using benchmark regression to verify the mechanism of carbon emission reduction and assess the mediating impact of industrial structure renovation, improvement in energy use efficiency, and scientific and technological innovation capacity. It also validates Hypothesis 2.

$$\mathrm{M_{it}} = \alpha_0 + \beta \mathrm{Dige_{it}} + \mathrm{X_{it}} + \mathrm{u_i} + \mathrm{v_t} + \varepsilon_{\mathrm{it}} \quad (2)$$

$$CE_{it} = \alpha_0 + \gamma_1 Dige_{it} + \gamma_2 M_{it} + X_{it} + u_i + v_t + \varepsilon_{it} \quad (3)$$

M_{it} symbolizes the mediator variable, including industrial structure, science and technology innovation, and energy efficiency. β, γ_1, and γ_2 denote parameter vectors to be estimated, and the symbols of the other variables are the same as in Equation (1).

3.1.3. Threshold Model

This paper aims to further investigate the effect of the explanatory variable development level on carbon emission using Equation (1). Drawing on Hansen's (1999) research, a regression model is constructed utilizing a logarithmic estimation of industrial businesses' R&D projects exceeding enormous scales as a certain threshold variable. The objective is to determine if the association between the digital economy and industrial carbon emission reductions demonstrates nonlinear characteristics [27].

When a single threshold effect is present, the regression model is as follows:

$$CE_{it} = \alpha_0 + \alpha_1 Dige_{it} I(Dige \le \lambda_1) + \alpha_2 Dige_{it} I(Dige > \lambda_2) + X_{it} + u_i + v_t + \varepsilon_{it} \quad (4)$$

When a double threshold effect is present, the regression model is as follows:

$$CE_{it} = \alpha_0 + \alpha_1 Dige_{it} I(Dige \le \lambda_2) + \alpha_2 Dige_{it} I(\lambda_2 < Dige \le \lambda_3) + \alpha_3 Dige_{it} I(Dige > \lambda_3) + X_{it} + u_i + v_t + \varepsilon_{it} \quad (5)$$

3.2. Selection of Experimental Variables

3.2.1. Dependent Variable

The intensity of carbon emissions (CEs) represents the quantity of CO_2 emissions generated per unit of output. In contrast to a metric that solely examines carbon emissions, carbon intensity incorporates the national economy and fluctuations in carbon emissions to offer a more accurate evaluation of industrial carbon emissions within each province. Industrial carbon emissions were calculated by selecting eight energy sources utilizing industrial consumption data from the China Energy Statistics Yearbook. The energy sources comprise natural gas, crude coal, gasoline, electricity, fuel oil, crude oil, liquefied petroleum gas, and diesel fuel. The following is the calculating formula.

$$C = \sum_{i=1}^{8} C_i = \sum_{i=1}^{7} \lambda_i * E_i + \lambda_8(\gamma * E_8) \quad (6)$$

C denotes the total industrial carbon emissions. "i = 1, 2, …, 8" denotes the eight major energy sources in Table 1, respectively. C_i represents the carbon emissions of the ith energy source; E_i represents the total consumption of eight industrial energy sources; λ_1–λ_7 represent the carbon emission coefficients of the first seven energy sources, respectively; and λ_8 is the coefficient of GHG emissions of the coal-power fuel chain. γ represents coal-powered electricity's share of overall generation. Table 1 illustrates the precise carbon emission coefficients.

Table 1. Table of carbon emission factors.

Major Energy-Consuming Fuels for Industry	Raw Coal	Crude Oil	Diesel Fuel	Gasoline	Fuel Oil	Liquefied Petroleum Gas	Petroleum	Coal-Fired Power
Carbon emission factor	1.9003	3.0202	3.0959	2.9251	3.1705	3.1013	2.1622	1.3023

Note: Carbon emission factors for crude coal, crude oil, diesel, gasoline, and fuel oil are in units of t kg/t kg; for liquefied petroleum gas and natural gas are in units of t kg/t m^3; and for coal power are in units of t kg/t kWh. Data in Table 1 are derived from the Guidelines for the Preparation of Provincial Greenhouse Gas Inventories (Trial).

3.2.2. Explained Variable

This research discusses the findings obtained by Wang et al. (2021) [28]. It identifies 18 indicators from three dimensions of expansion of the digital economy to create a national inter-provincial digital economy development evaluation indicator set, as displayed in Table 2. The metrics include the number of fixed telephone consumers, overall telecommunication business, and e-commerce turnover of industrial enterprises. This paper selected positive indicators and used the entropy value means to measure 18 indicators across three dimensions of industrial digital economy development. This process resulted in the industrial digital economy expansion index for each province, autonomous region, and municipality. Among them, this article examines four indicators, including the primary revenue of the electronic information manufacturing sector, to assess the progress of the digital economy in specific sectors like telecommunication and the Internet, categorized by digital industry type.

