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How does the synergistic effect of green finance and digital finance affect carbon emission efficiency? An example from the Yangtze River Economic Belt

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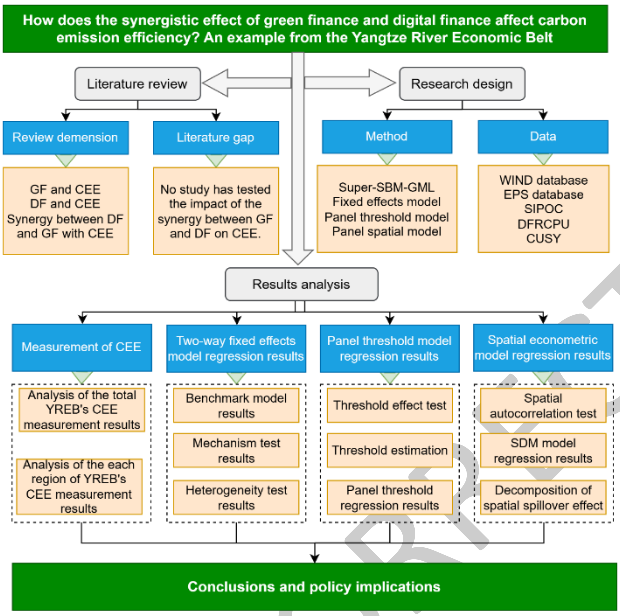
Graphical abstract



Abstract

Green finance (GF) and digital finance (DF) are important enablers for the digitization and greening of the economy, and they are also vital drivers of carbon emission efficiency (CEE). The paper incorporates GF, DF, and CEE into the same research framework to empirically explore the nexus between the synergy of GF and DF and the CEE of the Yangtze River Economic Belt (YREB). The findings are as follows. First, the synergy between GF and DF positively affects the CEE of YREB. This is mainly achieved by facilitating innovation in green technology and lowering carbon emission intensity. Second, the synergy between GF and DF contributes more clearly to CEE for cities in the upper reaches of YREB, cities of high population densities, and cities with high green innovation capacity. Third, there is a single threshold effect of the synergy between GF and DF on the CEE of YREB. When the collaborative development level between GF and DF is larger than 0.6659, the synergy between GF and DF can be more conducive to driving the improvement of CEE. Fourth, the synergy between GF and DF generates a positive spatial spillover effect on the CEE in YREB, which contributes to the CEE of the local cities in YREB and the neighboring cities in YREB. The findings can provide implications for formulating low-carbon development policies.

Keywords: green finance; digital finance; synergistic effect; carbon emission efficiency; Yangtze River Economic Belt

1. Introduction

Against the backdrop of the increasingly serious issue of climate change, the significance of promoting the transition of economic systems to low-carbonization has been widely recognized globally (Lei, 2024). China faces enormous pressure for a low-carbon transition (Wu *et al.* 2023). The Yangtze River Economic Belt (YREB) is vital for China's economic development, ecological environment protection, and restoration (Liu *et al.* 2024a). It plays a crucial role in the greening and low-carbonization of economic development. The progress and effectiveness of its low-carbon transition are related to the formulation of sustainable development coping strategies and the realization of carbon reduction targets in China and globally. Therefore, focusing on the carbon reduction capacity of YREB is necessary.

The role of the financial sector in carbon emission reduction can't be ignored. To address ecological challenges and improve carbon emission efficiency (CEE), the financial industry has developed two new types of financial forms and services: green finance (GF) and digital finance (DF). GF is the financial services provided to support green economic activities. DF is a new financial service model formed by applying digital technologies to the financial industry. Notably, DF can accurately identify, assess, and manage the risks and returns of green projects by its efficient, convenient, and inclusive nature, thus providing GF with more scientific and intelligent decision-making support (Zhao *et al.* 2023). This helps to improve the innovation ability and market competitiveness of GF products, thereby promoting the prosperous development of the low-carbon industry. Therefore, GF and DF can be regarded as sharing common objectives in enhancing resource utilization, improving environmental protection benefits, promoting low-carbonization of the economic structure, and expanding the space for green development.

