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Research article

Research on the coupling coordination relationship between the digital economy and high-quality energy development: Evidence from China

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ABSTRACT

The deep integration of the digital economy and high-quality energy development is a vital breakthrough in promoting the digital transformation and upgrading of energy, and it is also a critical path to achieving green and low-carbon development. However, the degree of integration of the two has yet to be discovered. This article measures the coupling coordination degree of the digital economy and high-quality energy development using panel data from 30 provinces in China from 2013 to 2020, explores the spatiotemporal evolution characteristics of the coupling coordination degree, and further analyzes the driving factors of the coupling coordination degree. The results show that:(1) The coupling coordination degree shows an upward trend, but there are apparent gradient differences and spatial non-equilibrium features in the coupling coordination degree among provinces. (2) The coupling coordination degree shows a "parabolic" spatial trend of "high east and low west" in the east-west direction and an "inverted U-shaped" spatial trend in the north-south direction. (3) The center of gravity of the coupling coordination degree moves to the southwest, clustering in the northeast-southwest direction and showing a spreading trend in the southeast-northwest direction. (4) The coupling coordination degree has a significant positive spatial correlation, and the cold-hot spot gradually develops into a distribution pattern with the Yangtze River Delta in China as the agglomeration center. (5) Economic development, industrial structure, government behavior, environmental regulation, urbanization, technological innovation, and external openness significantly impact the coupling coordination degree. In addition, economic development and human capital have a positive spatial spillover effect on the coupling coordination degree. Urbanization level and technological innovation have a negative spatial spillover effect on the coupling coordination degree. Accordingly, to promote the coupling and interaction between the digital economy and high-quality energy development, the government should take effective measures in optimizing the industrial structure, scientifically promoting the urbanization process, and enhancing the scientific and technological innovation capacity.

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1. Introduction

Global climate warming is a severe challenge shared by the international community. The Intergovernmental Panel on Climate Change (IPCC) pointed out that the global average temperature from 2011 to 2020 increased by 1.1 °C compared to the pre-industrial revolution (1850–1900) [1]. By the end of the century, temperatures will further rise by 1–5.7 °C [2]. To address the climate warming issue, countries around the world have successively proposed strategies for the low-carbon transformation of their economies and societies. Energy is a necessary material basis and power source for economic and social development, but it is also a significant source of carbon dioxide. In 2022, energy-related carbon dioxide emissions accounted for nearly 90 % [3]. Therefore, promoting energy transformation has become the key to green and low-carbon development.

Currently, the digital economy based on the rapid development of digital technologies such as 5G, big data, and artificial intelligence has set off a new round of industrial revolution, providing opportunities for energy transformation. Numerous studies have shown that the digital economy can accelerate the low-carbon energy transition by increasing renewable energy consumption [4–7]. The International Energy Agency (IEA) also points out that digitalization can optimize the energy system by breaking the traditional boundaries between energy demand and supply [8]. In addition, with the innovation and integrated application of digital technologies, digital finance can facilitate the energy transition to digitalization [9]. New infrastructure can contribute to the transformation of energy structure by improving green total factor productivity and green finance [10]. Digital inclusive finance can promote the carbon-neutral transformation of energy by increasing corporate investment in information and communication technology and green technology [11].

Meanwhile, the energy system also provides application scenarios for developing the digital economy. For example, smart grids and new power construction are applications of digital technology in the energy field [12,13]. In addition, the core sectors of the digital economy are concentrated in highly power-intensive industries such as computer communications and the Internet, which require electric energy supplies for regular operation [14]. Therefore, the digital economy provides an opportunity for energy transformation, the energy system provides strong support for developing the digital economy, and the digital economy and the energy system are interdependent and interactive coupling relationships.

As the world's largest energy consumer, China has consistently attached great importance to the issue of energy transformation. The State Council of China released the white paper "China's Energy Development in the New Era" on December 21, 2020, which pointed out that the Chinese government should continue to deepen energy reform, build a diversified and clean energy system, and unswervingly follow a new road of high-quality energy development (HQED). On January 29, 2022, China's National Development and Reform Commission (NDRC) and National Energy Administration (NEA) pointed out that the Chinese government should accelerate the construction of a clean, low-carbon, safe, and efficient energy system and achieve HQED. Simultaneously, China's digital economy is also developing rapidly. The data from the "Global Digital Economy White Paper 2023″ show that China's digital economy increased by $4.1 trillion from 2016 to 2022, with a compound annual growth of 14.2 %, which is 1.6 times as large as the overall compound annual growth rate of the digital economy of the five countries of the United States, China, Germany, Japan, and South Korea during the same period. During the critical period of HQED and explosive growth of the digital economy, the Chinese government has repeatedly emphasized seizing the historic opportunity of the convergence between the digital revolution and energy

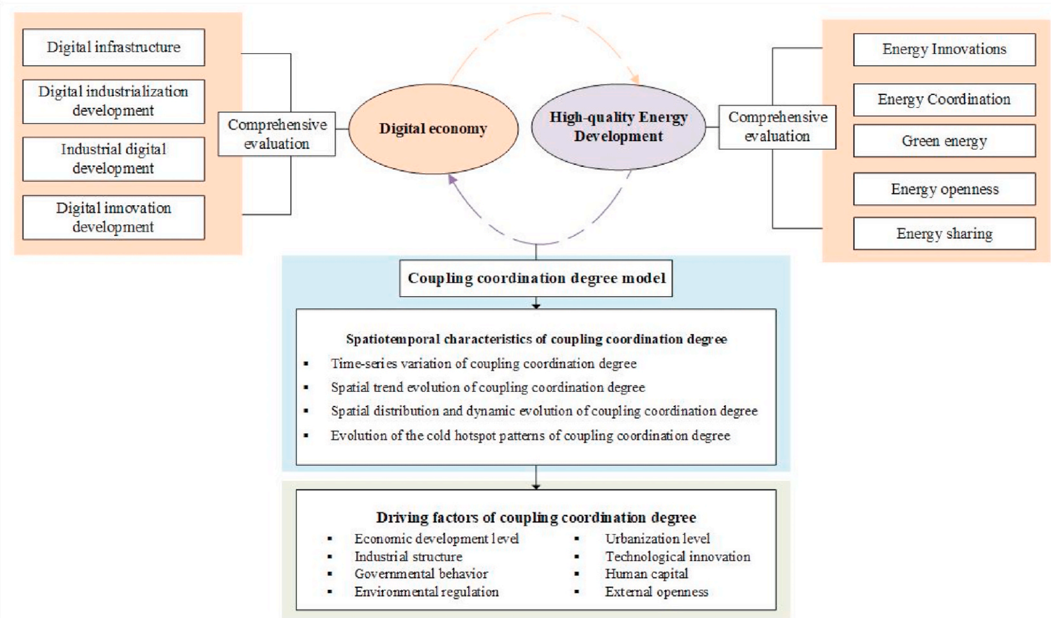

Fig. 1. The framework chart of the study.

revolution to improve the quality of energy development and contribute to carbon neutrality goals [14]. Actually, some developed countries have taken the lead in promoting the coupled and coordinated development of the digital economy and energy. For example, France's Total Energy began to apply artificial intelligence technology to provide new intelligent solutions for oil development in 2018. Germany introduced the "Energy Transformation Digitalization Act" in 2019 and began to lay out energy Internet projects. British Petroleum (BP) and Microsoft reached a strategic cooperation in 2020 and began to promote the digital transformation of the energy system. However, what is the level of coupling and coordination between China's digital economy and HQED? How is the spatiotemporal pattern of coupling and coordination between China's digital economy and HQED evolving? What factors influence the coupling and coordination of China's digital economy and HQED? These questions remain to be answered. In addition, as China is one of the largest emerging economies, our study of the coupling interaction and driving factors between its digital economy and HQED can not only provide a decision-making basis to improve the quality and efficiency of China's energy industry but also offer an empirical reference for energy development in other emerging countries.

The potential academic contribution of this paper is in three aspects. Firstly, this paper analyzes the coupling mechanism between the digital economy and HQED for the first time, which provides a path analysis for promoting HQED and also offers new ideas for developing the digital economy. Secondly, based on constructing the evaluation index system of the digital economy and HQED, this paper measures the coupling coordination degree (CCD) of the two, analyzes the spatiotemporal evolution characteristics of CCD, which provides a reference for the Chinese government to correctly understand the integration level of the digital economy and HQED and further promote the synergistic development of the two. At the same time, HQED is a new concept put forward by the Chinese government. However, it will become an essential issue for countries worldwide as the green transition and low-carbon development receive widespread attention from the international community. Therefore, the study for the coupling and coordination of the digital economy and HQED will also provide a reference basis for the energy development of other countries. Thirdly, this paper reveals the potential drivers of coupling and coordination between the digital economy and HQED and provides a direction of efforts to promote the coupling and coordination development of the two.