Table 2. China's inter-provincial digital economy development level indicator system.

Norm		Indicators (Unit)	Function
Digital economy development vector	Traditional infrastructure	Number of fixed telephone subscribers (10,000 subscribers)	+
		Broadband subscribers of the Internet (10,000 subscribers)	+
		Number of domain names (10,000 units)	+
		Number of webpages (10,000 pages)	+
	New digital infrastructure	IPv4 addresses (10,000 units)	+
		Length of long-distance optical cable lines (10,000 km)	+
		Base stations of mobile phones (10,000 units)	+
		Number of mobile phone year-end subscribers (10,000 Subscribers)	+
Digital industrialization	Industrial scale	Business volume of telecommunication services (CNY 100 million)	+
		Income from software products (CNY 100 million)	+
		Income from IT services (CNY 100 million)	+
	Type of industry	Main business income of the electronic information manufacturing industry (CNY 100 million)	+
		Capacity of mobile phone exchanges (10,000 subscribers)	+
		Broadband subscriber ports of Internet (10,000 ports)	+
		Number of legal entities in the information transmission, software, and information services industry (PCS)	+
Industrial digitization		Number of computers in use in industrial enterprises at the end of the period (PCS)	+
		Number of websites owned by industrial enterprises (PCS)	+
		E-commerce turnover of industrial enterprises (CNY 100 million)	+

3.2.3. Control Variables

This research utilizes a variety of control variables, degree of openness to the outside environment (lnOpen), fiscal decentralization, and environmental protection expenditures (lnEpe) to remove any influence of non-research variables on the empirical results to better examine the economic connection between industrial carbon emissions and digital economic development. Logarithmic values are assigned to environmental regulation, the level of openness to the outside environment, and administration expenditure on environmental protection.

3.2.4. Intermediary Variable

This article employed technological innovation level, industrial structure transformation, and energy use efficiency as mediating variables to enhance the examination of the underlying and fundamental factors that contribute to assessing the effect of the explanatory variable on carbon discharge reduction in industries [29].

The variables comprising the categories mentioned above are defined in Table 3.

Table 3. Various types of variables and their meanings.

Variable Types	Symbols	Variable Names	Calculation Method
Explained variable	lnCE	Industrial carbon intensity	Calculated through the carbon emission calculation method provided by the IPCC and the energy consumption and carbon emission coefficients provided by the China Energy Statistical Yearbook and Guidelines for the Preparation of Provincial Greenhouse Gas Inventories. Unit: 10,000 tons/CNY 10 billion, taking logarithms.
Explanatory variable	Dige	Level of development of the digital economy	Eighteen indicators, including the number of fixed-line telephone users, the total amount of telecommunication services, and the e-commerce turnover of industrial enterprises, are selected to construct China's inter-provincial digital economy development evaluation index system, and the comprehensive score is calculated by the entropy weight method.
Control variables	lnEpe	Government environmental expenditures	Government expenditure on energy conservation and environmental protection (CNY 100 million) in logarithmic terms.
	lnGre	Environmental regulation	Expressed as urban garden green space (hectares) taken in logarithms.
	lnOpen	Degree of openness to the outside world	Total exports and imports of goods by region (USD 100 million) taken in logarithms.
	Fin	Fiscal decentralization	The ratio of general public budget expenditure to GDP by province (%).
Intermediary variables	Ind	Industrial structure upgrade	The sum of the value added by the primary sector as a share of GDP*1, the value added of the secondary sector as a share of GDP*2, and the value added of the tertiary sector as a share of GDP*3.
	Ener	Energy utilization efficiency	The ratio of the total amount of electrical energy and raw coal utilized by industries in each province converted into standard coal to the value-added of the secondary industry.
	Tech	Technological innovation level	The intensity of investment in research and experimental development (%).

3.3. *Channel for Acquiring Data*

Based on the accessibility of data, this article utilizes a sample of panel data from 30 provinces in China, excluding Tibet, Hong Kong, Macao, and Taiwan, for the period 2013 to 2021. The main data were gathered from a variety of sources such as the China Energy Statistical Yearbook, China Information Yearbook, Guidelines for the Preparation of Provincial Greenhouse Gas Inventories, provincial statistical yearbooks, China Science and Technology Industry Yearbook, China Statistical Yearbook, China Electric Power Statistical Yearbook, China Information Industry Yearbook, and China Electric Power Statistical Yearbook. Interpolation or analogous reasoning was employed to complete the absent data.

