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Research on the Mechanism of Two-Way Interaction between Digital Economy and Household Energy Transition in China

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ABSTRACT

The article selects the inter-provincial panel data from 2015 to 2022, and examines the bidirectional impact of digital economy and China's household energy structure and utilization efficiency and its mechanism of action by using the double-fixed panel model, the mediation and threshold effect model, and the coupled coordination model. The results show that the digital economy has a significant positive impact on household energy structure and utilization efficiency; from the perspective of the impact mechanism, the digital economy can promote the improvement of household energy utilization efficiency and the optimization of structure through the mediating effect of technological innovation; the threshold effect finds that when the digitalization level exceeds 0.661, the digitalization is in the optimal state for driving household energy utilization efficiency in the provincial area; Secondly, this paper focuses on the two-way relationship between the two, and finds that the overall coupling situation is good, and the regional digitalization level and energy efficiency in the "inverted triangle" pattern show a high degree of coupling, and the coupling and coordination phenomenon, which was originally mainly concentrated in the eastern region, has begun to spread to the western region. The purpose of this paper is to promote the acceleration of the national energy transition by playing the positive role of digital economy in promoting the rationalization and advancement of the energy consumption structure, and then reverse the development of China's digital economy, injecting the dual kinetic energy of green and digital into the high-quality development of the economy as a whole.

KEYWORDS

Digital economy; Green energy efficiency; High quality development; Threshold effect

1. INTRODUCTION

In recent years, the proposed dual-carbon goal has prompted various industries to actively respond to the change, in which the energy industry, as the core area to promote green and low-carbon development, its transformation and upgrading is the key path and inevitable choice to realize the "dual-carbon" goal. In the energy industry, the in-depth integration of energy technology and digital technology has become an important way of industrial upgrading, and digital transformation has become an important enabling tool for energy transformation. The 12th Dual Carbon Strategy and Energy Digitization Summit pointed out that 2024 is the key year to promote innovation and realize breakthroughs in industrial upgrading. The integration of energy technology and digital technology is of great significance in supporting the implementation of dual-carbon strategy, promoting industrial upgrading innovation and service expansion, and it is an inevitable choice for the new energy industry to realize high-quality development.

The report of the twentieth CPC National Congress clearly pointed out that in-depth promotion of the energy revolution, accelerate the planning and construction of a new type of energy system for the new journey to promote the development of high quality energy has pointed out the direction. The second session of the 14th National People's Congress "Government Work Report" pointed out that in-depth promotion of digital economic innovation and development, the formulation of policies to support the high-quality development of the digital economy, and actively promote the industrialization of digital industry, industrial digitization. The transformation of the energy sector not only plays a key supporting role in realizing the high-quality development of China's economy, but also serves as the strategic core for reaching the goal of carbon peak and carbon neutrality.

As one of the major areas of energy consumption, accelerating the clean energy transition in the household sector has become an important means of combating air pollution. Therefore, it is of great practical significance to explore the evolution of the digital economy, energy efficiency and structural optimization, and to systematically analyze the close relationship between the degree of development of the digital economy and the green total factor energy productivity, in order to enhance the efficiency of energy use, promote the transformation of China's household energy to a low-carbon direction, realize the sustained and healthy socio-economic development, and achieve the "dual-carbon" goal. It is of great practical significance to enhance energy utilization efficiency, promote the transformation of Chinese household energy to decarbonization, realize healthy socio-economic development and achieve the "dual carbon" goal.

2. LITERATURE REVIEW

2.1. Literature Related to Energy Transition

Driven by both "carbon neutrality" and "big data", the international community has generally recognized the importance of accelerating the transformation and optimization of energy structure. Against this background, many scholars have conducted in-depth research and analysis on energy structure transformation and optimization. Among them, some scholars have explored the potential key factors affecting energy structure transformation from different perspectives. They include the environmental control policy (Liu Yachin et al., 2022) [1], the adjustment status of industrial structure (Zou Xuan et al., 2019) [2], the level of economic development (Zhang Qianqian et al., 2017) [3], the advancement of the urbanization process (Fan DeCheng et al., 2012) [4], and the requirement of policy-based transformation (Fan Ying et al., 2021) [5]. These studies provide valuable references for our comprehensive understanding of energy structure transition.

Academics have demonstrated in-depth thinking when exploring the multiple dimensions of the energy mix transition. Researchers have explored its far-reaching impacts, focusing on both the direct ecological and environmental effects and the potential impacts on the level of social welfare. First, focuse on the impact of energy structure transition on the ecological environment. Wang Yong et al. (2019) pointed out that the global ecological environment is experiencing profound changes as traditional fossil energy is gradually replaced by renewable energy [6]. This transition has significantly reduced greenhouse gas emissions and played a key role in mitigating global climate change. Secondly, we should not ignore the impact of energy structure transition on social welfare level. Hu Junfeng et al. (2011) show that the transformation of energy structure is not only related to economic development, but also directly related to the improvement of social welfare [7].

At present, there is no recognized methodology in the academic community for measuring energy mix transition, and therefore, accurately assessing the extent of energy mix transition has become an important issue for relevant research. In examining energy consumption, several ideas exist for reference. Li Changsheng et al. (2022) and Fang et al. (2023) have suggested that the final consumption ratio of a particular fossil energy source can be used to characterize the structural transformation of energy consumption [8, 9]. In addition, Xu et al. (2023) constructed an index of oil and gas substitution for coal and an index of non-fossil energy substitution for fossil energy, and constructed an index of double substitution of energy structure by calculating the geometric mean of these two indices, so as to reflect the change of energy consumption structure more comprehensively [10]. Meanwhile, Li Rongjie et al. (2020) constructed a multidimensional index system by using various methods such as principal component analysis, hierarchical analysis method (AHP) and weighted multidimensional vector angle index method [11]. Given the relative scarcity of official data on energy production in various regions of China and the fact that clean energy is mainly used for power generation, the existing literature usually chooses clean energy power generation as a proxy variable for energy production transformation (Fangetal, 2023; Liu Pingkuo et al., 2022) [8, 12]. Each of these methods has its own characteristics, but all of them need to be improved and optimized in practical applications.

2.2. Literature Related to the Digital Economy

According to China's Digital Economy White Paper (2022), the growth rate of China's digital economy in recent years has significantly exceeded the average growth rate of GDP in the same period, showing a strong momentum of development. This trend has attracted extensive attention from academics, and relevant research results have emerged continuously. Scholars have mainly carried out theoretical research on the concept of digital economy, its development characteristics, its impact on the real economy, and its relationship with economic growth (Li Haihua et al., 2021; He Weida et al., 2020) [13, 14].

With the deepening of theoretical research, the measurement of digital economy has become the focus of empirical research. In order to comprehensively assess the current situation and future trend of the digital economy, scholars have actively constructed a digital economy indicator system. Sheng Bin et al. (2022) proposed an indicator system covering digital infrastructure, digital technology application, digital industry and other dimensions, which provides a powerful tool for accurately measuring the development of digital economy [15]. Wan et al. (2022) further refine the digital economy indicators, use big data analysis and statistical methods, and explore the differences and links between digital economy in different regions and industries [16].

