Digital Economy, Green Technology Innovation and Carbon Reduction Effect

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Abstract. In this paper, a measurement system of digital economy and green technology innovation is constructed, baseline regression model and intermediary effect model are established to analyze the impacts between them. The empirical analysis is conducted by using data from 2008 to 2021 to explore the mechanism of digital economy and green technology innovation on carbon emission reduction, and the impact of digital economy on green technology innovation is analyzed. The findings indicate that: (1) Digital economy has a significant positive effect on green technology innovation, and carbon emission reduction. (2) Green technology innovation can effectively restrain carbon dioxide emissions. Moreover, the digital economy partially mediates carbon emission reduction through promoting green technology innovation. Based on aforementioned conclusions, relevant recommendations are provided in this paper, this paper offers a theoretical foundation and practical guidance for achieving low-carbon development more effectively.

Keywords: digital economy · green innovation · carbon emission reduction

1 Introduction

The development of global industrialization has given rise to energy predicaments, concomitantly leading to an irreparable ecological and climatic damage caused by a substantial amount of carbon dioxide emissions [1]. Green technology innovation is characterized by both "innovation" and "green", which not only reflects the concept of green sustainable development, but also conforms to the requirements of high-quality economic development in modern times. It is an effective way to solve the dilemma between economic growth and energy conservation as well as emission reduction [2]. Through the innovation of green technology, enterprises can obtain incentives for innovation and additional earnings, and at the same time, selling excess carbon emission rights to make profits. Under the constraint of carbon emission, profit-seeking enterprises will choose technological innovation to promote low-carbon production and reduce carbon emission per unit output [3].

Digital economy encompasses a range of economic activities that leverage digital knowledge and information as key production factors, utilize modern information networks as important carriers, and harness the power of information and communication

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technology to drive efficiency improvements and optimize economic structures [4]. The digital economy, essentially a technological innovation, relies on advanced digital technologies such as artificial intelligence and 5G. It has emerged as a pivotal force in driving sustainable green innovation for enterprises and industrial upgrading, serving as a new engine and catalyst for the transformation and upgrading of China's economic structure and green technology innovation [5].

Although the digital economy has emerged a new driving force for green development, it remains unclear what the transmission mechanism is for carbon emission reduction effects and how green technology innovation plays a role. Furthermore, what are the rules and characteristics of the impact of digital economy on green technology innovation? Based on these issues, this paper constructs a calculation system for digital economy and green technology innovation by building upon previous research. An empirical analysis is conducted using data from 2008 to 2021 to explore the mechanism of digital economy and green technology innovation in reducing carbon emissions, as well as analyzing the impact of digital economy on green technology innovation. This paper provides a theoretical basis and practical reference for achieving low-carbon development.

2 Theoretical Hypothesis and Model Construction

2.1 Theoretical Assumptions

With the advent of digital economy, an increasing number of scholars have turned their attention to exploring the relationship between digital economy and carbon emissions. The rapid expansion of digital technology and its associated industries has resulted in a surge in electricity consumption, which in turn has led to a corresponding increase in carbon emissions [6]. However, numerous scholars contend that the advancement of digital technology is conducive to mitigating carbon dioxide emissions and enhancing environmental quality. The implementation of a digital-based carbon trading platform not only facilitates the promotion of carbon emission reduction and intensity reduction but also serves as a crucial pathway towards achieving carbon neutrality. In terms of internet development, it can effectively curb resource depletion, but also significantly enhance the energy and carbon emission performance [7].

The development of the digital economy has significantly reduced the emission of various pollutants, driven the growth of low-carbon industries, and lowered carbon emission intensity [8]. Furthermore, it can promote improvements in both the quality and quantity of green technology innovation among enterprises by stimulating market incentives for such innovations. [9]. Based on this, this paper proposes the following hypothesis:

H1: Digital economy plays a significant role in green technology innovation
H2: The digital economy can help promote carbon reduction

The innovation and application of digital technologies for carbon emission reduction can facilitate the clean production of enterprises and promote CO_2 emission reduction. In particular, digital economy enterprises, which are large energy consumers, can reduce

their carbon footprint through low-carbon operations and influence other types of enterprises' CO_2 emissions through digital technology output. Green technology innovation plays a partial mediating role in the regional digitization level and manufacturing GTFP [10].

The development of digital economy has significantly facilitated the improvement of urban green technology innovation, and reduced urban carbon emission through the mechanism of green technology innovation [11]. The increase in regional innovation output and optimization of capital factor allocation efficiency are important intermediary channels for the digital economy to enable urban green development. [12]. Therefore, this paper proposes the following hypothesis:

H3: Green technology innovation plays an intermediary role in digital economy and carbon emission reduction.

