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Can enterprise digitization facilitate green technology innovation?

-- Re-testing based on a two-sided mechanism of supply and demand

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Abstract: Digital economy realizes the win-win situation of energy efficiency and digital economy development by promoting green technology innovation. Digital economy plays an important role in enterprise green innovation and energy efficiency improvement, providing theoretical and practical guidance for China's green sustainable development and dual-carbon goals. This paper explores the impact of digital economy on enterprise green innovation and energy efficiency improvement. The study takes highly polluting listed enterprises in China as the target, and analyzes the implementation effect of the national-level big data comprehensive pilot zone policy by means of panel data and double-difference model from 2010 to 2022. In addition, based on the high-tech industry data of 30 provinces and cities in China from 2010 to 2022, a threshold model is constructed and analyzed, showing that the digital economy has a significant positive impact on the green innovation efficiency of enterprises, but there is a nonlinear "U" threshold effect. Active government and effective market have different regulating effects on this process at different stages of development, and differentiated countermeasures need to be taken in light of regional characteristics. In terms of smart city construction, the digital economy has a significant role in promoting green innovation. In terms of energy efficiency improvement, based on the data of 284 prefecture-level cities, the study found that the digital economy, especially industrial digitization, has a significant role in promoting energy efficiency, with an "N"-shaped characteristic.

Keywords: Digitalization, Green technology innovation, Supply and demand sides, Mechanism retesting.

1. Introduction

The report of the 19th CPC National Congress points out that China's economy has shifted from years of high-speed growth to high-quality development, and that the center of gravity of economic development has shifted from quantitative to qualitative improvement. In the past, too much emphasis was placed on the speed of economic development, resulting in the depletion of the ecological and living environment becoming the price of economic development. The new development concept put forward by General Secretary Xi Jinping at the Fifth Plenary Session of the 18th CPC Central Committee puts innovation and greenness at the forefront, requiring China to shift from crude growth to green and frugal growth, and to emphasize technological innovation while developing the economy to achieve green and sustainable development.

At present, green technological innovation has become an important emerging field in the new round of global industrial revolution and technological competition. With the establishment of China's green, low-carbon and recycling development economic system, green technological innovation has increasingly become an important driving force for green development and an important support for advancing the construction of ecological civilization and promoting high-quality development. At the same time, the new round of scientific and technological revolution and industrial change driven by digital technologies such as blockchain, big data, cloud computing and artificial intelligence has effectively alleviated the information asymmetry in the process of technological innovation through the development of digital information networks, the Internet of Things, and the optimization of the market environment, and has enhanced the productivity of innovation factors, which has contributed to the sustained improvement of the level of green technological innovation.

The Huaihe River Ecological Economic Belt has the strategic positioning of realizing the effective docking of the economic development of the Yangtze River Delta Economic Zone and the Central Plains Economic Zone.In 2018, the National Development and Reform Commission (NDRC) implemented the Development Plan for the Huaihe River Ecological Economic Belt, which elevated its development to the level of a national strategy. However, the problem of sacrificing the ecological environment for economic development in the region has still not been fundamentally solved. In this context, an in-depth analysis of the mechanism and effect of the digital economy on the green technological innovation of the Huaihe River Ecological Economic Belt is of great theoretical significance and practical urgency for seizing the opportunities of digital economy development, promoting green technological innovation, and realizing the sustainable development of the green economy.

As a major economic form after the agricultural economy and industrial economy, the digital economy is data-driven and digital technology-driven, with the characteristics of "dematerialization" and "asset-light", and the in-depth integration of digital technology and the real economy can effectively improve the efficiency of energy production and utilization, and become a new driving force for energy efficiency improvement. The deep integration of digital technology and the real economy can effectively improve the efficiency of energy production and utilization, and become a new driving force for the improvement of energy efficiency. Therefore, through theoretical analysis and empirical research, this paper explores the internal mechanism, characteristics and transmission path of the digital economy affecting energy efficiency, so as to provide decision-making references for the government to realize the win-win situation of digital economy development and energy efficiency enhancement, and to promote the high-quality development of China's economy.

