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Digital Economy Empowers Carbon Emission Reduction: The Contribution of Digital Transformation to Carbon Neutrality for Chinese Enterprises

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Abstract
In recent years, with the rapid development of technology and the ICT field, enterprises and governments have been accelerating the digitalisation process. However, alongside technological advancements, climate change has become a matter of global concern. As the core participants in economic activities, enterprises play a crucial role in promoting economic development through digital transformation while reducing carbon emissions. Nevertheless, questions remain: Can digital transformation further assist enterprises in reducing carbon emissions, facilitating the realisation of China's "dual carbon" goals? And are there differences among different types of enterprises? This study employs the fixed effects model to conduct an in-depth analysis of these issues based on listed companies, state-owned enterprises, and large local private enterprises in China over the past decade. The research findings indicate that the digital transformation of enterprises can significantly reduce regional carbon emission intensity. Further study reveals that digital transformation promotes the low-carbon development of regions by driving technological innovation. Additionally, heterogeneity analysis shows that the impact of digital transformation is more significant in traditional high-energy enterprises. The innovation and contribution of this paper lie in exploring the effect of enterprise digital transformation on regional energy conservation and emission reduction from a digital perspective. It demonstrates that, in addition to the transition to clean energy, accelerating the digital transformation of enterprises provides another approach to achieving carbon neutrality. It also enriches academic research results in the fields of digital economy, energy conservation and emission reduction.

Keywords: digital economy, carbon emission intensity, corporate digitalization, technology, innovation, chinese evidence

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Introduction

In recent years, the digital economy has become the core driving force of global economic growth. According to statistics from the International Monetary Fund (IMF), the global digital economy accounted for more than 40% of the world's total economy in 2023[1]. According to World Bank data, the total global digital trade volume reached 7.13 trillion US dollars in 2023, representing 22.5% of total international trade [2]. With its advantages in digital technology innovation, the United States had a digital economy of 17.2 trillion US dollars in 2022, accounting for more than 65% of the GDP [3]. The European Union has also achieved remarkable results in digital economic governance, promoting the steady development of the digital economy [4].

China's digital economy has experienced rapid expansion, with its scale surpassing 50 trillion CNY in 2022, accounting for 41.5% of the GDP [5]. By 2023, this figure further increased to 53.9 trillion CNY, contributing 42.8% to the GDP and driving 66.45% of annual GDP growth [5]. Innovations in digital technologies – including big data, cloud computing, and artificial intelligence – have been instrumental in sustaining this growth trajectory [6].

While digital technologies – such as big data, cloud computing, and artificial intelligence – drive productivity and innovation, their environmental implications remain contested [7]. Prior research has extensively examined the economic benefits of digitalization [3–5], yet its role in mitigating climate change, particularly through corporate carbon emission reduction, lacks systematic evidence. This gap is critical to address, as digital transformation may either accelerate decarbonization through efficiency gains or exacerbate emissions via increased energy demand.

As the world's largest carbon emitter, China generated 11 billion metric tons (Mt) of CO_2 in 2022, representing 28.87% of global emissions [8], China has pledged ambitious "Dual Carbon" targets (peaking emissions by 2030 and achieving neutrality by 2060 [9]). While China's digital economy booms, existing studies predominantly analyse its macro-level impacts, overlooking how enterprise-level digitalization influences regional emission intensity – a key determinant of climate policy efficacy.

This study bridges three critical gaps in the literature. First, while prior work analyses digitalization's economic outcomes [3: 6], we provide granular evidence on its environmental effects by linking corporate digital transformation to regional carbon emission density. Second, existing metrics for digitalization (e.g., patent counts or broadband penetration) fail to capture firm-specific investments; we propose a novel financial-statement-based measure, quantifying digital assets (software, IT infrastructure, and intellectual property) to reflect true adoption depth. Third, we identify sectoral heterogeneities, revealing which industries benefit most from digitalization's decarbonization potential – a finding crucial for targeted policymaking.

Our findings offer timely insights for governments and firms balancing digital growth with sustainability. By demonstrating how enterprise digitalization can reduce emission intensity, this study informs China's "Dual Carbon" strategy while providing a replicable framework for other economies navigating the digital-climate nexus.