Some scholars have also explored the intrinsic links between the digital economy and these areas from the perspectives of innovation efficiency and carbon productivity. Zheng Yaxin (2020) found through empirical research that the digital economy has a significant role in promoting innovation efficiency [17]. She argued that the digital economy provides strong support for innovation activities by reducing innovation costs, improving innovation efficiency, and promoting knowledge spillover. Guo Feng et al. (2022) analyzed the advantages of digital economy in promoting green and low-carbon development from the perspective of carbon productivity [18]. The study points out that the digital economy provides an effective means to achieve carbon emission reduction and carbon neutrality by improving energy use efficiency, reducing carbon emissions and promoting industrial restructuring.

2.3. Mechanisms of the Digital Economy's Impact on Green Energy Efficiency

Digital technology has a positive impact on green energy efficiency through continuous technological innovation [19]. The digital economy, the core of which lies in the booming development of information and communication technology (ICT) and digital information technology, has laid a solid foundation for the in-depth integration of the digital economy with various economic and social sectors, as well as for the innovation of operation modes and the enhancement of efficiency [20]. Sadorsky's research shows that the booming development of the Internet has had a positive impact on electricity consumption [21]. Moyer argues that although ICT technology plays a positive role in reducing energy intensity and promoting renewable energy production to reduce carbon emissions, it also has a positive impact on green energy efficiency by reducing the impact on carbon dioxide. Moyer argues that while ICTs have played a positive role in reducing energy intensity and promoting renewable energy production to reduce carbon emissions, they have also reduced the demand for carbon-based energy sources and triggered a drop in energy prices, which has impacted the renewable energy market, resulting in relatively limited net economic benefits [22]. Zia details how ICTs can enhance energy efficiency by digitizing the transmission system at the micro level. Zia elaborated on how ICT technologies can enhance energy efficiency by digitizing the transmission system at the micro level [23]. Li Shouguo points out that although the popularization of the Internet has increased energy demand and led to a rise in global carbon emissions, its positive effects such as technological innovation and improved energy efficiency can offset the negative impacts and ultimately reduce environmental pollution [24]. Li Tao et al. further showed that the digital economy has a significant positive effect on total factor energy efficiency [25]. With data as the core production factor, digital economy effectively reduces the excessive consumption of tangible resources and energy in the traditional production process, promotes the optimization and adjustment of factor structure, and improves the efficiency of factor utilization [26]. With the continuous development of digital economy, the barriers to resource flow among provinces will be greatly reduced, which will motivate the regions to increase green technology innovation, thus realizing sustainable development with low energy consumption and high quality.

2.4. Literature Review

Existing literature on digital economy and energy structure mostly focuses on the unidirectional relationship, with little intrinsic and deeper considerations. The support of digital economy can make every link of the industry chain participate in the reshaping of the energy industry, and the continuous upgrading of the energy revolution has also driven the wave of industrial digitization, and the digital transformation of energy has become the underlying logic of the future zero-carbon society. This project firstly analyzes the intermediary and threshold effects between the two, and secondly, based on the synergistic relationship between the two and the coupling of the degree of coordination measurement, through the construction of the evaluation index system, in-depth investigation of the interaction between the digital economy and the coordinated development of the transformation of the energy structure.

This paper intends to examine how the introduction of technological innovation will affect the household energy structure and the digital economy in the steady state by constructing a mediation and threshold effect model, and then quantitatively analyze the intrinsic connection between the digital economy and the household energy structure by constructing a coupling coordination model. This paper redefines the digital economy in the framework of OECD 2022, and aims to provide theoretical basis and policy recommendations for the geographic regions with poor coupling harmonization, , and also contributes to the smooth development of the two-way transformation of China's digital economy and energy sector.

3. THEORETICAL MECHANISMS AND RESEARCH HYPOTHESES

3.1. The Single Mechanism of the Digital Economy on Household Energy in China and the Mediating Effect of Technological Innovation

The G20 Summit defined the digital economy as a cluster industry with digital technology as the core driving force, with big data, Internet of Things, artificial intelligence and blockchain as the main components. As an ecological model of the new era, the digital economy can lead the digital transformation of industries and empower economic and social life.

The digital economy has profoundly changed the structure of life and society, and the structure of household energy use and its green energy utilization efficiency have also been reshaped. Driven by the digital economy, the structure of household energy use is developing towards intelligence and diversification. The Internet of Things, big data, cloud computing and other technologies are widely used, smart home systems are popularized, and household energy management is convenient and efficient. Smart meters, sockets and other devices can monitor and control energy consumption in real time, realizing energy saving and emission reduction. At the same time, the digital economy enhances the efficiency of green energy utilization, and it is easier for families to access green energy information and choose environmentally friendly, low-carbon energy, promoting an increase in its share in household energy consumption.

Digitalization not only reshapes the structure of household green energy use and improves household energy efficiency, but also has an impact on household green energy efficiency through the mediation of technological innovation. By accelerating technological innovation, digitalization has revolutionized home energy management. From real-time monitoring and data analysis, to the application of smart home appliances, to the emergence of energy management software and services, digitalization is helping to improve the green energy efficiency of households and promote the realization of sustainable development goals. Accordingly, the following hypotheses are proposed, and the logical relationships are as follows**错误!未找到引用源。** The logical relationship is shown in Figures 1 and 2:

H1: Digitalization enhances green energy efficiency by enabling the optimization of household energy use structure through technological innovation.

H2: Digitization to improve green energy efficiency through technological innovation for energy use efficiency improvement.

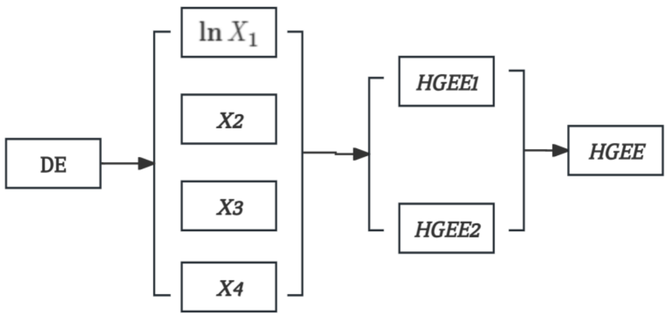

Figure1. Single mechanism of action of the digital economy on household energy in China

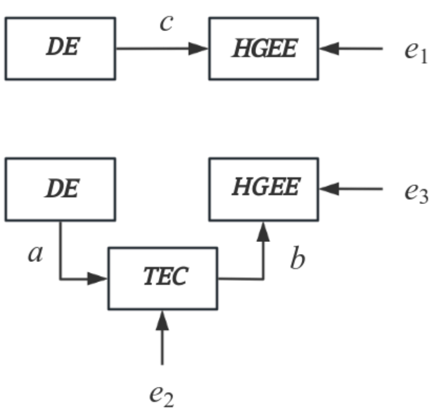

Figure2. Illustration of the mediation effect

3.2. Threshold Effects of the Digital Economy

The impact of the digital economy on household green energy efficiency may be non-linear with a threshold effect, influenced by the level of regional digitization. At the early stage of the development of the digital economy, factors such as technology diffusion, infrastructure and economic costs limit its driving effect. As the level of digitization increases, the marginal effect of the digital economy becomes apparent, and digital technology is widely used in various fields to improve household energy efficiency. At the stage of high-level digital economy development, digital technology penetrates into household energy management, realizes refined management, optimizes the way of energy use, promotes the popularization and application of green energy, enhances utilization efficiency and achieves the best driving effect. Accordingly, the following assumptions are made, with the specific relationships shown in figure 3:

H3: There is a threshold effect of digitalization in enabling the reconfiguration of household energy use structures.