4. Empirical Evidence and Analysis

4.1. *Descriptive Statistics Analysis*

The average industrial carbon intensity is 4.30, with a highest value of 6.0724 and a lowest value of 1.7400, as shown in Table 4 using a descriptive statistical analysis. This empirical result suggests that the intensity of carbon emissions varies significantly across various provinces. The explanatory variable's median is 0.0873, and the mean value is 0.13. The skewness value of the digital economy is 1.9892, and its data show a right-skewed distribution. The multitude of the distribution of the explanatory variables is smaller than the median, and the median is smaller than the mean value. The digital economy in China is comparatively falling behind in general terms. Furthermore, the explanatory variables exhibit a wide range of values, from 0.0038 to 0.6713, and the discrepancy between their maximum and minimum values is greater than 100 times. This finding indicates that significant disparities characterize the digital economy of China's provinces. A descriptive statistical analysis of the control and mediating variables revealed that the levels of each variable were within the normal range, with no outliers. This enables the subsequent phase of the thesis's analysis and research.

Table 4. Summary statistics.

Variables	Obs	Mean	SD	Min	Median	Max	Skewness
lnCE	270	4.30	0.738	1.7400	4.2346	6.0724	−0.2087
Dige	270	0.13	0.125	0.0038	0.0873	0.6713	1.9892
lnEpe	270	5.00	0.565	3.1433	5.0449	6.6167	−0.2695
lnGre	270	11.16	0.836	8.4705	11.1975	13.1861	−0.4194
lnOpen	270	6.30	1.673	1.1928	6.2417	10.6315	−0.0434
Fin	270	25.40	12.121	1.8139	23.0803	75.3428	1.1941
Ind	270	2.50	0.321	1.1432	2.4265	3.9770	1.6955
Ener	270	0.43	0.335	0.0427	0.3158	1.9168	2.0812
Tech	270	1.81	1.149	0.4500	1.5250	6.5300	1.7281

Source: Organized by the author.

This paper computes the average values of industrial carbon intensity and the digital economy for each province from 2013 to 2021. As illustrated in Figure 2, a time-series depiction of the digital economy against the carbon intensity is generated in this paper. From 2013 to 2021, the digital economy has experienced progressive growth, while the carbon intensity has shown a gradual decline. This study concludes that industrial carbon emissions may be hindered by the digital economy based on an analysis of the patterns of both phenomena.

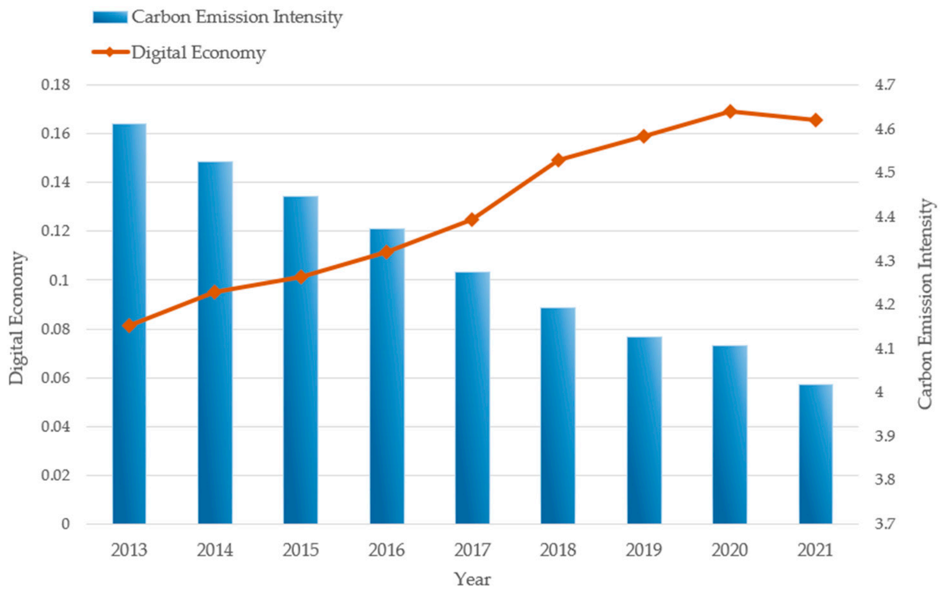

Figure 2. Time-series diagram of the digital economy and carbon emission intensity.

4.2. Reference Regression

The investigation employed a two-way fixed effect model and found that the regression coefficient of the digital economy on the industry carbon intensity in the baseline regression analysis was −0.633. The coefficient in Column 1 of Table 5 was found to be statistically significant at the 1% level. The finding suggests that the advancement of the digital economy has effectively decreased industrial carbon emissions in 30 provinces. After including the control variables (as shown in Column 2), the regression coefficient of the digital economy on industrial carbon intensity is −0.742. The resulting coefficient stays statistically significant at the 1% level. By quickening digital evolution, industrial companies can effectively enhance the ratio of factors in their production process. This enables manufacturing enterprises to improve the efficiency of utilizing factor resources and total factor productivity, ultimately achieving "digital carbon reduction". Concurrently, the real-time monitoring and collection of large-scale ecological environment data can be facilitated by the use of digital technology, particularly remote sensing technology, big data, and other technologies. This enables a precise understanding of energy consumption and carbon emission trends, thereby enhancing the government's ability to conserve energy and reduce emissions. As a result, Hypothesis 1 is verified.