The rest of the article is as follows: Section 2 is the literature review. Section 3 is the coupling mechanism between the digital economy and HQED. Section 4 introduces the data sources, indicator construction and research methodology. Section 5 analyzes the empirical results. Section 6 presents the main conclusions and policy recommendations. The framework chart of the study is shown in Fig. 1.

2. Literature review

Energy is a powerful support for economic and social development, and at the same time, the environmental problems caused by energy consumption are also a severe challenge to humanity. In the context of global warming, one of the most important ways to solve the problem is to promote HQED. Current research on HQED mainly focuses on analyzing theoretical connotations. Some scholars consider that HQED is an innovative, coordinated, green, open, and shared approach to new energy development [15,16], as well as the relentless pursuit of the three primary goals of safety, reliability, economic viability, and green and low-carbon [17]. Other studies pointed out that green energy production, green energy consumption, and energy eco-efficiency are intrinsic requirements of HQED [18]. Meanwhile, addressing the issues of energy security, energy poverty, and energy inequality to make clean energy accessible to people of different income levels is the ultimate goal of HQED [19–22]. It follows that the rich connotation of HQED has yet to form a unified standard and still needs further exploration.

Driven by the new round of scientific and technological revolution, the digital economy, with data resources as the key elements and digital technology as the support, is flourishing, profoundly affecting the energy industry through its remarkable characteristics of rapid innovation and strong permeability. In this context, the academic community has launched a series of discussions on the digital economy's empowerment of energy development, mainly including five aspects.

The first is the impact on HQED. From a macro perspective, Wang et al. [15] found that the digital economy can promote the high-quality development of regional energy through innovation, economic growth, and employment. In addition, Liu and Wu [23] explored the impact of digitization from a micro perspective and found that digitization can promote the high-quality development of energy enterprises. The sub-indicators that constitute digitization (digital technology, digital capital investment, digital labor supply, and digital transaction management) can also positively affect the high-quality development of energy enterprises. The second is the impact on energy transformation. Scholars found that the digital economy can optimize the structure of renewable energy consumption and renewable energy power generation [5,24], promote the development of clean energy [25], and facilitate the green and low-carbon transformation of energy [4,7]. The third is the impact on energy utilization efficiency. Scholars found that the digital economy can not only improve regional energy utilization efficiency [26–29] but also enhance energy utilization efficiency in industry, manufacturing, and other industries [30,31]. The fourth is the impact on energy poverty. Scholars found that the digital economy can alleviate energy poverty. Moreover, technological innovation, economic development, and government governance play an essential role as mechanisms in the process of reducing energy poverty [32–34]. The fifth is the impact on energy technology. Some scholars found that digitalization has promoted energy technology innovation, such as energy storage technology innovation, providing an opportunity for low-carbon energy transition [35,36].

In addition, with the rapidly developing digital economy, digital technologies such as the Internet, big data, and blockchain are increasingly being integrated into the development of the real economy. Energy, as a traditional real economy, is an inevitable trend for integration and development with the digital economy. A few scholars have already started relevant research. For example, Wang et al. [37] studied the integration level of the digital industry and energy industry, and Chen et al. [14] explored the coupled and coordinated development status of the digital economy and energy industry. Although their studies mainly started in the energy industry, they also provided empirical references for the research of this paper.

To conclude, scholars have gradually gained a deeper understanding of the connotation of HQED, and their empirical tests on the digital economy's empowerment of energy development have become increasingly rich. They have also covered research on the integrated development of the digital economy and energy. However, quantitative research on the coupled and coordinated relationship between the digital economy and HQED remains blank and needs to be further explored.

3. Coupling mechanism

As the primary form of the new round of technological revolution, the digital economy provides a new power source for HQED. Firstly, digital technology is the underpinning of the digital economy. Its enabling effect is mainly reflected in three levels. (1)From a macro perspective, the widespread use of digital technology is beneficial to promoting the transparency of energy supply-side and demand-side information, enabling real-time sharing of energy supply and demand data between the government and market participants [38], helping the government establish energy consumption feedback mechanisms and energy information monitoring and management systems, and improving the government's refined management level and responsiveness in energy consumption, energy supply, etc., thus optimizing energy allocation, improving energy utilization efficiency, and realizing HQED. (2) From a meso perspective, digital technology can break industrial boundaries, promote the extension and integration of industries, empower the transformation and upgrading of traditional industries, and continuously give rise to new industries, such as the biochip industry and Internet healthcare, thereby reshaping the new form of industrial structure and promoting the upgrading of industrial structure to a higher level. The upgrading of industrial structure means that the center of gravity of industrial development transfers between industries and the proportion of industrial scale changes. For instance, traditional industries with high energy consumption and pollution transform into emerging industries with energy conservation, environmental protection, and cleanliness. High-productivity industries continue to squeeze out low-productivity industries, ultimately improving energy utilization efficiency [39]. (3)From a micro perspective, on the one hand, digital technology can empower energy enterprises to build a new intelligent energy industry and enable energy companies to achieve digital management in their production, supply, and other links, thereby promoting the interconnection and interaction in all links, expanding inter-enterprise cooperation and making synergistic development of upstream and downstream industry chain, alleviating the distortion in element and product markets caused by information asymmetry, reducing energy losses caused by resource mismatch, and enhancing energy utilization efficiency. On the other hand, digital technology can help promote the innovative development of enterprises, allowing them to develop green production processes and intelligence equipment and promoting digitalization, low-carbonization, and refined development of production links to reduce energy losses and improve energy performance. Secondly, as the core of the digital economy, data elements reconfigure the system of production elements in the process of integration with traditional production elements, broaden the boundaries of production possibilities, and produce amplification, superposition, and multiplication effects on production behaviors, thus improving energy utilization efficiency [40].

As one of the essential players in the new technological revolution, HQED provides vital support for developing the digital economy. Firstly, HQED has continuously created new application scenarios for the digital economy, such as new power construction and new energy development. It stimulates digital technological innovation while promoting the digital transformation of energy, provides market space for the sustained growth of the digital economy, and becomes a powerful traction force for developing the digital economy. Secondly, data elements are an essential part of supporting the development of the digital economy. HQED is rich in connotation and can gather massive amounts of data during its development process. In the traditional economic development process, these data have low productive value. However, in the era of the digital economy, digital technologies such as the Internet and cloud computing can be used to process data and transform them into new production elements, bringing a broader growth space for developing the digital economy. Thirdly, critical sectors of the digital economy, such as computer communications and the Internet, are highly power-intensive industries that require power supply to operate normally [14]. Therefore, the energy system provides the material foundation for developing the digital economy.

In conclusion, the digital economy affects HQED through the empowerment of digital technology and the integration of data elements, and HQED affects the development of the digital economy by providing data element input, stimulating digital technology innovation, and providing material guarantees. Therefore, there is a coupling and interactive relationship between the digital economy and HQED that is interdependent and mutually reinforcing.

4. Materials and methods

4.1. Data sources

Based on data availability, this paper chooses the data from 30 provinces in China from 2013 to 2020 as the research sample. The data used in this paper come from the *China Statistical Yearbook*, *China Energy Statistical Yearbook*, and the statistical yearbook of provincial administrative regions in the relevant years. The digital economy inclusive finance index from the Digital Finance Research Center of Peking University and the digital innovation index from the Enterprise Big Data Research Center of Peking University.

Table 1
Index system of the digital economy.

System Layer	Index layer	Unit	Direction
Digital infrastructure	Number of Internet broadband port access ports	Million	+
	Internet broadband penetration rate	Households/person	+
	Number of Domains	Million	+
	Cell phone base stations	Million	+
	Length of fiber optic cable	Km	+
	Mobile Phone Penetration	Pieces/Hundred people	+
Digital industrialization	Percentage of employment in the information industry	%	+
	Total Telecommunications Business	Billion Yuan	+
	Software business income	Billion Yuan	+
Industrial digital	The percentage of companies with e-commerce trading activities	%	+
	Enterprise e-commerce sales	Billion Yuan	+
	Enterprise e-commerce purchases	Billion Yuan	+
	Number of computers per 100 people in the enterprise	Unit	+
	Number of websites per 100 companies among enterprises	Unit	+
	Digital inclusive finance index	/	+
Digital innovation	Digital innovation index	/	+
	R&D Investment Intensity	%	+
	R&D personnel full time equivalents	Person-year	+

4.2. *Construction of the index system*

As the connotation of the digital economy continues to expand, scholars have made numerous explorations in constructing the digital economy index system. However, a unified evaluation system has yet to be formed. Because of this, this paper comprehensively refers to relevant research [41,42], follows the principles of data availability and scientificity, and constructs the digital economy index system from the following four dimensions (Table 1).