The synergy between GF and DF can fully integrate the strengths of GF and DF, playing the double-wheel drive effect of "technology empowerment + financial guidance", thus forming a strong synergy to promote the improvement of CEE in YREB. Specifically, first, to achieve a highly efficient allocation of resources. DF can use digital technologies to help financial institutions scientifically assess the degree of greenness and low-carbon of projects so that GF resources can be more efficiently allocated to green and low-carbon areas (Yin *et al.* 2024). This can reduce unnecessary waste of resources (Shi and Yang, 2024), thereby reducing carbon emissions to improve CEE. Second, to lower financing costs and thresholds. Traditional GF often suffers from high investment risk, high financing thresholds, unbalanced distribution of resources, and lower quality and efficiency of services in its development (Hossain *et al.* 2024; Xie *et al.* 2024). The intervention of DF breaks these restrictions and enhances the transparency and credibility of the financial market. The synergy between GF and DF can not only promote the innovation and development of DF (Cheng *et al.* 2023) but also prompt the development of GF to release the signal of improving the quality of the ecological environment (Shi and Yang, 2024). This can push the industries in YREB to actively undergo decarbonization transformation, which in turn will enhance the CEE of YREB. Third, to promote the coordinated development between regions. The synergy between GF and DF can realize information sharing and resource integration of low-carbon projects by building a regional GF service platform (Liu *et al.* 2024b). This contributes to promoting the formation of low-carbon industry cluster effects, thus playing a role in reducing carbon emissions (Yin *et al.* 2024). YREB can leverage the power of the synergy between GF and DF to alleviate the imbalance of regional low-carbon development, further enhancing CEE.

However, it should be pointed out that although the synergy of GF and DF can bring many benefits to the low-carbon development of YREB, the integration and development of GF and DF are facing many issues at this stage. For example, insufficient information construction, an imperfect GF market development system (Liu *et al.* 2024b), a shortage of composite talents, difficulties in financial regulation, and serious greenwashing behavior of enterprises (Guo *et al.* 2024). These issues may cause the synergy of GF and DF to have an unfavorable impact on the low-carbon development of YREB. The paper explores the impact of the synergy between DF and GF on CEE using the two-way fixed effects model, panel threshold model, and spatial econometric model with a sample of 106 cities in YREB in 2011-2021.

The contributions are as follows. First, studies on the nexus between GF and carbon emissions and the nexus between DF and carbon emissions have been relatively well investigated. However, there is not yet a study exploring the synergy of GF and DF with the impact of CEE from the view of YREB cities. The paper includes GF, DF, and CEE in the same framework, analyzes the nexus between the synergy of GF and DF and the CEE of YREB, and examines the mechanisms involved. This can fill the existing study gap. Second, the paper uses the level of synergy development between GF and DF as a threshold variable to test the possible non-linear impact of the synergy between GF and DF on the GEE of YREB using a panel threshold model. This can extend the scope of existing studies and enrich the relevant literature on the three topics of GF, DF, and CEE, thus providing useful insights into the benign synergy between GF and DF. Third, the paper explores the spatial spillover effect of the synergy between GF and DF on CEE in YREB. This can provide lessons for narrowing the low-carbon development gap among YREB regions and promoting synergistic carbon reduction among YREB regions.

2. Literature review

2.1. Studies about the impact of GF on CEE

Existing studies reveal that GF mainly affects CEE by exerting resource allocation effect, market incentive effect, technological innovation effect, and policy orientation effect.

From the perspective of the resource allocation effect, GF can effectively guide the flow of production factors to green industries (Liu *et al.* 2024b). This can compress the development space of high-carbon industries (Ran and Zhang, 2023) and support the sustainable development of low-carbon industries, thus achieving the purpose of improving the welfare performance of carbon emissions (Wang and Gao, 2024). Furthermore, GF can help to price environmental benefits reasonably, which can drive the resource flow towards low-carbon projects with lower marginal abatement costs, ultimately positively affecting CEE.

From the perspective of the market incentive effect, GF can encourage more and more investors and consumers to be more concerned about the environmental performance of enterprises by forming a benign price mechanism, competition mechanism, and information disclosure mechanism (Hu *et al.* 2023). This will create incentives for innovation and industrial optimization (Wang and Gao, 2024), and motivate enterprises to adopt more environment-friendly and low-carbon production methods to enhance CEE. Moreover, GF can support carbon financial product innovation, enrich carbon market trading varieties, improve carbon market mechanisms, etc., which can facilitate the growth of CEE.

From the perspective of the technological innovation effect, GF can provide financial support for enterprises to use energy-saving equipment and clean technologies (Liu *et al.* 2024b). This facilitates the promotion of enterprises to increase R&D efforts, introduce low-carbon production technologies (Chen *et al.* 2025), update production equipment, and improve energy use efficiency (Cheng *et al.* 2023). As a result, the energy consumption of enterprises can be reduced, and the transformation and application of technological achievements can be accelerated to improve CEE.

From the perspective of the policy orientation effect, improving the GF policies and regulating the GF standards will have a normative and orientate function on financial institutions, enterprises, and consumers, thus contributing to the low-carbonization of economic development. GF policies can guide financial institutions to tilt financial resources towards industries with high CEE (Wang and Gao, 2024). This can reinforce the policy constraints on enterprises to reduce emissions. At this point, enterprises will upgrade production technologies, renovate production equipment, and improve environmental protection facilities to meet environmental protection standards and satisfy GF thresholds, thus improving energy utilization (Zhang *et al.* 2024a) and promoting CEE growth. In addition, the publicity of the GF policies will promote a shift in consumers' consumption preferences towards green and low-carbon ones, which will make consumers more favorable to environment-friendly products and services (Gong *et al.* 2024), thus increasing the CEE.