H3: There is a threshold effect of digitization in promoting efficiency gains in energy use.

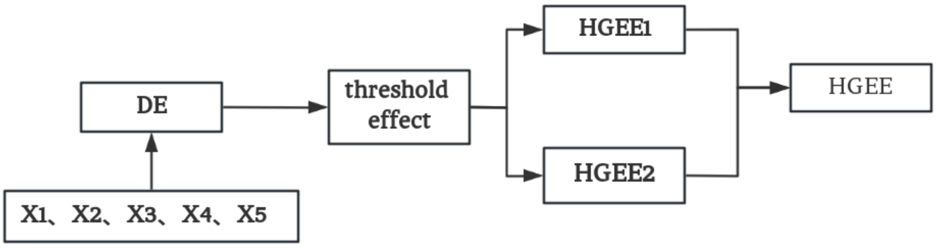

Figure3. Threshold effect model

3.3. Digital Economy and Household Energy Structure in China: A Two-Way Coupling and Coordination Mechanism

In the current context, the relationship between the digital economy and the energy mix has clearly demonstrated a non-unidirectional correlation. With the optimization of household energy structure and the popularization of clean energy, it also promotes the development of digital economy. On the one hand, the widespread application of clean energy provides more stable and environmentally friendly energy support for the digital economy. On the other hand, the change in household energy structure has given rise to new business models and services.

This two-way coupling and coordination mechanism plays an important role in promoting the high-quality development of the regional economy. On the one hand, the development of digital economy promotes the optimization of household energy structure, improves the efficiency of energy use and reduces environmental pollution, providing strong support for the sustainable development of the regional economy. On the other hand, the change of household energy structure also promotes the innovation and development of digital economy, and injects new vitality into the regional economy. Therefore, this paper proposes that the impact of the digital economy on China's household energy structure is counteracted by the digital economy, thus affecting the high-quality development of the regional economy. The specific relationship is shown in Figure 4:

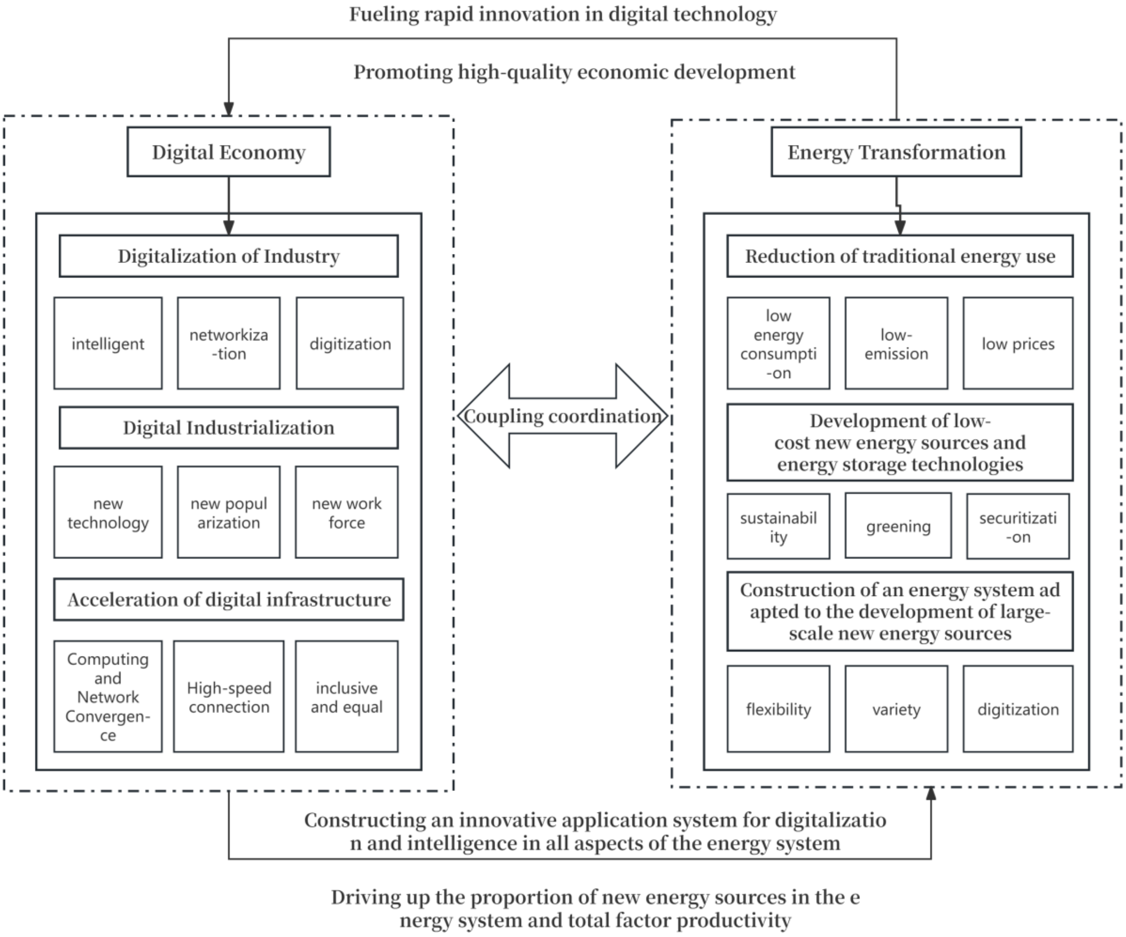

Figure4. Illustration of coupling coordination

4. INDICATOR CONSTRUCTION AND RESEARCH METHODOLOGY

4.1. Indicator Construction and Data Sources

4.4.1. Indicator construction

(1) Description of variables. This paper draws on the research of Chen Siyi (2021) to analyze the structure of energy consumption in the household sector, including coal, petroleum products, natural gas, heat and electricity, by standardizing the calculation of conversion coefficients, unifying them into the standard coal unit, and de-measuring them [27]. Because coal has a high carbon content, it needs to be examined separately in order to promote the "de-coalization" of household energy consumption. Using data from the National Bureau of Statistics (NBS), combining the Super-SBM and SDM methods, and adopting the entropy method to convert the undesired outputs into a composite index, we accurately calculate the HGEE of each province in China.2 Finally, we choose the HGEE of Chinese households as an evaluation index, and assess its level in terms of optimization of the structure of energy use (HGEE1) and the efficiency of energy use (HGEE2).