China's economy has entered the stage of high-quality development, and energy is an essential part of it. Taking the path of high-quality development is an inevitable choice in line with the development of the times. In recent years, scholars have constructed different evaluation systems to assess the level of China's HQED, but the evaluation criteria used are different. To this end, this article refers to the white paper "China Energy Development in the New Era" and related research [43,44] to construct an evaluation index system for HQED from five aspects: energy innovation, energy coordination, green energy, energy openness, and energy sharing (Table 2).

4.3. *Research methods*

4.3.1. *CCD model*

The CCD model is calculated with the following steps.

As the evaluation index data have different magnitudes and index attributes, the selected indexes are standardized using the extreme value method to unify the comparison criteria. However, the data may be 0 after standardization. The standardized data are shifted by 0.0001 units to avoid such a meaningless situation. The formulas are equations (1) and (2):

Positive indicators:

$$Z_{ij} = \frac{X_{ij} - Min(X_{ij})}{Max(X_{ij}) - Min(X_{ij})} + 0.0001 \tag{1}$$

Negative indicators:

$$Z_{ij} = \frac{Max(X_{ij}) - X_{ij}}{Max(X_{ij}) - Min(X_{ij})} + 0.0001 \tag{2}$$

To avoid the influence of subjective elements, we use the entropy value method to determine the index weights and derive the comprehensive score of the digital economy and HQED. We assume that a_j and b_j denote the weights of each indicator of the digital economy and HQED, respectively, $x_1, x_2, x_3, ..., x_p$ are indicators reflecting the digital economy, and $y_1, y_2, y_3, ..., y_q$ are indicators reflecting HQED, then the comprehensive score formula of the digital economy and HQED is as equation (3):

$$U_1 = \sum_{j=1}^{p} (a_j \times x_j) \quad U_2 = \sum_{j=1}^{q} (b_j \times y_j) \tag{3}$$

Table 2
Index system of HQED.

System Layer	Index layer	Unit	Direction
Energy Innovations	R&D personnel full time equivalents	Person-year	+
	Local financial investment in science and technology	Billion Yuan	+
	Technology transaction turnover	Billion Yuan	+
	Energy industry investment	Billion Yuan	+
	Tertiary industry share	%	+
Energy Coordination	GDP/Total energy consumption	Billion Yuan/million tons of standard coal	–
	Total energy production/total energy consumption	%	+
	energy consumption/population	10,000 tons of standard coal/10,000 people	+
Green energy	Energy consumption elasticity	/	–
	Energy production elasticity	/	–
	Sulfur dioxide emissions	Million tons	–
	Industrial smoke (dust) emissions	Million tons	–
	General industrial solid waste disposal volume	Million tons	–
	Energy conservation and environmental protection expenditure/general public budget expenditure	%	+
	Industrial pollution control completed investment	Billion Yuan	+
Energy openness	Total import and export trade/GDP	%	+
Energy sharing	City gas penetration rate	%	+
	Natural gas consumption population/total population	%	+
	Electricity generation/population	Billion kWh/million people	+

Table 3
Classification of the CCD.

D	Classes	*D*	Classes
0~0.09	Extreme disorder	0.50–0.59	Barely coordinated
0.10–0.19	Serious disorder	0.60–0.69	Primary coordination
0.20–0.29	Moderate disorder	0.70–0.79	Intermediate coordination
0.30–0.39	Mild disorder	0.80–0.89	Well coordination
0.40–0.49	Near disorder	0.90–1.00	High-quality coordination

The level of coordination between the digital economy and HQED can be measured by constructing the CCD model. The formulas are equations (4) and (5):

$$C = \{U_1 \times U_2 / [(U_1 + U_2)/2]\}^{1/2} \tag{4}$$

$$D = \sqrt{C \times T} \quad T = \alpha U_1 + \beta U_2 \tag{5}$$

in the formula, C is the coupled degree. D is the CCD. T is the comprehensive evaluation index of the digital economy and HQED. U_1 and U_2 are the level of the digital economy and HQED, respectively. α and β are undetermined coefficients. This paper considers the digital economy and HQED to be equally important, namely, $\alpha = \beta = 0.5$. Referring to the current study [45], this paper classifies the CCD of the two systems into ten levels (Table 3).

4.3.2. Kernel density curve

The kernel density curve is a non-parametric estimation method that can be used to characterize the evolutionary trends and patterns of random variables. In order to examine the dynamic evolution trend of CCD, this paper uses the kernel density curve to analyze the distribution location, morphology, and extensibility of CCD. The formula is as equation (6):

$$\varphi(x) = \frac{1}{nh} \sum_{i=1}^{n} K\left|\frac{x_i - x}{h}\right| \tag{6}$$

In the formula, *(x)* is the probability density function estimate of CCD. h is the bandwidth. $x_1, x_2, \cdots, x_n$ are n sample points. x is the sample mean. $K|\cdot|$ is the kernel function.

4.3.3. Trend surface analysis

Trend surface analysis is a mathematical method that uses mathematical surfaces to simulate the spatial distribution and variation trends of the elements of a geographic system. This paper uses the trend surface to portray the spatially divergent trends of CCD. Let $Z_i(x_i, y_i)$ be the actual observed value of the geographic element *i* and $T_i(x_i, y_i)$ be the fitted value of the trend surface. The formula is as equation (7):

$$Z_i(x_i, y_i) = T_i(x_i, y_i) + \varepsilon_i \tag{7}$$

in the formula, (x_i, y_i) is the geographic coordinate, and ε_i is the deviation between the real value and the fitted value.

4.3.4. Standard deviation ellipse model

The standard deviation ellipse model can further depict the spatial evolution process of CCD as a spatial statistical tool to characterize the distribution features of geographical elements. It usually includes the center of gravity of distribution, the standard deviation of the long and short axes, and the azimuthal angles. The formulas are equations (8)–(11):

$$\text{Spatial distribution center of gravity}: \overline{X_w} = \sum_{i=1}^{n} \omega_i x_i \Bigg/ \sum_{i-1}^{n} \omega_i \quad \overline{Y_\omega} = \sum_{i=1}^{n} \omega_i y_i \Bigg/ \sum_{i=1}^{n} \omega_i \tag{8}$$

$$\text{Standard deviation of x} - \text{axis}: \sigma_x = \sqrt{\sum_{i=1}^{n} (w_i \overline{x}_l \cos\theta - w_i \overline{y}_l \sin\theta)^2 \Bigg/ \sum_{i=1}^{n} w_i^2} \tag{9}$$

$$\text{Standard deviation of y} - \text{axis}: \sigma_y = \sqrt{\sum_{i=1}^{n} (w_i \overline{x}_l \sin\theta - w_i \overline{y}_l \cos\theta)^2 \Bigg/ \sum_{i=1}^{n} w_i^2} \tag{10}$$

$$\text{Azimuth}: \tan\theta = \frac{\left(\sum_{i=1}^{n} w_i^2 \overline{x_i}^2 - \sum_{i=1}^{n} w_i^2 \overline{y_i}^2\right) + \sqrt{\left(\sum_{i=1}^{n} w_i^2 \overline{x_i}^2 - \sum_{i=1}^{n} w_i^2 \overline{y_i}^2\right)^2 + 4\sum_{i=1}^{n} w_i^2 \overline{x_i}^2 \overline{y_i}^2}}{2\sum_{i=1}^{n} w_i^2 \overline{x_i}^2 \overline{y_i}^2} \tag{11}$$

in the formula, *n* denotes the number of provinces. (x_i, y_i) denotes the latitude and longitude coordinates of area *i*. $(\overline{X_w}, \overline{Y_w})$ denotes the weighted mean center of gravity coordinates. w_i indicates weight. σ_x and σ_y are the standard deviations along the x and y axes, respectively. $\overline{x_i}$ and $\overline{y_i}$ denote the deviation of each province from the mean center of gravity coordinates. θ is the elliptical azimuth, which is the angle formed by rotating clockwise from due north to the long axis of the ellipse.

4.3.5. Hot spot analysis model

The hot spot analysis (Getis-Ord G_i*) model can be used to explore the local aggregation of elements in a certain area and their clustering patterns. However, before conducting hotspot analysis, a global spatial autocorrelation test is required. The Global Moran's Index formula is as equation (12):

$$I_G = \frac{n \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} \sum_{i=1}^{n} (x_i - \overline{x})^2} \tag{12}$$

in the formula, x_i and x_j are the CCD of province *i* and province *j*, respectively. $\overline{x}$ denotes the mean value of the CCD. w_{ij} is the spatial weight. *n* is the number of provinces. I_G takes values in the range of $(-1,1)$. $I_G > 0$ indicates the existence of positive spatial correlation. $I_G < 0$ indicates the existence of negative spatial correlation.