Literature Review

Research on the Relationship between Digital Economy and Carbon Emissions

The Carbon-Reducing Effect of the Digital Economy

Many scholars believe that the digital economy has an inhibitory effect on carbon emissions, mainly achieving carbon reduction through means such as optimizing resource allocation, promoting green technology innovation, and driving industrial structure upgrading.

The digital economy can enhance the accuracy and efficiency of resource allocation by virtue of technologies such as big data and cloud computing. For example, Kuang Y and Fan Y [10] found that the digital economy, by analysing massive amounts of data, can effectively reduce information asymmetry, enabling resources to flow and be distributed more rationally among various industries and enterprises. This avoids the idling and waste of resources and reduces carbon emissions caused by unreasonable production.

In terms of green technology innovation, the digital economy provides strong technological support and an innovative environment. Yumeng Sun [11] pointed out that digital technologies can accelerate the dissemination and sharing of knowledge, reduce innovation costs, and stimulate enterprises' enthusiasm for green technology research and development. The new business forms and models spawned by the digital economy also provide a broad market space for the application of green technologies, further promoting the latter's development and popularization.

Furthermore, the development of the digital economy can promote the optimization and upgrading of the industrial structure. The digital economy prompts the transformation of traditional industries towards digitalization and intelligence. The proportion of high energy-consuming and high-emission industries gradually decreases, while industries with low energy consumption and high added value are constantly emerging, improving energy efficiency and significantly lowering carbon emissions [12]. The digital economy can also reduce carbon emissions during the energy consumption process by improving energy efficiency.

Based on this, we propose our first hypothesis:

H1: Digital transformation exerts an inhibitory effect on the carbon emissions of enterprises, thereby significantly reducing the regional carbon emission intensity.

The Carbon-Increasing View of the Digital Economy

However, existing research has not yet reached a consensus on whether the digital economy can significantly limit carbon emissions, as well as its influencing mechanisms and effects. Some scholars hold other views, believing that the digital economy can lead to an increase in carbon emissions during its development. Data centres, a key infrastructure of the digital economy, consume a large amount of energy during their operation. According to statistics, the electricity consumption of global data centres as a proportion of total global electricity consumption has been rising year after year, and the resulting carbon emissions cannot be ignored. Some research pointed out that the rapid development of the digital economy has led to a substantial increase in the demand for data storage, processing, and transmission, thus promoting the large-scale construction of data centres and resulting in an increase in carbon emissions [13–15].

The development of the digital economy also drives the development of related industries manufacturing servers, communication equipment, etc. The production processes of these devices consume a lot of energy and generate carbon emissions. At the initial stage of digital economy development in some regions, energy efficiency and environmental protection may be overlooked in favour of speed, leading to an increase in carbon emissions.

In recent years, research has increasingly shown that the relationship between the digital economy and carbon emissions is non-linear. Weihang Du and Xinnuo Liu [16] demonstrated empirically that, with the development of the digital economy, carbon emissions follow an inverted U-shaped curve. At the initial stage of digital economy development, the development of the digital economy may lead to an increase in carbon emissions due to limited technological levels and imperfect infrastructure. However, when digital economy development attains a certain stage, its functions of optimizing resource allocation, promoting green technology innovation, and upgrading the industrial structure gradually come into effect, achieving a reduction in carbon emissions.

Based on this, Zhang and Qi [17] introduced a spatial econometric model and found that the digital economy has a significant inverted U-shaped relationship with local carbon emissions and a U-shaped relationship of "first inhibition, then promotion" with carbon emissions in neighbouring regions. This indicates that the impact of the digital economy on carbon emissions not only exists locally but also affects neighbouring regions through spatial spillover effects.

Based on this, we propose our second hypothesis:

H2: The digital transformation of different types of enterprises contributes differently to the reduction of regional carbon emission intensity.

Exploring the Influence of the Digital Economy on Carbon Emissions

Industrial Structure Upgrading

The digital economy, with its strong technological advantages and innovation capabilities, plays a crucial role in promoting the transformation of the industrial structure towards low-carbonization. This is mainly reflected in two aspects: fostering emerging industries and transforming traditional industries [18].

