A study of the impact of the digital economy on regional energy efficiency

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Abstract. The digital economy, emerging as a new form of economic system, holds a crucial position in enhancing energy efficiency. It does so by streamlining the distribution of resources with the help of data and augmenting the flow efficiency of production factors. This paper examines the precise role and mechanism of the digital economy in enhancing energy efficiency from both theoretical and empirical perspectives. This paper utilises panel data from China's provinces and cities over a fifteen-year period, ranging from 2006 to 2021. The fixed-effects model is employed to investigate the precise pathway in which the level of digital economy development influences energy efficiency. The study reveals that the digital economy has a notable impact on enhancing energy efficiency. The analytical mechanism indicates that the digital economy effectively improves energy efficiency by advancing regional marketisation, optimising the industrial structure, and fostering innovation and the adoption of new technologies. Owing to considerable disparity among diverse parts of China, the digital economy seems to have a positive impact on the eastern and central regions, while its influence remains restricted in the western regions. Meanwhile, the areas encompassed by the Yangtze River Economic Belt are the most viable for advancement in energy efficiency through the digital economy. The influence of the digital economy on energy efficiency is markedly inconsistent due to the considerable variation in resource allocation among various regions. The role of the digital economy in enhancing energy efficiency is particularly evident in regions with moderate resource endowment. Thus, this study contends that realisation of the digital economy's capacity requires the government to consider the regional development disparities and resource endowment circumstances. To achieve balanced regional growth and comprehensive progress in energy efficiency, the government must develop tailored policies that promote marketisation, optimise industrial structure, and incentivise technological advancement. Therefore, the implementation of these measures is crucial.

Keywords: Digital economy, Total factor energy efficiency, Fixed effects modeling.

1. Introduction

China is in a transformative phase, moving away from an antiquated model of growth fueled by consumption of resources and contributing to environmental degradation, a shift that is essential for sustainable development. The promotion of a green, high-quality development path is central to its agenda. The digital economy emerges as a game-changer in this respect, integrating with the real economy where digital knowledge and information are pivotal, driven by digital technologies, and reliant on robust information networks. Researchers have constructed various measurements for the digital economy's maturity, with infrastructure level (Başol Oğuz and Yalçın Esin Cumhur, 2021)[1], progress in digital industrialization, and degree of industrial digitization (Kunkel S and Tyfield D, 2022)[2] acting as primary indicators. To quantify this development, methodologies such as PAC and the Topsis entropy value method have been employed (He Di et al. 2022)[3]. The importance of the digital economy in stimulating high-quality economic growth has been documented, showing its role in enhancing entrepreneurial activities (Heping G and Fuxiang W, 2022)[4]. It reconfigures consumer-business interactions, propels targeted and timely R&D, consolidates enterprise R&D assets, and fosters collaborative innovation [3]. Moreover, by expediting enterprise digitization, the potential for zenhanced technological innovation and management efficiency is high, which may significantly influence total factor productivity levels.

Despite China's position as one of the world's leading carbon emitters, government efforts at various levels have been working toward green, high-quality development that privileges environmental protection and decarbonization. A major strategy in this transition involves enhancing energy efficiency while maintaining economic growth to reduce reliance on fossil fuels, a significant contributor to carbon emissions. To measure progress in energy efficiency, several models are utilized, such as the SFA model (Assimo Filippini and Lester C, 2016)[5], the improved DEA model (Lo Storto, 2017)[6], the global SBM model (Zhao X et al.)[7] and the super-efficient SBM model (Yang and Wei, 2018)[8]. Overcoming technological and managerial inefficiencies is key to improving energy efficiency[5]. Factors such as regional urbanization, digital transformation (Reis and Melão, 2023)[9], economic development level (Ohene-Asare et al., 2020)[10], economic openness, the scale of tertiary industry (Su J et al, 2021)[11], financial development, and fixed asset investment also play a role in this area [9].Research indicates that adjusting the energy input mix can lower energy consumption[10]. Supporting innovation and fostering a supportive environment for scientific and technological advancement is also crucial for enhancing energy efficiency [3].

Existing research examining the nexus between the digital economy and energy efficacy corroborates a non-linear enhancement of total factor energy efficiency attributed to internet influences, coupled with a discernible network effect[8]. Moreover, research has validated that energy efficiency is significantly affected by digital insurance services, digital credit services, the extent of digital financial coverage and the degree of digitisation of digital finance (Risman A et al., 2022)[12]. The promotion of urban carbon emission reduction can be effectively facilitated by the development of the digital economy[4]. Presently, it is unclear how the digital economy impacts energy efficiency, although some research indicates that it has influence on market trade[7] and remedying resource mismatch [5].