In spatial statistics, the hotspot analysis tool in ArcGIS software is usually used to measure the G_i* value of each element. The statistical significance of G_i* can be tested by the standardized Z value, and a positive Z value belongs to the hot spot area. In contrast, a negative Z value belongs to the cold spot area. The formula is as equation (13):

$$G_i = \sum_{j=1}^{n} w_{ij} x_j \Bigg/ \sum_{j=1}^{n} x_j \quad Z = \frac{G_i^* - E(G_i^*)}{\sqrt{Var(G_i^*)}} \tag{13}$$

in the formula, w_{ij} is the spatial weight matrix, $E(G_i^*)$ and $Var\ (G_i^*)$ are the mathematical expectation and standard deviation of G_i*, respectively.

4.3.6. Spatial econometric model

Considering the possible spatial correlation of CCD among provinces, we selected a spatial econometric model to analyze the influencing factors of CCD. The spatial econometric models commonly used in academia today are the Spatial Durbin Model (SDM), the Spatial Lag Model (SLM), and the Spatial Error Model (SEM) proposed by Elhorst [46]. Among them, the SDM, which considers the spatial correlation of dependent variables and independent variables at the same time, is a general form of the spatial econometric model. The formula is as equation (14):

$$\begin{cases} CCD_{it} = \alpha + \rho w_{ij} CCD_{it} + \beta_1 X_{it} + \beta_2 w_{ij} X_{it} + \delta_t + \nu_i + \mu_{it} \\ \mu_{it} = \lambda w_{ij} \mu_{it} + \varepsilon_{it} \end{cases} \tag{14}$$

in the formula, CCD_{it} is the explained variable. X_{it} is the explanatory variable. w_{ij} is the spatial weight matrix. α and $\beta_i (i = 1, 2)$ are estimated coefficients. ρ is the spatial autocorrelation coefficient. λ is the spatial lag coefficient. δ_t is the time-fixed effect. ν_i is the individual fixed effect. μ_{it} is the standard error term. Among them, the formula (8) is the SDM when $\lambda = 0$. The formula (8) is the SAR when $\lambda = \beta_2 = 0$. The formula (8) is the SEM when $\rho = \beta_2 = 0$. This article will conduct a series of tests on the three models of SDM, SAR, and SEM and then select the most appropriate model.

5. Results

5.1. Time-series variation of CCD

The article draws the kernel density curves of CCD in 2013, 2017, and 2020 (Fig. 2). It analyzes the dynamic evolution trend of CCD from three aspects: the distribution position, shape, and extension of the kernel density curves. (1) From the distribution position, the kernel density curve of CCD gradually moved to the right in 2013–2020, indicating that the level of CCD among provinces in China showed an overall upward trend. (2) From the distribution pattern, the kernel density curve of CCD in 2013–2020 showed a single-peak shape, which indicated that there was no polarization in CCD of each province in China. The peak value of the curve decreased year by year, and the curve's width gradually changed from "high and narrow" to "short and wide." These changes indicated that the absolute difference of CCD among provinces in China had an expanding trend, and there was a prominently spatial non-equilibrium characteristic. (3) From the distribution extension, the kernel density curve of CCD in 2013–2020 trailed to the right

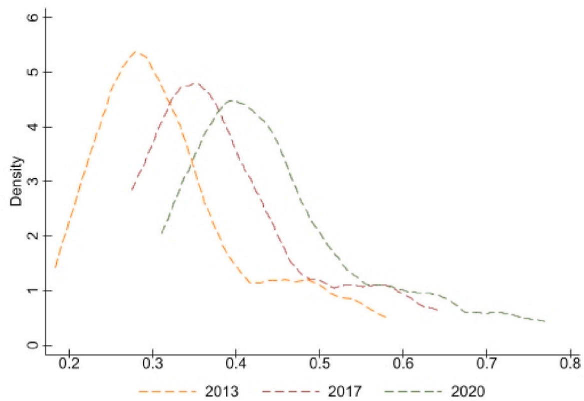

Fig. 2. The kernel density curve of CCD from 2013 to 2020.

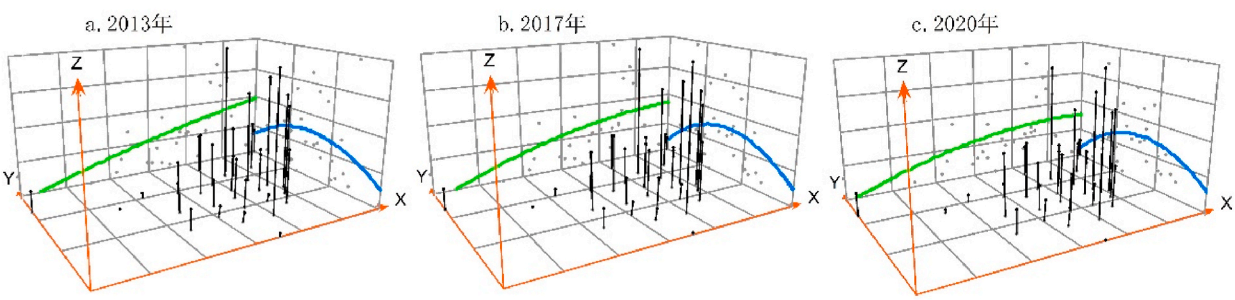

Fig. 3. The spatial trend of CCD from 2013 to 2020.

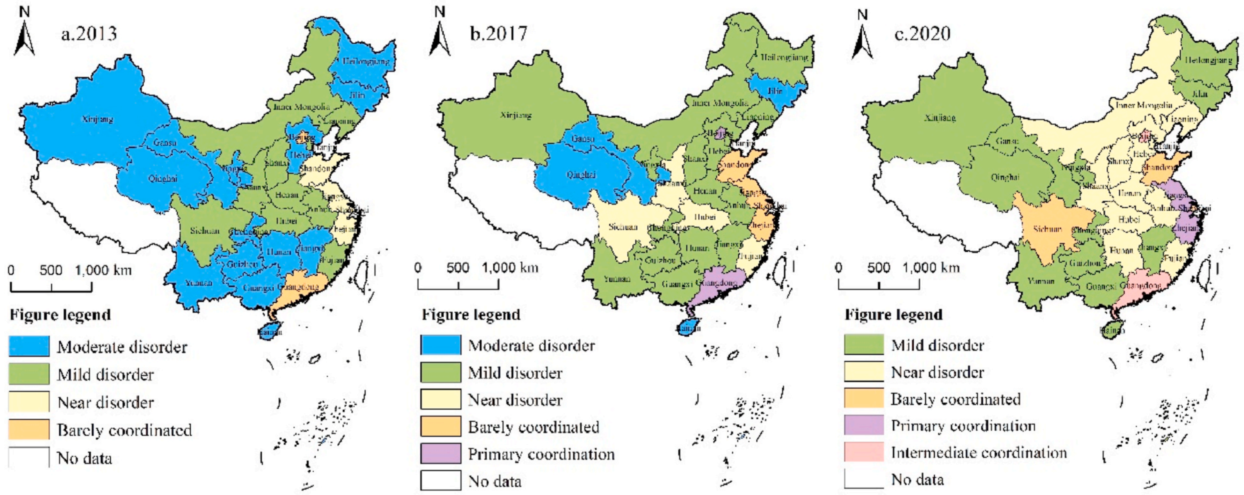

Fig. 4. The spatiotemporal pattern of CCD from 2013 to 2020.

and tended to broaden, which indicated that provinces with a higher level of CCD had also gradually widened the gap with provinces with a lower level of CCD while maintaining sustained growth. That is, there were apparent gradient differences in CCD among Chinese provinces. It may be due to the influence and constraints of location conditions, energy endowment, digital infrastructure, and other factors that have affected the coupling process of the digital economy and HQED.

5.2. Spatial trend evolution of CCD

The article draws the spatial trend of CCD in 2013, 2017, and 2020, as shown in Fig. 3 (the X-axis arrow points to the east direction, the Y-axis arrow points to the north direction, and the Z-axis arrow represents the level of CCD). (1) Overall, the CCD in 2013–2020 showed a spatial trend of "high east and low west, high south and low north". There were apparent spatial directional characteristics. The eastern and central regions of China had a higher CCD. (2) In the east-west direction of the trend surface, the CCD exhibited a "parabolic" spatial structure of gradually increasing from west to east. In addition, the arc of the trend line projection slowed down from 2013 to 2020, indicating that the difference in CCD between the eastern and western regions of China tended to shrink. It may be because the digital economy, as a new economic form, has characteristics such as sharing and openness. It produces positive spatial spillover effects by strengthening the flow of information and knowledge, which narrows the difference in the coupling coordination between the eastern and western regions while promoting the benign interaction between the digital economy and HQED. (3) In the north-south direction of the trend surface, the CCD showed an inverted "U" spatial structure, indicating that the CCD in the central region of China was higher than that in the southern and northern regions. It may be because the central region, as the second tier of China's economic development, has stimulated its development potential under the driving leadership of strategies such as the "Plan to Promote the Rise of the Central Region (2016–2025)" and the "Promoting High-quality Development of the Central Region in the New Era," making the digital economy and the HQED can be better integrated.