2.2. Studies about the impact of DF on CEE

Existing studies suggest that DF can affect CEE mainly from four perspectives: scale effect, wealth effect, technology effect, and structural effect.

From the view of the scale effect, DF can leverage the scale effect (Zhong *et al.* 2023) by promoting digital platforms, reducing service costs (Li *et al.* 2023), and accurately identifying the demand for financial services. This expands the coverage of financing services and favors the promotion of economic growth by enabling enterprises to obtain financing more quickly to expand their scale of production (Zhao *et al.* 2023). Expansion of economic scale will lead to more resource consumption, thus increasing carbon emissions (Cheng *et al.* 2024), which is not conducive to the improvement of CEE.

From the view of the wealth effect, DF can promote residents' consumption through the provision of convenient payment and credit services (Li *et al.* 2023). This helps to increase consumers' purchasing power and willingness to consume and speeds up the process of consumer decision-making (Cheng *et al.* 2024), thus creating a wealth effect (Zhang *et al.* 2023) and further boosting economic growth. It will stimulate high-carbon consumption and trigger more energy consumption, leading to more carbon emissions (Liu *et al.* 2021), which in turn will have a dampening effect on CEE.

From the view of the technical effect, DF can stimulate market vitality and innovation by generating inclusive (Zhao *et al.* 2023), long-tail, and precise effects, and satisfy the diversified financing needs, linkage needs, and wealth needs of many sectors. It can help reduce business risks and financing costs, stimulate enterprises to carry out technological reforms and innovations, and prompt enterprises to actively undertake social responsibilities (Razzaq and Yang, 2023). This can facilitate the improvement of environmental performance (Hao *et al.* 2023; Jin *et al.* 2023), thus enhancing CEE.

From the view of structural effect, DF can support the development of low-carbon industries (Li *et al.* 2023) more effectively through its unique financing model and risk assessment system. These industries usually have lower carbon emission intensity, higher resource use rate, and more reasonable energy use structure (Zhong *et al.* 2023). The development of DF enables these industries to obtain more financial support, thus accelerating their growth and expansion. This can optimize the industrial structure and improve the allocation of production factors (Jin *et al.* 2024; Liu and Hu, 2025), thus contributing to the growth of CEE (Wu *et al.* 2023).

2.3. Studies about the impact of synergy between GF and DF on CEE

GF and DF are vital forces for economic low-carbon transition, and their synergistic effects on CEE have received increasing attention from academics. Existing studies have shown that the synergy of GF and DF positively affects carbon emission abatement by strengthening environmental regulation and law enforcement, facilitating technological innovation and industrial upgrading, enhancing resource utilization, and promoting market expansion and financial service innovation.

From the aspect of strengthening environmental regulation and enforcement, GF guides the low-carbon transition through the allocation of funds, and DF leverages technologies to improve the transparency of environmental data and the effectiveness of regulation. The synergy between GF and DF can prompt government departments to strengthen policy orientation and standard-setting in the areas of GF and DF (Mirza *et al.* 2023). This contributes to forming an effective environmental regulatory system, which is normative and directive for financial institutions, producers, investors, and consumers (Hossain *et al.* 2024; Huang and Ren, 2024; Qin *et al.* 2024; Yin *et al.* 2024). It can lead to the low-carbon transition in production and living, thus improving CEE.

From the aspect of contributing to technological innovation and industrial upgrading, DF provides stronger technical support to GF and promotes the research, development, and application of low-carbon technologies (Safi *et al.* 2024). This helps promote the development of green industries and the green transformation of highly polluting industries (Huang and Ren, 2024). Additionally, the synergy between GF and DF can accelerate the diffusion of technologies, reduce financial transaction costs, and enhance transparency of environmental benefits, which can lead to a cycle of “green preferences” for capital. Ultimately, this can drive the energy transition, reduce carbon emissions, and improve CEE (Hossain *et al.* 2024).

From the aspect of enhancing resource use efficiency, the synergy between GF and DF can make the factors of production (such as labor, capital, energy, technologies, etc.) be more efficiently allocated and utilized through pinpointing the inefficient aspects of resource utilization (Liu *et al.* 2024b). Furthermore, the synergy between GF and DF can also promote information sharing and co-operation among enterprises and help to recycle resources, thus prompting more factors of production to be guided into low-carbon and energy-saving fields (Yin *et al.* 2024). This can help to increase energy resilience, enhance the competitiveness of low-carbon industries (Lei *et al.* 2025), etc., thereby driving the growth of CEE.