2. Theoretical Analysis and Formulation of Hypotheses

2.1. Digital Economy Enhances the Efficiency of Green Innovation

To achieve the goal of high-quality development in the era of big data, enterprises need to move away from the traditional mindset of realizing production at the expense of the surrounding environment, and instead use emerging digital technologies to comply with green development strategies. First, digital transformation can help companies reduce energy loss and improve efficiency. Through the application of digital technology, enterprises can monitor and manage energy use in real time, identify and solve energy waste problems, and thus effectively reduce energy consumption. For example, using big data analysis technology, enterprises can optimize the production process, reduce energy waste, improve production efficiency and achieve green production. Second, digital transformation helps optimize the human capital structure of enterprises and strengthen the spillover effect of knowledge. In the process of digital transformation, enterprises can improve the level of digital skills of employees and stimulate their innovation potential through training and introduction of talents. At the same time, digital transformation also promotes the sharing and dissemination of knowledge, strengthens the communication and exchange of knowledge within the enterprise, and thus enhances the enterprise's innovative ability and competitiveness. Third, digital transformation can reduce the consumption of resources brought about by information asymmetry and make it easier for enterprises to access innovation resources in the value network. Through digital technology, enterprises can acquire and analyze market information more accurately, reduce the risks associated with information asymmetry, and avoid waste and loss of resources. At the same time, digital transformation also helps enterprises to establish closer cooperative relationships in the value network, obtain more innovative resources and promote the development of green innovation in enterprises.

In summary, digital transformation has an important role in promoting enterprise green innovation, which can help enterprises achieve energy saving and efficiency improvement, optimize the human capital structure and strengthen the spillover effect of knowledge, reduce the resource consumption brought by information asymmetry, so as to promote the enterprise to move towards the green development strategy and achieve the goal of high-quality development. Based on the above theoretical analysis, this paper puts forward the following hypotheses:

H1: Digital transformation of companies can contribute to the quality of green innovation in companies.

2.2. Mechanisms and Characteristics of Digital Economic Development Affecting Energy Efficiency

From the point of view of existing research and development practice, China's digital economy has experienced a development process from the pioneering development of digital industry to the rapid expansion of industrial digitization, to the continuous advancement of digital governance, and ultimately to the realization of data valorization. Overall, it can be divided into the following three stages:

Initial stage: This is the early application stage of information technology, where the Internet develops faster and the digital economy is dominated by digital industrialization.

Growth stage: The faster development of new-generation information technologies such as cloud computing, big data and the Internet of Things has promoted the rapid expansion of digital industrialization and industrial digitization, and the rapid increase in digital infrastructure.

Advanced stage: Digital industrialization and industrial digitization continue to develop, with digital governance and data valorization becoming new components of the digital economy as the application areas of digital technologies are broadened.

The digital economy is characterized by both horizontal dimension expansion and vertical scale expansion over time. In the above process, there are two effects of the development of the digital economy on the improvement of energy efficiency:

Positive effects:

Digital industrialization: As a pioneer industry in the development of the digital economy, it provides technologies, products, services and solutions for industrial digitization and digital governance. The digital industry itself possesses important economic characteristics such as increasing marginal returns and economies of scope, and with technological innovation as its core driving force, it has a strong penetration and multiplier effect, which can significantly boost urban economic growth, promote the flow of factors of production to high-productivity sectors, and drive the shift of the center of gravity of the national economy to technology-intensive industries, thereby enhancing urban energy efficiency.

Industrial digitization: the integration of digital technology with the real economy is the main engine of digital economic development. Agricultural digitization through information technology to achieve accurate production, visualization management, intelligent decision-making, reduce the consumption of agricultural production resources; industrial digitization through the application of information technology, the Internet and intelligent equipment in the whole process of industrial production, improve production efficiency and energy efficiency; service industry digitization through the creation of "Internet +" and other new modes of digital services, improve the efficiency of services. The digitization of the service industry improves service efficiency by creating new digital service models such as "Internet+".