5.3. Spatial distribution and dynamic evolution of CCD

The article draws the spatial pattern distribution and center of gravity migration path of CCD in 2013, 2017, and 2020, respectively (Fig. 4, Fig. 5).

(1) As seen in Fig. 4, the CCD in 2013–2017 tended to increase, with a spatial pattern of high in the east and low in the west. In 2013, the overall level of CCD in China was low, with 93.33 % of provinces in the coupling disorder stage. The coupled coordination rank varied significantly, exhibiting four types: moderate disorder, mild disorder, near disorder, and barely coordinated. The provinces with a relatively high CCD were spatially clustered in the eastern region. By 2017, the overall level of CCD had increased substantially. The percentage of provinces in the coupling disorder stage decreased to 80 %. The number of provinces reaching coordination status increased from two to six, all belonging to the eastern region. Specifically, compared with 2013, Beijing and Guangdong developed from barely coordinated to primary coordination. Zhejiang, Shanghai, Jiangsu, and Shandong transitioned from near disorder to barely coordinated. Sichuan, Shaanxi, Hubei, and Fujian developed from mild disorder to near disorder. Qinghai, Gansu, Jilin, and Hainan had no significant change in development status and remained in the stage of moderate disorder. The remaining provinces upgraded from moderate disorder to mild disorder. As seen in Fig. 5

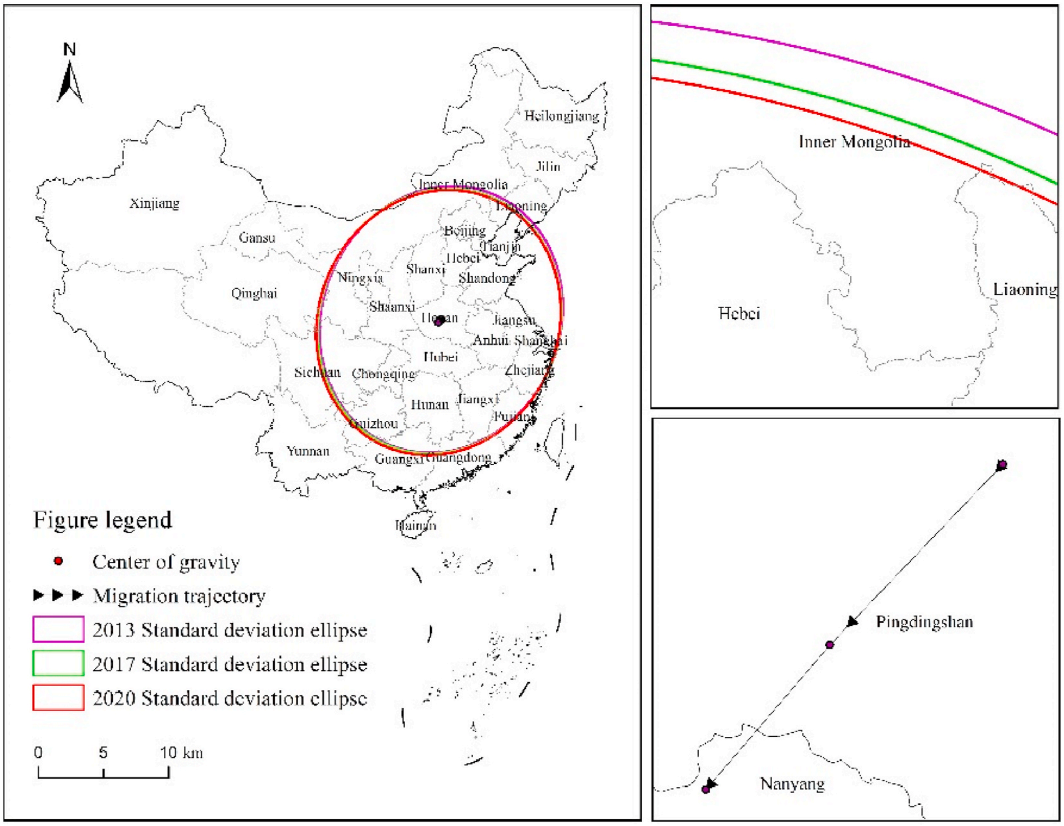

Fig. 5. The center of gravity migration path of CCD.

Table 4
Main parameter statistics of standard deviation ellipse.

Year	Center of gravity coordinate	Long axis/km	Short axis/km	Migration distance/km	Azimuth/°
2013	113.13°E，33.78°N	1109.71	972.80		22.71
2017	112.97°E，33.67°N	1100.29	979.45	19.22	22.20
2020	112.85°E，33.57°N	1102.69	980.85	14.86	23.16

and Table 4, from the dynamic trend, the center of gravity of CCD from 2013 to 2017 moved in the southwestern direction within the territory of Pingdingshan City, Henan Province, with a displacement distance of 19.22 km, which indicates that the CCD in the western and southern regions of China during this period was gradually improving. From the directional distribution changes, the standard deviation ellipse of CCD showed the distribution characteristics of the northeast-southwest direction. The ellipse rotation angle θ of CCD was 22.71° in 2013 and 22.20° in 2017, respectively, which was roughly deflected in the east-west direction, probably because the eastern and western regions in China have different resource endowments, resulting in the coupled development differ in the short term. However, the distribution pattern of the high east and low west remains unchanged. From the long and short axes lengths, the long axle lengths showed a shortening trend, and the short axle lengths showed an increasing trend, which indicated that the CCD showed a clustering trend in the northeast-southwest direction and a diffusion trend in the southeast-northwest direction, respectively.

(2) As seen in Fig. 4, the level of CCD in 2013–2017 improved significantly. The proportion of provinces in the coupling disorder stage dropped to 76.67 %, and the provinces entering the intermediate coordination stage appeared. In addition, the provinces with the most lagging development during the same period were mainly concentrated in the northeast, southwest, and northwest regions. However, the overall spatial distribution pattern of the high east and low west remained the same. Specifically, compared with 2017, Beijing and Guangdong transitioned from primary coordination to intermediate coordination. Jiangsu and Zhejiang transitioned from barely coordinated to primary coordination. Sichuan province joined the ranks of barely coordinated. Four provinces, Gansu, Qinghai, Hainan, and Jilin, transitioned from the moderate disorder stage to the mild disorder stage. Nine provinces including Liaoning and Inner Mongolia escalated from mild disorder to near disorder. As shown in Fig. 5 and Table 4, from the dynamic trends, the center of gravity of the CCD in 2017–2020 moved southwestward within

Nanyang City, Henan Province, with a displacement distance of 14.86 km, which indicated that the CCD in the western and southern regions of China was continuously improving. From the migration speed, the migration speed of the center of gravity of the CCD was 3.84 km/year in 2013–2017 and 3.71 km/year in 2017–2020, which slowed down in comparison. Thus, it is clear that the speed of CCD in the western and southern regions improves faster and then slower, and the limitations of resource endowment and other constraints make it challenging to provide sustainable power for the coupled coordination between the digital economy and HQED. From the directional distribution changes, the standard deviation ellipse of CCD still maintained the spatial distribution trend of northeast-southwest direction, the ellipse turning angle θ was 23.16°, and the deflection angle increased compared with 2017, which indicated that the overall increase of CCD in southeastern regions was higher than that in northwestern regions during this period. From the long and short axes lengths of the standard deviation ellipse, the dual axes lengths showed an increasing trend in 2017–2020, indicating that the overall spatial pattern of CCD tended to be decentralized during this period.

In total, the overall level of CCD in 2013–2020 qualitatively improved. The center of gravity of CCD migrated to the southwest, the ellipse rotated clockwise, and the rotation angle went up overall. The lengths of the long axis showed an overall decreasing trend and a clustered distribution in the northeast-southwest direction. The lengths of the short axis showed an increasing trend and a diffusion trend in the southeast-northwest direction, and the gap in CCD between the western and southern regions narrowed. One possible explanation is that the application of digital technologies such as big data, cloud computing, and the Internet of Things has broken down barriers to the flow of resource elements, enabled effective cross-regional integration of resources, and promoted balanced development among regions.

5.4. Cold-hot spot pattern evolution of CCD

Before conducting the cold-hot spot analysis, this paper first measures the global autocorrelation index of CCD (Table 5). As shown in Table 5, the global autocorrelation indices of CCD were all positive. They all passed the significance level test of 5 %, indicating that the CCD had a significant positive spatial correlation.