Table 5. Reference regression.

Variables	(1)	(2)
	lnCE	lnCE
Dige	−0.633 ***	−0.742 ***
	(−3.35)	(−3.95)
lnEpe		−0.116 ***
		(−3.89)
lnGre		−0.203 ***
		(−4.02)
lnOpen		0.023
		(1.06)
Fin		0.005 *
		(1.93)
_cons	4.379 ***	6.954 ***
	(175.87)	(11.89)
Time-fixed effect	Yes	Yes
Provincial fixed effect	Yes	Yes
N	270	270
R^2	0.987	0.989

Note: t-values are in parentheses. *** $p < 0.01$, * $p < 0.1$.

4.3. Robustness Check

This research provides a robustness check to verify the validity of the empirical research and prevent issues with measurement error, misinterpreting causation, extreme values, and endogeneity of the digital economy's development level.

4.3.1. Endogenous Issues

The swift growth of the Internet-connected economy has aided the decrease in industrial carbon emission intensity. However, this novel economic model will also be impacted by industrial carbon emission intensity, indicating a reciprocal relationship between the two. Furthermore, this research utilizes the auxiliary variable to address the endogeneity issue resulting from omitted variables due to the limited control variables chosen. This paper utilizes methods researched by Huang et al. (2019) [30], Chen et al. (2023) [9], and Chen et al. (2023) [31]. The interaction term between the natural logarithm of post office counts per 10,000 square km in 1984 and the deferred one period of the explanatory variable is used to examine each province's digital economy.

To confirm the validity of the instrumental factors chosen in this paper, they were evaluated alongside the variables mentioned earlier, and the findings are displayed in Table 6. The preliminary outcomes demonstrate that the chosen instrumental variables in research exhibit statistical significance at the 1% level. The data demonstrate the high connection between the instrumental variables and the primary explanatory variables. At the 5% level of statistical significance, the Kleibergen-Paap rk LM test rejects the initial hypothesis of under-identification of instrumental variables. Furthermore, at the 10% significance level of the Stock–Yogo test, the Kleibergen-Paap Wald F-statistic surpasses the critical value. As a consequence, the assumption that weak instrumental variables exist is refuted, thereby confirming the correlation that exists between prospective endogenous variables and instrumental variables. It shows that the instrumental variables chosen in this article are reasonable.

Table 6. 2SLS regression results for instrumental variable approach.

Variables	The First Stage	The Second Stage
IV-Dige	0.099 *** (0.008)	
Dige		−1.108 ** (0.497)
Time-fixed effect	Yes	Yes
Provincial fixed effect	Yes	Yes
Control variable	Yes	Yes
Kleibergen-Paap rk LM statistic		4.738 **
Kleibergen-Paap Wald rk F statistic		141.543
Stock–Yogo weak ID test critical values: 10% maximal IV size		16.38

Note: Standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$.

After addressing the endogeneity issue in the second phase of the calculation, the degree of the digital economy's effect on the industrial amount of carbon discharges of each province was determined to be −1.108. At the 5% level, this coefficient is statistically meaningful. Growth in the Internet-based economy can still reduce industrial carbon dioxide emissions in all provinces, demonstrating the high dependability of the benchmark results presented in this research.

4.3.2. Substitution of Explanatory Variables

This study re-evaluates the level of development of the explanatory variable by updating the measurement of explanatory factors and using the entropy weight TOP-SIS approach to ensure the robustness of the re-evaluation. The fundamental idea entails calculating weights for evaluating the degree of digital economic development using the objective empowerment methods and the information provided by indicator observations and their variability. Subsequently, the TOPSIS approach is employed to quantitatively assess the proximity of the level of digital economic development to the desired target, which is then followed by a regression analysis. The results of the robustness test are displayed in Table 7. The computed coefficients of digital economic development's impact on industrial carbon emissions passed the 1% significance test, and the baseline results match the initial results. This outcome implies that the findings put forth in this article possess both validity and reliability.

Table 7. Robustness test.

Variables	(1)	(2)
	Replacement of Explanatory Variables	**Excluding Extreme Values**
Dige	−0.932 *** (−4.62)	−0.621 *** (−3.32)
lnEpe	−0.107 *** (−3.61)	−0.123 *** (−4.11)
lnGre	−0.204 *** (−4.09)	−0.194 *** (−3.90)
lnOpen	0.022 (1.07)	0.017 (0.76)
Fin	0.005 ** (1.98)	0.005 * (1.74)
_cons	6.944 *** (12.03)	6.931 *** (12.08)
Time-fixed effect	Yes	Yes
Provincial fixed effect	Yes	Yes
N	270	270
R^2	0.989	0.989

Note: t-values are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.3.3. Excluding Extreme Values

With the potential adverse effects of outliers in the dataset on the regression outcomes in mind, all the indicators are shrunk by 1% in this paper. The estimated coefficients of the primary explanatory variables continue to be substantially negative at the 1% level, as shown in Table 7. This indicates that the findings of the initial regression analysis mentioned in the article are reliable.