After researching the literature mentioned above, this study determines that there are limited investigations into the link between digital economy and energy efficiency on both a national and international level. Additionally, existing studies have not delved into the specific mechanisms behind this connection at a provincial level. Therefore, the study constructs an evaluation index system for the level of digital economy development from three dimensions: digital infrastructure, digital industry development, and digital economic environment. The study examines China's economic development level using the entropy weight method. The study utilises super-efficient SBM model[8] to measure the total factor energy efficiency of 30 Chinese provinces. The direction and magnitude of the impact of digital economy on energy efficiency is then clarified through the benchmark regression model. Furthermore, a heterogeneity analysis model is created to examine variations in the relationship between digital economy and energy efficiency. Finally, the effect of the development level of the digital economy on energy consumption is examined.

This paper aims to explore the mechanism of the digital economy's impact on energy efficiency by adopting China's panel data for 16 years from 2006-2021. The study uses a fixed effects model and selects the degree of marketisation, technological innovation, and industrial structure upgrading as the pathways. This study explores the influence of the digital economy on energy efficiency based on the data of thirty provinces, taking into account their geographic location, resource endowment, and whether they are located in the Yangtze River Economic Belt. This study targets deficiencies present in current academic discourse, offering a fresh theoretical viewpoint on the digital economy’s role in fostering enhancements in energy efficiency. The outcomes of this paper furnish key understandings that are instrumental for the creation of policies tailored to encourage equitable development across regions as well as the augmentation of energy efficiency at a broader level.

2. Research design and sample description

Based on theoretical analyses and relevant assumptions outlined in the preceding section, this article has chosen to utilise 16-year panel data derived from thirty provinces within the country spanning from 2006 to 2021 in order to construct a two-way fixed effects model.

$$tfee_{it} = \alpha_0 + \alpha_1 digit_{it} + \alpha_2 Control_{it} + u_i + \gamma_t + \varepsilon_{it} \tag{1}$$

where: *i* represents the province and *t* represents the year. $tfee_{it}$ denotes the total factor energy efficiency of the *i*th province in year *t*. $digit_{it}$ represents the composite index of digital economic development $Control_{it}$ refers to the control variable. Lastly, u_i, γ_t, ε_{it} denote the individual and time effects and the random disturbance term, respectively. This paper examines the coefficient of the key explanatory variable α_1 "digital economy development level."

In this paper, we reference the work of Yang Zhongshan and Wei Xiaoxue (2018) [8]who utilise the super-efficient SBM model, incorporating non-desired outputs, to gauge the overall factor energy efficiency ($tfee_{it}$) of thirty-one provinces throughout China between 2006 and 2021. They operate under the assumption that the input factors used in the production process consist of capital, labour, and energy, while the desired outputs are GDP (or economic outputs), and the non-desired outputs comprise of industrial pollutantsc, regional statistical yearbooks, China Energy Statistical Yearbook, China Science and Technology Statistical Yearbook, and the compilation of statistical data covering 60 years of new China.

The principal explanatory variable in this study is the degree of advancement within the digital economy.($digit_{it}$, which refers to the digital economy measurement system developed by He Di et al. (2023)[3]. The entropy weight TOPSI method is employed to measure the digital economy's level of development in thirty-one provinces and regions of the country. Causal identification is performed on 31 provincial panels in China from 2006 to 2021 in this paper. The data is sourced from the China Statistical Yearbook.

To better capture the effect of China's digital economy on regional energy efficiency and minimize the risk of biased estimations from omitted variables, this study incorporates a set of control variables outlined below(Data from China Statistical Yearbook).: Population Density (Pop) is calculated by dividing the total number of residents by the area of each province. The Degree of Governmental Intervention (Govr) is calculated through local public financial expenditure. The Intensity of Environmental Regulation (Regu) is calculated by measuring industrial wastewater emissions, as well as industrial waste water and waste emissions. Environmental regulation intensity (Regu) was determined using the entropy weighting method, taking into account industrial wastewater, sulfur dioxide emission, and dust emission. Foreign direct investment (FDI) is expressed as a proportion of GDP. industrial structure rationalisation index (Struct), expressed as the sum of the proportions of added value of primary industries and secondary industries to GDP*1 and GDP*2, respectively, as well as the proportions of added value of tertiary industries to GDP*1, GDP*2, and GDP*2. The industrial structure rationalisation index (Struct) is calculated by adding the proportion of primary industry value added to GDP*1, the proportion of secondary industry value added to GDP*2, and the proportion of tertiary industry value added to GDP.

