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Research on the Coupling Mechanism between Digital Economy Development and Household Energy Transition in China

-- An Empirical Analysis Based on Provincial Panel Data

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Abstract: In order to explore the relationship between the digital economy and China's household green energy structure and utilization efficiency, an empirical test is conducted based on the data of 31 Chinese provinces from 2015 to 2022 using a two-way panel fixed-effects model as well as a coupling model. The results show that the digital economy has a significant positive effect on household green energy structure and utilization efficiency; secondly, this paper focuses on the bi-directional relationship between the two, and finds that the overall coupling situation is good, and the digitalization level and household green energy utilization efficiency in the regions under the "inverted triangle" pattern are highly coupled. The study finds that the overall coupling is good, and the digitalization level and household green energy utilization efficiency in the "inverted triangle" pattern are highly coupled. This study provides a reference for accelerating the national energy transition, boosting China's digital economy in the reverse direction, and providing green and digital kinetic energy for realizing the overall high-quality development of the economy.

Keywords: Digital economy, Green energy efficiency, Coupling mechanism.

1. Introduction

Against the background of the current global green economy, China is committed to promoting the construction of an ecological civilization and sustainable economic development. In view of the increasingly serious problem of global warming and the rising call for emission reduction, low-carbon development has become the common pursuit of the international community. As one of the important sources of carbon emissions, the energy consumption of households is gradually attracting the deep attention of the international community and the scientific community.

According to statistics, China's total energy production in 2020 will be 4.08 billion tons of standard coal, an increase of nearly 2.77% year-on-year, while consumption exceeds production, reaching 4.98 billion tons of standard coal, an increase of 2.16% year-on-year. For a long time, coal has been the main source of China's energy consumption, and the proportion of coal consumption in 2020 will be as high as 56.8%. Although China has achieved the goal of prioritizing the development of electric power during the 13th Five-Year Plan period, it is still facing the challenges of irrational structure of energy production and consumption, weak foundation of new energy technology innovation, and low efficiency of energy utilization.

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 "14th Five-Year Plan" of modern energy system clearly points out that by 2035, China's energy quality development will make decisive progress. Transformation of the energy sector is not only the key pivot point for realizing China's high-quality economic development, but also the core battlefield for reaching the goal of carbon peak and carbon neutrality. Therefore, accelerating the clean and low-carbon transformation of the energy sector and enhancing the energy efficiency of all green elements are crucial to solving the contradiction between energy supply and demand in China.

Therefore, it is of great significance to study the development trend of digital economy, energy efficiency and structural optimization, and to explore the intrinsic connection between the level of development of digital economy and the green energy structure and utilization efficiency of Chinese households in order to improve energy efficiency, promote the transformation of Chinese households' energy to low carbon, and realize the high quality development of the society and economy as well as the goal of "dual-carbon". It is of great practical significance.

2. Literature Review

Tapscott, an American scholar, is the original proponent of the concept of digital economy [1], and Carlsson believes that the digital economy is a new type of economic form formed after the emergence of the Internet technology, emphasizing the in-depth application of the Internet [2]. With the evolution of the times, the connotation of digital economy has been continuously adjusted and enriched, although a unified standard definition has not yet been formed, but the connotation of digital economy proposed by the Hangzhou G20 Summit has been widely recognized in the academic community. This paper adopts the definition that digital economy refers to economic activities relying on digital knowledge and information as the core production factors, relying on modern information networks as the key carriers, and relying on the effective use of information and communication technologies to promote the efficiency improvement and optimization of economic structure [3].