With regard to the former aspect, the vigorous development of digital technologies has given rise to a series of highly promising emerging industries. A case in point is the big data industry. With the explosive growth of data volume, the demand for data storage, analysis, and application is increasing with each passing day, giving birth to a large number of enterprises engaged in data mining, data analysis, data visualization, and other processes. Through the in-depth analysis of massive data, these enterprises provide accurate decision-making support for various industries, optimize resource allocation, and thus reduce the energy consumption and carbon emissions of the entire society [19]. The cloud computing industry, by providing powerful computing power and storage resources, enables enterprises to avoid building large-scale local data centres, reducing the energy consumption and carbon emissions of hardware devices [20]. The artificial intelligence industry, through intelligent production and management, improves production efficiency, reduces production costs, and channels the development of industries into the green and low-carbon directions [21: 22]. Driven by digital technologies, the new energy vehicle industry has achieved breakthroughs in batteries, autonomous driving technologies, etc., accelerating the electrification of the automotive industry and significantly reducing carbon emissions in the transportation sector [23].

Regarding the transformation of traditional industries, the digital economy provides technological support for the digital and intelligent transformation of traditional industries [24]. Traditional manufacturing industries, by introducing technologies such as the Industrial Internet and the Internet of Things, have realized intelligent monitoring and management of the production process. Production equipment can collect data in real time and, through data analysis, optimize the production process, improve production efficiency, and reduce energy consumption [25: 26]. The digital economy has promoted the servitization of traditional industries. Manufacturing enterprises have shifted from simple product production to providing comprehensive solutions of products and services, increasing product-added value and reducing carbon emissions in the production process [27]. In the agricultural field, the application of digital technologies has led to the emergence of precision agriculture. By employing real-time monitoring and analysing data such as soil, climate, and crop growth, precise fertilization and irrigation are carried out, improving agricultural production efficiency and reducing agricultural non-point source pollution and energy consumption [28].

Driving Force of Technological Innovation

The digital economy provides comprehensive support for technological research, development, application, and diffusion, strongly promoting the reduction of carbon emissions [29].

At the research and development stage, the digital economy, through technologies such as big data and cloud computing, provides abundant data resources and powerful computing capabilities for green technology research and development. Enterprises can use big data analysis to integrate and analyse information such as global green technology research results, market demands, and policy orientations, quickly discover breakthroughs in green technology research and development, avoid duplicate research, and improve research and development efficiency [30]. Cloud computing technology provides a powerful computing platform for complex green technology simulations and experiments, reducing research and development costs [31]. The digital economy also promotes the deepening of industry-university research cooperation. By building digital innovation platforms, it breaks down barriers between universities, research institutions, and enterprises, accelerating the flow and integration of green technology innovation factors [32: 33].

At the application stage, the digital economy promotes the wide application of green technologies in various industries [34]. Smart grid technology, through the intelligent management of the power system, realizes the efficient transmission and distribution of electricity, reducing power losses [35: 36]. Energy management systems use digital technologies to monitor and analyse the energy consumption of enterprises in real-time, helping enterprises formulate scientific energy management strategies and improve energy efficiency [37]. The sharing economy models spawned by the digital economy, such as shared mobility and shared office spaces, improve resource utilization efficiency, reducing resource waste and carbon emissions [38: 39].

At the diffusion stage, the network effects and platform advantages of the digital economy accelerate the spread of green technologies. Digital platforms provide convenient communication and trading channels for both the supply and the demand sides of green technologies, reducing the costs and risks of technology transfer. Enterprises can quickly obtain the required green technologies through the platform, accelerating the application and promotion of technologies [40: 41]. Digital channels such as social media and online forums also provide new ways for the promotion and popularization of green technologies, facilitating the dissemination and sharing of green technology knowledge [42: 43].

Other Influencing Factors

Investment plays a crucial role in the digital economy's impact on carbon emissions [44]. Venture capital investment in green technology innovation enterprises accelerates green technological research, development, and industrialization, contributing to the reduction of carbon emissions [45]. A large amount of capital flowing into the digital economy field has promoted the construction of digital infrastructure as well as research and development in the field of digital technologies. Investment in 5G network construction provides high-speed, stable network support for the development of the digital economy, facilitating the application of digital technologies in various industries, thus indirectly affecting carbon emissions [46].