Table 1. displays the descriptive statistics for the variables.

Table 1. Descriptive statistics of variables

Variable	Obs	Mean	Std. Dev.	Min	Max
DIGIT	480	0.047	0.056	0.002	0.458
Govr	480	0.271	0.12	0.111	0.846
Pop	480	0.115	0.173	0	1
Regu	480	0.003	0.003	0	0.028
FDI	480	0.021	0.019	0	0.121
Struct	480	0.221	0.18	-0.099	1.042

Within the economic transition, the burgeoning digital economy emerges as a powerful tool for boosting energy efficiency. To examine the impact of the digital economy on energy efficiency, this study employs a two-way fixed effect model, using 16 years of panel data gathered from 31 provinces ranging from 2006 to 2021. The resulting regression outcomes are detailed in Table 2. The findings from the data in column 1 of Table 2 reveal that $digit_{it}$ coefficient is 1.3479, which is statistically significant at the 1% level of significance. Upon incorporating year fixed effects, the results in column 2 show a significant $digit_{it}$ coefficient of 1.6290 at the 1% level of significance. Furthermore, when year and region fixed effects are added, the result in column 3 portrays a $digit_{it}$ coefficient of 0.567 statistically significant at the 5% level. The outcomes presented in columns (1), (2), and (3) indicate that the digital economy exerts a markedly beneficial influence on the energy efficiency of regions.

3. Robustness testing

To eliminate possible interference from omitted variables and measurement errors in the digital economy and energy efficiency analysis, and to guarantee credible results amidst differing variables and samples, this paper reconstructs the fixed-effects model via replacement of both explanatory and explained variables.

To replace the explanatory variables, the SBM-GML method is employed to gauge Super-SBM, which measures energy efficiency. Adequacy of the conclusion is under observation after substituting the explanatory variables. The regression results presented in the table 2 column 4 below exhibit consistency with the previous findings, demonstrating the sturdiness of the results.

To substitute the explanatory variables, this study bases on Zhao Tao's (2019)[13] investigation and recalculates the comprehensive digital economic development index with the help of the entropy value method, employing its digital economy index system. The table 2 column 5 displays the regression findings, which are largely in line with the earlier conclusions and demonstrate the strength of the results.

Table 2. Benchmark regression results and robustness testing

VARIABLES	(1) TFEE	(2) TFEE	(3) TFEE	(4) TFEE (SBM-GML)	(5) TFEE
DIGIT(Zhao Tao, 2019)[13]					1.4921**
					(0.707)
DIGIT	1.3479***	1.6290***	0.5670**	3.9705*	
	(0.222)	(0.408)	(0.272)	(2.989)	
Constant	0.9055***	0.8837***	0.8497***	0.6782	0.6035**
	(0.042)	(0.109)	(0.129)	(0.446)	(0.224)
Observations	480	480	480	450	480
R-squared	0.5594	0.6058	0.8722	0.5357	0.5759
city fe	no	no	yes	yes	yes
year fe	no	yes	yes	no	no
controls	yes	yes	yes	yes	yes

Robust standard errors in parentheses*** $p<0.01$, ** $p<0.05$, * $p<0.1$

4. Heterogeneity test

This paper examines heterogeneity with regards to the partitioning of the Yangtze River economic belt, disparities in provincial resource endowments, and differences in provincial geographic locations.

The Yangtze River region is amongst the most economically active, open, and innovative areas in China. It was among the first regions to initiate the construction of a digital economy in the country, bolstered by its natural resources. The region has achieved rapid growth in the digital economy and maintains its position at the forefront of the country, in both growth rate and total volume. Thus, this study conducts an analysis of heterogeneity based on whether a province is situated in the Yangtze River Economic Belt. The findings are presented in Table 3.Column 1 of the table indicates that for the provinces outside the Yangtze River Economic Belt, the coefficient value of the digital economy's effect on energy efficiency is -0.0519, and the significance level is 10%. This indicates a negative correlation between the digital economy's development and energy efficiency's improvement in this province group. Additionally, the digitisation of the economy does not appear to enhance overall energy efficiency. Table 2's second column lists the provinces in the Yangtze River Economic Belt. In these regions, the digital economy exhibits a coefficient of 0.8295 with regards to energy efficiency, which is found to be significant at the 1% level of significance. This revelation implies that the expansion of the digital economy in the Yangtze River Economic Belt plays a significant role in improving energy efficiency within that region.