Based on the preliminary test of global autocorrelation, the article can further investigate the spatial clustering characteristics of CCD from the local spatial autocorrelation. In addition, the article divides the calculated $Z(G_i^*)$ values depending on the "Natural Breaks" (Table 6). Then, the article draws the spatial distribution of cold-hot spot of CCD in 2013, 2017, and 2020, respectively (Fig. 6).

As shown in Fig. 6, in 2013, the cold-hot spot areas of CCD overall showed a gradient distribution pattern from east to west, in which the hot spot areas were clustered spatially, and the cold-hot spot areas with insignificant spatial agglomeration showed an "X" structure in the northeast-southwest-northwest-southeast, with a more dispersed distribution. The provinces in the hot spot area are Anhui, Liaoning, Hubei, Jiangsu, Shanghai, Zhejiang, Beijing, Tianjin, Hebei, Shandong, and Henan, mainly clustered in the eastern region. The only two western provinces in the cold spot area are Gansu and Sichuan, and the percentage of the cold-hot spot areas with insignificant spatial agglomeration was 56.67 %. In 2017, the cold-hot spot of CCD overall showed the hot spot area - insignificant spatial agglomeration areas - the cold spot areas with a gradient distribution pattern from east to west, and the hot spot areas of CCD were mainly distributed in the eastern region, with a trend of expansion to the southeast. The hot spot areas were mainly located in 12 provinces, including Anhui and Hubei. Compared with 2013, there was less Liaoning and two more provinces, Jiangxi and Fujian, and only Sichuan Province remained in the cold spot area. The proportion of areas with insignificant spatial agglomeration of the cold-hot spot remained unchanged, and the distribution was still relatively scattered. In 2020, the number of provinces in the hot spot area reduced to 8, mainly concentrated in the Yangtze River Delta region of China. The cold spot area was still only in Sichuan Province, and the areas of insignificant spatial agglomeration were mainly clustered in the north and south ends of China, with a block-like distribution. Comprehensively, the cold-hot spot of CCD gradually developed from a gradient distribution pattern from east to west into a distribution pattern with the Yangtze River Delta region of China as the center of agglomeration, and the regions with insignificant spatial agglomeration are stably distributed in the north and south ends of China. It may be because the State Council of China released the "Outline of the Yangtze River Delta Regional Integrated Development Plan" in 2019 and proposed comprehensive energy demonstration projects such as the Energy Internet of Things and "Internet + Smart" energy, promoting the coupling and interaction of the digital economy and HQED.

5.5. Analysis of driving factors for the CCD

5.5.1. Driving factors selection

Many factors influence the coupled coordination of the digital economy and HQED. Combined with the relevant research [14,37], the article selects economic development level, industrial structure, governmental behavior, environmental regulation, urbanization

Table 5
I_G value of CCD.

Year	2013	2014	2015	2016	2017	2018	2019	2020
Moran' *I*	0.161	0.164	0.163	0.175	0.175	0.132	0.160	0.148
Z	2.617	2.642	2.635	2.793	2.802	2.231	2.619	2.458
P	0.009	0.008	0.008	0.005	0.005	0.026	0.009	0.014

Table 6
Rank of the cold hotspot of the CCD.

$Z(G_i^*)$	(-∞,-2.58]	(-2.58,1.96]	(-1.96,1.65]	(-1.65,1.65)
Rank	Cold spot (99 % confidence level)	Cold spot (95 % confidence level)	Cold spot (90 % confidence level)	No significant spatial agglomeration
$Z(G_i^*)$	[1.65,1.96)	[1.96,2.58)	[2.58, +∞)	
Rank	Hot spot (90 % confidence level)	Hot spot (95 % confidence level)	Hot spot (99 % confidence level)	

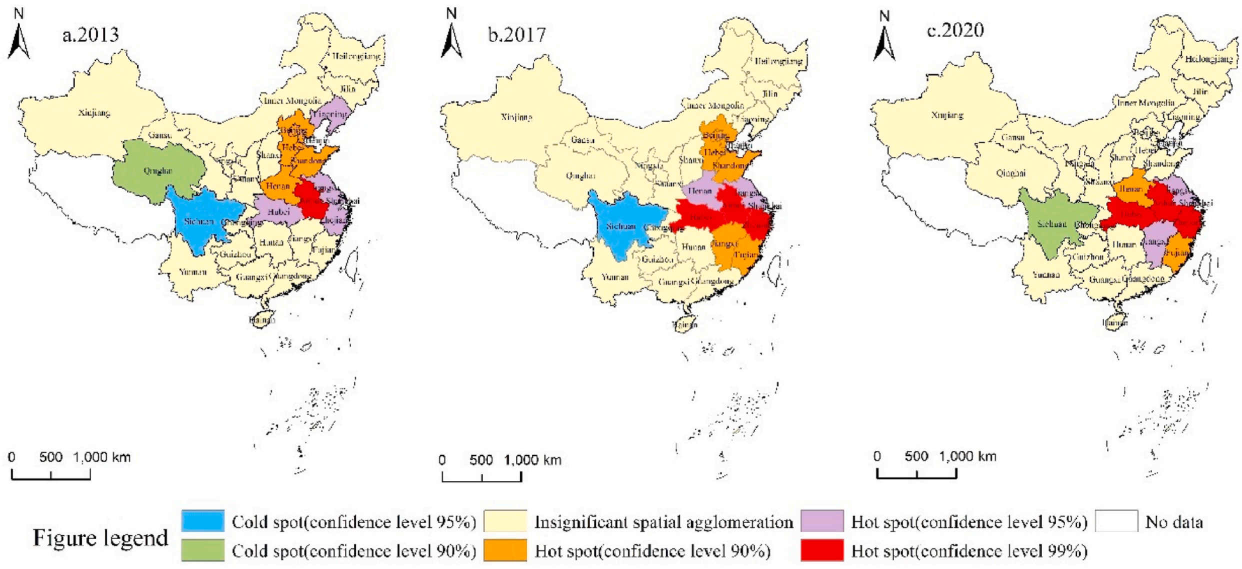

Fig. 6. The spatial distribution of cold-hot spot of CCD from 2013 to 2020.

Table 7
Meaning of driving factor.

	Variable Name	Variable Symbols	Variable Measurement
Explained variables	Coupling coordination degree	*CCD*	Calculation results of the coupling coordination model
Explanatory variables	Economic development level	*pgdp*	GDP per capita
	Industrial structure	*ins*	Tertiary industry share
	Governmental behaviour	*gov*	General fiscal budget expenditure/GDP
	Environmental regulation	*envir*	Industrial pollution control completed investment
	Urbanization level	*urb*	Urban population/total population at year-end
	Technological innovation	*tec*	Number of patent applications granted
	Human capital	*edu*	Number of higher education students per 100,000 people
	External openness	*open*	Total imports and exports/GDP

level, technological innovation, human capital, and external openness as influencing factors (Table 7).

Economic development level. The digital economy is a product of the combination of economic activities and the Internet. An excellent economic situation can directly influence the level of Internet industry infrastructure, which in turn affects the development of the digital economy [47]. At the same time, economic development can affect energy use efficiency [48], which in turn affects HQED, so the economic development level can affect the coordinated development of the two.

Industrial structure. There is a close connection between the digital economy and three major industries, especially the tertiary industry represented by e-commerce, which occupies an essential position in the digital economy, so adjusting the industrial structure will significantly impact the development of the digital economy. In addition, the difference between different industries makes the energy consumption intensity of each industry different [49], so the optimization and adjustment of the industrial structure will affect HQED. Therefore, the industrial structure may also affect the coordinated development of the two.

Governmental behavior. Governmental behavior will influence the construction of digital infrastructure, which will, in turn, affect the development of the digital economy [47]. In addition, some studies suggested that local governments can impact local energy use efficiency while achieving economic growth goals [50], and energy use efficiency is closely related to HQED. Therefore, governmental intervention behavior will affect the coordinated development of the two.

Environmental regulation. As a new economic form, the digital economy inevitably affects the environment in the development process. As a regulatory measure to reduce environmental pollution, environmental regulation will bring direct costs to the digital economy industries, prompt the digital economy industries to adjust their production behavior, and ultimately affect the development level of the digital economy. Numerous studies suggested that environmental regulation can impact energy efficiency [51,52], and a meaningful way to achieve HQED is to improve energy use efficiency, so environmental regulation impacts HQED. Therefore, environmental regulation is selected as the influencing factor of the CCD.

Urbanization level. The urbanization level can affect regional infrastructure construction, and the digitalization and intelligence of infrastructure construction will accelerate the digitalization of cities and industries, thereby affecting the development of the regional digital economy [47]. The development of urbanization makes the population and economic activities concentrate in cities and towns, which generates an aggregation effect and scale benefit and positively affects energy efficiency [48], so the level of urbanization is a factor affecting the CCD.