From the aspect of promoting market expansion and financial service innovation, the synergy between GF and DF can promote the expansion of the GF market (Zhou *et al.* 2022) and provide a broader market space for the improvement of CEE. Through the introduction of carbon trading, carbon quotas, and other market mechanisms, GF can more effectively guide enterprises to reduce carbon emissions (Yin *et al.* 2024) and improve CEE. Furthermore, the synergy between DF and GF can promote the greening of financial services (Qin *et al.* 2024) and improve the low-carbon financial support system. This can provide more green financing options for enterprises, which can help promote low-carbon development and have a positive effect on CEE.

2.4. Literature gap

The existing literature has mainly studied the relationship between DF and energy transition (Li *et al.* 2023), industrial structure transformation (Zhong *et al.* 2023), green innovation (Hao *et al.* 2023), green growth (Razzaq and Yang, 2023), and carbon emission intensity (Zhang *et al.* 2023). Besides, the existing literature has also tested the impact of GF on energy use (Cheng *et al.* 2023), green technology innovation (Huang *et al.* 2024), green development efficiency (Liu *et al.* 2024b), carbon emission reduction (Ran and Zhang, 2023), low-carbon transition of the economy (Zhang *et al.* 2024b), and carbon emission reduction welfare performance (Wang and Gao, 2024). However, there is less literature on exploring the synergistic effects of GF and DF. Some studies have examined the impact of the synergy between GF and DF on the profitability of financial institutions (Mirza *et al.* 2023), green economic growth (Zhou *et al.* 2022), green environment (Qin *et al.* 2024), energy use efficiency (Shi and Yang, 2024), pollution and carbon reduction (Yin *et al.* 2024), and sustainable development (Safi *et al.* 2024). Yet, no study has tested the impact of the synergy between DF and GF on CEE. The paper innovatively studies the impact of the synergy of GF and DF on the CEE of YREB based on the efficiency perspective, which can fill the gap in the existing literature.

3. Research design

3.1. Model construction

For investigating exactly how the synergy between GF and DF affects the CEE of YREB, the paper constructs equation (1).

$$LGEE_{it} = \mu_1 + \alpha_1 SGD_{it} + \varphi_1 Control_{it} + \sigma_i + \sigma_t + \varepsilon_{it} \tag{1}$$

Among them, $LCEE_{it}$ means carbon emission efficiency. SGD_{it} indicates the synergy between green finance and digital finance. $Control_{it}$ means the group of control variables. μ_1 signifies a constant term, σ_i indicates city fixed effect, σ_t represents year fixed effect, ε_{it} indicates a random error term.

At different levels of GF and DF development, their effects on CEE may be quite different. There may be a non-linear nexus between the synergy of GF and DF and the CEE of YREB. The panel threshold model can better show the non-linear causal connection between the variables. The paper adopts this model to examine whether the impact of the synergy of GF and DF on the CEE of YREB has a threshold effect. The model is set as equation (2).

$$\begin{aligned} LCEE_{it} = {} & \mu_2 + \eta_1 SGD_{it} \times I\left(SGD_{it} \le \gamma_1\right) \\ & + \eta_2 SGD_{it} \times I\left(\gamma_1 < SGD_{it} \le \gamma_2\right) \\ & + \ldots + \eta_n SGD_{it} \times I\left(\gamma_{n-1} < SGD_{it} \le \gamma_n\right) \\ & + \eta_{n+1} SGD_{it} \times I\left(SGD_{it} > \gamma_n\right) + \varphi_2 Control_{it} + \varepsilon_{it} \end{aligned} \tag{2}$$

Where $I(*)$ is the indicator function and $\gamma_1, \gamma_2 \ldots \gamma_n$ are thresholds for n different levels.

Cities in YREB have close economic ties, a clear division of labor in industry, and a relatively well-developed regional economic system. This makes the development of GF, DF, carbon emission scale, and CEE of a city not only affected by its own factors but also may be influenced by neighboring cities or cities with economic links. Thus, the paper uses the Spatial Durbin Model (SDM) to study the spatial effect of the synergy of GF and DF on the CEE of YREB. The model is set as equation (3).

$$\begin{aligned} LCEE_{it} = {} & \mu_3 + \beta \sum_{j=1}^{106} W_{ij} LCEE_{jt} + \vartheta_1 SGD_{it} \\ & + \varphi_3 Control_{it} + \theta_1 \sum_{j=1}^{106} W_{ij} SGD_{jt} \\ & + \varphi_4 \sum_{j=1}^{106} W_{ij} Control_{jt} + \sigma_i + \sigma_t + \varepsilon_{it} \end{aligned} \tag{3}$$