As regional resource endowments affect energy efficiency, the assessment of heterogeneity is essential. To address this issue, this paper conducts a heterogeneity test based on varying levels of energy endowment: low, medium and high. Subsequently, 30 provinces are categorised based on the number of resource-based energy cities they have, and then assigned to the relevant endowment category. The outcomes of this study are summarised in Table 3 column 3 shows the coefficient is 0.4925, significant at the 5% significance level. This indicates that the advancement of the digital economy has a favourable influence on enhancing energy efficiency in regions with low energy resources. The results from Column 4 suggest that the link between the digital economy and energy efficiency is less noticeable in provinces with medium resource endowment, compared to the other two categories. However, the coefficient in Column 5 shows that the impact of the digital economy on energy efficiency is significantly positive (at the 10% significance level) among provinces with high resource endowment. This indicates that the growth of digital economy contributes positively to energy efficiency in high resource endowment areas.

Economic development variances, strategic orientations, and industrial configurations lead to uneven deployments of digital technologies, products, and services among regions. This investigation delves into how locational determinants influence the nexus between digital economy expansion and total factor energy efficiency (TFEE) across China Thirty provinces. The study conducts a differentiation analysis based on the geographic positioning of provincial zones. Within Table 3, the sixth column reveals an elasticity measure for the digital economy on TFEE in the eastern provinces marked at 0.5436, demonstrating significance at the 10 percent level. This indicates a substantial enhancement of energy efficiency attributed to the digital sector in the economically advanced east. The seventh column reveals a more pronounced elasticity factor of 2.2515 for the digital economy's role in TFEE within central provinces, also significant at the 10 percent threshold, suggesting robust gains in energy efficiency. In contrast, the eighth column delineates the western provinces, revealing a digital economy's TFEE elasticity of -0.7320, underscoring a non-significant digitization impact. From these findings, it is discernible that digital economy promotion vastly improves energy efficiency primarily in the eastern region.

Table 3. Heterogeneity test

	(1)	(2)	(3)	(4)	(5)	*(6)*	*(7)*	*(8)*
VARIABLES	*TFEE Not In the Yangtze River Economic Belt*	*TFEE In the Yangtze River Economic Belt*	*TFEE Low*	*TFEE Middle*	*TFEE High*	*TFEE East*	*TFEE Middle*	*TFEE West*
DIGIT	-0.0519*	0.8295***	0.4925**	5.9400	3.8842*	*0.5436**	*2.2515**	*-0.7320*
	(1.460)	(0.236)	(0.213)	(4.424)	(1.915)	*(0.258)*	*(2.535)*	*(2.248)*
Constant	1.0243***	0.8517***	0.7911***	2.3782	2.0961***	*1.0741****	*-0.0864*	*1.3778***
	(0.190)	(0.241)	(0.192)	(2.101)	(0.372)	*(0.272)*	*(0.903)*	*(0.499)*
Observations	176	304	256	112	112	*208*	*96*	*176*
R-squared	0.8347	0.8890	0.9035	0.8595	0.9309	*0.9006*	*0.7867*	*0.8338*
city fe	yes	yes	yes	yes	yes	*yes*	*yes*	*yes*
year fe	yes	yes	yes	yes	yes	*yes*	*yes*	*yes*
controls	yes	yes	yes	yes	yes	*yes*	*yes*	*yes*

Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

5. Mechanisms of influence test

Mn The level of marketisation promotes energy efficiency through price signals, competition and incentives for innovation. Under marketization, energy costs are incorporated into firms' operations, prompting them to take measures to enhance energy efficiency for cost reduction and improved competitive standing. During this process, the digital economy significantly enhances the process of marketisation through improved market transparency, reduced transaction costs and support for new business models, including e-commerce and the sharing economy, which expedite transactions, enhance market dynamics and are convenient. Consequently, this paper utilises Wu J et al (2023)[14] marketisation index to assess the degree of marketisation in every province. A two-way fixed effects model has been developed by employing panel data from 30 provinces. The outcomes are demonstrated in Column 1 of Table 4. Based on these results, it can be inferred that the digital economy has a favourable impact on the marketisation of the region, with a significant coefficient of 4.5883 at the 10% significance level.