2.2 Model Construction

(1) Baseline regression model

To examine the influence of digital economy on green technology innovation and verify H1, this paper constructs benchmark econometric model 1:

$$g\_tech_t = \alpha_0 + \alpha_1 d\_eco_t + \alpha_2 i\_val_t + \alpha_3 fdi_t + \alpha_3 u\_pop + \varepsilon_t \quad (1)$$

The dependent variable g_tech represents green technology innovation, and independent variable d_eco represents digital economy. The control variables fdi and u_pop represent direct foreign investment and urban population ratio, and α_i represents coefficients of the regression and ε_t represents random error.

In order to examine the influence of digital economy and green technology innovation on carbon emission reduction, and verify H2, this paper builds benchmark econometric model 2:

$$c\_emi_t = \beta_0 + \beta_1 g\_tech_t + \beta_2 d\_eco_t + \beta_3 fdi_t + \beta_4 u\_pop + \beta_5 i\_num + \varepsilon_t \quad (2)$$

The dependent variable e_eco represents carbon dioxide emission, while the independent variables are g_tech and d_eco. The control variable i_num denotes the number of industrial enterprises. β_i represents coefficients of the regression.

(2) The mediation effect model

To delve deeper into the indirect mechanism by which the digital economy contributes to reducing carbon emissions. This paper employs the mediation effect model to test H3. The specific Settings are as follows:

$$M_t = \gamma_0 + \gamma_1 d\_eco_t + \gamma_2 fdi_t + \gamma_3 u\_pop + \varepsilon_t \quad (3)$$

$$c\_emi_t = \rho_0 + \rho_1 M_t + \rho_2 d\_eco_t + \rho_3 fdi_t + \rho_4 u\_pop + \varepsilon_t \quad (4)$$

where, M_t is the intermediary variable, primarily green technology innovation, while γ_i and ρ_i represent the coefficients of the regressions.

3 Empirical Analysis

3.1 Variable Description and Data Source

(1) Carbon emission reduction (c_emi): This study is illustrated by the measurement of carbon dioxide emissions. Measurement of carbon dioxide emissions is based on the relationship between total energy consumption and carbon emission coefficient. Generally, the estimated carbon dioxide emission for 1 ton of standard coal ranges from 2.66 to2.72 tons, and an emission coefficient value of 2.7 utilized in this paper. Therefore, the formula for calculating carbon dioxide emissions is as follows: Carbon Dioxide Emission = Energy Efficiency Consumption (10,000 tons of standard coal) × Emission Coefficient (2.7).

(2) Green innovation technology (g_tech): In order to overcome a single index to measure green technology innovation, this paper provides a more comprehensive evaluation of green technology innovation from four aspects including new product development expenditure for industrial enterprises above designated size. The entropy weight method is then utilized to determine the weight of each measure. Refer to Table 1 for further details.

(3) Digital economy (d_eco): This paper presents a comprehensive index for measuring the development level of digital economy. To ensure accuracy and comprehensiveness, an evaluation index system based on the research of Zhu Jiexi and Li Junjiang is constructed [12]. Referring to the research conducted by Wang Xiangyan et al. [13], the entropy method had been employed to assign weights of each digital economy calculation. Refer to Table 2.

Other control variables. The urban population ratio (u_pop) is the ratio of the urban population to the total population. fdi is represented by the amount of foreign capital actually utilized, and industrial output value (i_val) is represented by the GDP of the secondary industry. The number of industrial enterprises (i_num) also has an impact on carbon emission, so it is also included in the control variable. The data used in this study are from China Statistical Yearbook 2008–2021.

Table 1. Measurement of green technology innovation index

	Measurement	**Unit**
Green technology innovation	Expenditure for new product development of industrial enterprises above designated size	10000 yuan
	Number of valid invention patents of industrial enterprises	Piece
	Number of scientific research and development institutions	Unit
	Research and experimental development personnel in research and development institutions	10000 people

Table 2. Measurement of digital economy composite index

	First-level index	Measurement	Unit
Digital economy Composite Index	Digital economy infrastructure	Cable line length	10000 m
		Mobile phone exchange capacity	10000 households
		Internet broadband access port	10000
		Number of domain names	10000
		Number of IPv4 addresses	10000
	Development of digital economy application	Mobile phone penetration rate	%
		Internet penetration rate	%
		Information employment	10000 people
		Number of Internet users	10000 people
		Internet broadband access users	10000 people

3.2 Empirical Analysis

(1) The impact of digital economy on green technology innovation

The regression results of the impact of digital economy on green technology innovation are shown in Table 3.