4.4. Intermediary Effect

This empirical study utilizes the stepwise regression method and two-way fixed-effect model to analyze the influence of the digital economy on industrial carbon emissions. This study focuses on the structural effect, energy consumption effect, and technological effect. The outcomes are presented in Table 8. The regression coefficients for the influence of the digital economy on the overall enhancement of industries and technological advancement are 1.680 and 2.452, respectively. Both coefficients are statistically significant at the 1% level, indicating that this emerging economy has a considerable effect on encouraging the enhancement of the industrial structure and technical innovation of the national economy. This progress in digital technology could increase the proportion of environmentally friendly and low-carbon industries in the total economy while also enabling industrial intelligence, greening, and integration. The sharing and efficient utilization of data can enhance and reorganize the production, design research, and development of products while also lowering the expenses associated with corporate innovation, thereby offering technical assistance for environmentally friendly innovation.

Table 8. Results of the mediating mechanism test.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	Ind	lnCE	R&D	lnCE	Ener	lnCE
Dige	1.680 *** (3.79)	−0.626 *** (−3.27)	2.452 *** (6.17)	−0.506 ** (−2.54)	−0.513 ** (−2.41)	−0.524 *** (−3.14)
Ind		−0.069 ** (−2.47)				
R&D				−0.096 *** (−3.13)		
Ener						0.423 *** (8.22)
_cons	1.406 (1.02)	7.050 *** (12.16)	1.902 (1.54)	7.137 *** (12.37)	2.816 *** (4.25)	5.761 *** (10.78)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Time-fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Provincial fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
N	270	270	270	270	270	270
R^2	0.67	0.99	0.98	0.99	0.93	0.99
Sobel test	−0.115 (z = −2.070, p = 0.038)		−0.236 (z = −2.790, p = 0.005)		−0.217 (z = −2.315, p = 0.021)	

Note: t-values are in parentheses. *** $p < 0.01$, ** $p < 0.05$.

Furthermore, the regression coefficient for the relationship between the digital economy and energy consumption efficiency is −0.513, and this finding is statistically significant at a significance level of 5%. The finding suggests that digital technology can efficiently mitigate the issue of information asymmetry, decrease the transaction costs and resource consumption of enterprises in the transaction process, and enhance the efficiency of commodity circulation, thereby reducing energy consumption during transportation and distribution.

The regression coefficients for industrial structure and scientific and technological innovation on carbon dioxide intensity are −0.069 and −0.096, respectively, after the mediating variables are incorporated into the econometric model. The coefficients exhibit statistical significance at the 5% and 1% significance levels. This outcome suggests that industrial structure and scientific and technological innovation have a complete mediating effect. The regression coefficient for the correlation between energy efficiency and carbon emissions is 0.423, indicating a statistically significant positive association at a significance level of 1%. The outcome suggests a direct correlation between the carbon intensity and the amount of energy consumed by industries per unit of secondary production. The digital economy accomplishes the objective of promoting environmentally friendly and low-carbon industries by enhancing energy utilization efficiency.

Therefore, technological advancement, energy conservation, and industrial upgrades have a mediating impact on reducing industrial carbon footprints enabled by the digital economy. The findings for Sobel's tests demonstrate the existence of this effect. By using STATA17 to calculate the data, we could obtain the proportion of the mediating effect to the total effect. Upon ascertaining that the mediating effects of energy usage efficiency increase, scientific and technological progress, and industrial structure upgrades contributed 15.6%, 31.8%, and 29.3% to the overall effect, respectively, Hypothesis 2 was validated.

4.5. Threshold Effect

This work employs the Bootstrap method to sample the data 300 times to assess the threshold effect based on Hansen's threshold effect test premise. Table 9 presents a concise overview of the detection outcomes obtained from the threshold model.

Table 9. Threshold test.

Threshold Variable	Threshold Number	Threshold Value	95% Confidence Interval	F-Value	*p*-Value	10% Threshold Value	5% Threshold Value	1% Threshold Value
Dige	Single threshold	10.6843	[10.5299 10.7499]	23.43	0.0433	18.7239	22.0925	31.8500
Dige	Double threshold	10.6843 7.9669	[10.5299 10.7499] [7.8495 7.9793]	8.49	0.4333	14.4125	17.0024	23.4141

