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The Impact of the Digital Economy on Urban Energy-Environment Efficiency

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Abstract: This study takes the panel data of 278 prefecture-level cities in China from 2011 to 2022 as samples, constructs a super-efficiency SBM model to measure urban energy-environment efficiency, uses the entropy method to synthesize the digital economy composite index, and introduces the green innovation index as a mediating variable. Breaking through the traditional analysis framework in the empirical method: Firstly, through the fixed-effects model and mediating-effect test, it reveals the direct impact of the digital economy on energy-environment efficiency and the transmission path of green innovation. Secondly, it divides the eastern, central, and western regions and low-carbon pilot cities for heterogeneity tests to identify the moderating effect of policy intervention. Thirdly, it strengthens the robustness of the conclusions by replacing the super-efficiency CCR model, shortening the sample period, and performing winsorization. The study finds that the digital economy significantly improves energy-environment efficiency through green technology innovation. These conclusions provide an empirical basis for optimizing the layout of digital infrastructure and improving the regional collaborative emission-reduction mechanism.

Keywords: Digital economy; Energy-environment efficiency; Super-efficiency SBM; Green development

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1. Introduction

Against the backdrop of global climate governance and the accelerated advancement of the "dual-carbon" goals, the digital economy, as the core driving force of the new round of scientific and technological revolution, is profoundly reshaping the operating logic of the urban energy-environment system through technological penetration, factor recombination, and model innovation [1].

Data from the China Academy of Information and Communications Technology shows that from 2016 to 2022, China's digital economy scale increased from 22.4 trillion yuan to 50.2 trillion yuan, and its proportion in GDP rose from 30.3% to 41.5%, with a growth rate far exceeding that of traditional economic sectors. At the same time, the United Nations' "Digital Economy Report 2019" points out that China and the United States account for 90% of the global digital platform market value. Chinese "super-platforms" represented by Tencent and Alibaba are accelerating the digital transformation of energy consumption, production, and governance [2]. However, with the exponential expansion of the digital economy, there are still significant controversies regarding its synergistic relationship with urban energy-environment efficiency. On the one hand, digital technologies may improve energy-environment efficiency and reduce environmental loads through smart grid optimization, real-time carbon emission monitoring, and green supply chain management [3]. On the other hand, the expansion of high-energy-consuming infrastructure, such as data centers and the "rebound effect," may also exacerbate energy consumption and carbon emissions [4]. In this contradictory context, clarifying the mechanism of action and spatial spillover effect of the digital economy on urban energy-environment efficiency has become a key proposition for achieving the coordinated development of the "dual-carbon" goals and high-quality digital economy.

Existing research has conducted preliminary explorations on the relationship between the digital economy and energy-environment efficiency. At the theoretical level, scholars generally recognize the "technology-enabling" effect of the digital economy; that is, it optimizes energy allocation efficiency through the Internet of Things, big data, and artificial intelligence [5]. However, there are two limitations in the existing literature: First, the spatial scale mostly focuses on provincial panels or specific urban agglomerations, lacking a systematic test of the heterogeneous characteristics of 278 prefecture-level cities. Second, the mechanism analysis is mostly limited to industrial structure or human capital, with insufficient discussion on the mediating path of green technology innovation.

2. Research design

2.1. Research hypotheses

As a key engine for promoting the green development of the economy and society, the digital economy is providing innovative paths for low-carbon transformation through multi-dimensional technological integration. After digital technologies are embedded in the industrial production process, intelligent algorithms can be used to optimize production process parameters, reducing the energy consumption intensity per unit of output [6,7]. In terms of industrial upgrading, the digital economy drives the transformation of traditional manufacturing industries to intelligent manufacturing and constructs a green industrial system covering the entire industrial chain by cultivating emerging industries such as smart energy and environmental protection technology. Therefore, the following hypotheses are proposed:

(1) The digital economy can promote urban energy-environment efficiency.

The promoting effect of the digital economy on urban energy-environment efficiency can be achieved through its impact mechanism on the level of green innovation. Empirical research shows that in cities with a high level of digital economy development, the increase in green total factor productivity can be more than 1.3 times that of traditional cities [8]. The high permeability and network externality of digital technologies break geographical barriers and promote the diffusion of green innovation technologies through the cross-regional flow and sharing of data factors [9,10]. The improvement of green innovation capabilities strengthens the regional synergy effect [11]. The digital economy optimizes the efficiency of regional resource allocation through big data analysis and cloud computing, achieving accurate matching of energy supply and demand and reducing the overall carbon emission intensity [12]. Therefore, the following hypothesis is proposed:

(2) The digital economy can promote urban energy-environment efficiency by influencing the level of urban green innovation.

2.2. Model specification

Mediating-effect model: This paper refers to the mediating-effect model proposed by Wen *et al*. to examine whether the level of the digital economy has an indirect impact on the improvement of urban energy-environment efficiency by promoting the level of urban green innovation [13]. The specific models are as follows:

$$NC_{it} = \beta DIG_{it} + \sum \delta ControlV_{it} + \alpha_t + \epsilon_{it}$$

$$GC_{it} = \beta DIG_{it} + \sum \delta ControlV_{it} + \alpha_t + \epsilon_{it}$$

$$NC_{it} = \rho wIR_{it} + \beta DIG_{it} + \gamma GC_{it} + \sum \delta ControlV_{it} + \alpha_t + \epsilon_{it}$$

Among them, GC_{it} represents the green innovation level of the i-th region at time t. γ is the impact coefficient of the mediating variable GC_{it} on the explained variable NC_{it}, and $ControlV_{it}$ represents the control variables of the i-th region at time t.

