The mechanism of the impact of the digital economy on green technology innovation

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Abstract. This article is based on the green patent application data of A-share listed companies on the Shanghai and Shenzhen stock exchanges from 2010 to 2020. It empirically analyzes the actual impact and underlying mechanism of the digital economy on green technology innovation, further analysis was conducted on the moderating effect of environmental policy uncertainty in the relationship between the two. Research indicates: (1) digital economy level has a remarkable promoting effect on green technology innovation in enterprises. (2) The results of the moderating effect indicate that perceived uncertainty strengthens green innovation orientation of enterprises, generating a significant positive moderating effect in the relationship between digital economy level and green technology innovation in enterprises. The research can provide marginal empirical support for the coordinated development of the digital economy and green economy under the dual carbon goals.

Keywords: digital economy; green technology innovation; enterprise uncertainty perception.

1 Introduction

In the context of green environmental transformation, exploring how to leverage the digital economy to promote enterprise green technology innovation has become an important topic of concern in various sectors of society. In recent years, China's digital economy has been rapidly developing, exerting comprehensive and profound impacts on enterprise production, daily life, and the environment. Data plays an increasingly significant role, indicating a fundamental change in the economic paradigm[1]. Research also suggests that the digital industry itself not only possesses environmental characteristics but also has an important role in reducing emissions in other industries through its innovation spillover effects [2]. So, it is important to discuss the influence of the digital economy level on green technology innovation so as to promote the innovation capability and competitiveness of enterprises, and achieve sustainable development goals.

During rapid economic development, we are also facing serious pollution problems caused by extensive development methods, excessive energy consumption, and environmental pollution and destruction at the cost of sacrificing the environment[3]. The "14th Five-Year Plan" points out the importance of "building a market-oriented green technology innovation system," which confirms the significance of green technology innovation from an institutional perspective. On the one hand, with the improvement of living standards and widespread promotion through

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digital media, public awareness of the environment is becoming stronger. Under the new market demand and public supervision, enterprises are driven to use green technology and seize the opportunity for the R&D of green products[4]. On the other hand, the government uses internet technology to supervise the pollution behavior of enterprises. With a relatively high internet penetration rate, any excessive discharge by companies will be quickly discovered and widely disseminated, forcing companies to adjust their energy consumption structure and reduce pollution emissions under high-intensity and high-exposure environmental regulations[5]. Therefore, exploring the impact of the digital economy on green technology innovation is of great significance.

The contribution of this study is twofold: on the theoretical level, it comprehensively examines the impact of the digital economy on enterprise green technology innovation based on a large sample of data, enhancing relevant research on enterprise green technology innovation and avoiding estimation bias caused by small sample size; on the practical level, it provides a basic guiding framework for the micro-enterprises and government to further strengthen the policy and management system construction of enterprise green technology innovation system and enriches boundary conditions of enterprise green technology innovation based on the environmental uncertainty perspective, providing a new perspective for re-examining enterprise green technology innovation while also providing practical reference for green transformation that leverages enterprise green technology innovation to help transform industrial and economic structures under the background of sustainable development strategies.

2 Theory and hypotheses

2.1 The impact of the digital economy on enterprise green technology innovation.

The digital economy has a great empowering effect. Firstly, the development of the digital economy has brought about technological innovations that are cost-effective, efficient, and resource-conserving. Further improvements in digital infrastructure can optimize the utilization efficiency of various resource elements in innovation activities, saving a significant amount of labor and material costs, reducing energy consumption, lowering level pollution emissions, and promoting green technology innovation. Secondly, digital economy provides more innovation favorable conditions for the rapid development and breakthrough innovations in enterprise green technology. For example, the continuous development of technologies such as cloud computing and big data analysis enables enterprises to conduct information, resource, and technology exchanges and collaborations more conveniently[6], enhancing both internal and external cooperation capabilities, improving innovation efficiency[7], and collectively driving green technology innovation. Thirdly, the digital level economy offers a data-driven model for innovation. In the current prevalence of the digital economy, data has become one of the necessary driving forces for enterprise innovation. Enterprises can collect abundant data through digital business operations and transactions, enterprises can use digital technologies and analytics to identify environmental issues, enabling them to better utilize vast amounts of data for innovation[8], proactively develop green products, and thereby promote the advancement of green technology. Therefore, we propose the following hypothesis:

Hypothesis 1: There is a positive impact between the digital economy and business green technology innovation, meaning as digital economy level becomes more prominent, business

green technology innovation is enhanced.