Among them, W_{ij} means the spatial weight matrix. The paper represents it by constructing a multidimensional spatial weight matrix by considering the factors of economic distance, industrial similarity and financial connectivity. $W_{ij} = \sum_{k=1}^{3} \beta_k * W_{ij}^{(K)}$. β_k is the weight of the *k*-th factor. $W_{ij}^{(1)} = \frac{1}{d_{ij} \times \left|E_i - E_j\right|}$, which stands for the economic distance weight matrix. d_{ij} denotes the distance between the *i*-th city and the *j*-th city. *E* is an indicator of the degree of economic development, which is expressed using per capita GDP. $W_{ij}^{(2)} = \frac{\sum_{k=1}^{n} X_{ik} \times X_{jk}}{\sqrt{\sum_{k=1}^{n} X_{ik}^2 \times \sum_{k=1}^{n} X_{jk}^2}}$, which represents the industry similarity weight matrix. X_{ik} and X_{jk}

denote the share of industry k in the industrial structure of city i and city j, respectively. n is the total number of industries. $w_{ij}^{(3)} = \frac{F_{ij}}{\sum_{k=1}^{n} F_{ik}}$, which represents the financial connectivity weight matrix. F_{ij} represents the financial transaction volume between city i and city j. ϑ_1 means the degree of direct effect of the synergy between GF and DF on the CEE of YREB. θ_1 signifies the intensity of the spatial spillover effect of the synergy between GF and DF on the CEE of YREB.

3.2. Variable definition and measurement

3.2.1. Explained variable

Carbon emission efficiency (LCEE). Efficiency is typically measured using the traditional Data Envelopment Analysis (DEA) method. Two main scenarios occur with this method when calculating efficiency. One is that the efficiency values are less than 1, and the other is that the efficiency values are equal to 1. The former means the efficiency values are invalid, and the latter means the efficiency values are valid. When considering unexpected output and comparative analyses of effective decision-making units (DMUs), the traditional DEA model is no longer applicable. Tone (2003) proposed a non-angle, non-radial Super-Slacks-Based-Measure (Super-SBM) model based on input-output slack variables. This enables effective DMUs to be extracted from the reference set, allows for efficiency larger than 1, and incorporates unexpected outputs. Therefore, the paper uses the Super-SBM model to measure the CEE for each city of the YREB, which is shown in equation (4).

$$\rho^* = min \frac{1 + \frac{1}{m}\sum_{i=1}^{m} \frac{s_i^-}{x_{ik}}}{1 - \frac{1}{s_1 + s_2}\left(\sum_{r=1}^{s_1} \frac{s_r^g}{y_{rk}^g} + \sum_{t=1}^{s_2} \frac{s_t^b}{y_{tk}^b}\right)} \tag{4}$$

$$s.t.\begin{cases} x_{ik} \geq \sum\limits_{j=1, j\neq k}^{n} x_{ij}\lambda_j - s_i^- \\ y_{rk}^g \leq \sum\limits_{j=1, j\neq k}^{n} y_{rj}\lambda_j + s_r^g \\ y_{tk}^b \geq \sum\limits_{j=1, j\neq k}^{n} y_{tj}\lambda_j - s_t^b \\ 1 - \frac{1}{s_1 + s_2}\left(\sum\limits_{r=1}^{s_1} \frac{s_r^g}{y_{rk}^g} + \sum\limits_{t=1}^{s_2} \frac{s_t^b}{y_{tk}^b}\right) > 0 \\ \lambda \geq 0, s^g \geq 0, s^b \geq 0, s^- \geq 0 \end{cases}$$

Among them, ρ^* is the value of CEE. k means the number of DMUs $(j = 1, 2, \ldots, n)$. x is the input vector. y^g is the expected output vector. y^b is the unexpected output vector. The input-output variables are calculated as follows. Labor input: total number of employees per year. Energy input: annual electricity consumption (Li and Lei, 2024a). Capital input: fixed asset capital stock using the perpetual inventory method. Expected output: gross domestic product (GDP). Unexpected output: carbon emissions based on electricity consumption, natural gas, liquefied petroleum gas, and heat.

Finally, the paper algorithmizes ρ^* to get LCEE, which is presented in equation (5).

$$LCEE = log\left(\rho^*\right) \tag{5}$$

3.2.2. Explanatory variable

The synergy between green finance and digital finance (SGD). The coupling coordination model can quantitatively analyze the dynamic correlation relationship between multiple elements and their coordinated development status. Therefore, the paper uses this model to measure the level of synergistic development of GF and DF. The specific measurement steps are as follows.