The current literature on the development of the digital economy on the current energy transition of Chinese households generally concludes that there are positive spillover effects of the digital economy on the current green energy structure and utilization efficiency of Chinese households [4]. Zhang Sanfeng et al. (2019) showed that the development of technology has enabled digitalization to bring positive effects on the high efficiency of green energy [5]. As an innovative production factor, the digital economy plays an important role in the manufacturing process mainly due to the use of technology and its integration. According to the theory proposed by Schumpeter, innovation means establishing a new production function. Wang Dongfang et al. (2019) applied this theory to the impact of digital economy on green energy efficiency, and argued that digital economy, as a kind of technological innovation and a production element with network characteristics, produces a multiplier effect in all aspects of production, transaction and consumption [6]. Zhou et al. (2016) further elaborated that the digital economy, with data as the main production element, can significantly reduce the excessive consumption of physical resources and energy in the traditional manufacturing process, accelerate the adjustment of the elemental structure, and enhance the efficiency of elemental use [7]. Along with the continuous progress of digital economy, the barriers to the flow of resources in different regions will be significantly lowered, which will promote the implementation of green technological innovation in each place to achieve the goal of low energy consumption and high quality development. In addition, the digital economy can also stimulate the passion of innovation in each region and promote the transformation of industrial structure towards high-end and rationalization. According to Han Pioneer et al. (2014), the development of production technology is the basic driving force for the improvement of manufacturing structure [8]. Digitalization has the characteristics of technological progress, and its application in production operation will lead to the reconfiguration of production resources and elements, optimize the production system and organizational structure, and improve the efficiency of resource allocation. At the same time, the popularization of digital economy will promote the optimization and upgrading of industrial structure in an all-round way, and match the regional development level. In such an environment, digitalization will change the degree of economic dependence on energy resources and the efficiency of their use, improve the efficiency of resource allocation, and continue to enhance green energy efficiency [9].

The literature has analyzed the digital economy and energy structure in one direction, and lacks an in-depth examination of the relationship between the two. This project aims to redefine the digital economy under the OECD framework by constructing a coupling model and referring to the 2022 U.S. "Updated Digital Economy Measurement" report, which will provide a theoretical basis and policy recommendations for geographic areas with poor coupling, and at the same time make some contributions 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 Action of the Digital Economy on Household Energy in China

The digital economy has reshaped the structure of household energy use. In the past, household energy consumption relied mainly on traditional fossil energy sources, such as coal and oil. However, with the popularization and application of digital technology, more and more households are using renewable energy sources such as solar and wind power. This shift not only helps to reduce carbon emissions and alleviate environmental pollution, but also lowers the cost of household energy consumption. For example, many households have installed solar power systems, which convert light energy into electricity through solar panels, not only to meet the daily electricity needs of the household, but also to sell the excess electricity to the grid company, realizing a two-way flow of energy. Accordingly, the following assumptions are made:

H1: There is a positive contribution of digitization to the optimization of the energy use structure of Chinese households.

H2: There is a positive contribution of digitalization to the improvement of green energy use efficiency in Chinese households.

3.2. Mechanisms of Coupling the Digital Economy and the Energy Structure of Chinese Households

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. Accordingly, the following assumptions are made:

H3: There is a coupling effect between the digital economy and the efficiency and structure of green household energy use in China.

4. Indicator Construction and Research Methodology

4.1. Indicator Construction and Data Sources

4.1.1. Indicator Construction

This paper draws on the research of Chen Siyi (2021) to analyze the energy consumption structure of the household sector by standardizing the calculation of the conversion factor, unifying it into the standard coal unit, and de-quantifying it [10]. Using the data from the National Bureau of Statistics (NBS) and combining the Super-SBM and SDM methods, we accurately calculate the energy efficiency HGEE of each province in China.2 Finally, we choose the green energy efficiency (HGEE) of Chinese households as an evaluating index, and assess the level of its level in terms of the optimization of the structure of energy use (HGEE1) and the efficiency of energy use (HGEE2).

The measurement of digitalization in this paper refers to the study of Yanru Li et al. (2023), which uses the improved entropy method to measure the scale of digital economy [11]. This paper focuses on digitization (DE) as the core explanatory variable, subdividing the indicators into three categories: industrial digitization, digital industrialization and digital infrastructure, and selecting 10 sub-indicators.

The indicator data are standardized by using the method of polar deviation (Tian Jiali, 2022) [12], in order to eliminate the existence of the influence of the scale between each indicator. 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 solve the weights (Cai Qiang, 2022; Sun Miaoying, 2022) [13, 14], and the specific results are shown in Table 1.