These findings indicate that the single barrier for the number of R&D projects in industrial firms over the prescribed size achieved statistical significance at the 5% level. However, the double threshold failed the significance test. This study utilizes the single-threshold model to analyze the nonlinear effect of the explanatory variable on industrial carbon intensity to guarantee the accuracy and dependability of the empirical findings. Based on the results of the threshold regression analysis (Table 10), there is a nonlinear link between the main elements that explains the drop in industrial carbon emissions. When the values of the primary explanatory variable are less than 10.6843, the explanatory variable has a significant negative impact on industrial carbon emissions. The coefficient for this effect is −2.233. The coefficient is −1.696 when the explanatory variable's level of development exceeds the threshold, and the digital economy's influence on industrial carbon emissions is diminished. The implementation of several policies, such as the establishment of a national-level experimental zone for big data; the creation of "smart cities"; and the launch of the "East Counts, West Counts" project, showcases the increasing influence of the evolution of the emerging economy. Once this emerging economy attains a certain standard of development, the potential of decreasing industrial carbon emissions remains. However, the "Jevons paradox" and the "energy rebound effect" may diminish the emission reduction consequences of an emerging economy fundamentally propelled by data. The manufacture of goods has become more efficient as a result of advancements in digital technology, which has also seen a rise in demand for products at lower prices. Simultaneously, the digital economy's emergence of new industries and technologies can improve the level of intensive management in traditional industries, enabling industrial enterprises to expand production scale, increase efficiency, and enhance quality. The "Jevons paradox" and the "energy rebound effect" can both contribute to firms' increased demand for energy, which can undermine the dampening effect of the digital economy on carbon footprints. As demonstrated by the empirical findings presented above, this research's Hypothesis 3 has been proven to be statistically significant.

Table 10. Threshold effect regression results.

Variables	(1)
	lnCE
Dige ≤ 10.6843	−2.233 ***
	(0.283)
Dige > 10.6843	−1.696 ***
	(0.210)
Control variables	Yes
_cons	10.651 ***
	(1.079)
N	270

Note: Standard errors are in parentheses. *** $p < 0.01$.

4.6. Heterogeneity Analysis

(1) Heterogeneity of policy effects

This Internet-based economy is the primary catalyst for the ongoing technological and scientific revolution as well as the transformation of industries. It also represents a strategic advantage for countries seeking to lead in future growth. In August 2015, the State Council announced the Outline of Action for Promoting the Development of Big Data to advance the development and usage of big data in China and speed up the creation of a data powerhouse. This document recommended the implementation of pilot programs as a strategy to facilitate the industry's progress. In September of the year, as mentioned above, Guizhou initiated the creation of the inaugural nationwide comprehensive pilot area for big data to encourage the efficient utilization and thorough analysis of big data resources. In October 2016, the following provinces were given the green light to establish national-level comprehensive big data pilot zones: Beijing–Tianjin–Hebei and the Pearl River Delta were two of the cross-regional comprehensive pilot zones; Shanghai, Henan, Chongqing, and Shenyang were four regional demonstration zones; and Inner Mongolia was the first ethnic minority autonomous region to be included in the national comprehensive pilot zone on big data. The eighteenth CPC National Congress prioritized the execution of digital economy strategies as a direction of national strategy. It took active economic measures to advance modernization and development in the Chinese style, with particular emphasis on the development of comprehensive big data pilot areas. This creation of the data mentioned above centers on big data, which will facilitate the integration of digital technologies with real-world applications, spur innovation in the digital industry, and establish digital industry clusters that are globally competitive. This process would result in an imbalance in the scale, quality, and utilization of big data between the integrated big data pilot regions and non-pilot regions, impacting industrial carbon emission reduction activities to varying degrees [32].

Based on national policy documents, this paper divides thirty provinces into two categories: comprehensive pilot zones of big data and non-comprehensive pilot zones of big data. Table 11 presents this research's findings, which investigates the effect of different regulations and economic strategies on carbon dioxide footprints from industries in the digital economy. This regression coefficient of −1.004 establishes a relationship between industrial carbon emission intensity and digital emerging economy evolution in the pilot areas of the Comprehensive Big Data Pilot Zones, which satisfies the 1% significance test. As data in the digital economy have expanded in scope, quality, and applicability, the industrial carbon intensity of the provinces has decreased significantly. The regression analysis between the digital economy and carbon intensity in the non-big data pilot regions was −0.061, failing the significance test. Non-pilot regions have not established a more comprehensive big data industry chain. They are unable to promote the platform ecosystem to empower the digital transformation of industries and regions. Consequently, the digital emerging economy has not been able to effectively reduce the intensity of carbon emissions within regions.

Table 11. Heterogeneity regression results.

Variables	Policy Effect		Degree of Development of Industrialization–Informatization Integration	
	(1) Comprehensive Big Data Pilot Zone Pilot Areas	(2) Non-Big Data Comprehensive Pilot Area Pilot Areas	(3) High Level of Development	(4) Low Level of Development
Dige	−1.004 ***	−0.061	−0.682 ***	0.120
	(−4.26)	(−0.15)	(−3.24)	(0.08)
_cons	5.664 ***	7.151 ***	4.778 ***	8.440 ***
	(3.98)	(10.14)	(5.25)	(10.15)
Control variables	Yes	Yes	Yes	Yes
Time-fixed effect	Yes	Yes	Yes	Yes
Provincial fixed effect	Yes	Yes	Yes	Yes
N	90	180	180	90
R^2	0.99	0.98	0.99	0.99

Note: t-values are in parentheses. *** $p < 0.01$.