First, measuring the GF. The purpose of the GF is to improve the quality of economic development by adopting diversified financial instruments dedicated to facilitating energy conservation and consumption reduction. The paper uses a comprehensive evaluation method to measure GF, which is divided into seven components: green credit (GC), green investment (GIV), green insurance (GIS), green bond (GB), green support (GS), green fund (GFD), and green equity (GE). The specific indicator system is shown in **Table 1**. Then, according to Ran and Zhang (2023), the entropy value method is adopted to assign weights to the seven sub-indicators to calculate the comprehensive evaluation index of GF development in YREB. The measurement process is divided into the following points. (1) The range method is adopted to standardize the original data (eliminating dimensions). (2) Calculating the proportion of each sub-indicator to the total (measuring the relative importance of the sub-indicators). (3) Calculating the entropy value (based on the proportion and natural logarithm to calculate the entropy value to reflect the degree of dispersion of the indicator). (4) Calculating the coefficient of variation (the smaller the entropy value, the larger the coefficient). (5) Determining the weights by the coefficient of variation (final weights are obtained by normalization).

Second, measuring the DF. Currently, the metrics of DF are mainly divided into two types. One is to adopt the DF Inclusion Index compiled by the Internet Finance Research Centre of Peking University (Guo *et al.* 2020). The second is to synthesize the DF metrics by crawling and aggregating the selected relevant word frequencies through web crawler technology (Razzaq and Yang, 2023). Given that most of the existing studies measure DF using the first method, the paper also uses the results of this method to represent the DF development capacity of YREB. Notably, the entropy method is also used here for treating the relevant indicators.

Finally, measuring the level of synergy between GF and DF. Here, the coupling coordination model is adopted to calculate the degree of coupling C, the degree of coordination T, and the degree of coupling coordination D, respectively, which are described in equations (6)-(8).

$$C = 2\sqrt{\frac{GF \times DF}{\left(GF + DF\right)^2}} \tag{6}$$

$$T = \alpha_1 \times GF + \alpha_2 \times DF \quad (7)$$

$$D = \sqrt{GF \times DF} = SGD \quad (8)$$

Where α_1 and α_2 represent the weights of GF and DF, respectively, and $\alpha_1 + \alpha_2 = 1$. The paper argues that GF and DF are equally significant in the coordinated development of coupling, so $\alpha_1 = \alpha_2 = 0.5$ is set.

3.2.3. Control variables

To more comprehensively analyze the impact of the synergy of GF and DF on the CEE of YREB, six control variables are added in the paper, namely human capital (HR), economic development (ED), fiscal decentralization (FD), population density (PP), foreign direct investment (FDI), and industrial structure (IS). The specific measurements are listed in **Table 2**. Notably, the paper performs logarithmic processing on all control variables.

3.3. Data sources

The paper takes 106 cities of YREB from 2011 to 2021 as the study object. The initial sample is obtained by collating relevant data from the WIND database (https://www.wind.com.cn/), EPS database (https://www.epsnet.com.cn/), State Intellectual Property Office of China (http://www.cnipa.gov.cn/) (SIPOC), Digital Finance Research Centre of Peking University (https://idf.pku.edu.cn/) (DFRCPU), and China Urban Statistical Yearbook (CUSY) in 2011-2021. To ensure data quality, the paper removes the badly lacking data and fills in the small amount of lacking data using the interpolation method. Finally, a total of 1166 observations are obtained.

Table 1. The GF development level evaluation indicator system

Total indicator	Sub-indicators	Measurement of sub-indicators	Indicator attributes
GF development level	GC	Total environmental project credit/total regional credit	+
	GIV	Investment in environmental pollution control/regional GDP	+
	GIS	Environmental pollution liability insurance income/total premium income	+
	GB	Total green bond issuance/total all bond issuance	+
	GS	Financial environmental protection expenditures/financial general budget expenditures	+
	GFD	Total market capitalization of green funds/total market capitalization of all funds	+
	GE	(Carbon trading + energy rights trading + emissions trading)/total equity market transactions	+

Table 2. The measurement of control variables

Variables	Measurement
HR	Number of employees/total population
ED	Per capita GDP
FD	Fiscal budget revenues/fiscal budget expenditures
PP	Number of people per unit of land area
FDI	Amount of foreign capital actually used/GDP
IS	$IS = 1 - \frac{1}{3}\sum_{n=1}^{3}\left\|S_n^y - S_n^l\right\|$, $S_n^y = Y_n / Y$, denoting the share of value added of the *n*-th industry in GDP. $S_n^l = S_n / S$, representing the share of *n*-th industry employment in total employment.