The measurement of digitization in this paper refers to the study of Li Yanru et al. (2023), strictly follows the principles of relevance, representativeness and accessibility, takes the connotation of digital economy as the basic principle when selecting indicators, and uses the improved entropy value method to measure the scale of digital economy [28]. This paper focuses on digitalization (DE) as the core explanatory variable, subdividing the indicators into three categories of industrial digitization, digital industrialization and digital infrastructure, and selecting 10 sub-indicators. In the data processing, since they are all positive indicators, they need to be pre-processed.

In this paper, the index data are firstly standardized by using the method of extreme deviation (Tian Jiali, 2022) [29], in order to eliminate the existence of the influence of the scale between each index. At the same time, in order to ensure the objectivity and referability of the results of the calculation of indicator weights, this paper uses the entropy weighting method to carry out the weighting solution (Cai Qiang,2022; Sun Miaoying, 2022) [30, 31], and the specific results are shown in Table 1.

Table1. Digital Economy Measurement Indicator System

Composite indicators	Indicator category	Indicator name	unit of measure	Indicator properties
Level of development of the digital economy	Industrial digitization	Provincial e-commerce turnover	trillion dollars	+
		Websites per 100 businesses	classifier for individual things or people, general, catch-all classifier	+
		Number of enterprises with e-commerce trading activities	ten	+
	digital industrialization	Revenue from software operations	ten thousand dollars	+
		Electronic information manufacturing growth rate	%	+
		Employment in the information and communications industry	all the people	+
		Proportion of fixed investment in ICT industry to total investment in society as a whole	%	+
	digital infrastructure	Provincial Internet penetration rate	%	+
		Number of IPV4 addresses	ten dollars	+
		Fiber optic line length	kilometer	+

The improved entropy method was used for the determination of indicator weights:

$$W_i = \frac{g_j}{\sum_{j=1}^{n} g_j} \tag{1}$$

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{2}$$

$$e_j = \frac{1}{\ln m \sum_{i=1}^{m}(p_{ij} \ln p_{ij})} \tag{3}$$

$$g_j = 1 - e_j \tag{4}$$

Among them:

The final comprehensive assessment is measured:

$$s_i = \sum_{i=1}^{n} w_j a_{ij}$$

Among them, thes_i the larger, indicates that the sample effect is better, the higher the digitization level of the province.

In addition, the raw data of each indexa_{jj} In addition, the weights of the indicators were determined after their dimensionless processing by the extreme value method before measurement, and the dimensionless processing formula was as follows:

$$x_{ij} = \frac{a_{ij} - min(a_{ij})}{max(a_{ij}) - min(a_{ij})} \tag{5}$$

The weights of the three types of indicators obtained using the entropy method are as follows**错误!未找到引用源。**, and then weighted comprehensively to get the comprehensive score of provincial digitization level.

Table2. Weights of the various indicators

Indicator category	Indicator name	Indicator properties	entropy (physics)	coefficient of variation	weights
Industrial Digitization	Provincial e-commerce turnover	+	0.835	0.165	0.127
	Websites per 100 businesses	+	0.933	0.167	0.051
	Number of enterprises with e-commerce trading activities	+	0.857	0.143	0.110
digital industrialization	Revenue from software operations	+	0.876	0.124	0.095
	Electronic information manufacturing growth rate	+	0.854	0.146	0.112
	Employment in the information and communications industry	+	0.878	0.112	0.094
	Proportion of fixed investment in ICT industry to total investment in society as a whole	+	0.855	0.145	0.111
digital infrastructure	Provincial Internet penetration rate	+	0.897	0.103	0.079
	Number of IPV4 addresses	+	0.877	0.123	0.094
	Fiber optic line length	+	0.835	0.165	0.079

This paper examines the impact of digitalization on green energy efficiency of Chinese households, and explores the mechanism of technological progress as a mediating variable to promote green energy efficiency. Through technology and other means to optimize the energy consumption structure and enhance energy utilization in each province, which in turn affects the green energy efficiency of households in each province. Referring to the study of Lin Chunlei and Cui Linjing (2023) [32], technological innovation is selected as the mediating variable, including innovation input and innovation results as the second-level indicators, as well as R&D personnel, R&D expenditure, the number of R&D projects, and the number of patents granted as the third-level indicators, and the entropy method is utilized to evaluate the technological innovation capacity of each city.

Table3. Construction of technological innovation indicators

Level 1 indicators	Secondary indicators	Tertiary indicators
Level of technological innovation	Innovative inputs (0.473)	R&D investment intensity (0.203)
		R&D manpower inputs (0.27)
	Innovations (0.527)	Number of patents granted (0.236)
		Turnover of technology contracts (0.291)

Considering the complexity of the factors affecting energy efficiency, this paper refers to Xia Li's study [33], selects the level of economic developmentX_1 urbanization levelX_2 energy consumption structureX_3 the degree of government interventionX_4 and the degree of opening up to the outside worldX_5 as control variables.

Table4. Selection of some relevant variables

serial number	variant	descriptive	unit (of measure)
intermediary variable	technological innovation (TEC)	Using the entropy method to comprehensively evaluate through the four aspects of R&D personnel, R&D expenditure, number of R&D projects and patent authorizations	/
control variable	Level of economic development $(X)_1$	Annual real per capita GDP in provinces	the Yuan or Mongol dynasty (1279-1368)
	Level of urbanization $(X)_2$	Total urban population as a percentage of total population	%
	Energy consumption structure $(X)_3$	Renewable energy production as a percentage of total primary energy production	%
	Level of government intervention $(X)_4$	General fiscal expenditure as a percentage of GDP	%
	Degree of openness to the outside world $(X)_5$	Total exports and imports as a percentage of GDP	%

(2) Sample Selection and Data Sources

Based on an in-depth study of feasibility and data availability and timeliness, this paper prudently selects 31 provinces and autonomous regions in China as the research sample. The year 2015 was chosen as the starting year of the study because since that year, the widespread popularization of smartphones and other mobile terminals has laid a solid foundation for the vigorous development of the digital economy. Taking 2015 as the starting point of the study helps us to analyze the far-reaching impact of the digitalization process on the economy and society in a more comprehensive and precise manner.

In this paper, the green energy efficiency panel data of Chinese provinces in 2015-2022 is used as a research sample, and the data is obtained from the Gross national product by province and household data by province from the China Statistical Yearbook (2015-2022). Total energy inputs by province from China Energy Statistics Yearbook (2015-2022). Labor input and capital stock by province are from China Urban Statistical Yearbook (2015-2022) and provincial statistical yearbooks. Data on provincial emissions of wastewater, SO2 and other undesired outputs are from the China Environmental Statistics Yearbook and the China Energy Statistics Yearbook (2015-2022).

In the data selection, the main focus was on the end consumption and output of the province, while considering non-desired outputs, including agro-industrial and domestic emissions, to measure household green energy efficiency. Descriptive statistics, including sample size, mean, standard deviation and maximum value, were performed on the raw data of 31 provinces and cities according to the selected indicators. The sample size was constant, but there were some missing data in each province, which were made up by interpolation. Therefore, the study data are unbalanced panel.