(2) Heterogeneity in the degree of development of industrialization–informatization integration

The integration of informatization and industrialization involves a comprehensive combination at a high level, where both processes merge and progress together, mutually enhancing each other in an upward spiral development path, paving the way for a new industrialization approach. The increasing convergence of information technology and industrialization has opened up new possibilities for industry to investigate green development in search of a new model for global sustainable development. The emergence and utilization of new information technologies have brought about substantial modifications in conventional production management techniques and corporate operating models. The third industrial revolution has enabled the incorporation and enlargement of information technology and traditional industry, resulting in significant progress in state-of-the-art science and technology. It has accelerated China's transition from traditional manufacturing to "smart manufacturing" by strengthening the country's capacity for independent innovation.

This article will categorize thirty provinces based on the degree of information technology–industrialization integration in 2020 to examine the implication of digital economy development on industrial CO_2 discharges. The empirical evidence is displayed in Table 11. The regression coefficient of the explanatory variable on the intensity of industrial carbon emissions is significantly negative at a 1% level in regions where digital technology is well integrated and diffused throughout the industrial sector. This outcome indicates that the R&D and iterative upgrades to information technology in industrial fields may successfully lower industrial carbon emission intensity in each province. The initial term regression coefficient of the core explanatory variable on industrial carbon emission intensity in underdeveloped regions with limited industrialization and information integration is positive but not statistically significant. The creation and operation of digital infrastructures consume significant quantities of energy in the early stages of the digital economy, leading to increased industrial carbon intensity. In this stage, the digital economy's economies of scale and scope have not yet been completely developed, and the synergistic progress of economic, social, and ecological benefits cannot be achieved.

5. Discussion

It is known from existing studies that the economic activities of human societies are the main cause of global carbon emissions [33–35]. Based on the Sustainable Development

Goals of the 2030 Agenda for Sustainable Development, this paper selects the digital economy and industrial carbon production intensity as research objects to explore the facilitating function of the digital economy on greenhouse gas reduction. This article collates and summarizes the relevant literature to conclude that industrial structure [36], science and technology [37], and energy use [38] are the three main channels of action through which the emerging economy empowers carbon-rich gas reduction. This is supported by the empirical findings presented in this paper regarding mediation effects. While most of the literature takes regional heterogeneity [39] as a research precaution for further analyses of digital economy-enabled carbon mitigation, this paper chooses heterogeneity in big data policy effects and heterogeneity in the degree of development of digitalization and industrialization convergence as the focus of the study. Such research makes it possible to more thoroughly examine how various stages of the expansion of the digital economy impact industrial carbon intensity.

In addition to empirical analyses of the theory, this paper has found several interesting studies based on these findings. The research substantiates Hypothesis 3, which posits that the influence of the digital economy on industrial carbon footprint exhibits nonlinear features. Essentially, the "energy rebound appearance" and the "Jevons paradox" mitigate the digital economy's inhibitory effect on industrial carbon footprints when the values of the core explanatory variables surpass the threshold. In the same vein, Teng and Zheng (2023) investigated the influence of digitization on the carbon discharges of manufacturing enterprises from the standpoint of the "Jevons paradox". Researchers determined that the digitalization of productive enterprises and the total carbon discharge of firms are inextricably linked, resulting in a "Jevons paradox" in which the carbon discharge of enterprises will increase [40]. Their research and Hypothesis 3 of this paper share similarities.

Certain academicians have reached diverse conclusions in response to this paper. Liu and Xu (2023) found that the establishment of digital infrastructure has caused a rise in energy usage during the early stages of the digital economy, leading to a subsequent rise in carbon emissions. Nevertheless, the implementation of digital technology will improve the sustainability of energy utilization and low-carbon governance of enterprises, thereby reducing carbon footprints once the digital economy has reached a certain milestone in its development. Consequently, they determined that the digital economy's influence on carbon discharge is characterized by an inverted U-shape that is currently increasing and then decreasing [41]. Cao et al. (2024) also utilized the digital economy index as a variable that determines a threshold. However, their findings indicated that the digital economy had a noteworthy stimulating effect on carbon discharge efficiency once the threshold was surpassed, but it possessed a restraining impact on carbon emission efficiency before reaching the threshold [42]. This implies that the study's U-shaped pattern characterizes the effect of the digital economy on carbon production.