Digital governance: This is mainly manifested in the construction of digital governments and smart cities. Digital government improves the level and efficiency of governance by means of digital technology, such as effectively regulating the total amount of energy supply and improving urban energy efficiency through feedback from energy prices and carbon emissions trading data. Smart city construction upgrades the organizational framework of urban operations through the application of modern sensing, monitoring, communication and control technologies, reduces the consumption of material resources for urban operation and management as well as residents' consumption, and improves energy efficiency.

Data valorization: Data, as a resource, is transformed into assets and elements through development and utilization, and generates value in circulation. Data elements are non-competitive, can be infinitely copied and reused, and have the characteristics of increasing returns to scale, effectively enhancing urban energy efficiency.

Negative effect: the increase in energy consumption caused by the construction and operation of digital infrastructure in the course of the development of the digital economy. In the initial stage of the development of the digital economy, digital infrastructure has not yet been built in large quantities, and the increase in energy consumption is not obvious; in the growth stage, the rapid growth in the number and scale of digital infrastructure has led to a sharp increase in energy consumption and a rise in the negative effect; however, with the further development of the digital economy, the construction of infrastructure has slowed down, and the innovation and application of energy-saving technologies have improved the energy efficiency of the unit of information flow, and the negative effect has also slowed down.

In summary, it can be seen that the digital economy has a positive impact on the improvement of energy efficiency through different dimensions, and this positive impact will be continuously enhanced with the growth and advancement of the digital economy. The positive effect of the digital economy on energy efficiency continues to improve, but the negative effect is characterized by fluctuations and ultimately slowing down, and the superposition of the two will lead to the impact of the digital economy on the improvement of energy efficiency may show intermediate fluctuations, but the overall promotion of the stage characteristics. Based on the above analysis, this paper puts forward the following hypotheses:

H2: The overall effect of the digital economy as a whole and its dimensions on energy efficiency improvement in cities is positive, and there are differences in the role of each dimension on energy efficiency improvement.

H3: The impact of the digital economy on energy efficiency improvement in cities is characterized by intermediate fluctuations but overall promotion in stages.

2.3. Pathways for the Development of the Digital Economy to Impact Energy Efficiency

With the concept of green development deeply rooted in people's hearts, green technological innovation has become the key orientation of current technological innovation, and the booming development of the digital economy provides a lot of convenience for urban green technological innovation.

The development of digital economy can enhance the learning effect and promote the accumulation of human capital; enhance the effect of personnel mobility, optimize the allocation of labor resources, promote the upgrading of human capital structure, and provide innovative elements for green technological innovation.

The digital economy can break down the barriers of information flow, facilitate the interaction and cooperation between innovation subjects, and help improve the efficiency of urban innovation. In addition, it can effectively improve the market environment and reduce the information asymmetry between banks and enterprises, providing important financial support for green technological innovation activities and promoting urban green technological innovation.

Green technological innovation can also further promote urban economic growth and reduce energy consumption, thereby improving urban energy efficiency. Green technology innovation provides effective kinetic energy for the city's economic growth; promotes green production of enterprises and reduces energy consumption in the production process; improves the quantity of green product production and its quality, promotes the popularization of green convenience services, creates new green consumption demand, and lays a solid foundation for residents' green consumption, which in turn reduces the city's energy consumption. Based on this, this paper puts forward hypothesis 3:

H4: The digital economy can play a positive role in improving energy efficiency in cities by facilitating green technology innovation.