Table 1. 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:

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

Among them:

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

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

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

The final comprehensive assessment is measured:

$$s_i = \sum_{i=1}^{n} w_j a_{ij} \tag{5}$$

Among them, if the s_i is larger, it 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:

$$x_{ij} = \frac{a_{ij} - min(a_{ij})}{max(a_{ij}) - min(a_{ij})} \tag{6}$$

The weights of the three types of indicators obtained using the entropy method are as follows Table 2. The weights of the three types of indicators using entropy value method are shown in Table 2, and then weighted comprehensively to get the comprehensive score of provincial digitization level.

Table 2. 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

Considering the complexity of the factors affecting energy efficiency, this paper refers to Xia Li's study [15], and chooses the economic development level X_1 urbanization level X_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.

Table 3. Selection of partially relevant variables

serial number	variant	descriptive
control variable	Level of economic development (X1)	Annual real per capita GDP in provinces
	Level of urbanization (X2)	Total urban population as a percentage of total population
	Energy consumption structure (X3)	Renewable energy production as a percentage of total primary energy production
	Level of government intervention (X4)	General fiscal expenditure as a percentage of GDP
	Degree of openness to the outside world (X5)	Total exports and imports as a percentage of GDP

4.1.2. Sample Selection and Data Sources

This paper considers the feasibility of the study and the availability and timeliness of the data, and chooses 31 provinces and autonomous regions in China as the research object. The year 2015 is chosen as the starting year because the popularization of smartphones and other mobile terminals has laid the foundation for the digital economy since 2015. Therefore, taking 2015 as the starting point, the impact of the digitalization process on the economy and society can be more comprehensively and accurately analyzed.

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).

4.2. Research methodology

4.2.1. Baseline Regression Model

In order to examine the impact of digitalization on green energy efficiency of Chinese households, the following benchmark regression model is constructed:

$$HGEE_{it} = \alpha_1 + \alpha_2 DE_{it} + \alpha_3 Cont_{it} + \mu_i + \sigma_t + \varepsilon_{it} \quad (7)$$

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. cont is the control variable: containing the level of economic development x_1 urbanization level x_2 energy consumption structure x_3 government intervention level x_4 the degree of government intervention, the degree of openness to the outside world, and the level of economic development, urbanization, energy consumption structure x_5 Cont is the control variable. μ_i is individual fixed effects. σ_t represents year fixed effect. ε_{it} represents the random error term.

4.2.2. Coupled Models

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 using the extreme difference method, and the entropy weighting method is used to objectively assign weights to each indicator. 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:

$$C = 2 * \sqrt{(U_1 * U_2)(U_1 * U_2)^2} \quad (8)$$

$$T = a * U_1 + b * U_2 \quad (9)$$

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, U1, U2 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 ∈ [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.

5. Empirical Analysis

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

Using OLS regression and two-way fixed effect model to study the impact of digitization on provincial household energy consumption structure and energy use efficiency, the significance and goodness of fit of the two-way fixed effect model is better than OLS regression, so the two-way fixed effect model is used to analyze the impact of industrial digitization on provincial household energy structure and energy use efficiency, and the results of the study are as follows table 4. Model (1) shows that at the 5% significance level, digitalization has a significant positive effect on the improvement of provincial household energy use efficiency, and every 1% increase in the degree of digitization will increase energy use efficiency by 0.605%. Digitization effectively reduces the cost, providing a digital basis and guarantee for the growth of green energy use scale, assumption H1 is valid. Model (3) shows that, at the 1% significance level, digitalization has a significant positive effect on the optimization of the provincial household energy structure, digitalization of every 1% increase, the degree of optimization will be up 1.063%. Digitization through the digital transformation and upgrading of the energy-related industrial chain, effectively improve the efficiency of energy use and the degree of utilization of scientific and technological resources, and promote the overall efficiency of energy use, assumption H2 holds.