In current research, the mediation effect model is the preferred method by numerous academicians to confirm the effect of the digital economy on carbon emissions. As stated by Wang et al. (2023), this growing economy could significantly improve its carbon emission performance by promoting economic growth, improving its industrial structure, and speeding up technological advancement. In contrast to the theoretical analyses in this paper, Wang et al. examined the channel through which the degree of economic advancement influences carbon emission performance and determined that the digital economy can indirectly influence the scale of manufacturing emissions [43]. Xiang et al. (2023) argued that the web-based economy impacts urban carbon emissions by improving the allocation of resources, as well as promoting technological advancement and upgrading the industrial structure [23]. Moreover, within the context of the industrial field, which is the focus of this article, specific research has shown that implementing industrial digital transformation can effectively decrease carbon emissions by enhancing energy efficiency and strengthening collaboration among entities involved in emission reductions [8]. Wu and Deng (2023) determined that the digital economy could indirectly enhance industrial carbon productivity through green technological advancement and industrial structure upgrades, in addition to directly affecting China's industrial carbon productivity, after conducting theoretical analyses and empirical studies [44].

The Internet-based economy is an unavoidable outcome of the ongoing scientific and technological revolution. Digital production factors play a vital role in driving productivity growth and shaping the evolution and advancement of economic structures. To achieve the objective of sustainable development, humans should focus on fully studying the brand-new channels of carbon footprint reduction empowered by the emerging economy within the realm of the digital sector and its spatial spillover effects in the era of information.

6. Conclusions, Limitations, and Future Perspectives

6.1. Research Conclusion

This research investigates the mechanism of operation and the impact of the digital economy on the intensity of industrial carbon emissions. The empirical findings indicate that this novel economic model reduces the intensity of industrial carbon emissions. The carbon emission intensity will decrease by 0.742 percent for every 1 percent increase in the degree of development of the digital economy. This empirical result maintains its stability following three robustness tests: the replacement of explanatory variables, the resolution of endogeneity issues, and the elimination of extreme values. This paper's Hypothesis 1 is substantiated in this regard.

The Internet-driven economy reduces industrial carbon intensity by impacting energy efficiency, technological innovation, and industrial structure through mechanisms of action. Typically, upgrading industrial structures and promoting scientific and technological innovation significantly reduce industrial carbon emissions. Additionally, digital technology can further decrease carbon emissions by positively impacting industrial structure and scientific and technological innovation. Furthermore, by optimizing energy consumption, the digital economy may serve as an opponent to carbon emissions. Hypothesis 2, which was proposed in this paper, has been confirmed in this respect.

Concurrently, the digital economy's advancement and a decrease in carbon dioxide emissions from industrial companies exhibit a distinct nonlinear correlation. The digital economy could drastically decrease carbon emissions when they fall below a specific threshold. However, the "energy rebound phenomenon" and the "Jevons paradox" may become substantial factors once this threshold is surpassed. The "energy rebound phenomenon" and the "Jevons paradox" may partially mitigate the emission mitigation effects of the digital economy once it reaches a specific stage of development. Hypothesis 3, which was proposed in this paper, has been confirmed in this respect.

Heterogeneity investigations revealed that the rapid progress of a new information-driven economy has diverse impacts on the quantity of industrial carbon emissions. The impact is more pronounced in regions that have developed comprehensive big data demonstration areas and advanced levels of industrialization–information integration development.

6.2. Limitations and Future Perspectives

Intending to promote a sustainable and environmentally friendly world and enhance the overall ecological conditions on a worldwide scale, it is crucial to strongly support the progress of the digital economy. The current research presents theoretical insights into sustainable development strategies in China by demonstrating the effect of the digital economy on facilitating the reduction in industrial carbon emissions, as supported by statistics from various provinces. Nevertheless, there are areas for improvement in this research. Initially, this article was founded on data gathered from 30 provinces in China for analysis, as the Tibet Autonomous Region and other regions were unable to be studied due to the sample size limitation. Secondly, this study should have included numerous indicators due to the data's limited availability. For instance, the digital industrialization dimension of the digital economy indicator system needs more data regarding indicators such as the radio and television industry. In addition, this study needs to completely integrate data from emerging industries, including the industrial Internet and cloud computing, as a result of the limited availability of data. Lastly, a comprehensive examination of the decrease in carbon dioxide effects of the digital economy requires a longer period, and the investigation into China's digital economy started late. This study conducted a preliminary short-term analysis by selecting data from 2013 to 2021 based on its completeness. Consequently, it is imperative to expand the time frame and increase the sample size to enhance the enduring influence of the digital economy on industrial carbon production research in future papers.

The digital economy's effect on the reduction in carbon production is a highly intricate research question. The mediating effect is analyzed in this paper only concerning three paths: industrial structure, science and technology, and energy use. Nevertheless, the digital economy's influence on the mitigation of carbon emissions will be unrestricted to these three channels of action. We must also concentrate on other mediating factors, including environmental regulation and human resources. In the interim, this study primarily examines carbon footprints from a static perspective. The subsequent phase will involve the use of a dynamic economic model to investigate the spatial spillover impact of the digital economy on industrial greenhouse gas emissions.

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