2.3. Variable selection

According to Shi *et al*., this paper draws on and uses the super-efficiency SBM method [14]. Taking labor, capital, and energy as inputs, regional GDP as the desired output, and industrial sulfur dioxide, industrial smoke and dust, and industrial wastewater as the undesired outputs, it measures the energy-environment efficiency. It also refers to Zhao *et al*., taking the logarithmic digital economy index as the explanatory variable [15], the logarithm of the number of green patent authorizations as the mediating variable, and the financial development level, environmental regulation, industrial structure upgrading, foreign direct investment, and scientific and technological development level as control variables. Based on the panel data of 278 prefecture-level cities in China from 2011 to 2022, it explores the impact mechanism of the digital economy on energy-environment efficiency.

3. Empirical analysis

3.1. Baseline regression

The results of the baseline regression after adding all control variables show that the regression coefficient of the digital economy level on urban energy-environment efficiency is 0.0769, which is significant at the 1% level. This indicates that for every one unit increase in the digital economy, urban energy-environment efficiency increases by 0.0769 units. After adding the fixed-effects and random-effects models, the direction and significance of the regression coefficient remain unchanged, but the value decreases, indicating that the control variables can more accurately reflect the impact of the digital economy. The results show that the digital economy has a significant promoting effect on industrial carbon emission efficiency, verifying hypothesis 1. (1) The sample period of the study is adjusted to 2015–2022 after the implementation of the "Broadband China" pilot policy for testing. The results show that the regression coefficient of the digital economy on industrial carbon emission efficiency is still significantly positive, verifying the robustness of the conclusion. (2) The super-efficiency CCR model is used to remeasure the energy-environment efficiency. The regression results show that the digital economy coefficient is significantly positive at the 1% level, and the test results remain robust. (3) The variables are winsorized at the 1% level to eliminate the influence of extreme values. The promoting effect of the digital economy on energy-environment efficiency remains significant, indicating the reliability of the conclusion.

3.2. Mediating-effect

The results of the mechanism test of the digital economy on urban energy-environment efficiency show that the regression coefficient of the digital economy on the level of green innovation is 1.9702, which is significant at the 1% level, indicating that the digital economy significantly promotes green innovation and drives urban green development. Improving green innovation capabilities is the key to improving energy efficiency. By greening technologies and industries, it can reduce undesired outputs and increase desired outputs, thereby improving energy-environment efficiency.

3.3. Heterogeneity test

(1) The results of the regional heterogeneity regression show that the digital economy in the eastern, central, and western regions can all promote urban energy-environment efficiency. However, the total effects in the central and western regions did not pass the 1% significance test, while the mechanism of the digital economy in the eastern region promoting energy-environment efficiency through green technology innovation is significant. (2) The results of the policy heterogeneity regression show that the digital economy in both low-carbon economic policy pilot cities and non-pilot cities can promote energy-environment efficiency. However, the significance of the total effect of the digital economy in non-pilot cities indirectly promoting energy-environment efficiency through green innovation has decreased, as shown in **Table 1**.

Table 1. Heterogeneity test

Usage method	Variable	Direct effect	Indirect effect	Total effect
All samples	lndig	0.0817***	1.9702***	0.0291***
	lngc			0.0270***
The east	Lndig	0.1051***	1.9202***	0.0557***
	Gc			0.0257***
Middle part	Lndig	0.0257***	1.7940***	0.0166
	Gc			0.0241***
West	Lndig	0.0358***	1.9474***	-0.0053
	Gc			0.0218***
Low-carbon economic policy pilot city	Lndig	0.0829***	2.0001***	0.0257***
	Gc			0.0293***
Non-low-carbon economic policy pilot cities	Lndig	0.0794***	1.9957***	0.0278*
	Gc			0.0255***

4. Conclusions and suggestions

4.1. Conclusions

Based on the panel data of prefecture-level cities from 2011 to 2022, this paper uses methods such as mediating-effect tests to empirically analyze the impact and mechanism of the digital economy on urban energy-environment efficiency. The results show that the digital economy significantly promotes energy-environment efficiency; the level of green innovation plays a mediating role in the impact of the digital economy on energy-environment efficiency, and this effect is more significant in the eastern region and low-carbon pilot cities.

4.2. Suggestions

First, accelerate the development of the digital economy, optimize the construction of digital infrastructure, promote the application of digital technologies in energy and environmental management, and improve urban energy-environment efficiency.

Second, strengthen policies to support green innovation, encourage enterprises to increase investment in green technology research and development, especially in the eastern region and low-carbon pilot cities, and give full play to the mediating role of green innovation between the digital economy and energy-environment efficiency.

Third, improve the regional coordinated development mechanism, promote the in-depth integration of the digital economy and green innovation, realize inter-regional technology sharing and experience exchange, and promote the overall improvement of energy-environment efficiency.

Fourth, strengthen policy guidance, combine the development of the digital economy with low-carbon economic pilot projects, explore effective paths for the digital economy to drive green transformation, and help achieve the “dual-carbon” goals.

Disclosure statement

The author declares no conflict of interest.

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