Table 4. 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. Research on the Degree of Harmonization between Green Energy Efficiency of Chinese Households and High-Quality Development of the Digital Economy Based On the Coupling Approach

In order to explore the spatial distribution characteristics of the coupling degree and coupling between household green energy efficiency and the high-quality development of digital economy at the provincial scale, the coupling index scores of each province in China (excluding Hong Kong, Macao and Taiwan) were calculated, and the results are shown in Figure 1:

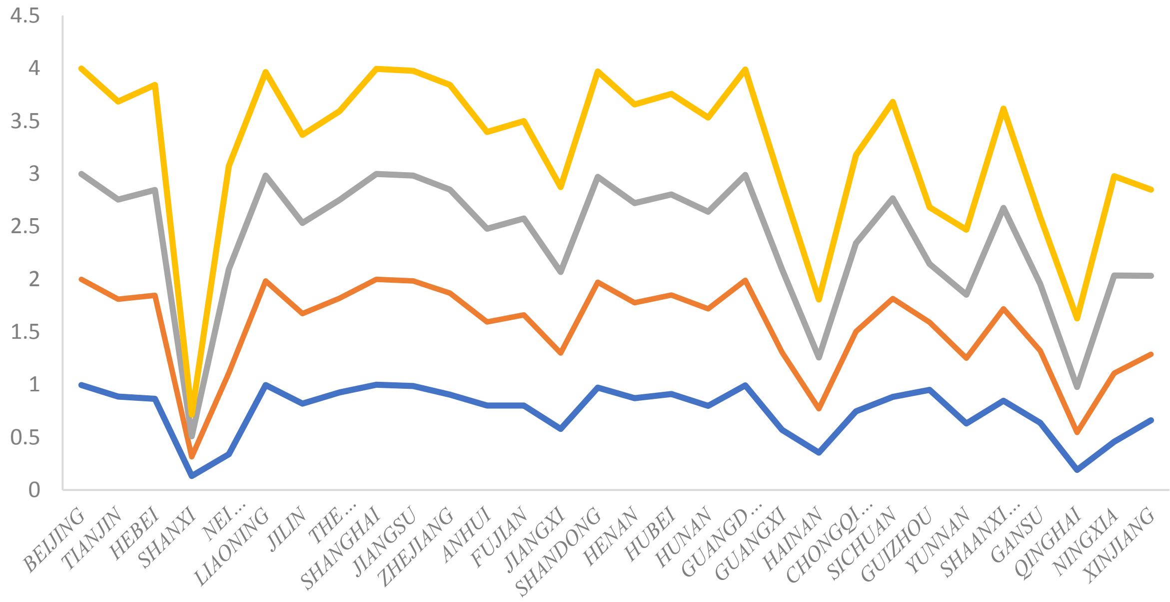

Figure 1. Visualization of the coupling degree and its evolutionary trend

(1) In 2015, the highly coupled region showed a clear distribution of the "inverted triangle" structure of "Coastal + Yangtze River Delta Economic Belt", indicating that the degree of regional digitization of the southern coastal provinces and the energy consumption structure of the higher degree of interaction between.

(2) In 2017, the "inverted triangle" pattern is still clear, and the digitalization level and energy consumption structure of the regions under the "inverted triangle" pattern are highly coupled. Other regions, except Shanxi, Ningxia and Qinghai, have eliminated the uncoupled state, and the overall coupling degree has been improved.

(3) 2017-2019 highly coupled areas from the "inverted triangle" to the development of centralized and continuous layout, coupling degree distribution differences between the east and west began to highlight the pattern. The coupling situation in the eastern region is significantly better than that in the west, but there are depressions in Shanxi and Jiangxi.

(4) In 2019, there is a new change in the highly coupled region: the coupling phenomenon, which was originally mainly concentrated in the eastern region, has begun to spread to the western region. Both in the east and in the west, the interaction between innovation capacity and energy consumption structure is deepening.

The above spatial pattern of change indicates that: the coupling of regional digital economy level and energy use structure has gradually deepened with the improvement of digitalization level in recent years, and the breadth along the "inverted triangle" structure of Yangtze River Delta Economic Belt has radiated from highly coupled areas to uncoupled areas. The areas along the Yangtze River Delta Economic Belt are highly coupled and concentrated in regional innovation capacity and energy utilization efficiency. In addition, the positive supporting effect of the improvement of the energy utilization level of the whole society on the further improvement of the digitization level is also strengthened over time, and hypothesis H3 is verified.