As shown in Table 3, $R^2 = 0.875$ and ${R_A}^2 = 0.820$ indicate that the regression model has a high degree of fit, and $F = 15.761 (p = 0.000)$ indicates that the direction regression is significant. Specifically, the regression coefficient of digital economy (d_eco) is 0.635 and $P = 0.016$, indicating that digital economy has a significant positive effect on green technology innovation, thus H1 has been verified. Moreover, both the industrial output value (i_val) and urban population ratio (u_pop) have significant positive effects on green technology innovation. However, the regression analysis indicates that the actual utilization of foreign capital (fdi) does not have a statistically significant effect.

(2) The impact of digital economy and green technology innovation on carbon emission reduction

The regression results for the impact of digital economy and green technology innovation on carbon emission reduction are presented in Table 4. As evidenced by the regression results in Table 4, $R^2 = 0.998$ and ${R_A}^2 = 0.997$ indicate a high degree of

Table 3. Regression results of digital economy on green technology innovation

Model		**Nonstandardized coefficient**		**Standard coefficient**	**t**	**Sig.**
		B	Standard error	Trial version		
1	(Constant)	-0.335	0.171	——	-1.960	0.082
	d_eco	0.635*	0.216	1.871	2.947	0.016
	i_val	1.070*	0.308	3.117	3.477	0.007
	fdi	-0.321	0.205	-0.798	-1.563	0.152
	u_pop	0.181*	0.050	0.527	3.628	0.006
$R^2 = 0.875$ $R_A{}^2 = 0.820$ $F = 15.761 (p = 0.000)$						

Note: * means statistically significant at the 5% level

model fit, and $F = 1017.315$ ($p = 0.000$) indicates that the direction regression is significant. The regression coefficient of digital economy (d_eco) is 0.715 with a significant level of $P = 0.000$, while the regression coefficient of green technology innovation (g_tceh) is -0.254 with a significant level of $P = 0.015$. These results suggest that both digital economy and green technology innovation have a remarkable negative impact on carbon emissions, indicating their effectiveness in reducing carbon dioxide emissions. Therefore, H2 has been confirmed. Actual utilization of foreign capital (fdi) also has an inhibitory effect on carbon dioxide emissions. The regression coefficient of urban population ratio (u_pop) is 0.076 with a p-value of 0.018, indicating that an increase in the urban population ratio leads to higher carbon dioxide emissions and reduces emission reduction efforts. However, there was no significant impact observed from industrial output value (i_val) and the number of industrial enterprises (i_num).

Table 4. Regression results of carbon emission reduction

Model		Nonstandardized coefficient		Standard coefficient	t	Sig.
		B	Standard error	Trial version		
1	(Constant)	0.362	0.038	——	9.638	0.000
	d_eco	-0.715*	0.046	-0.719	-15.620	0.000
	g_tech	-0.254*	0.085	-0.087	-2.996	0.015
	fdi	-0.299*	0.057	-0.254	-5.268	0.001
	u_pop	0.076*	0.026	0.076	2.896	0.018
	i_val	-0.213	0.192	-0.212	-1.109	0.304
	i_num	-0.001	0.021	-0.001	-0.055	0.957
$R^2 = 0.998$ $R_A{}^2 = 0.996$ $F = 1017.315 (p = 0.000)$						

Note: * means statistically significant at the 5% level

Table 5. Regression results of mediating effect of green technology innovation

Variable	c_emi	g_tceh	c_emi
	(1)	(2)	(3)
d_eco	-0.713*	0.544*	-0.681*
g_tceh	——	——	-0.254*
fdi	-0.351*	-0.321	-0.299*
control variable	control	control	control
N	14	14	14
R^2	0.998	0.917	0.999
$R_A{}^2$	0.996	0.794	0.998

Note: * means statistically significant at the 5% level

(3) Testing the mediating role of green technology innovation

The regression results of mediating effects are presented in Table 5. As shown in column (1), the impact of digital economy on carbon dioxide emissions is statistically significant at the 5% level, with a coefficient of -0.713. Column (2) demonstrates that digital economy has a positive and significant effect on green technology innovation, while column (3) reveals that the impact of digital economy on carbon dioxide emission remains negative and significant at the 5% level (-0.681). The findings suggest that the digital economy plays a partial mediating role in reducing carbon emissions through green technology innovation, as evidenced by the establishment of hypothesis H3. Additionally, foreign capital utilization also has a partial intermediary effect on carbon emissions reduction through green technology innovation.