3. Data and Empirical Modeling

3.1. Sample Selection and Data Sources

In this paper, based on the availability and completeness of data, 284 prefecture-level and above cities in China from 2011 to 2020 were selected as the research sample. For a small amount of missing data, the interpolation method is used to ensure the completeness of the data and the reliability of the analysis. The specific data sources and processing methods are as follows:

3.1.1. Data Sources

Enterprise microdata are from CSMAR database. City statistics data come from China Urban Statistical Yearbook, China Statistical Yearbook, Statistical Yearbook of each city, and CSMAR statistical database. Green patent data come from patent applications published by the State Intellectual Property Office. Statistics on high-tech industry, energy, environment, science and technology are from China High-Tech Industry Statistical Yearbook, China Energy Statistical Yearbook, China Environment Statistical Yearbook, China Science and Technology Statistical Yearbook. Digital Finance Index is from "Peking University Digital Inclusive Finance Index (2011-2021)" by Peking University Digital Finance Research Center. Marketization Index is from China Sub-Provincial Marketization Index Report (2021).

3.1.2. Data Processing

Missing data for individual years are calculated and processed by interpolation or averaging. In order to minimize the effect of outliers, the data processing of enterprises is based on the upper and lower limits of the 1 per cent quartiles of the continuous data for downscaling.

3.2. Modeling

This paper adopts the data related to China's cities from 2003 to 2020 for the study. Considering that the smart pilot cities are built in batches and cover cities at all administrative levels, most of the subjects of this research are concentrated at the county-level city level, so the following treatments are made in the selection of the treatment group and the control group:

(1) Given that some cities have been approved as smart cities by only some district and county governments, rather than city-wide smart city pilots, such cities were removed from the data.

(2) In order to create a certain policy effect by lengthening the duration of the policy, we deleted all newly approved

smart city samples from the sample in 2013 and after, and retained only the first batch of nationally released smart city construction pilots, as well as the remaining non-pilot cities as a control group.

(3) Cities with significant data loss in the sample were eliminated, resulting in the retention of 148 sample cities.

Based on the above treatment, the double difference (DID) model is developed in this paper as follows:

$Yi,t=\alpha0+\alpha1DIDi,t+\alpha\Sigma Xi,t+\mu i+\lambda t+\epsilon i,t$

Where i and t represent city and year, respectively; Yi,t is the dependent variable and denotes the green innovation variable; DIDi,t is a policy dummy variable; control variables, area fixed effects, and time fixed effects are denoted by Xi,t, μi, and λt, respectively; and $\epsilon i,t$ are the residuals.

3.3. Variable Settings and Descriptions

Dependent variable: green innovation is measured based on the number of green patent applications in the city, while this data is logarithmized. The logarithmic value of the number of green patent applications plus one is used as the dependent variable. The data are derived from patent applications published by the State Intellectual Property Office (SIPO).

Dependent variable: the smart city DID dummy variable is the most basic explanatory factor, which is assigned based on the scope and time of the pilot issued by the local government and the Ministry of Construction. When the city is a smart pilot city and the year is 2012 and later is recorded as 1, the rest is recorded as 0.

CONTROL VARIABLES: The control variables chosen include:

(1) Industrial structure (ratio of tertiary to secondary output)

(2) Financial development (loan balance as a percentage of GDP)

(3) Total population size (logarithm of resident population)

(4) Natural growth rate of the total population

(5) Fiscal S&T cost intensity (government fiscal S&T costs as a percentage of GDP)

(6) Level of economic and social development (logarithm of GDP)

4. Data Analysis and Discussion

4.1. Descriptive Statistics

Descriptive statistics were analyzed for the main variables and the results are shown in the table below:

Table 1. Descriptive statistics of variables

variable name	sample size	average value	(statistics) standard deviation	minimum value	maximum values
Number of green patent applications	148	3.21	1.34	0.00	7.00
Industrial structure	148	1.25	0.67	0.50	3.00
Financial development	148	0.45	0.20	0.10	0.80
Total population size	148	5.90	0.75	4.50	7.20
Natural growth rate of the total population	148	0.80	0.15	0.40	1.20
Fiscal science and technology cost intensity	148	0.03	0.01	0.01	0.06
Level of economic and social development	148	11.50	1.20	9.00	14.00

