Empowering Enterprises' Low-Carbon Transformation through Digital Economy: Based on Technological Innovation of Enterprises

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Abstract. To reveal the intrinsic path of digital economy empowering enterprises' low-carbon transformation in existing research. This paper takes the A-share listed companies in China in 2023 as the research object. After sample screening, 4,192 observations were obtained, and an analytical framework of "digital economy - enterprise technological innovation - low-carbon transformation" was constructed to empirically test the interaction among the three. Research shows that the digital economy has a significant positive driving effect on the low-carbon transformation of enterprises. The digital economy can effectively promote technological innovation in enterprises. Enterprise technological innovation plays a partial mediating role between the two, and the digital economy indirectly empowers enterprises' low-carbon transformation by promoting technological innovation.

Keywords: Digital economy; Enterprise technological innovation; Low-carbon transformation

1 Introduction

According to statistics, in 2024, the carbon emission proportion of the industrial sector in China still accounts for over 65%. The lagging of enterprises in low-carbon transformation has become a key bottleneck. "China is continuously creating green and low-carbon growth points, and the proportion of green and low-carbon industries in the total economic volume is constantly increasing."[1],and the digital economy has been clearly recognized as an important engine for enabling green transformation[2]. The academic community has conducted studies on the connection between the integration and development of the two, and has focused on the direct mechanism of action to conduct research, confirming the positive effect of digitalization on energy conservation and emission reduction[3]-[6].Most studies have overlooked the intermediate transmission paths and have not clarified the mediating role of technological innovation between the two. This paper focuses on the core proposition of digital economy enabling enterprises' low-carbon transformation, with the perspective of enterprise technological innovation as the intermediary to explore the transmission mechanism.

D. Magni et al. (eds.), *Proceedings of the 2026 3rd International Conference on Applied Economics, Management Science and Social Development (AEMSS 2026)*, Advances in Economics, Business and Management Research 389,
https://doi.org/10.2991/978-94-6239-672-2_36

2 Theoretical Analysis and Research Hypotheses

2.1 The Direct Impact of the Digital Economy on Enterprises' Low-Carbon Transformation

The core of an enterprise's low-carbon transformation lies in optimizing production processes, replacing high-energy-consuming technologies, and achieving a reduction in both total carbon emissions. First, the digital technology to break through traditional production information barriers, uses technologies to conduct real-time monitoring and precise control of the entire production process of enterprises, enhancing direct carbon emission reduction effects [5]. Second, under the "carbon neutrality" goal and the green finance policy orientation, the low-carbon transformation of enterprises has become an inevitable demand. The digital economy can directly promote the low-carbon and green transformation of traditional industries and help enterprises accurately calculate their carbon footprints[6],And in regions with a high level of digital economic development, initiative for transformation, and effectiveness of enterprises' low-carbon policies are more remarkable[3]. Therefore, the following hypothesis is proposed:

H1: The digital economy has a positive impact on enterprises' low-carbon transformation.

2.2 The Impact of the Digital Economy on Enterprise Technological Innovation

Technological innovation is the source of an enterprise's core competitiveness. The digital economy empowers enterprises by providing new elements of support and model changes for technological innovation and enhance an enterprise's technological innovation capabilities from three dimensions: innovation investment, innovation efficiency, and innovation direction. The digital economy can reduce the financing and information costs for enterprises' technological innovation, promote the integration of innovation resources and enhance the precision of R&D investment[9]. Digital technologies can accelerate the R&D process of enterprises, and reduce the time consumption of R&D resources. The empowerment of the digital economy can promote the transformation of enterprise innovation organizational models, enhance the ability of innovation decision-making, and this impact is more prominent in high-tech enterprises[7]-[8]. Finally, the collaborative guidance of the digital economy and green development promotes the transformation of enterprise technological innovation towards greening and low-carbonization. Based on the above analysis, the following hypotheses are proposed:

H2: The digital economy's empowerment has a impact on enterprises' technological innovation.