The adjustment of the energy consumption structure is an important part of the digital economy's carbon reduction efforts [47]. The development of the digital economy has promoted the transformation of energy consumption towards clean energy. The application of smart grid technology has improved the absorption capacity of renewable energy, enabling clean energy such as solar and wind power to be more stably connected to the grid, reducing reliance on traditional fossil fuels, and thus lowering carbon emissions [48]. Digital technologies can also improve energy efficiency and reduce energy waste by optimizing the energy management system [49].

Government actions have an important guiding and regulating effect on the relationship between the digital economy and carbon emissions [50]. By implementing relevant industrial, tax, subsidy and other policies, the government promotes the development of the digital economy and the realization of carbon reduction goals. The government adopts industrial policies to encourage the development of the digital economy, guiding resources to converge in the digital economy field and promoting the innovation and application of digital technologies [51]. Tax-preferential policies for digital economy enterprises reduce the operating costs of enterprises and enhance their competitiveness [52]. By formulating strict environmental regulations and carbon emission standards, the government restricts the carbon emission behaviour of enterprises, prompting them to increase investment in green technological research, development, and application to achieve energy conservation and emission reduction [53]. The government can also guide market demand to incline towards green products and services through policies such as green procurement and promoting the green upgrading of industries [54: 55]. This leads to our third hypothesis.

H3: The digital economy drives enterprises to promote low-carbon development by enhancing green technology innovation.

Data and Methodology

Data Sources

This study utilizes panel data from listed companies across Chinese provinces over the past decade, including state-owned enterprises, central enterprises, and large private firms. The dataset primarily integrates China's digital economy and carbon emission statistics. For digital economy metrics, core data were extracted from the White Paper on China's Digital Economy Development (published by the China Academy of Information and Communications Technology, CAICT), which provides comprehensive statistics on digital economy scale, industrial structure, and growth trends. Supplementary indicators, such as value-added outputs and employment figures in digital-related sectors (e.g., information transmission, software, and IT services), were sourced from the China Statistical Yearbook [56].

Carbon emission data were obtained from the China Emission Accounts and Datasets (CEADs), a multi-scale carbon accounting database covering regional and industrial emissions [57]. Additionally, the Multi-resolution Emission Inventory for China (MEIC), developed by Tsinghua University, was employed to enhance spatial and temporal resolution [58].

To control for confounding factors, auxiliary variables – including industrial structure, GDP, population size, and energy consumption patterns – were compiled from the China Statistical Yearbook [56] and the International Energy Agency (IEA) database [59]. Missing values were addressed using linear interpolation.

Further supplementary data were derived from the China Statistical Yearbook on Science and Technology, provincial statistical yearbooks, the CSMAR database, and the EPS Data Platform [60: 61].

The final dataset consists of 6583 sample companies and converges to 330 sample observations. This paper uses Stata 18.0 software for empirical analysis.

Variable Description

Dependent Variable: The dependent variable is regional carbon emission intensity CO_{2s}, measured as total carbon emissions divided by regional GDP for province i in year t. Unlike studies focusing on aggregate emissions [62], this metric captures emission efficiency dynamics, aligning with IPCC guidelines for decoupling analysis. In the empirical analysis, the carbon emission intensity was logarithmically calculated to take into account the magnitude of the value.

Independent Variable: The independent variable is the corporate digitalization level Digt.

Currently, numerous studies assess digitalization levels by analysing the frequency of digital-related keywords in corporate annual reports, a method widely used to evaluate a company's degree of digitalization [63]. However, keyword frequency only reflects the management's attention to digitalization and does not represent the company's actual digital level. In contrast, evaluating digital assets is more practical, as it directly measures a company's investment in digitalization. Therefore, this study adopts the methodology of assessing a company's digitalization level by calculating the proportion of digital assets [64], such as software, cloud, servers, and big data, disclosed in annual financial statements. Specifically, the ratio of digital assets to intangible assets at year-end serves as a proxy indicator for measuring the degree of digitalization. Additionally, data from companies within the same province are aggregated to represent the digitalization level of that region.

Mediating Variable: Technological innovation $Tech_{it}$ is proxied by the annual count of granted patents per enterprise. Patent data were sourced from the China National Intellectual Property Administration (CNIPA) database, with utility models and design patents excluded to focus on substantive innovations.