2.2 Moderating effect of enterprise uncertainty perception

The theory of uncertainty suggests that uncertainty in the external environment can lead to fluctuations in profits[9]. When enterprises perceive an increase in uncertainty in environmental policies, it is beneficial to encourage them to seek innovation to adapt to and resolve the risks brought about by uncertainty[10]. On the one hand, in the era of the digital economy, enterprises need to pay more attention to the trend of environmental protection policies when facing uncertain environments. Enterprises may use digital technology to obtain more information, reduce information asymmetry, enhance interpretation and analysis of environmental policies, and reduce the risks brought about by uncertainty, making it more likely to promote innovation of green technology". On the other hand, enterprise uncertainty perception will also encourage them to strengthen research and application in green technology to adapt to environmental changes and social responsibilities, and improve their ability for sustainable development. By strengthening enterprises' awareness of environmental protection and investing in environmental innovation research and development[10], they can better adapt to the development trends of future environmental policies and achieve sustainable development. Therefore, we propose the following hypothesis:

Hypothesis 2: The enterprise uncertainty perception is positively moderating the impact between the digital economy level and enterprise green technology innovation. Based on the discussion above, the basic model for this research is presented in Figure 1. It empirically analyzes the actual impact and underlying relationship of the digital economy on green technology innovation, further analysis was conducted on the moderating effect of environmental policy uncertainty in the relationship between the two.

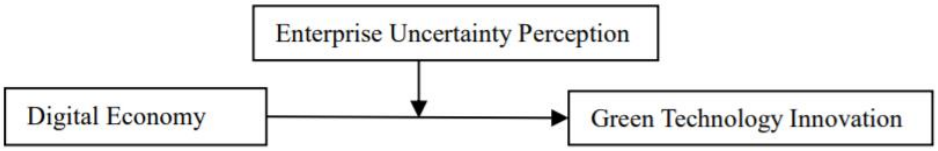

Fig. 1. Basic Model

3 Research methodology

3.1 Econometric model

To test the research hypotheses mentioned above, we first construct the following basic model (1) for the main effects:

$$GTI_{it} = \alpha_{it} + \beta_{it} Dig_{it} + \gamma Z_{it} + \varepsilon_{it} GTI_{it} Dig_{it} \quad (1)$$

In which, represents digital economy level for enterprise i in industry j in year t; represents green technology innovation degree for enterprise i in year t; α_{it} represents the constant term; z_{it} represents all control variables involved in the regression; ε_{it} represents the error term.

In order to further explore the moderating effect of perceived uncertainty by companies, this article introduces key variables and their interaction terms with the digital economy, establishing the following regression models:

$$GTI_{it} = \alpha_{it} + \beta_{it} Dig_{it} + \delta_i Dig_{it}\, fepu_{it} + fepu_{it} + \gamma Z_{it} \varepsilon_{it} \quad (2)$$

Where $fepu_{it}$ represents the degree of uncertainty perception for enterprise i in industry j in year t, and $Dig_{it}\, fepu_{it}$ represents the multiplicative term between the digital economy level and the moderating variable of enterprise uncertainty perception. Others are consistent with the meaning mentioned earlier.

3.2 Variables description

3.2.1 Dependent Variable: green technology innovation

This article follows the method of Xu Jia et al. to measure corporate green technology innovation using data of green patent application. The overall green patent (GTI) is selected in this article and logarithmic transformation is applied, denoted as GTI.

3.2.2 Independent Variable: digital economy level

This article refers to the measurement method of the comprehensive development level of the digital economy proposed by Zhao Tao et al.[5], which draws on two aspects: Internet development and inclusive digital finance. For the measurement of Internet development at the city level, the method proposed by Huang Qunhui et al.[10] is adopted, as shown in Table 1. Through principal component analysis, obtained the digital economy comprehensive development index, denoted as Dig, is obtained.