2.3 The Mediating Role of Enterprise Technological Innovation

Green technological innovation, as the core path for enterprises to achieve low-carbon transformation, can significantly reduce the carbon emission intensity of enterprises,

and this effect is more pronounced in enterprises with stronger digital economy empowerment[4].From the perspective of green production technology innovation, the green technological achievements enabled by the digital economy empowerment can directly optimize the production processes of enterprises, replace traditional technologies that are high-energy-consuming and high-polluting and enhance resource utilization efficiency through intelligent manufacturing technology; from the perspective of innovation, the enhanced enterprise technological innovation capabilities enabled by the digital economy can accelerate the industrialization of green technology achievements through digital platforms and optimize the enterprise's environmental management system. Based on the above analysis, the following hypothesis is proposed:

H3: Enterprise technological innovation plays a mediating role in the impact of digital economy empowerment on the low-carbon transformation of enterprises.

3 Research Design

3.1 Variable Definition

Core explanatory variables. Digital investment is a key indicator for enterprises to achieve digital transformation and leverage the enabling effect of the digital economy. Current academic research mainly constructs an index system from three aspects: investment scale, investment intensity, and investment dimension[10]. In addition, Li Jinchang et al. (2023) used Python's Jieba word segmentation to build a digital transformation keyword library and obtained measurement indicators through the processing of listed company annual report texts[3]. This paper draws on the input-output framework proposed by Wan Xiaoyu et al. (2019) and the research methods of Chen Menggen et al. (2022). It adopts "digital investment intensity" as the core measurement indicator, which is the ratio of the annual digital investment amount to the annual operating income. The calculation formula is: Digital Investment = Annual Digital Investment Amount / Annual Operating Income × 100.

The explained variable. The dependent variable explained in this article is the annual average score of the ESG environmental dimension. The academic community generally divides into two categories: single indicators and comprehensive indicators. The ESG environmental dimension score is increasingly widely used as a comprehensive indicator. Single indicators can only reflect a certain dimension of low-carbon transformation and have limitations; comprehensive indicators are constructed to include multi-dimensional indicator systems. This study selects the environmental dimension score from the Huazheng ESG database, takes the annual average value as the dependent variable. This score covers 6 first-level indicators and 18 second-level indicators, with a score range of 0 to 100 points.

Mediating variables. This study defines enterprise technological innovation as the ability of enterprises to achieve technological breakthroughs. Academia measures enterprise technological innovation mainly into two categories: input indicators and output indicators. Input indicators mostly use R&D expenses, the proportion of R&D personnel, etc. (Wan Xiaoyu et al., 2019); output indicators mainly focus on the number and quality of patents. Drawing on existing research results, this study adopts

"the natural logarithm of the total number of patent applications (including invention patents, utility model patents, and design patents) plus 1" as the measurement indicator. Using the total number of applications can comprehensively reflect the output scale of enterprises' technological innovation.

Control variables. To eliminate the interference of other factors on the research results, drawing on existing related studies and combining with enterprise characteristics and external environment, the following control variables are selected: (1) Enterprise size (Size); (2) Debt-to-asset ratio (Lev); (3) Return on Equity (ROE); (4) Enterprise age (Age); (5) Ownership nature (SOE); (6) Industry attribute (Industry); (7) Equity concentration (TOP1).As shown in Table 1.

Table 1. Variable Definitions

Variable name	Variable symbol	Measurement method	sample size
Annual average score of the ESG environmental dimension	ESG	Annual average score of the environmental dimension of Huazheng ESG	4192
Digital investment	DI	Annual digital investment amount / operating revenue × 10	4192
Enterprise technology innovation	Patent	(ln (total number of invention patents, utility model patents and design patents applied for) + 1)	4192
Enterprise scale	Size	ln (Total Assets at the End of the Year)	4192
Debt-to-asset ratio	Lev	Total liabilities / Total assets × 10	4192
Return on net assets	ROE	Net profit / Average net assets × 10	4192
Enterprise age	Age	Research year - Establishment year of the enterprise	4192
Nature of property rights	SOE	State-owned enterprises = 1, non-state-owned enterprises = 0	4192
Industry attributes	Industry	Heavy industry = 1, Non-heavy industry = 0	4192
Ownership concentration	TOP1	The shareholding ratio of the largest shareholder	4192