Technological innovation drives the changes in alternative inputs to the production process, enabling greater output with lower energy input. Through the development and implementation of advanced production technologies and processes, enterprises have achieved automation and intelligence in the production process, whilst streamlining and optimising resource usage. Through the application of information technology and big data, enterprises can now more effectively monitor and manage their energy consumption, leading to greater regulation of energy flows and a significant reduction in inefficient energy use. This technological advancement has enabled improved energy efficiency. This paper aims to use the number of patent applications granted as a provincial technological innovation indicator, standardized with Z-scores, drawing on the methodology of Heping G et al. (2022)[4]. The panel data of 30 provinces supports this research. A two-way fixed-effects model was constructed to study the relationship between technological innovation and digital economy development. The findings from Table 4, Column 2 demonstrate that the digital economy exerts a positive impact on technological innovation, with a coefficient of 1.2420, which is statistically significant at the 5% level.

Industrial structure upgrading involves a shift in the economy from low value-added and high energy-consuming traditional industries towards high value-added and low energy-consuming emerging industries. Emerging industries typically utilise advanced technologies and exhibit greater energy efficiency compared to traditional industries, which tend to be more energy-dependent. Hence, this paper adopts the approach of He Di et al (2023)[3], utilizing panel data from 30 provinces. It constructs an individual fixed effect model of industrial structure advanced and digital economy development level, and the results are shown in Table 4 column 3. The text already adheres to the principles, therefore, the improved version is: Column 3 shows that coefficient is 1.7422, which is significant at the 10% significance level. The above statement suggests that the growth of the digital economy facilitates the refinement of industrial structure, enables the modernisation of conventional industries and the establishment of new ones, and ultimately contributes to a boost in energy efficiency.

Table 4. Mechanisms of influence test

VARIABLES	(1) *Market*	(2) *Innovate*	(1) *Advance*
DIGIT	1.4650*	1.2420**	1.7422*
	(0.796)	(0.584)	(0.909)
Observations	480	480	480
R-squared	0.9481	0.8399	0.9240
city fe	yes	yes	yes
year fe	yes	yes	no
controls	yes	yes	yes

Robust standard errors in parentheses *** $p<0.01$, ** $p<0.05$, * $p<0.1$

6. Conclusions

This study investigates the relation between digital economy growth and energy efficiency. Utilizing 16 years (2006-2021) of panel data from Chinese provinces and cities, we apply a fixed effect model to examine the digital economy's impact on energy efficiency. Results indicate that the digital economy significantly enhances total factor energy efficiency through optimized resource allocation and production factor flows. Further, the digital economy promotes energy efficiency via improved market mechanisms, industrial modernization, and technological innovation. Geographically, the effects are heterogeneous: positive in eastern and central provinces, but muted in the western regions. Along the Yangtze River Economic Belt, digitalization notably propels energy efficiency. High and low resource-endowed regions experience substantial efficiency gains, contrasted with minimal impact in medium-endowed areas. These outcomes inform our policy recommendations. Drawing from our analysis, this document suggests the subsequent policy prescriptions.

In light of regional disparities in resource endowments, economic status, and industrial composition, it's critical for policy designs to reflect local specificities rather than adopting a uniform approach. Targeted government support for technological advancement is essential, particularly in eastern and central regions. Focused policies in tax incentives, financial support, and workforce training should be implemented to catalyze the efficient application of digital technologies in energy-saving ventures.

Additionally, enhancement of regional integration, especially within the Yangtze River Economic Belt, is recommended. Emphasizing infrastructure interconnectivity and investment in high-speed internet and IT services infrastructure will be pivotal. Improving service accessibility and quality will enable regional beneficiaries to leverage digitization, optimizing energy efficiency.

Lastly, market liberalization policies aimed at fostering transparent and competitive markets are necessary to support the digital economy. Streamlining regulatory frameworks, reducing administrative hurdles, and promoting regulatory transparency will establish a conducive environment for high-tech industries. Government incentives should advance industrial upgradation to higher added value and reduced energy consumption sectors through tax benefits, financial support, and skill development initiatives.

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