4.2. Research Methodology

4.2.1. Mediating effects model

In order to test whether there is a mediating effect of technological innovation in this process, the following model is constructed:

$$TEC_{it} = \beta_1 + \beta_2 DE_{it} + \beta_3 Cont_{it} + \mu_i + \sigma_t + \varepsilon_{it} \tag{6}$$

$$HGEE_{it} = \theta_1 + \theta_2 DE_{it} + \theta_3 TEC_{it} + \theta_4 Cont_{it} + \mu_i + \sigma_t + \varepsilon_{it} \tag{7}$$

Where: *i, t* represent province and year subscripts, respectively. The explanatory variables are the green energy efficiency of households in each province ($FGEE_{it}$). The digitization level of each province (DE_{it}) is the core explanatory variable. μ_i reflects individual fixed effects, and σ_t represents year fixed effects. ε_{it} represents the random error term. Science and technology innovation (TEC) is the mediating variable, if β_2 and θ_3 are significant at the same time, it indicates that there is a mediating effect, if they are not significant at the same time, then further Bootstrap test will be conducted.

4.2.2. Threshold effect model

In order to test the threshold effect of digitalization on green energy efficiency in Chinese households, the following threshold effect model was constructed:

$$HGEE_{it} = \gamma_1 + \gamma_2 DE_{it}(DE \leq \omega_1) + \gamma_3 DE_{it}(\omega_1 < DE \leq \omega_2) + \gamma_4 DE_{it}(DE > \omega_2) + \gamma_5 Cont_{it} + \mu_i + \sigma_t + \varepsilon_{it} \tag{8}$$

4.2.3. Coupled coordination degree model

Since the data outlines and units of the indicators measuring the level of development of digital economy and green energy efficiency of Chinese households are different, in order to increase the scientificity of the calculation, this paper programmatizes the data, determines the weights of each indicator by using principal component analysis, calculates the index of the energy consumption situation and the level of digital development, and analyzes the coupled degree of coordination between Chinese households' energy consumption and the degree of coordination of the high-quality development of the digital economy.

The coupling coordination evaluation index system is established, the positive and negative indicators are standardized by the polar deviation method, and the entropy weighting method is used to objectively assign weights to each indicator. Since this method is commonly used, it will not be repeated. After calculating the weights of each index, linear weighting is carried out to calculate the comprehensive index of the corresponding system.

In order to study the coupling relationship between green energy efficiency of Chinese households and the degree of coordination of high-quality development of digital economy, the following coupling degree model is established:

$$\mathrm{C} = 2 * \sqrt{(\mathrm{U}_1 * \mathrm{U}_2)(\mathrm{U}_1 * \mathrm{U}_2)^2} \tag{9}$$

$$\mathrm{T} = \mathrm{a} * \mathrm{U}_1 + \mathrm{b} * \mathrm{U}_2 \tag{10}$$

The evaluation criteria of coupling degree C are as follows: C=0 no coupling, 0<C≤0.3 for low level coupling, 0.3<C≤0.5 for antagonistic coupling, 0.5<C≤0.8 for friction coupling, 0.8<C≤1 for high level coupling, C=1 for complete coupling.

Where, U_1, U_2 is the calculated system composite index indicating the green energy efficiency of Chinese households and digital development, C represents the coupling degree of the degree of coordination between the green energy efficiency of Chinese households and the high-quality development of the digital economy, C $\in$ [0, 1], the larger the value of C, the stronger the degree of interconnection between energy consumption and the development of the digital economy. The degree of coupling between green energy efficiency of Chinese households and high-quality development of digital economy in China's provincial areas is calculated by the coupling degree model.

T reflects the coupling contribution of each subsystem to the composite system. *a*, *b* reflect the weights of the first-level indicators corresponding to each subsystem, *a*+*b*=1, in this paper, we approximate that the two systems are equally important, so *a*, *b* are taken as 0.5.

This paper synthesizes the previous studies and classifies the degree of coordination as shown in**错误!未找到引用源。** .

5. Harmonization levels

serial number	partition	Level of coordination	serial number	partition	Level of coordination
1	0.00-0.09	extreme disorder	6	0.50-0.59	sue for harmonization
2	0.10-0.19	severe disorder	7	0.60-0.69	Primary coordination
3	0.20-0.29	moderate disorder	8	0.70-0.79	Intermediate level coordination
4	0.30-0.39	mild disorder	9	0.80-0.89	good coordination
5	0.40-0.49	on the verge of becoming dysfunctional	10	0.90-1.00	Quality coordination

In order to more objectively reflect the overall effect and coordination effect of the two systems of energy consumption and digital economy, this paper also constructs a coupled coordination degree model of digital economy and green energy efficiency of Chinese households:

$$D = \sqrt{C * T} \tag{11}$$

Among them, T is the comprehensive index of energy consumption and digital economic development, D is the degree of coordination, the value range is [0, 1], the larger the value of D, the higher the level of integration of energy consumption and digital economic development, and vice versa, the lower the level of integration and development; α and β are the contribution coefficients of the level of energy consumption and digital economic development, respectively, $\alpha + \beta = 1$, *and* this paper assumes that $\alpha = \beta = 0.5$. Based on the coupling coordination degree model, the degree of coordination of the Chinese household provinces coupled with energy consumption and digital economic development was calculated. Based on the coupling coordination model, the coupling coordination degree of energy consumption and digital economy development in Chinese family provinces is calculated.

5. EMPIRICAL ANALYSIS

5.1. Impact of Digitization on Provincial Household Energy Efficiency and Consumption Structure

Model (1) (3) shows that digitization has a significant positive contribution to the improvement of energy use efficiency and structural optimization of households in the provincial area, and for every 1% increase in the degree of digitization, the energy use efficiency will be increased by 0.605%, and the degree of optimization will be uplifted by 1.063%.

Table6. Impact of digitization on the structure and efficiency of household energy consumption in provincial areas

mould	(1)	(2)	(3)	(4)
explanatory variable	HGEE1	HGEE2	HGEE1	HGEE2
DE	1.043***	2.764**	0.601**	0.401*
lnX1	2.828**	2.929***	0.101**	0.104**
X2	1.210**	1.567**	0.093**	0.026**
X3	3.584**	2.603**	0.260***	0.002
lnX4	3.273**	1.2138*	0.605*	0.403*
Individual fixation	be	clogged	be	clogged
Year fixed	be	clogged	be	clogged
R^2	0.913	0.823	0.921	0.801