5.3. Grey forecasting Model to Predict the Future of Energy Digitization

In this paper, the collected data on household energy use efficiency and the level of development of digital economy in China's provinces are used to make gray model predictions, and the predictions of energy use efficiency are shown in Table 5 below:

Table 5. Projections of Household Energy Utilization Efficiency in China's Provincial Areas

area	2023E	2024E	2025E	2026E	2027E	2028E	2029E	2030E
Beijing	1.014	1.062	1.112	1.165	1.22	1.278	1.338	1.401
Tianjin	1.078	1.058	1.039	1.021	1.002	0.984	0.967	0.949
Hebei	0.948	1.036	1.128	1.225	1.326	1.431	1.541	1.657
Shanxi	0.338	0.343	0.348	0.353	0.358	0.363	0.368	0.374
Nei Monggol	0.393	0.388	0.383	0.379	0.374	0.37	0.365	0.361
Liaoning	0.542	0.533	0.524	0.516	0.508	0.499	0.491	0.484
Jilin	0.575	0.57	0.565	0.561	0.556	0.552	0.547	0.542
Heilongjiang	0.799	0.81	0.822	0.834	0.846	0.859	0.871	0.884
Shanghai	1.175	1.18	1.186	1.192	1.198	1.204	1.21	1.216
Jiangsu	1.072	1.064	1.057	1.049	1.042	1.034	1.027	1.02
Zhejiang	0.673	0.66	0.647	0.634	0.621	0.609	0.597	0.585
Anhui	0.633	0.602	0.573	0.545	0.519	0.493	0.469	0.446
Fujian	0.964	0.955	0.946	0.937	0.929	0.92	0.911	0.903
Jiangxi	0.6	0.605	0.61	0.615	0.621	0.626	0.631	0.636
Shandong	0.553	0.511	0.473	0.437	0.404	0.374	0.346	0.32
Henan	0.517	0.522	0.527	0.531	0.536	0.541	0.546	0.551
Hubei	0.742	0.745	0.749	0.753	0.756	0.76	0.764	0.768
Hunan	0.607	0.614	0.621	0.628	0.635	0.642	0.65	0.657
Guangdong	1.01	1.011	1.012	1.012	1.013	1.014	1.015	1.016
Guangxi	0.426	0.422	0.418	0.414	0.41	0.407	0.403	0.399
Hainan	1.475	1.448	1.421	1.395	1.37	1.345	1.321	1.297
Chongqing	0.579	0.578	0.577	0.575	0.574	0.573	0.572	0.571
Sichuan	0.578	0.58	0.582	0.583	0.585	0.587	0.588	0.59
Guizhou	0.333	0.329	0.324	0.32	0.316	0.311	0.307	0.303
Yunnan	0.342	0.335	0.328	0.322	0.315	0.309	0.303	0.297
Xizang	1.429	1.459	1.49	1.521	1.553	1.586	1.619	1.653
Shaanxi	0.363	0.357	0.351	0.345	0.34	0.334	0.328	0.323
Gansu	0.523	0.525	0.527	0.528	0.53	0.532	0.534	0.535
Qinghai	1.399	1.422	1.445	1.468	1.492	1.516	1.541	1.566
Ningxia	0.472	0.45	0.428	0.408	0.388	0.37	0.352	0.335
Xinjiang	0.287	0.274	0.262	0.251	0.24	0.23	0.22	0.21

Based on the data, projections show that Hainan's energy efficiency will decline in the future. Comparatively speaking, the green energy efficiency of Shanxi and Xinjiang is lower, but the energy utilization efficiency of Shanxi is gradually increasing, while Xinjiang is on a downward trend. Analyzing the magnitude of changes in energy efficiency, this paper finds that Beijing, Hebei, Anhui, Shandong and Hainan all show large fluctuations.