Technological innovation. Technological innovation not only helps to make up for the deficiencies in basic hardware, software, and components in the digital economy but also assists in overcoming core technologies and complex algorithms in the digital economy, which is the fundamental driving force for developing the digital economy [53]. In addition, technological innovation is the primary source of technological progress and acts on energy efficiency by driving technological advancement [48], so technological innovation is a factor affecting the CCD.

Human capital. As a critical element of the digital economy, human capital significantly influences the development of the digital economy [54]. Demiral and Demiral [55] point out that human capital can impact energy efficiency. Therefore, human capital is considered a factor affecting the CCD.

External openness. The degree of external openness affects the depth of industrial participation in economic globalization. The digital economy industry and the energy industry can participate in economic globalization through import and export, absorb advanced science and technology, and contribute to developing domestic industries, so external openness is a factor affecting the CCD.

5.5.2. *Spatial econometric model selection*

According to the I_G results in the previous paper, the CCD has an apparent spatial correlation. Therefore, we need to use spatial econometric models to study the driving factors of CCD. This paper uses the Lagrange multipliers (LM) test, Hausman test, and likelihood ratio (LR) test to make the model selection more rigorous (Table 8). Among them, the LM-error and LM-lag both pass the 1 % significance test, indicating that both the error term and the lag term have spatial correlation, so this paper needs to construct the SDM. The Hausman test rejects the hypothesis of using random effects. The LR double-fixed effects test shows that the paper needs to use the double-fixed SDM. The LR test shows that the SDM cannot degenerate into the SAR and the SEM. Therefore, this paper finally chooses the double-fixed SDM.

5.5.3. *Regression results and discussion*

The article uses the spatial adjacency weight matrix to regress Equation (8), and the regression results are displayed in Table 9. It can be known from the regression coefficients that the CCD is significantly and positively influenced by seven factors: economic development level, industrial structure, government behavior, environmental regulation, urbanization level, technological innovation, and external openness. From the lagged term coefficients, economic development level, urbanization level, technological innovation, and human capital significantly influence the CCD in neighboring regions, among which economic development level and human capital are positively influencing factors, and urbanization level and technological innovation are negatively influencing factors. Overall, the CCD is jointly influenced by the economic development level, urbanization level, and technological innovation of the local and neighboring provinces.

To further examine the magnitude and direction of the spatial spillover effects of the drivers, this paper draws on Lesage's study to estimate the direct and indirect effects of the influences [56] (Table 10).

5.5.3.1. Direct effects. The economic development level significantly and positively affects the CCD, which indicates that economic development can facilitate the coordinated development of the digital economy and HQED. The improvement of economic development can improve energy utilization efficiency while providing good primary conditions for developing the digital economy, thus accelerating the coupling and coordination process of the digital economy and HQED. This is consistent with the research results of [14].

The industrial structure significantly and positively affects the CCD, which indicates that transforming the industrial structure into

Table 8
Model selection test results.

Test method	Test index	Statistics	*P*-value
LM test	LM-lag	11.703	0.001
	Robust LM-lag	5.910	0.015
	LM-error	8.188	0.004
	Robust LM-error	2.394	0.122
Hausman test	Fixed effect or random effect	36.35	0.004
LR double fixed effects test	Double fixed or spatial fixed	18.18	0.052
	Double fixed or time fixed	583.91	0.000
LR test	LR-spatial-lag	28.36	0.000
	LR-spatial-error	27.69	0.001

Table 9
Regression results.

Variables	Regression coefficient	Variables	Lagging term coefficient
pgdp	0.092***	W × *pgdp*	0.097**
	(0.00)		(0.05)
ins	0.001**	W × *ins*	−0.001
	(0.02)		(0.23)
gov	0.079**	W × *gov*	−0.074
	(0.05)		(0.45)
envir	0.024***	W × *envir*	−0.020
	(0.00)		(0.43)
urb	0.003***	W × *urb*	−0.004**
	(0.00)		(0.03)
tec	0.024***	W × *tec*	−0.042***
	(0.00)		(0.00)
edu	0.081	W × *edu*	0.392**
	(0.15)		(0.04)
open	0.025*	W × *open*	−0.045
	(0.10)		(0.40)
R^2	0.622	Observations	240

Robust standard errors are in parentheses. ***、**、* reflect significance levels of 1 %, 5 %, and 10 %, respectively.

Table 10
Direct effect, indirect effect of the SDM.

Variables	Direct effect	Indirect effect
pgdp	0.092***	0.096**
	(0.00)	(0.04)
ins	0.001**	−0.001
	(0.01)	(0.26)
gov	0.084**	−0.074
	(0.03)	(0.45)
envir	0.024***	−0.021
	(0.00)	(0.44)
urb	0.003***	−0.004**
	(0.00)	(0.02)
tec	0.024***	−0.042***
	(0.00)	(0.00)
edu	0.079	0.379*
	(0.17)	(0.05)
open	0.025*	−0.043
	(0.09)	(0.44)
R^2	0.622	
Observations	240	

Robust standard errors are in parentheses. ***、**、* reflect significance levels of 1 %, 5 %, and 10 %, respectively.

"clean" and "green" can enhance efficiency in energy use and promote HQED. In addition, optimizing industrial structure can provide more robust industrial and economic support for developing the digital economy, thus effectively synergizing the digital economy and HQED.

Government behavior significantly and positively affects the CCD. It may be because the government, an essential player in stabilizing economic and social development, can better allocate resources and optimize industrial layout, thereby optimizing the coordinated relationship between the digital economy and HQED. This is consistent with the research results of [14].

The positive effect of environmental regulation on the CCD passed the 1 % significance test, suggesting that strict environmental control measures can urge the digital economy industry to innovate technologically and provide high-tech green technologies for the energy industry to improve the quality of regional energy development. In addition, environmental regulation can force the energy industry to make structural adjustments and better integrate with digital technology. Thus, environmental regulation can enhance the CCD. This is consistent with the research results of [37].

The effect of urbanization level on the CCD passed the 1 % significance level test with a positive direction, implying that urbanization development contributes to the coupling and coordination of the digital economy and HQED. The reason may be that urbanization development will accelerate the allocation of resources, such as innovative talents, which can enhance energy utilization efficiency while promoting the development of the digital economy. This is consistent with the research results of [14].

The technological innovation significantly and positively affects the CCD, which may be because technological innovation has a positive driving influence on the development of the digital economy. The iterative update of the digital technology can better integrate with the energy industry and promote HQED, so technological innovation can effectively improve the CCD. This is consistent with the research results of [37].

The positive effect of human capital on the CCD does not show statistical significance, probably because China has a certain degree of structural deficiency in talent supply, which still needs to adapt to the requirements of promoting efficient synergy between the digital economy and HQED.

The effect of external openness is significantly positive, reflecting that the advanced technology and experience brought by external openness can promote the development of the digital economy through the "spillover and penetration effect" and raise energy utilization efficiency, thus improving the CCD.

5.5.3.2. Indirect effects. The coefficient of economic development level is significantly positive, suggesting that economic development has a positive spatial spillover effect, which positively affects the improvement of CCD in surrounding provinces.

The influence of industrial structure on the CCD is not significant. This is probably because the industrial structure is affected by factors such as economic base and location conditions, resulting in considerable regional heterogeneity in the industrial structure, ultimately making the industrial structure have an insignificant effect on the conductive action of CCD in surrounding provinces.

Government behavior has an insignificant effect on the CCD. A possible explanation is that the government regulates depending on the coordinated development status of each region. Since the progress of coordinated development of each region is different, the regulatory policies made by the government based on the province do not apply to other regions. Therefore, it is insignificant that local governmental behavior affects the CCD in surrounding provinces.

Environmental regulation has an insignificant influence on the CCD. The reason may be that each region has heterogeneity in the coordinated development status, and the intensity of environmental regulation to adapt to is different. Therefore, the local environmental regulation has an insignificant effect on the CCD in surrounding provinces.

Urbanization level significantly and negatively affects the CCD, demonstrating that urbanization level has a negative spatial spillover effect. This is probably because regions with a higher level of urbanization have more robust innovation vitality, negatively affecting the CCD in surrounding provinces through the "siphon effect."

The negative effect of technological innovation passes the 1 % significance level test, implying that technological innovation has a negative spatial spillover effect. It may be because the "trickle-down effect" created by technical advancement is weaker than the "polarization effect," which has an inhibitory effect on the CCD in surrounding provinces.

The positive effect of human capital is significant, showing that human capital has a positive spatial spillover effect. This may be because the "knowledge spillover effect" formed by human capital can positively influence the CCD in surrounding provinces.

The coefficient of external openness fails the significance test. This may be because there is a "Matthew effect" in the external openness. Therefore, the effect of external openness on the CCD in surrounding provinces is not apparent.