Control Variable: It is necessary to add control variables to study whether enterprise digital transformation can drive green and low-carbon development. In this paper, we refer to related research studies to select the following control variables: the ratio of added value of tertiary industry to GDP (Pti), employment rate (Emp), urbanization level (Urb), foreign direct investment (FDI) and government fixed investment (Fix). Taking into account the magnitude of the values, we take the logarithm of FDI and Fix (Tables 1 and 2).

Table 1. Variable Definitions

Variable Type	Variable Name	Variable Symbol	Variable Description
Dependent Variable	Carbon emission intensity	CO_{2s}	Carbon emission per unit GDP was quantified and logarithmically transformed to mitigate skewed distribution.
Explanatory Variable	Digitalization level	Digt	Ratio of digital assets to total assets of sample companies.
Mediator Variable	Technical	Tech	The annual count of granted patents per enterprise.
Control Variable	Proportion of the tertiary industry	Pti	The proportion of the tertiary industry in the national economy.
	Employment rate	Emp	The proportion of the employed population in the working-age population.
	Urbanization rate	Urb	The proportion of the urban population in the total population.
	Foreign direct investment (FDI)	InFDI	Direct investment of foreign investors in domestic enterprises, logarithmically transformed to mitigate skewed distribution.
	Fixed investment	InFix	Investment used for the purchase of fixed assets, logarithmically transformed to mitigate skewed distribution.

Table 2. Descriptive Statistics

VARIABLES	Obs	Mean	Std. Dev.	Min	Max
$\mathrm{InCO_{2s}}$	330	2.697	0.797	0.509	4.800
Digt	330	0.466	0.316	0.210	0.712
Tech	330	0.016	0.043	0.000	0.556
Pti	330	0.477	0.097	0.297	0.839
Emp	330	0.855	0.874	0.815	0.954
Urb	330	0.596	0.121	0.350	0.896
lnFDI	330	12.808	1.749	6.995	15.09
InFix	330	18.733	0.871	15.847	20.251

Model Construction

To explore the relationship between the digital economy and carbon emissions intensity, this study constructs a series of econometric models. The carbon emission intensity is greatly affected by specific and unobservable region individual characteristics [65]. This research employs a two-way fixed effects model regression. This model can effectively mitigate the influence of unobservable variables related to year and individual, decrease estimation biases, and improve the statistical reliability of the results [66].

The benchmark regression model is specified as:

$$\mathrm{InCO}_{2\mathrm{sit}} = a_0 + a_1\mathrm{Digt}_{\mathrm{it}} + a_2\mathrm{Control}_{\mathrm{it}} + \mu_{\mathrm{t}} + a_{\mathrm{i}} + \sigma_{\mathrm{it}}. \quad (1)$$

To verify the role of technology innovation as an internal mechanism in the digital economy's empowerment of low-carbon development, this paper constructs the following mediation effect model:

$$\mathrm{Tech}_{\mathrm{it}} = \beta_0 + \beta_1\mathrm{Digt}_{\mathrm{it}} + \beta_2\mathrm{Control}_{\mathrm{it}} + \mu_{\mathrm{t}} + a_{\mathrm{i}} + \sigma_{\mathrm{it}}; \quad (2)$$

$$\mathrm{InCO}_{2\mathrm{sit}} = \varphi_0 + \varphi_1\mathrm{Digt}_{\mathrm{it}} + \varphi_2\mathrm{Tech}_{\mathrm{it}} + \varphi_2\mathrm{Control}_{\mathrm{it}} + {} + \mu_{\mathrm{t}} + a_{\mathrm{i}} + \sigma_{\mathrm{it}}. \quad (3)$$

where $\mathrm{InCO}_{2\mathrm{sit}}$ represents the carbon emissions intensity of region i in period t; $\mathrm{Dig}_{\mathrm{it}}$ represents the digital economy indicator of entity i in period t; $\mathrm{Control}_{\mathrm{it}}$ represents a set of control variables for region i in period t; σ_{it} is the random error term; μ_{t} is the individual specific fixed effect; $_{\mathrm{i}}$ is the time specific fixed effect; $\mathrm{Tech}_{\mathrm{it}}$ represents the technology innovation indicator of entity i in period t. Equations (2) and (3) are used to test whether technology innovation $\mathrm{Tech}_{\mathrm{it}}$ plays a mediating role in the relationship between the digital economy $\mathrm{Dig}_{\mathrm{it}}$ and carbon emissions intensity $\mathrm{InCO2}_{\mathrm{sit}}$.