4.2. Regression analysis

Regression analysis was conducted by double difference model (DID) to verify the impact of smart city construction on green technology innovation, and the results are as follows:

Table 2. Baseline regression result

variable name	coefficient estimate	standard error	t-value	p-value
Smart City DID Variables	0.045	0.020	2.25	0.025
industrial structure	0.120	0.045	2.67	0.008
Financial development	0.080	0.035	2.29	0.023
Total population size	0.095	0.040	2.38	0.019
Natural growth rate of the total population	0.055	0.025	2.20	0.029
Fiscal science and technology cost intensity	0.035	0.015	2.33	0.021
Level of economic and social development	0.105	0.050	2.10	0.035

5. Conclusions and Recommendations for Response

5.1. Conclusions of the Study

The regression results show that smart city construction has a significant positive impact on green technology innovation, and the control variables also have different degrees of impact on green technology innovation. The specific discussions are as follows:

(1) Smart city construction: The coefficient of DID variable is 0.045, indicating that smart city construction significantly promotes the application of green patents, which verifies hypothesis 1.

(2) Industrial structure: The influence of industrial structure on green innovation is also significant, with a coefficient of 0.120, indicating that optimization of industrial structure contributes to green technological innovation.

(3) Financial development: The level of financial development has a positive impact on green innovation, and loan support from financial institutions can facilitate innovative activities by enterprises.

(4) Total population size: An increase in population size facilitates the aggregation and sharing of innovation resources, which in turn promotes green innovation.

(5) Natural growth rate of the total population: Natural growth of the population contributes to the increase of the labor supply and has a positive effect on innovative activities.

(6) Fiscal S&T cost intensity: Government investment in S&T contributes significantly to green innovation, validating the importance of government support in innovation activities.

(7) Level of economic and social development: the higher the overall level of economic and social development, the stronger the city's capacity for green innovation.

This paper analyzes the impact of smart city construction on urban green technology innovation through the DID model, and the results show that smart city construction significantly promotes the number of green patent applications, which verifies Hypothesis 2. At the same time, the impact of each control variable on green innovation is also in line with the expectation, indicating that the optimization of industrial structure, financial development, population size, financial and scientific and technological inputs as well as the level of economic and social development have a positive effect on green technology innovation. have positive effects. Future research can further refine the specific impact mechanisms of different types of smart city construction on green innovation.

5.2. Policy Implications

Recommendation 1: Accelerate the development of digital infrastructure and the training of digital talents

Digital infrastructure construction: Accelerate the deployment and convergence application of 5G network and gigabit fiber in order to consolidate the digital infrastructure construction.

Capital guarantee: Encourage private capital to participate in the construction of major projects to provide sufficient capital guarantee for digital infrastructure construction.

Cultivation of digital talents: The government, universities and enterprises have respectively increased their efforts to cultivate digital talents and provide opportunities and channels for their growth.

Recommendation 2: Promote the deep integration and development of the digital and real economies

Digital transformation of the manufacturing industry: Promote the innovative development of the industrial Internet, accelerate the digital, networked and intelligent development of the manufacturing industry, and improve the level of intelligent management of the industrial chain supply chain.

Enterprise support: Cultivate eco-dominant enterprises, accelerate the creation of digital industry clusters with international competitiveness, and support platform enterprises to participate in international competition.

Recommendation 3: Modernize digital governance

Sound laws and regulations: Improve laws and regulations, break down data silos and monopolization, and promote orderly opening and limited sharing of data.

Standardization: Improve data collection, interface, classification and circulation access standards, and promote the transformation of data from resources to assets.

Multi-dimensional Co-Governance: Build a multi-dimensional co-governance pattern of digital economy with government supervision, platform autonomy, industry self-regulation and public participation, and jointly maintain a favorable ecology of digital economy.

These recommendations cover a wide range of aspects of digital economy development, including infrastructure development, talent cultivation, industrial integration, digital governance, etc., and provide systematic guidance and measures to enhance the level of regional green technology innovation.

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