In the future, up to 2030, projections show that Hebei, Tibet and Qinghai are expected to outperform other provinces in terms of energy utilization efficiency, demonstrating the potential for energy transition development in these regions.

Table 6. Forecast of China's provincial digital economy development level

area	2023E	2024E	2025E	2026E	2027E	2028E	2029E	2030E
Beijing	0.617	0.691	0.775	0.869	0.975	1.093	1.226	1.374
Tianjin	0.102	0.105	0.109	0.113	0.117	0.121	0.125	0.13
Hebei	0.095	0.096	0.096	0.096	0.097	0.097	0.097	0.098
Shanxi	0.08	0.086	0.091	0.097	0.104	0.111	0.118	0.126
Nei Monggol	0.047	0.048	0.049	0.05	0.05	0.051	0.052	0.053
Liaoning	0.103	0.103	0.102	0.102	0.102	0.102	0.102	0.102
Jilin	0.032	0.03	0.028	0.026	0.025	0.023	0.022	0.02
Heilongjiang	0.034	0.033	0.031	0.029	0.028	0.026	0.025	0.024
Shanghai	0.508	0.533	0.558	0.585	0.613	0.643	0.674	0.706
Jiangsu	0.502	0.528	0.556	0.584	0.615	0.647	0.68	0.716
Zhejiang	0.426	0.461	0.5	0.542	0.587	0.636	0.69	0.747
Anhui	0.253	0.251	0.25	0.248	0.246	0.245	0.243	0.241
Fujian	0.232	0.253	0.276	0.301	0.328	0.357	0.39	0.425
Jiangxi	0.201	0.219	0.238	0.257	0.276	0.296	0.315	0.336
Shandong	0.279	0.281	0.283	0.284	0.286	0.288	0.289	0.291
Henan	0.172	0.178	0.184	0.189	0.196	0.202	0.208	0.215
Hubei	0.203	0.216	0.229	0.243	0.258	0.274	0.291	0.309
Hunan	0.157	0.163	0.17	0.177	0.184	0.191	0.199	0.207
Guangdong	1.139	1.287	1.454	1.642	1.855	2.096	2.368	2.675
Guangxi	0.104	0.112	0.122	0.132	0.144	0.156	0.169	0.184
Hainan	0.024	0.024	0.024	0.025	0.025	0.025	0.025	0.025
Chongqing	0.135	0.142	0.149	0.157	0.165	0.173	0.182	0.191
Sichuan	0.253	0.273	0.295	0.319	0.345	0.373	0.403	0.436
Guizhou	0.08	0.086	0.091	0.097	0.104	0.111	0.118	0.126
Yunnan	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.062
Xizang	1.433	1.464	1.496	1.528	1.561	1.595	1.629	1.664
Shaanxi	0.156	0.172	0.19	0.209	0.23	0.253	0.279	0.307
Gansu	0.034	0.034	0.034	0.034	0.034	0.035	0.035	0.035
Qinghai	0.009	0.008	0.008	0.007	0.006	0.006	0.005	0.005
Ningxia	0.02	0.021	0.021	0.022	0.023	0.023	0.024	0.025
Xinjiang	0.091	0.097	0.104	0.111	0.117	0.124	0.131	0.138

After analyzing Table 6, it can be clearly seen that China's provinces generally show positive growth in the process of digital economy development. Among them, the digital economy of Guangdong Province is particularly eye-catching, not only showing a significant upward trend, but also growing at an extremely rapid rate. This indicates that Guangdong Province is expected to be one of the fastest growing provinces in terms of digitalization in the future, and may even surpass other provinces to become a leader in the digitalization field. Meanwhile, Beijing is also showing impressive speed in its digitization development.

5.4. Robustness Tests

In order to ensure the accuracy of the research results, this paper, in view of the research of other scholars to take the following methods for the robustness test[16]: first, the interpreted variables for the extreme value processing, eliminating the minimum and maximum values, and then use the same empirical method to re-test; second, replace the model, taking into account the household energy structure and the impact of the efficiency of the use of the level of coupling and coordination degree of the digital economy with a certain degree of lag, and therefore take the data of a lagged period substituted for the re-test. Secondly, replace the model, considering that the impact of household energy structure and utilization efficiency and the coupling coordination degree of digital economy level has a certain lag, so take the data of the lagged period and substitute it into the re-examination.