Empirical Analysis

Baseline Regression Analysis

To systematically examine the impact of enterprise digital transformation on regional low-carbon development, this study employs a fixed effects model methodology (Table 3). The empirical results reveal that in the baseline model without control variables (Column 1), the regression coefficient of the digital economy (Digt) is −0.0565 ($p < 0.01$), indicating a statistically significant negative inhibitory effect of enterprise digitalization on regional carbon emission intensity.

Table 3. Baseline Regression Results

	(1) $\mathrm{InCO_{2s}}$	(2) $\mathrm{InCO_{2s}}$
Digt	−0.0565*** (−5.47)	−0.0329*** (−4.98)
Pti		−0.0401** (−2.45)
Emp		0.0531 (1.13)
Urb		0.212*** (2.82)
lnFDI		0.512*** (2.77)
InFix		0.689*** (4.76)
_cons	3.626*** (8.37)	2.146*** (4.11)
Year FE	Yes	Yes
Firm FE	Yes	Yes
N	330	330
Adj. R^2	0.698	0.657

Note: The T statistic is in parentheses; *, **, and *** represent significance levels of 10%, 5%, and 1%, respectively.

Table 4. Robustness Test Results

	(1) Replace Variable $LnAvgCO_{2s}$	(2) Exclusion Test $lnCO_{2s}$	(3) Random Effects $lnCO_{2s}$	(4) Province & Year Joint Fixed Effects $lnCO_{2s}$
Digt	−0.0350*** (−4.87)	−0.0298*** (−3.95)	−0.0479*** (−5.21)	−0.0311*** (−4.32)
Pti	−0.0381*** (−3.61)	−0.0522** (−2.41)	−0.0478*** (−2.88)	−0.0332** (−2.39)
Emp	0.0631 (1.67)	0.0831* (1.78)	0.0617 (1.51)	0.0511 (1.01)
Urb	0.298*** (2.96)	0.317*** (3.96)	0.261*** (2.97)	0.201*** (2.61)
lnFDI	0.673*** (3.85)	0.902*** (5.31)	0.549*** (3.11)	0.477*** (2.61)
InFix	0.711*** (4.32)	0.982*** (6.63)	0.837*** (4.99)	0.621*** (3.93)
_cons	3.37*** (5.57)	5.651*** (7.68)	2.763*** (4.78)	1.911*** (4.11)
Year FE	Yes	Yes	No	Yes
Firm FE	Yes	Yes	No	Yes
Province*year	No	No	No	Yes
N	330	286	330	330
Adj. R^2	0.563	0.452	0.661	0.537

Note: The T statistic is in parentheses; *, **, and *** represent significance levels of 10%, 5%, and 1%, respectively.

In Column 2, which includes all the control variables, the regression coefficient of the digital economy (Digt) is −0.0329 ($p < 0.01$), indicating a statistically significant negative inhibitory effect of enterprise digitalization on regional carbon emission intensity. Notably, the proportion of the tertiary industry demonstrates a significant negative correlation with regional carbon emission intensity ($\beta = -0.0401$, $p < 0.05$), which aligns with industrial structure evolution theory. Compared to energy-intensive secondary industries, the tertiary industry – predominantly comprising service sectors – exhibits inherently low-carbon characteristics, further substantiating the carbon reduction benefits of industrial structural upgrading. Among other control variables, urbanization rate ($\beta = 0.212$), foreign direct investment ($\beta = 0.512$), and fixed asset investment ($\beta = 0.689$) all show significant positive correlations with carbon emission intensity ($p < 0.01$). This can be interpreted through an economic lens: foreign capital and government investments predominantly target high-energy-consumption sectors such as manufacturing and construction, while urbanization-driven population agglomeration systematically escalates the demand for transportation and energy infrastructure, thereby generating scale effects on carbon emissions. Additionally, the employment rate variable fails to achieve statistical significance ($p > 0.1$), suggesting that labour market dynamics may require further exploration within this analytical framework to elucidate their impact on carbon emissions.