5.5.4. Robustness test

The paper needs a robustness test to ensure the empirical results' robustness. Considering that the regression results are sensitive to the selection of spatial weights, this paper constructs an economic distance matrix, an inverse distance matrix, and an economic and geographical distance nested matrix to verify the robustness of the results (Table 11). The economic distance matrix uses GDP per capita as the economic variable (data are from 2013 to 2020). The reciprocal of the linear distance expresses the inverse distance matrix, and the linear distance is calculated by latitude and longitude. The economic and geographical distance nested matrix is a combination of the economic distance matrix and the inverse distance matrix. As shown in Table 11, the regression coefficients' direction and significance did not change. The direction of the individual coefficients of the lagged items altered, but none passed the significance test, indicating that the results are robust.

6. Conclusion and policy implications

6.1. Conclusion

Based on the data from 30 Chinese provinces in 2013–2020, this article empirically analyzes the spatiotemporal evolution characteristics and driving factors of the coupling coordination between the digital economy and HQED. Five conclusions are as follows.

(1) The kernel density curve of CCD moves to the right, and the level of CCD among provinces in China shows an overall upward trend. The kernel density curve of CCD shows a single-peak shape, the peak value of the curve decreases year by year, and the curve's width gradually changes from "high and narrow" to "short and wide". Namely, the absolute difference in CCD among provinces in China has an expanding trend, and there is a prominently spatial non-equilibrium characteristic. The kernel density curve of CCD trails to the right and tends to broaden, and there are apparent gradient differences in the CCD among Chinese provinces.
(2) In the east-west direction of the trend surface, the CCD exhibits a "parabolic" spatial structure of gradually increasing from west to east. In addition, the arc of the trend line projection slows down from 2013 to 2020, and the difference in CCD between the eastern and western regions of China tends to shrink. In the north-south direction of the trend surface, the CCD shows an inverted "U" spatial structure, and the CCD in the central region of China is higher than that in the southern and northern regions.

Table 11
Robustness test results.

Variables	Economic distance matrix		Inverse distance matrix		Economic and geographical distance nested matrix	
	X	WX	X	WX	X	WX
pgdp	0.102***	−0.004	0.089***	−0.006	0.089***	−0.050
	(0.00)	(0.81)	(0.00)	(0.86)	(0.00)	(0.49)
ins	0.001**	0.000	0.001**	−0.000	0.001**	0.000
	(0.04)	(0.81)	(0.03)	(0.80)	(0.02)	(0.94)
gov	0.126***	−0.148***	0.089**	−0.241**	0.069*	−0.823***
	(0.00)	(0.00)	(0.02)	(0.04)	(0.07)	(0.01)
envir	0.020***	−0.002	0.024***	0.011	0.024***	0.034
	(0.00)	(0.84)	(0.00)	(0.54)	(0.00)	(0.37)
urb	0.002***	−0.000	0.003***	−0.002	0.003***	−0.006
	(0.00)	(0.93)	(0.00)	(0.20)	(0.00)	(0.10)
tec	0.028***	−0.016***	0.025***	−0.015**	0.023***	−0.029**
	(0.00)	(0.00)	(0.00)	(0.02)	(0.00)	(0.02)
edu	0.008	0.036	0.082	0.029	0.091	0.376
	(0.88)	(0.61)	(0.13)	(0.86)	(0.12)	(0.43)
open	0.043***	−0.008	0.030**	0.010	0.030*	0.028
	(0.40)	(0.71)	(0.05)	(0.78)	(0.05)	(0.66)
R^2	0.706		0.670		0.535	
Observations	240		240		240	

Robust standard errors are in parentheses. ***、**、* reflect significance levels of 1 %, 5 %, and 10 %, respectively.

(3) The level of CCD shows an overall increasing trend, with apparent hierarchical differentiation. In 2013, the proportion of provinces in the coupling disorder stage accounted for 93.33 %, and in 2020, the proportion of provinces in the coupling disorder stage decreased to 76.67 %. The center of gravity of CCD migrates to the southwest, and the standard deviation ellipse is distributed in the northeast-southwest direction. The standard deviation ellipse rotates clockwise, and the overall rotation angle shows an increasing trend. Namely, the overall increase in CCD in southeastern China is higher than that in northwest China. The long axis length of the standard deviation ellipse generally shows a downward trend, and the short axis length shows an increasing trend. That is, the CCD exhibits an agglomeration trend in the northeast-southwest direction and diffusion in the southeast-northwest direction.
(4) From the global autocorrelation, the CCD has a significant positive spatial correlation. From the local autocorrelation, the cold-hot spot of CCD gradually develops from the gradient distribution pattern from east to west into a distribution pattern with the Yangtze River Delta region of China as the center of agglomeration. The areas with insignificant spatial agglomeration are stably distributed in the north and south ends of China.
(5) Economic development, industrial structure, government behavior, environmental regulation, urbanization level, technological innovation, and opening up significantly and positively affect the CCD. At the same time, there is a positive spatial spillover effect of economic development and human capital. There is a negative spatial spillover effect of urbanization level and technological innovation.

6.2. Policy implications

Based on the above conclusions, this article makes the following policy recommendations.

(1) The coupled interaction and organic integration of the digital economy and HQED need to be actively promoted. Firstly, the government should pay attention to the enabling effect of the digital economy on HQED. On the one hand, the government should speed up constructing a data factor market system and boost the full circulation and use of data elements. This can promote the optimal allocation of production factors in the energy system and the interconnection and interaction of all links in the energy industry chain, thereby achieving HQED. On the other hand, the government should accelerate the innovative application of digital technologies such as artificial intelligence, the Internet of Things, and blockchain in the energy field, release the amplification, superposition, and multiplication effect of the digital economy on the energy industry, and provide assistance for the realization of HQED. Secondly, the government should guide and support the energy industry to actively use digital technologies to build a new type of energy infrastructure so that the two sides can match and interact more quickly. This can realize the digital transformation of energy while releasing the value of data elements and providing energy usage scenarios for the digital economy.
(2) The government should formulate differentiated development strategies based on each region's coupling and coordination relationships to promote the "same-frequency resonance" of the digital economy and HQED. For areas with a high CCD, the government should actively summarize the experience of coupled and coordinated development and fully play its radiation role to narrow the development gap while ensuring its own highly coordinated development. For example, eastern areas of China can build a coupling and coordination demonstration zone of the digital economy and HQED and give full play to its demonstration and diffusion effects, leading to developing regions with a low CCD. At the same time, for areas with a low CCD,

the government should seize the opportunity of the new round of scientific and technological revolution and industrial transformation, integrate its advantageous resources, adjust the industrial structure, and expand the connection between the digital economy and the energy industry, thereby improving the potential of integrating and progressing in the digital economy and HQED. For example, the western areas of China should grasp the opportunity of the construction of the "National Big Data Comprehensive Pilot Zone". Local governments can learn from the construction of the digital economy in advanced areas, enhance digital thinking, increase the investment in digital infrastructure, accelerate the application of digital technology in the energy field, and then promote the coupling and coordination of the digital economy and HQED.

(3) The government should establish a regional cooperation mechanism to strengthen the linkage effect between regions and narrow the coupled and coordinated development gap. The "East Data and West Calculation" project aims to guide the data resources in the eastern region of China to the western regions where renewable energy is abundant in an orderly manner. It not only alleviates the energy shortage problem in the eastern region but also makes up for the lack of data resources in the western region, thus promoting the collaborative and linked development of the eastern and western regions. In addition, the cross-domain flow of data elements brought about by this project will help open up the digital economic artery between the East and the West and promote the integrated development of digital economy and energy. Therefore, local governments should actively implement this project.

(4) In order to create a "growth pole" for coupled and coordinated development, local governments need to combine their comparative advantages, rationally adjust the industrial structure, moderately intervene in government intervention, scientifically promote the urbanization process, strengthen talent training, enhance scientific and technological innovation capabilities, and actively participate in international cooperation.

6.3. Limitations and future research

As the world's top energy consumer and the second-largest digital economy, China is representative of promoting the efficient integration of the digital economy and HQED, and the measures it has taken can provide a reference for other countries. However, there are some limitations to our study. Firstly, HQED has rich connotations, and its evaluation index system still needs to be harmonized. The indicators selected in this article may not be comprehensive and still need to be improved. Secondly, due to data limitations, the study is not refined to the city and county level, which may leave some information unexplored. Thirdly, the drivers of CCD may be omitted and need to be further explored in the future. Fourthly, the economic and environmental effects of the coupling and coordination of the digital economy and HQED are a vital issue worth considering. However, it has yet to be explored in this paper and can be further studied in the future.

Data availability statement

Data will be made available on request.

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Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Shuhe Wang: Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Anqi Wang:** Writing – review & editing. **Shizhe Liu:** Writing – review & editing. **Ce Zhang:** Writing – review & editing. **Lixing Qiao:** Writing – review & editing. **Xiaomin Li:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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