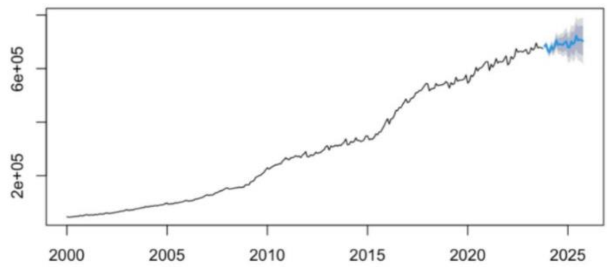

Figure 2. ADF test

The unit root test (ADF test) was used to test the smoothness reversibility of the digital economy and the green energy utilization efficiency of Chinese householdsin 31 provinces and cities in China from 2015 to 2022, and the conclusions obtained were consistent with the results of the baseline regression and had smoothness. The results are shown in Figure 2.

6. Conclusions and Suggestions

6.1. Conclusions

In this paper, the entropy weight method is used to construct indices for the digital economy and the green energy utilization efficiency and structure of Chinese households. Firstly, a two-way fixed-effects model is established to empirically analyze and judge the nonlinear influence characteristics and one-way influence mechanism of the two systems; secondly, a quantitative prediction is made on the two-way interaction linkage of the two systems through the coupling model combined with the grey prediction. The following conclusions are drawn:

(1)The digital economy has a significant positive contribution to the optimization of the provincial household energy mix. Using a two-way fixed-effects model, it was found that digitization could significantly improve energy efficiency, and for every 1 per cent increase in the level of the digital economy, energy efficiency would increase by 0.605 per cent. In addition, the digital economy can also significantly promote the optimization of the energy structure, and every 1% increase in the level of digitization will result in a 1.063% increase in the degree of optimization.

(2) Predicted future energy consumption in some areas of serious problems, digital monitoring demand is prominent. Household energy efficiency in Hainan province is performing well, but is likely to decline in the future as it faces stricter regulations on energy reduction. In Shanxi, household energy efficiency is improving, while in Xinjiang it is declining. Household energy consumption efficiency fluctuates widely in Beijing, Hebei, Anhui, Shandong and Hainan, with Beijing and Hebei on the rise and Anhui, Shandong and Hainan on the decline.

(3) High coupling accuracy between household energy utilization efficiency and high-quality development of digital economy in China. Examining the relationship between household energy consumption and the digital economy in China's provinces (excluding Hong Kong, Macao and Taiwan), we find that the coupling between the improvement of digitalization level and the use of energy efficiency has deepened. The Yangtze River Economic Zone is particularly obvious, showing an "inverted triangle" structure, with highly coupled areas gradually radiating to uncoupled areas.

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) We must deeply understand the double impact of the digital economy on the environment and energy development. On the one hand, the digital economy promotes the improvement of energy efficiency; on the other hand, it also brings new energy consumption and environmental pollution problems. Therefore, we need to comprehensively analyze the mechanism of the digital economy in promoting energy efficiency and environmental protection, in order to seek a balance between the growth of energy consumption and the green transformation of energy. For example, we can enhance the application of digital technologies such as smart grids and clean energy to improve energy utilization efficiency and reduce energy waste and pollution emissions.

(2) Strengthening the infrastructure of digital economy development is an urgent task. China's investment in digital equipment still needs to be upgraded, which limits the in-depth application of the digital economy in the energy sector. Therefore, we need to increase investment to improve the digital infrastructure, including high-speed networks, big data centers, cloud computing platforms, etc., in order to promote the comprehensive development of digital economy across the country. This will provide new impetus for the improvement of China's energy efficiency and help optimize the energy structure and green transformation.