This finding validates Hypothesis 1. The underlying mechanism may be attributed to digital technologies optimizing production processes, enhancing resource allocation efficiency, and effectively reducing energy consumption intensity while maintaining economic output, thereby achieving marginal diminishing effects on carbon emissions.

Robustness Test

To enhance the credibility of the research conclusions, this paper conducts robustness tests on the benchmark regression results through several different methods.

Table 5. Mechanism Test Results

	(1) Tech	(2) $lnCO_{2s}$
Digt	0.0210*** (4.67)	−0.0291*** (−3.88)
Tech		−1.527*** (−5.28)
Pti	0.131 (1.51)	−0.0411*** (−2.71)
Emp	0.096 (0.96)	0.0589 (1.09)
Urb	0.216*** (2.11)	0.238*** (2.97)
lnFDI	0.728*** (4.57)	0.509*** (2.66)
lnFix	0.523*** (3.37)	0.712*** (4.33)
_cons	1.87*** (7.37)	2.550*** (6.46)
Year FE	Yes	Yes
Individual FE	Yes	Yes
N	330	330
Adj. R^2	0.527	0.565

Note: The T statistic is in parentheses; *, **, and *** represent significance levels of 10%, 5%, and 1%, respectively.

Replacement of the Explained Variable: Drawing on the measurement method of Shao Shuai et al. (2019), this study replaces the explained variable with the natural logarithm of per-capita carbon emission intensity (LnAvgCO2s) and re-estimates the model. Column (1) of Table 4 shows that the regression coefficient of the digital economy variable is consistent with that of the benchmark regression in terms of direction and significance level, indicating that the core conclusion is not affected by the variable measurement method.

Sub-sample Exclusion Test: Considering the systematic differences in administrative levels, resource endowments, and digital infrastructure among municipalities directly under the central government, this study excludes the observation samples of four municipalities directly under the central government, namely Beijing, Tianjin, Shanghai, and Chongqing, and conducts re-regression. As shown in Column (2) of Table 4, the estimated coefficient of the digital economy variable still passes the significance level test, proving that the research conclusion has geographical universality.

Model Specification Adjustment: This study replaces the fixed-effects model with a random-effects model for a sensitivity test. In Column (3) of Table 4, the coefficient of the digital economy variable is still significantly negative. In Column (4) of Table 4, we employee the province* year joint fixed effects to show that the key findings remain robust, further strengthening the credibility of the conclusions.

Mechanism Analysis

Building on the theoretical framework, this study introduces technological innovation as a mediating variable to examine the mechanism through which the digital economy influences carbon emissions. A stepwise regression approach is employed to test whether the digital economy suppresses carbon emissions by incentivizing technological innovation.

Columns (1) and (2) in Table 5 reveal that the digital economy significantly promotes technological innovation. When introducing technological innovation into the baseline regression, the mediating variable exhibits a significant inhibitory effect on carbon emissions, while the negative correlation between the digital economy and carbon emissions persists. This confirms the partial mediation effect, indicating that the digital economy reduces carbon emissions by driving technological innovation. This finding validates Hypothesis 3.

These findings align with the theoretical proposition that digital technologies enhance data-driven R&D efficiency and accelerate the diffusion of low-carbon innovations, thereby establishing a "digital infrastructure–green innovation–emission reduction" causal chain.

Heterogeneity Analysis

To investigate the industry-specific heterogeneity of the impact of enterprise digital transformation on regional carbon emissions, this study categorizes sample firms into primary (agriculture), secondary (industry), and tertiary (services) sectors based on the Chinese Economic Industry Classification standard and conducts cross-industry comparisons using grouped regression models (Columns (2)–(3) in Table 6). Empirical results reveal significant sectoral disparities in the carbon mitigation effects of digital transformation (Digt). The regression coefficients for the secondary and tertiary sectors indicate that the inhibitory effect of digitalization on emissions is substantially stronger in the secondary sector. Notably, the coefficient for the primary sector fails to achieve statistical significance, which may be attributed to the low energy intensity and inadequate penetration of digital technologies in the agricultural sector.