Table 1. Digital economy evaluation index system

Primary	Secondary	Tertiary
Composite Development Index	Internet Adoption rate	Number of Internet Users per One Hundred People
	Number of Internet-related Employment	Ratio of Computer Services and Software Professionals
	Internet-related Output	Per Capita Telecommunication Service Volume
	Number of Mobile Internet Users	Number of Mobile Phone Users per One Hundred People
	Inclusive Development of Digital Finance	China's Digital Inclusive Finance Index

3.2.3 Moderating variables: enterprise uncertainty perception

This article employs text mining methods and adopts the approach of Nie Huihua et al. to construct a set of characteristic words (as detailed in Table 2). Information is extracted from the annual reports of Chinese A-share listed companies to construct an index measuring the level of corporate perception of policy uncertainty, denoted as fepu.

Table 2. Word List for Enterprise Uncertainty Perception Behavioral Componenta

economic policy	Municipal, policy, state, expand domestic demand, industrial policies, maintain growth, promote development, industrial development, laws, national economy, relevant departments, industrial structure adjustment, macro policies, local government, government, economic policy, Policy trends, income tax, value-added tax, tax reduction, industrial structure, tax incentives, stimulus policies, goods restriction orders, purchase restriction orders, affordable housing, macro control, industrial development, national policies, politics, military, policy environment, regulations, macro, government subsidy policies, regulation policies, government subsidies, tax policies, policy support
uncertainty	risk, business risk, chaotic, market risk, sometimes, credit risk, uncertainty, volatility, elusive, change, wandering, instability, unusual, intricate, random, very complex, unstable, changeable, changeable Political fluctuations, uncertain, unpredictable, tested,

Source: Originated from the method of Nie Huihua et al. (2020).

3.2.4 Control variables

In order to conduct a more comprehensive analysis, the following control variables are set to consider factors that may impact the digital economy: company size (Size), financial leverage (Lev), number of employees (Employee), return on assets (ROA), asset turnover ratio (AT), total compensation for directors, supervisors, and executives (Pay). Time and individual fixed effects are also controlled for.

4 Empirical results

4.1 Descriptive statistics and correlation analysis

Table 3 reports the basic descriptive statistics of the main variables in the model, including sample observations, means, and standard deviations. The results show that there are certain differences among different companies in green technology innovation. From the perspective of control variables, there are significant differences among different companies in various aspects.

Table 3. Descriptive statistical

	N	Mean	max	min	Std. Dev.
GTI	9 640	0.185	6.240	0	0.58
lnDig	9 640	-1.172	-0.000	-3.469	0.708
lnSize	9 640	3.117	3.438	2.902	0.068
lnLev	9 640	-0.865	0.437	-4.628	0.594
lnemployee	9 640	7.726	13.223	2.303	1.467
ROA	9 640	0.033	0.416	-1.634	0.077
AT	9 640	0.634	9.689	0	0.657
Pay	9 640	7 984.349	1 980 000.000	0	59 493.577

In order to conduct regression analysis, it is necessary to test the correlation between the explanatory variables, control variables, and the dependent variable, and ensure there is no multicollinearity between the control variables and the explanatory variables. The results of the correlation analysis are shown in Table 4.

Table 4. Correlation coefficient matrix

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1) GTI	1.000							
(2) lnDig	0.081*	1.000						
(3) lnSize	0.118*	0.064*	1.000					
(4) lnLev	0.035*	-0.040*	0.474*	1.000				
(5) lnemployee	0.139*	-0.024*	0.657*	0.273*	1.000			
(6) ROA	0.042*	0.013	0.046*	-0.211*	0.114*	1.000		
(7) AT	-0.026*	0.019*	-0.069*	0.078*	0.187*	0.111*	1.000	
(8) Pay	-0.003	0.007	0.023*	0.006	0.028*	0.022*	-0.008	1.000

Note: *, **, and *** represent 10%, 5%, and 1% significance tests, respectively. The following tables are the same.