Table 3. Descriptive statistics (all observations)

Variables	N	Mean	Max	Min
LCEE	1166	-0.8964	3.8678	-2.2230
SGD	1166	0.6110	0.8710	0.0001
HR	1166	0.1920	0.8255	0.0001
ED	1166	11.0445	15.6752	9.2365
FD	1166	0.5649	1.7481	0.0380
PP	1166	6.4776	9.8778	2.5734
FDI	1166	0.0076	0.0477	0.0001
IS	1166	0.8778	0.9914	0.5595

Notably, to show the temporal trends of all the variables and their distributional characteristics in regional terms, the paper is supplemented with the evolutionary trends of all the variables in time and the differences in their distributions in the overall region of the YREB, the lower, middle, and upper reaches of the YREB. From **Table 4**, the results suggest that the mean, maximum, and minimum values of all variables vary across years and regions during the sample period. This implies that there are clear spatial and temporal differences in YREB in CEE, synergistic development of GF and DF, human capital, economic development, fiscal decentralization, population density, foreign direct investment, and industrial structure.

Table 4. Descriptive statistics (exhibiting the characteristics of changes in each variable in time and region)

Region	Total YREB			Lower reaches			Middle reaches			Upper reaches		
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
Year	LCEE											
2011	-0.8817	0.2040	-1.9045	-0.9919	-0.4064	-1.4569	-0.8295	0.0342	-1.4161	-0.7908	0.2040	-1.9045
2012	-0.8857	0.3839	-1.7223	-0.9933	0.1432	-1.3825	-0.8272	0.3839	-1.4227	-0.8062	-0.0786	-1.7223
2013	-0.9880	0.0035	-1.7209	-1.1120	-0.6704	-1.5065	-0.9062	0.0035	-1.4899	-0.9142	-0.1612	-1.7209
2014	-0.9753	0.0130	-1.5094	-1.0883	-0.6225	-1.5094	-0.9135	0.0130	-1.4830	-0.8922	-0.2486	-1.4715
2015	-0.9261	0.0548	-1.7529	-1.0710	-0.4814	-1.7529	-0.8784	0.0189	-1.4145	-0.7805	0.0548	-1.4216
2016	-0.8956	0.1453	-1.5895	-1.0232	-0.4016	-1.5895	-0.8442	0.0575	-1.4476	-0.7791	0.1453	-1.3477
2017	-0.9866	0.0098	-2.2230	-1.0209	-0.1636	-1.5031	-0.9989	-0.2126	-2.2230	-0.9229	0.0098	-1.4865
2018	-0.9287	0.0077	-2.2008	-0.9601	0.0077	-1.4259	-0.9224	-0.0943	-2.2008	-0.8921	0.0040	-1.6009
2019	-0.8428	0.0476	-1.9178	-0.8943	0.0476	-1.4829	-0.8446	0.0256	-1.9178	-0.7675	0.0143	-1.5948
2020	-0.8445	0.0571	-2.0469	-0.9059	0.0002	-1.5220	-0.9070	-0.1631	-2.0469	-0.6801	0.0571	-1.7492
2021	-0.7050	3.8678	-1.9190	-0.8542	0.0777	-1.4517	-0.7916	0.4724	-1.8585	-0.3867	3.8678	-1.9190
Year	SGD											
2011	0.3892	0.5485	0.0001	0.4368	0.5485	0.2426	0.3890	0.4975	0.3247	0.3221	0.4692	0.0001
2012	0.4927	0.6440	0.3145	0.5266	0.6440	0.4368	0.5017	0.5780	0.4450	0.4338	0.5629	0.3145
2013	0.5523	0.6974	0.3573	0.5871	0.6974	0.4805	0.5672	0.6238	0.5139	0.4844	0.5982	0.3573
2014	0.5774	0.7297	0.4090	0.6079	0.7297	0.5072	0.5916	0.6607	0.5299	0.5165	0.6406	0.4090
2015	0.6089	0.7551	0.4210	0.6409	0.7551	0.5557	0.6238	0.6988	0.5616	0.5451	0.6668	0.4210
2016	0.6373	0.7842	0.4385	0.6667	0.7842	0.5940	0.6533	0.7101	0.5762	0.5760	0.6867	0.4385
2017	0.6648	0.8172	0.4495	0.6967	0.8172	0.6153	0.6816	0.7494	0.5988	0.5988	0.7115	0.4495
2018	0.6792	0.8290	0.4780	0.7132	0.8290	0.6328	0.6950	0.7746	0.6238	0.6115	0.7333	0.4780