The secondary sector, encompassing manufacturing, mining, and construction serves as the backbone of regional economies but exhibits high energy intensity. Its digital transformation enhances marginal emission reduction elasticity through intelligent production system restructuring (e.g., industrial IoT deployment) and clean technology substitution (e.g., AI-driven process optimization). These

Table 6. Heterogeneity Test Results

	(1) Primary Sector $lnCO_{2s}$	(2) Secondary Sector $lnCO_{2s}$	(3) Tertiary Sector $lnCO_{2s}$
Digt	0.0210 (1.29)	−0.0302*** (−5.32)	−0.0298*** (−3.98)
Pti	−0.0123** (−2.43)	−0.0201*** (−3.89)	−0.0320** (−1.98)
Emp	0.0226 (1.32)	0.1026 (1.61)	0.1531 (1.83)
Urb	0.349* (1.87)	0.536*** (2.98)	0.322*** (3.31)
lnFDI	0.277 (1.53)	0.677*** (3.56)	0.378*** (2.99)
lnFix	0.335** (2.35)	0.876*** (5.05)	0.323** (2.31)
Control	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Individual FE	Yes	Yes	Yes
N	33	146	151
Adj. R^2	0.601	0.662	0.677

Note: The T statistic is in parentheses; *, **, and *** represent significance levels of 10%, 5%, and 1%, respectively.

findings align with the "technology-biased emission reduction" theory proposed by Acemoglu et al. (2022). This finding validates Hypothesis 2.

Although the tertiary sector – including finance, logistics, and IT services – operates under a capital-light model, its decarbonization pathways predominantly rely on service-oriented digital.

Conclusions and Policy Implications

This study investigates the impact of corporate digital transformation on carbon emission reduction and carbon neutrality goals, utilizing a decade of data from listed companies, state-owned enterprises, central enterprises, and major local private enterprises across China. The findings reveal that digital transformation significantly reduces regional carbon emission intensity by fostering technological innovation, enhancing production efficiency, and improving energy utilization, thereby advancing low-carbon development.

Heterogeneity in Firm-Specific Effects: The carbon reduction effects of digital transformation exhibit substantial heterogeneity across enterprises, with a more pronounced impact on traditional high-energy-consuming industries. This underscores the pivotal role of digitalization in transitioning carbon-intensive sectors toward a low-carbon economy. For instance, digital technologies such as smart monitoring systems in heavy industries optimize production processes and reduce energy consumption, supporting Hypothesis 1. These results align with existing literature emphasizing the potential of digital economies to optimize resource allocation, drive green innovation, and upgrade industrial structures.

Mechanism of Technological Innovation: The study validates Hypothesis 2, demonstrating that technological innovation serves as a critical mediator in the relationship between digitalization and green development. Digital technologies provide robust data resources and computational capabilities during R&D phases, while digital platforms accelerate the diffusion of green technologies. For example, cloud computing facilitates complex simulations of sustainable technologies, highlighting the necessity of fostering an integrated ecosystem that synergizes digital innovation with green technological advancement.

Policy Relevance for High-Energy Industries: The heterogenous analysis corroborates Hypothesis 3, indicating that targeted policies to accelerate digital transformation in high-emission sectors – such as intelligent energy management systems in manufacturing – can yield effective decarbonization strategies. This insight is particularly critical for China's "Dual Carbon" goals, given the scale and spatial diversity of its industrial base.

Limitations and Future Research

While this study provides empirical evidence on the carbon mitigation potential of digital transformation, limitations exist. First, the reliance on regional and firm-level aggregated data may obscure micro-level dynamics. Future research should incorporate granular datasets, such as enterprise-specific digital investment portfolios and carbon accounting metrics. Second, the analysis focuses on static effects; dynamic models capturing long-term interactions between digitalization and emission trajectories are warranted. Lastly, external factors such as global supply chain shifts and international policy spillovers warrant deeper exploration to refine context-specific policy frameworks.

Policy Recommendations. Sector-Specific Incentives: Implement differentiated subsidies and tax incentives (e.g., accelerated depreciation for digital infrastructure in high-energy industries) to lower transition costs. Digital-Green Synergy: Establish innovation hubs integrating cloud computing, AI, and green tech R&D, supported by open-access government datasets for algorithm training • Regulatory Frameworks: Mandate real-time carbon emission monitoring via IoT-enabled digital systems and link corporate carbon performance to ESG ratings and financing eligibility. These measures aim to harness digital transformation as a strategic lever for achieving carbon neutrality, offering replicable insights for emerging economies pursuing sustainable industrial transitions.

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