3.3 Discussion

According to the above analysis, digital economy plays a constructive role in promoting innovation of green technology. The advancement and dissemination of modern science and technology not only facilitates industrial digitization but also compels enterprises' digital transformation, which enables numerous firms to adopt novel technologies, optimize production factor allocation, and lay a foundation for carrying out green technology innovation. The digital economy can enhance data processing and analysis capabilities, thereby facilitating the research and development process. Digital technology enables enterprises to conduct research and development more quickly and efficiently by simulating and testing new product performance, functionality, and other features using digital tools. Additionally, digital technology can improve production management and supply chain operations for companies. Through the process of digital manufacturing, enterprises can expedite product production and delivery while simultaneously enhancing production efficiency. Digital supply chain management enables enterprises to gain a comprehensive understanding of their entire supply chain operation, thereby facilitating better coordination and management throughout the entire production and supply

process. By leveraging digital technology, enterprises can more effectively engage with customers and comprehend their needs in order to develop products and services that are tailored to meet customer demands as well as innovative business models. The digital economy has a significant impact on carbon emissions. Essentially, the digital economy is the application of modern information technology, and the information industry itself is a low-energy and low-emission environmental protection industry that is vigorously developed by governments worldwide. Through the promotion of digital infrastructure, economic transformation and development are facilitated while reducing energy consumption in China's pursuit of technological advancement. The advancement of digital technology leads to enhanced energy efficiency, which in turn contributes to improved carbon emission performance. In terms of transmission mechanisms, the digital economy primarily impacts carbon emission performance through changes in energy consumption intensity and scale. On one hand, the digital economy plays a significant role in promoting GDP growth; on the other hand, widespread adoption of digital services and development within digital industries have reduced unnecessary energy consumption. Additionally, the impact of the digital economy on carbon emission performance exhibits a non-linear relationship under varying energy consumption structures and degrees of government intervention. As energy consumption structures improve, digital enterprises adopt cleaner methods of production that significantly promote reductions in carbon emissions. However, high levels of government intervention have a negative effect on the dividend effect of the digital economy.

Green technology innovation can effectively mitigate carbon dioxide emissions. The outcomes of green technology innovation can be transformed into green productivity, which not only facilitates the transition towards eco-friendly and low-carbon production and lifestyle but also promotes clean energy generation and transformation of energy structure. Furthermore, it contributes to optimizing and upgrading industrial structures, leading to a continuous reduction in energy consumption as well as carbon emissions. Additionally, green technology innovation plays a crucial role in reducing carbon emissions through industrial correlation, spillover effects, regional cooperation, and other approaches. It serves as an essential driver for economic and societal transformation towards low-carbon development while mitigating greenhouse gas emissions. The "technology dividend" effect of green technology innovation can significantly reduce urban carbon dioxide emissions and other greenhouse gases.

The digital economy can partially mediate carbon emissions through innovative green technologies. Unlike the traditional "ownership economy," the digital economy is a "participation economy" that allows more market players to participate without requiring equity correlation, thereby achieving a reduction in carbon emissions across the entire business ecosystem. From a technical perspective, the digital economy's big data, cloud computing, artificial intelligence and other technologies have the potential to revolutionize traditional industries' production and operation modes. This can lead to significant improvements in operational efficiency and energy conservation across various sectors such as energy and electricity, urban management, transportation, industrial production. Currently, our country's energy consumption intensity remains higher than the global average. However, by leveraging cloud computing technology to enhance enterprise energy efficiency and digital transformation to improve both enterprise and

city management efficiency, we can effectively promote a reduction in carbon intensity per unit of GDP. Moreover, improving the efficiency of energy and resource utilization plays a pivotal role in driving down carbon emissions.

4 Conclusion and Countermeasures

On the basis of existing research, this paper constructs a measurement system for digital economy and green technology innovation. It establishes benchmark regression and intermediary effect models, conducts empirical analysis using data from 2008 to 2021, explores the mechanism of digital economy and green technology innovation on carbon emission reduction, and analyzes the impact of digital economy on green technology innovation. The following conclusions can be drawn: (1) The digital economy has a significant positive impact on the innovation of green technology and leads to a substantial reduction in carbon emissions. (2) Green technology innovation is an effective means of curbing carbon dioxide emissions, and the digital economy partially mediates the reduction of carbon emissions through green technology innovation.

Based on the aforementioned conclusions, this paper proposes the following recommendations: (1) Actively fostering the digital economy, facilitating industrial digitization and digital transformation of insolvent enterprises, supporting green innovation for business continuity, and advance low-carbon development. (2) Enhancing breakthroughs in green and low-carbon core technologies through scientific and technological advancements, while promoting the innovation and development of green technologies. The utilization of data elements and digital technologies should be leveraged to support the advancement of green technology, with a focus on harnessing the potential of digital finance and green finance to drive innovation in this field. (3) Improving carbon trading mechanisms, increasing profits for enterprises' green innovation, continually increasing the support and subsidies for enterprises' green technology innovation, and providing perfect infrastructure for enterprises' green technology innovation.

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