4.2 Main results

This article uses the OLS multiple regression analysis method to test the research hypotheses. As shown in Table 5, the first column (Model (1)) indicates that under random effects, digital economy level has a positive impact on corporate green technology innovation. In order to obtain more robust estimation results, fixed effects are included in this article (Model (2)). From the second column, it can be seen that Hypothesis 1 is preliminarily validated, that is, the higher the level of digital economy, the higher the level of corporate green technology innovation.

In the main effect model, a moderating effect of the perceived level of uncertainty by companies was introduced. Specifically, the results in columns (3) and (4) of Table 5 indicate that the perceived level of uncertainty by companies significantly enhances the positive correlation between the digital economy and corporate green technology innovation, confirming Hypothesis 2.

Table 5. Regression results

Variables	(1) GTI	(2) GTI	(3) GTI	(4) GTI
lnDig	0.086***	0.069***	0.070***	0.054**
	(0.015)	(0.025)	(0.025)	(0.026)
lnfepu			0.026	0.241**
			(0.060)	(0.112)
c.lnDil#c.lnfepu				0.183**
				(0.081)
Constant	-2.451***	-0.429	-0.435	-0.425
	(0.498)	(0.782)	(0.782)	(0.782)
Control	Y	Y	Y	Y
Individual fixed effect		Y	Y	Y
Time fixed effect		Y	Y	Y
Observations	9, 640	9, 640	9, 640	9, 640

Note: The values reported in parentheses are robust standard errors clustered to the individual level. The following tables are the same.

4.3 Robustness testing

In order to provide more reliable and stable statistical inferences for the relationship between market orientation and innovation quality of enterprises, we have employed the following robustness testing methods:

4.3.1 adding control variables

At the enterprise level, control variables such as board size (surp) and net fixed assets (FS) were added. Model (2) in Table 6 shows the results are remarkable after adding control variables and are consistent with the direction of the original regression estimates. Therefore, the estimation results of this study are robust and reliable.

4.3.2 Replace the core explanatory variables

This study refers to the method proposed by Xu et al. and replaces the dependent variable with the proportion of green patent applications, forming a new core variable called RatioGTI. As shown in Model (3) in Table 6, regression analysis was conducted after replacing the variable, and the estimation results are significant and same as the initial regression estimation direction. So, the estimation results of the study are robust and reliable.

4.3.3 Centralization and return

This study conducted centering on the independent variable, moderator variable, and interaction term and re-estimated them in the main regression model. As shown in Model (4) in Table 6, the coefficients of the main effects are still positive and significant. In addition, the moderation effect reported in Model (5) in Table 6 is consistent with the direction of the moderation effect test mentioned earlier and is also significant. Therefore, the issue of multicollinearity does not affect the regression results reliability.

Table 6. Robustness test regression results

	(1)	(2)	(3)	(4)	(5)
Variables	GTI	GTI	RatioGTI	c_GTI	c_GTI
lnDig	0.069***	0.070***	0.021***		
	(0.025)	(0.025)	(0.008)		
c_lnDig				0.069***	0.069***
				(0.025)	(0.025)
c_lnfepu					0.028
					(0.060)
c.c_lnDig#c.c_lnfepu					0.185**
					(0.081)
Constant	-0.599	-0.768	0.128	-0.865	-0.843
	(0.791)	(0.799)	(0.248)	(0.790)	(0.790)
Control	Y	Y	Y	Y	Y
Individual fixed effect	Y	Y	Y	Y	Y
Time fixed effect	Y	Y	Y	Y	Y
Observations	9, 640	9, 640	9, 640	9, 640	9, 640

5 Conclusion

Through the analysis and discussion of the empirical test results, this study draws the following conclusions: (1) The enhancement of the digital economy promotes the improvement of corporate green technology innovation. Further research indicates that the positive correlation between the digital economy and green technology innovation is universal and stable, unaffected by factors such as company size, number of employees, and industry background. (2) This study examines the moderating effect of enterprise uncertainty perception. The results show that in the face of external uncertainties, the correlation between the digital economy and green technology innovation exhibits more significant characteristics.

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