5.2. Mediating Effects Modeling

In order to test the mediating effect of technological innovation, the mediating effect model was used to analyze the mediating role of technological innovation between digitization and green energy use of households in provincial areas, and the results of the study are as follows**错误!未找到引用源。** . Model (5) shows that digitization has a significant role in promoting technological innovation, and at the 1% significance level, every 1% increase in digitization level will increase technological innovation capacity by 2.711%. Model (6) shows that digitization has a significant role in promoting the optimization of provincial household energy structure, and model (7) adds the intermediary variable technological innovation on the basis of model (6), the coefficient of influence of industrial digitization on the optimization of energy structure decreases and is significant, which indicates that technological innovation plays a partly intermediary role in the optimization of the structural change of digitization and energy use, and its intermediary effect accounts for 28.05% of the total effect. 28.05% of the total effect. Digitalization reduces the cost of national technological innovation, technological innovation reduces the cost of energy use, promotes the efficient flow of technical personnel, and promotes the general development of the scale of clean energy use, so digitalization can promote green energy efficiency through technological innovation to optimize the structure of energy use in households, hypothesis H3 holds. Model (8) shows that digitization has a significant positive impact on energy use efficiency, model (9) in the model (8) based on the addition of intermediary variables, digitization of energy use efficiency coefficient decreases and significant, indicating that technological innovation in the digitization and provincial and regional energy use efficiency of households between the intermediary role, the intermediary effect of the total effect of 26.26%. Industrial digitization improves the efficiency of national technological innovation, provides a good digital environment for comprehensive technological innovation, and technological innovation improves the efficiency of energy resource allocation and promotes the upgrading of the energy industry structure to provide a guarantee of innovative elements, so industrial digitization can improve the green energy efficiency through technological innovation to promote the improvement of energy use efficiency, and the hypothesis H4 is valid.

Table7. Models of mediating effects

Variant	(5)	(6)	(7)	(8)	(9)
explanatory variable	TEC	HGEE1	HGEE2	HGEE1	HGEE2
DE	2.711^{***}	1.063^{***}	0.753^{***}	0.605^{**}	0.439^{**}
TEC			0.101^{***}		0.514^{**}
control variable	be	be	be	be	be
Individual fixation	be	be	be	be	be
Year fixed	be	be	be	be	be
R^2	0.871	0.928	0.871	0.922	0.891

5.3. Threshold Effect Modeling

Using digitalization (DE) as a threshold variable, we test whether there is a threshold effect of digitalization on the optimization of provincial household energy structure and the improvement of utilization efficiency, using "Bootstrap type sampling"for sampling, and the results of the study are shown in Table 8. This paper finds that there is a double threshold effect of digitalization on the optimization of provincial household energy structure and the improvement of utilization efficiency. This paper finds that the digital economy has a double threshold effect on the optimization of provincial household energy structure and utilization efficiency.

Model (10) digital economy on energy structure optimization process, at the 1% significance level, industry digitization passed the double threshold test, the threshold value of which is 0.221 and 0.532. When the digitization level is less than 0.221, the impact coefficient of digitization on the optimization of the provincial household energy structure is 0.413, indicating that even if the digitization is at the lower level, it still has a significant impact on the provincial When the digitization level is between 0.221 and 0.532, the impact coefficient of digitization on the optimization of energy structure is 1.231, indicating that with the increase of digitization level, the promotion effect on the optimization of energy structure is gradually enhanced; when the digitization level is greater than 0.532, the promotion effect of digitization on the optimization of energy structure is the strongest, and digitization has effectively promoted the modernization of energy science and use and the optimization of energy structure. Effectively promote the modernization of the use of energy science and scale development, promote the efficient circulation of various elements, promote the optimization of the energy structure to accelerate, assumption H5 is valid.

Model (11) industrial digitization on provincial household energy use efficiency enhancement process, digitization passed the double threshold test, the threshold values of which are 0.191 and 0.661. when the digitization level is less than 0.191, the impact coefficient of digitization is 0.301, at this time, digitization on the provincial household energy use efficiency is weak, but significant; when the digitization level is between 0.191 and 0.661, the driving effect of digitization is gradually enhanced; when the level of digitization exceeds 0.661, the driving effect of digitization on the provincial household energy efficiency is in the optimal state, at this time the penetration of digitization is stronger, effectively promoting the development of digital upgrading of energy use, and improving the allocation efficiency of the industry's various resource elements, the assumption that the H6 is established.

Table8. Threshold effects model

mould	(10)	(11)
outcome variable	HGEE1	HGEE2
Threshold variables	DE	DE
First threshold (w1)	0.221**	0.191**
Second threshold (w2)	0.532***	0.661*
DE≤ w1	0.413**	0.301*
w1<DE≤ w2	1.231***	0.693***
DE>w2	1.485***	0.872***
control variable	be	be
Individual fixation	be	be
Year fixed	be	be
R^2	0.894	0.811

5.4. Research on the Degree of Coordination Between Green Energy Efficiency of Chinese Households and High-Quality Development of the Digital Economy Based on the Coupled Coordination Approach

5.4.1. Provincial scale coupling analysis

In order to explore the spatial distribution characteristics of the coupling degree and coupling between household green energy efficiency and high-quality development of the digital economy at the provincial scale, the scores of coupling indexes of all provinces in China (excluding Hong Kong, Macao, and Taiwan) were calculated, and the results were found: Highly coupled regions show a clear distribution of the "inverted triangle"structure of "Coastal + Yangtze River Delta Economic Zone", while other regions have basically eliminated the uncoupled state, with a high degree of overall coupling. The coupling degree of some provinces (Shanxi, Ningxia, Jiangxi and Qinghai) is relatively low, which indicates that the relationship between innovation and energy consumption structure in these regions has yet to be further developed. This not only affects the economic development of these regions, but also restricts the optimization of their energy consumption structure and the development of their innovation capacity. Based on the above conclusions, the results are shown in Fig. 5 after selecting the poorer coupling areas (Shanxi Province and Gansu Province) as well as the more excellent coupling areas (Guangdong Province and Jiangsu Province) for further analysis in this paper:

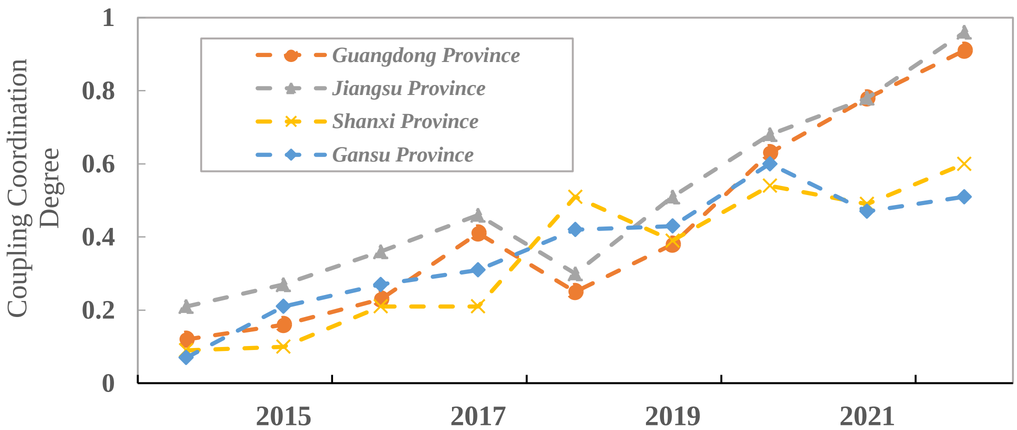

Figure 5. Visualization of coupling trends in representative areas

In terms of the coupling degree between the digital economy and the structure of household energy use, it can be seen from the figure that the evolution trend of the coupling degree of the four provinces is upward year by year. The overall coupling between Guangdong Province and Jiangsu Province has reached a high coupling stage in 2021. In the same time period, the coupling degree of Shanxi and Gansu provinces is lower than 0.6. Overall, the interaction between the digital economy and household energy consumption structure of Chinese provinces and cities in recent years is more significant, and the degree of match between the two is very high. The coupling between the digital economy and household energy use structure in Guangdong Province and Jiangsu Province is good, and they are gradually developing in a benign and orderly manner. However, the coupling status of regions such as Shanxi Province and Gansu Province as a whole is located after other provinces and cities, which is more obvious in 2015-2017 and 2020-2021. The reason for this may be related to the policy support, geographic location, economic level and human resources of each province and city.