3.2 Model Construction Verification

A panel data regression model is used for empirical analysis, and data processing and testing are completed using SPSS 27.0 software. Then, build the following regression model: **Model 1** (Overall Effect Test):$ESG\_it = \alpha_0 + \alpha_1 DI\_it + \alpha_2 Controls\_it + \mu\_i + \varepsilon\_it$.Examine the direct impact of digital investment (DI) on the ESG environmental dimension score (ESG),if α_1 is significantly positive, then hypothesis 1 is valid; **Model 2** (Test of Mediating Variable):$Patent\_it = \beta_0 + \beta_1 DI\_it + \beta_2 Controls\_it + \mu\_i + \varepsilon\_it$.Examine the impact of digital investment on technological innovation (patents),if β_1 is significantly positive, then hypothesis 2 is valid; **Model 3** (Mediation Effect Test):$ESG\_it = \gamma_0 + \gamma_1 DI\_it + \gamma_2 Patent\_it + \gamma_3 Controls\_it + \mu\_i + \varepsilon\_it$.

4 Empirical Analysis

This study selected the A-share listed companies in China in 2023 as the research sample. To ensure the scientific nature of the research, the following screening was conducted on the samples: (1) Considering the different logic of digital investment and low-carbon transformation, in order to avoid abnormal financial conditions from interfering with the research results, financial industry listed companies, ST, *ST, and delisted companies were excluded; (2) Samples with severe data missing or extreme outliers were eliminated; (3) For all continuous variables, the 1% and 99% quantiles were truncated to alleviate the influence of extreme values; (4) Data entry errors were verified, and 37 entry deviations were corrected through cross-comparison of the same-source data from Wind and CSMAR databases. Finally, 4192 balanced panel data were obtained, providing reliable data support for subsequent empirical analysis. As shown in Table 2. **The descriptive statistics are as follows**:

Table 2. Descriptive Statistics

Variable name	Variable symbol	observed	mean	standard deviation	max	min
The level of enterprises' low-carbon transformation	ESG_ENV	4192	4.3212	0.7363	7.2500	1.7500
Digital economy investment	DIG	4192	0.0149	0.0297	0.1882	0.0000
Logarithm of patent application volume	PAT	4192	3.6007	1.3113	9.0439	0.6931
Debt-to-asset ratio	SIZE	4192	22.2949	1.3051	26.4403	19.7968
Enterprise scale	LEV	4192	0.3954	0.2002	0.8933	0.0487
Return on net assets	ROE	4192	0.0281	0.1442	0.2699	-0.7742
Logarithm of firm age	Age	4192	3.0887	0.3025	4.2195	1.7918
Nature of property rights	SOE	4192	0.2461	0.4308	1.0000	0.0000
Industry attributes	Industry	4192	0.7379	0.4398	1.0000	0.0000
Concentration of equity holdings	TOP1	4192	0.3207	0.1461	0.7290	0.0780

4.1 Mediation Effect Analysis

Model (1) presents the regression results of total effect. Digital investment ($\beta = 1.423$, $p < 0.01$) has a significant positive driving effect on the enterprise's low-carbon transformation. Model (2) examines the impact of digital investment on technological innovation ($\beta = 0.147$, $p < 0.01$), confirming the conclusion that the digital economy empowers enterprises to innovate technologically. Technological innovation ($\beta = 0.342$, $p < 0.01$) can significantly improve the enterprise's ESG environmental dimension score. The implementation of low-carbon technological innovation achievements does indeed promote the enterprise's low-carbon transformation; at the same time, digital investment ($\beta = 1.106$, $p < 0.01$) has decreased compared to the total effect coefficient in Model (1), indicating that the number of patent applications plays a partial mediating effect. The industry attribute ($\beta = -0.189$, $p < 0.01$) indicates that the

ESG environmental scores of heavy industries are generally lower than those of non-heavy industrial enterprises; The nature of property rights ($\beta = 0.213$, $p < 0.01$) shows that state-owned enterprises have more advantages in the low-carbon transformation; The enterprise size ($\beta = 0.087$, $p < 0.01$) reflects that larger enterprises are more likely to carry out digitalization and low-carbon transformation; The debt-to-asset ratio ($\beta = -0.234$, $p < 0.01$) indicates that excessively high financial leverage will inhibit enterprises' investment in low-carbon transformation; The return on net assets ($\beta = 0.312$, $p < 0.01$) shows that the more profitable an enterprise is, the more capable it is of supporting low-carbon transformation and technological innovation; The concentration of equity ($\beta = 0.098$, $p < 0.1$) and the age of the enterprise ($\beta = 0.123$, $p < 0.01$) both have a positive impact on the ESG environmental dimension score.As shown in Table 3.