(3) Improve the top-level design of the digital economy and promote the balanced development of the digital economy in all provinces. The development of digital economy can help build a long-term mechanism for energy conservation and emission reduction, and promote the green development of energy. Local governments should strengthen the policy guidance of promoting energy conservation and emission reduction through the digital economy, especially for provinces with high energy dependence, and formulate more targeted policies to promote the transformation of their energy efficiency. At the same time, by strengthening the popularization of the digital economy in various regions, the development dividend of the digital economy can be further utilized to enhance energy efficiency and realize green and sustainable development.

In summary, the digital economy, as a new engine for China's economic development, is of great significance in promoting energy efficiency and environmental protection. We need to comprehensively recognize the dual impacts of the digital economy, strengthen infrastructure construction, improve top-level design, protect intellectual property rights and personal information security, and formulate appropriate environmental regulations and related policies to promote the coordinated development of the digital economy with energy and the environment, so as to achieve the goal of green and sustainable development.

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References

[1] TAPSCOTT D. The digital economy: promise and peril in the age of networked intelligence [M]. New York: McGraw-Hil, 1996:8-15.

[2] CARISSON B. The digital economy: what is new and what is not? [J]. Structural Change and Economic Dyn-amics, 2004, 15(3):245-264.

[3] G20 Initiative on Digital Economy Development and Cooperation [EB/OL]. (2016-09-20) [2023-09-26]. http://www.g20chn.org/hywj/dncgwj201609/t20160920_3474.htm

[4] LIN Kongtuan, ZHOU Hanzhu. Digital economy, technological innovation and transformation and upgrading of manufacturing industry--an empirical analysis based on provincial panel data [J]. Journal of Fujian Agriculture and Forestry University (Philosophy and Social Science Edition), 2024, 27(01):52-63.

[5] ZHANG Sanfeng, WEI Xiahai. Does information and communication technology reduce firms' energy consumption--evidence from survey data of Chinese manufacturing firms [J]. China Industrial Economy, 2019(2):155-173.

[6] WANG Dongfang, CAO Jianhua. Research on the impact of Internet development on total factor energy efficiency and network effects in China [J]. China Population-Resources and Environment, 2019, 29(1):86-95.

[7] ZHOU Xiaohui, LIU Yingying, PENG Liuying. Digital economy development and green total factor productivity improvement [J]. Shanghai Economic Research, 2021(12):51-63.

[8] HAN Xianfeng, HUI Ning, SONG Wenfei. Can informatization improve the efficiency of technological innovation in China's industrial sector [J]. China Industrial Economy, 2014(12):70-82.

[9] SU Ke, ZHOU Chao. Human capital, science and technology innovation and green total factor productivity--an analysis based on data from cities in the Yangtze River Economic Belt [J]. Economic Issues, 2021(5):71-79.

[10] CHEN Siyi. Research on the impact of urban-rural income inequality on household energy consumption structure [D]. Southwest University of Finance and Economics, 2021.

[11] LI Yanru, MENG Xue, FENG Xiaoping, HU Feng,. Research on the measurement of the development level of digital economy and influencing factors in Chinese provinces [J]. Practice and Understanding of Mathematics, 2023, (10):52-70.

[12] TIAN Jiali, HUANG Wenyan, PENG Jiachao, et al. Transmission mechanism and spatial effect of green finance empowering carbon neutrality [J]. Western Forum, 2022, 32(05):44-62.

[13] CAI Qiang, Wang Xuxu. Impact of green finance on high quality economic development under spatial perspective [J]. Jianghan Forum, 2022, (06):21-28.

[14] SUN Miaoying. Research on the coupling relationship between green finance and high-quality economic development in China [J]. Operation and Management, 2023, (07):177-184.

[15] XIA Li. Influence effect of industrial digitalization empowering the development of commerce and circulation industry--Based on the perspective of digital reform [J]. Research on Business Economy, 2022, (11):167-170.

[16] HAN Chunmei, CHENG Yue. Government Funding, Coordination Degree of Industry-University-Research Coupling and Regional Innovation Performance--An Empirical Test Based on the Yangtze River Economic Belt [J]. Science and Management, 2024, 44(02):1-9.