5.4.2. Provincial scale harmonization analysis

According to the formula for calculating the coordination index scores of each province, it is found that the developed coastal areas are mostly distributed with high-quality coordinated regional clusters, and are relatively stable with little change in the interval of the study year. The central and western regions have more changes in both spatial scale and index score scale, but only barely harmonized and not qualitatively changed. The overall level of harmonization in the country as a whole has risen.

In order to explore the dynamics of the type of coupling and coordination in each region, the degree of coupling is divided into two categories of uncoupling ($0<C<=0.4$) and coupling ($0.4<C<1.0$) with 0.4 as the boundary, and the degree of coordination is divided into two categories of coordinating ($0<D<=0.5$) and uncoordinating ($0.5<D<=1.0$) with 0.5 as the boundary, and the degree of coordination is divided into two categories of coordinating ($0<D<=0.5$) and uncoordinating ($0.5<D<=1.0$). In reality, there is no uncoupled but coordinated situation, the largest number of districts in both coupled and coordinated, accounting for 62% of the sample size, the number of districts in coupled but uncoordinated accounts for 20%, and the number of districts in uncoupled and uncoordinated accounts for 17%.

5.4.3. Coupled and coordinated prediction of the digital economy and the structural transformation and development of household energy consumption in China based on prediction modeling

(1) Prediction of the degree of coupling coordination. Gray prediction is based on gray correlation analysis, through the generation of the original data to find the law of the system changes, and then generate a strong regularity of the data series, and establish a gray GM (1, 1) differential equation model, so as to predict the future development trend of things in the status of the GM (1, 1) model is the essence of the original data series through the accumulation of the generation of the weakened random disturbances, explore its exponential growth pattern, and through the exponential curve simulation, and finally use the least squares method to solve the model parameters, and then predict the unknown data based on the known data information. The essence of GM (1, 1) model is to generate the original data series by accumulating them, weakening the influence of random disturbances, exploring the exponential growth law, simulating them through the exponential curve, and finally solving the parameters of the model by the method of least squares, and then predicting the unknown data according to the known data information. This paper constructs a time series model through GM (1, 1) in gray dynamic simulation to predict the coupling degree and coupling coordination degree of household energy consumption.

The standard type formulation of the first order linear constant coefficient differential equation for the gray GM (1, 1) model is:

$$\mathrm{u} = \mathrm{dx}(1)\mathrm{dt} + \mathrm{ax}(1) \tag{12}$$

Seeking a solution:

$$x^1(k) = (x^0(1) - u * a)e - a(k-1) + u * a \tag{13}$$

According to Eqs. (13) and (14), the GM (1, 1) differential equation can be solved to obtain the prediction model. The predicted value of the coupling coordination degree in 2015-2019 can be obtained and visualized as follows错误!未找到引用源。 is shown in Fig. 7. After the residual test is passed, the a posteriori difference test is carried out for the prediction model, and the variance ratio C=0.33766 and P=80% are calculated, which shows that the prediction model has a high accuracy.

After understanding the interaction relationship between digital economy and China's household energy efficiency development, the coupling coordination status and the degree of correlation, this paper adopts the gray prediction model to make predictions, and again for the typical coupling degree of the poor region selected above to carry out further analysis of the coupling coordination degree, and the results are shown in Figure 6:

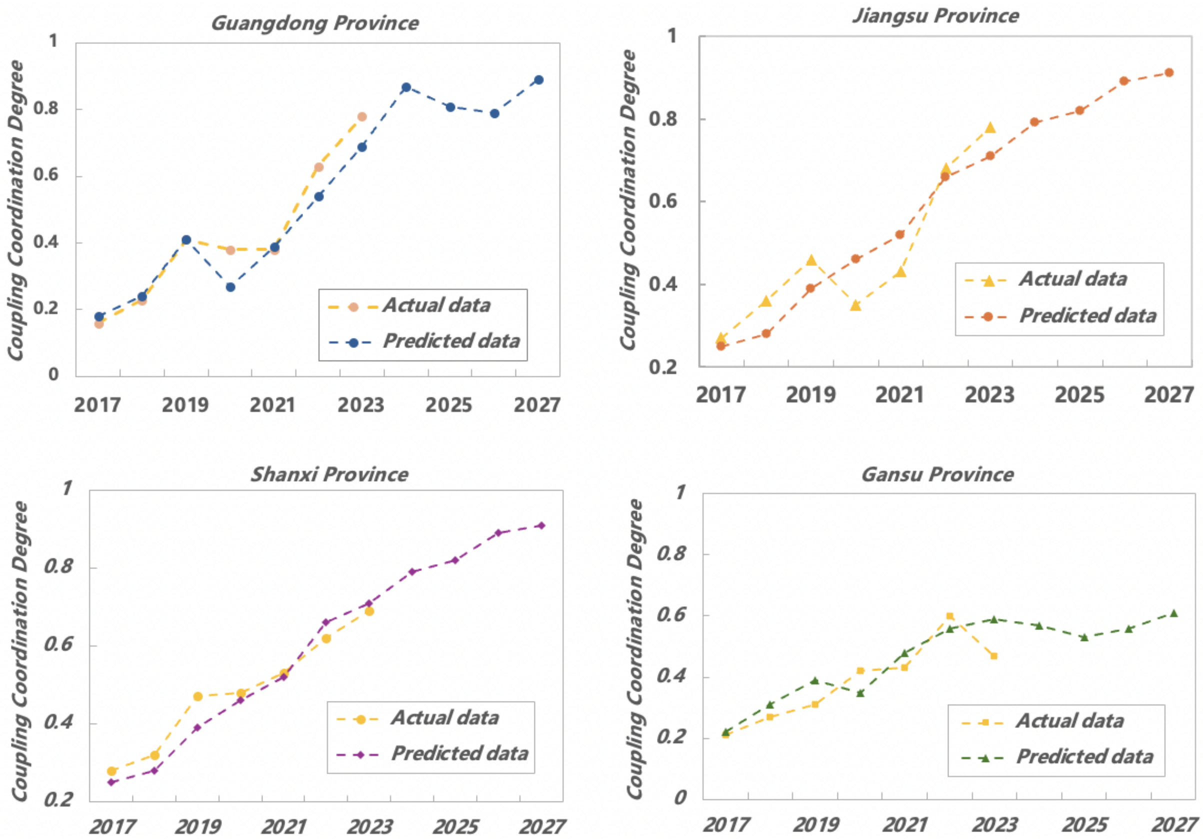

Figure 6. Visualization of fitted trends in coordination in representative regions

From the fitting results, it can be seen that the coupling harmonization degree of the four provinces shows an upward trend in the coming years. Compared with Gansu, Guangdong, Jiangsu and Shanxi are the first to reach the state of nearly complete coupling coordination, and the trend of Gansu is the least significant. This shows that there is still much room for improvement in the development of digital economy and the optimization and transformation of household energy structure in Gansu Province.