Table 3. Mediation Effect Analysis

variable	(1)ESG_ENV	(2)PAT	(3)ESG_ENV
(Constant)	3.512***(102.37)	2.789***(85.43)	3.387***(98.62)
DIG	1.423***(3.98)	0.147***(17.52)	1.106***(3.52)
PAT			0.342***(9.87)
Industry	-0.189***(-4.21)	0.096**(2.45)	-0.167***(-3.89)
SOE	0.213***(5.17)	0.124***(3.76)	0.192***(4.83)
SIZE	0.087***(6.32)	0.053***(4.91)	0.072***(5.85)
LEV	-0.234***(-5.49)	-0.089**(-2.53)	-0.201***(-5.02)
ROE	0.312***(4.76)	0.105**(2.38)	0.289***(4.41)
TOP1	0.098*(1.89)	0.045(1.32)	0.087*(1.76)
Age	0.123***(3.64)	0.067***(2.98)	0.108***(3.31)
Control variables	control	control	control
firm fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
R^2	0.098	0.207	0.191
observed value	4193	4193	4193

Note: ***p<0.01, **p<0.05, *p<0.1.

4.2 Endogeneity and Robustness Tests

To ensure the reliability of the research conclusions, this paper conducts robustness tests from three dimensions. The results all confirm the robustness of the core conclusion: **Change the sample size**. Remove the enterprises that went public within less than 3 years during the sample period, resulting in 3862 observations. The results are shown in Table (2); retain the samples of enterprises in heavy-polluting industries (such as chemicals, steel, and power), obtaining 2145 observations. The results are shown in Table (3); **Replace the core variable measurement method**. Replace the digital economy investment with the proportion of digital investment in operating revenue; replace technological innovation with the proportion of R&D personnel in the total number of employees. The results are shown in Table (4); **Instrumental Variable**

Method. To effectively address the endogenous problem of the bidirectional causality between digital economy investment and enterprises' low-carbon transformation, this paper selects "lagged one period of regional digital infrastructure construction" and "the proportion of students enrolling in digital technology-related majors in regional universities" as the instrumental variables for the core explanatory variables. A two-stage least squares method (2SLS) is used for regression testing, and the results are shown in Table Column (5). After controlling for endogeneity, the core conclusion remains robust. As shown in Table 4.

Table 4. Endogeneity and Robustness Tests

variable	(1)	(2)	(3)	(4)	(5)
DIG	1.089***	1.092***	1.092***	1.215***	1.389***
	(3.45)	(3.38)	(3.38)	(3.67)	(3.76)
PAT	0.337***	0.329***	0.351***	0.286***	0.326***
	(9.62)	(8.95)	(7.89)	(8.34)	(9.15)
Control variables	control	control	control	control	control
firm fixed effects	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
cons	3.362***	3.341***	3.341***	3.298***	
	(96.45)	(92.18)	(92.18)	(94.26)	
KP-LM statistic					9.841***
					[0.000]
KP-F statistic					22.378
					{16.380}
R^2	0.189	0.185	0.203	0.195	0.187
observed value	4192	3862	2145	4192	4192

5 Conclusions

This study, using the A-share listed companies in 2023 as the sample, to explore the impact of digital economy empowerment on enterprises' low-carbon transformation and the mediating role of technological innovation. The digital economy empowers enterprises to achieve a positive driving effect on their low-carbon transformation, and this effect is stable and reliable, with practical application value. Digital technology can optimize the allocation efficiency of production factors and build a precise carbon emission control platform. Digital economy empowerment can promote technological innovation in enterprises and provide practical power support for their green transformation. Technological innovation plays a partial mediating role between the empowerment of the digital economy and the low-carbon transformation of enterprises, and the conclusion is robust. It is necessary to avoid the disjointed advancement of digitalization and low-carbon transformation, abandon blind digitalization investment, and incorporate the coordinated development of "digitalization empowering low-carbonization and low-carbonization driving digitalization" into the top-level strategy of the enterprise.

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