5.5. Robustness Tests

In order to ensure the accuracy of the research results, this paper adopts the following method to conduct robustness test in view of other scholars' research [34]:

The smoothness reversibility test of the developed coupled coordination model is carried out using R language and the test results are shown in Fig. 7. The results show that the characteristic roots of the characteristic equations of the model are all within the unit circle. It indicates that the established model is smooth and can support the research of this paper.

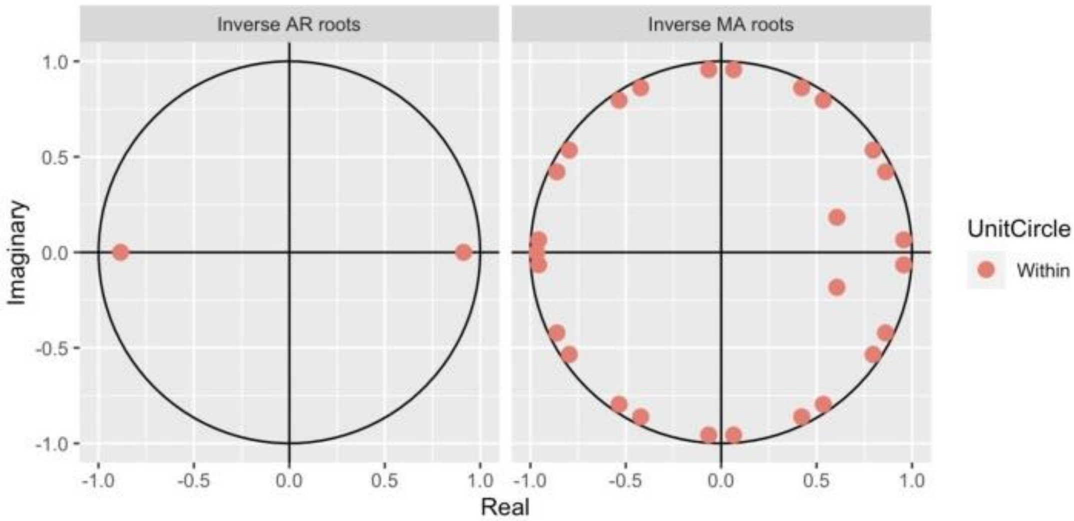

Figure 7. Smoothness test

6. CONCLUSIONS AND SUGGESTIONS

6.1. Conclusions

This paper uses entropy weight method to construct indexes for digital economy and energy use efficiency and structure, firstly, establish two-way fixed effect model, mediation effect and threshold effect model, empirically analyze and judge the non-linear influence characteristics of the two systems as well as the unidirectional influence mechanism; secondly, quantitatively predict the two-way interaction of the two systems through the coupling and coordination model combined with the grey prediction. The following conclusions are drawn:

(1) Mediating and double-threshold effects between the digital economy and the optimization of household energy structure in China. Technological innovation has a mediating effect between the digital economy and the optimization of energy use structure, accounting for 28.05% of the total effect. Digitalization reduces the cost of technological innovation, promotes the mobility of technological talent, and facilitates the use of clean energy, so digitalization can optimize the structure of household energy use through technological innovation and enhance green energy efficiency. The digital economy has a double threshold effect on the optimization of provincial household energy structure and utilization efficiency. In the process of industrial digitization to improve energy use efficiency, digitization passes the double threshold test, and the digitization level exceeds 0.661 to drive the best effect, which effectively promotes the digital upgrading of energy use and improves the efficiency of resource allocation.

(2) Chinese household energy utilization efficiency and the high-quality development of the digital economy have a high coupling and coordination accuracy. After an in-depth study of the relationship between household energy consumption and the digital economy in China's provinces (excluding Hong Kong, Macao and Taiwan), we find that while the level of digitization continues to increase, the degree of coupling and coordination with the efficient use of energy is increasing. The breadth of this trend is characterized by the "inverted triangle" structure along the Yangtze River Delta Economic Belt, i.e., it is gradually expanding from highly coupled areas to uncoupled areas. The centralized distribution of the coupling between regional innovation capacity and energy use efficiency is particularly significant in the areas along the Yangtze River Delta Economic Belt. In addition, over time, the increase in the level of energy utilization of the whole society has played a

positive role in supporting the further increase in the level of digitization, and this role is gradually being strengthened.

6.2. Suggestions

After an in-depth study of the digital economy in the field of environment and energy development in China, we put forward the following suggestions, aiming to give full play to the potential of the digital economy and realize a win-win situation in terms of the improvement of energy efficiency and environmental protection.

(1) Realize regional cooperation to drive the high-quality development of digital economy in low-coupling regions with high-coupling regions. The central and western regions are lagging behind in the high-quality development of the digital economy compared with the eastern regions, and the coupling and coordination between their digital economy and household energy utilization efficiency is low. In view of this, we urgently need to strengthen inter-regional cooperation and exchanges through the leadership and impetus of the eastern region, and appropriately adjust the allocation of digital resources, so that it is more inclined to the central and western regions. This move aims to further unleash the environmental improvement potential of the high-quality development of the digital economy in the central and western regions, thereby promoting the overall improvement of environmental quality nationwide.

(2) Accelerate the realization of the deep integration of the energy revolution and the digital revolution. Technological innovation plays a partly mediating role between the digital economy and the optimization of energy use structure. Therefore, promoting the ecological transformation of household energy consumption structure and upgrading the level of green technological innovation will be an important hand in promoting the high-quality development of the digital economy and the energy transformation of Chinese households. We will make full use of the new generation of information technology revolution technology to improve energy utilization efficiency and optimize the energy consumption structure; in the field of green and low-carbon innovation, we will strengthen the breakthrough efforts of key technologies, increase the supply of funds and human resources, create a good innovation environment, and achieve the purpose of energy saving and emission reduction.

(3) The formulation of appropriate environmental regulations and related policies should be based on the actual development of different regions, including the level of economic development, the degree of energy dependence, the level of human capital, the structure of energy use and other factors. Environmental regulation has a positive role in guiding the positive externalities of the digital economy, especially in the more economically developed eastern and central regions. Therefore, the level of environmental regulation tailored to local conditions can promote the digital economy to better contribute to the high-quality development of the economy and realize a win-win situation in terms of energy efficiency and environmental protection.

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