2019	0.6944	0.8484	0.4858	0.7271	0.8484	0.6312	0.7149	0.7898	0.6340	0.6227	0.7552	0.4858
2020	0.7065	0.8627	0.4826	0.7415	0.8627	0.6435	0.7271	0.7872	0.6579	0.6314	0.7674	0.4826
2021	0.7188	0.8710	0.5174	0.7559	0.8710	0.6661	0.7386	0.8116	0.6550	0.6420	0.7711	0.5174
Year	HR											
2011	0.1730	0.5524	0.0326	0.1923	0.5248	0.0332	0.1841	0.5524	0.0513	0.1320	0.2960	0.0326
2012	0.1797	0.6252	0.0197	0.1986	0.5521	0.0197	0.1858	0.6252	0.0269	0.1455	0.3192	0.0334
2013	0.2133	0.7476	0.0394	0.2332	0.5532	0.0497	0.2164	0.7035	0.0683	0.1814	0.7476	0.0394
2014	0.2110	0.5239	0.0407	0.2448	0.5239	0.0407	0.2064	0.3956	0.0633	0.1687	0.4071	0.0429
2015	0.2035	0.5163	0.0467	0.2393	0.5163	0.0478	0.2001	0.3833	0.0697	0.1572	0.3971	0.0467
2016	0.1963	0.5123	0.0010	0.2273	0.5123	0.0426	0.1993	0.3906	0.0693	0.1486	0.3822	0.0010
2017	0.1902	0.4487	0.0001	0.2171	0.4487	0.0461	0.1942	0.4067	0.0757	0.1473	0.3918	0.0001
2018	0.1913	0.8255	0.0001	0.2220	0.5164	0.0607	0.1819	0.4107	0.0825	0.1594	0.8255	0.0001
2019	0.1866	0.4875	0.0004	0.2170	0.4875	0.0686	0.1886	0.4063	0.0703	0.1412	0.3819	0.0004
2020	0.1828	0.5344	0.0013	0.2115	0.5344	0.0681	0.1971	0.4036	0.0841	0.1244	0.3512	0.0013
2021	0.1842	0.5806	0.0014	0.2072	0.5806	0.0273	0.2057	0.4009	0.0886	0.1250	0.3691	0.0014
Year	ED											
2011	10.6404	11.5593	9.3233	10.8485	11.5593	9.3473	10.6874	11.4869	9.4925	10.2878	11.5432	9.3233
2012	10.7768	12.5891	9.4725	10.9678	12.5891	9.4964	10.8192	11.6092	9.6548	10.4539	11.6325	9.4725
2013	10.9231	12.2002	9.2365	11.1318	12.2002	9.6872	10.9856	11.9228	9.7505	10.5504	11.8184	9.2365
2014	10.9103	11.7946	9.5430	11.0728	11.7946	9.7170	10.9622	11.7882	9.8926	10.6161	11.7160	9.5430
2015	10.9705	11.8274	9.6393	11.1299	11.8245	9.8938	11.0168	11.8274	9.9625	10.6874	11.7087	9.6393
2016	11.0463	12.9930	9.7285	11.1957	11.8885	9.9036	11.1242	12.9930	9.8726	10.7385	11.4379	9.7285
2017	11.1570	15.6752	9.8142	11.2843	11.9347	10.0798	11.1461	11.9345	10.1877	10.9904	15.6752	9.8142
2018	11.1755	12.0014	9.8633	11.3621	11.9944	10.1784	11.2173	12.0014	10.2373	10.8599	11.6424	9.8633
2019	11.2830	12.0582	10.1028	11.4836	12.0582	10.5116	11.2988	12.0104	10.6060	10.9797	11.7197	10.1028
2020	11.2516	11.9787	10.2832	11.4609	11.9787	10.5454	11.2415	11.7980	10.6404	10.9681	11.7241	10.2832
2021	11.3549	12.3957	10.2910	11.5613	12.1092	10.7042	11.3488	11.9253	10.7417	11.0707	12.3957	10.2910
Year	FD											
2011	0.5817	1.1425	0.0861	0.7448	1.1425	0.2893	0.5213	0.9547	0.2907	0.4261	0.8900	0.0861
2012	0.6015	1.2014	0.1137	0.7426	1.2014	0.3318	0.5691	1.0000	0.3344	0.4423	0.9468	0.1137
2013	0.6187	1.7481	0.0475	0.7600	1.3829	0.3468	0.6001	1.7481	0.3055	0.4418	0.9256	0.0475
2014	0.6176	1.1669	0.0380	0.7424	1.1669	0.3467	0.6160	0.9985	0.3594	0.4432	0.8877	0.0380
2015	0.6071	1.5403	0.0863	0.7189	1.4056	0.3268	0.6174	1.5403	0.3310	0.4361	0.8389	0.0863
2016	0.5935	1.3685	0.1162	0.7000	1.0645	0.3368	0.5904	1.3685	0.3270	0.4468	0.9267	0.1162
2017	0.5469	1.0714	0.1480	0.6793	1.0714	0.3359	0.5206	1.0606	0.2921	0.3924	0.8374	0.1480

2018	0.5357	1.1218	0.1565	0.6891	1.1218	0.3236	0.4679	0.8491	0.2499	0.4027	0.9717	0.1565
2019	0.4994	1.0562	0.1644	0.6325	1.0562	0.2877	0.4304	0.7103	0.2391	0.3968	0.9211	0.1644
2020	0.4825	1.0638	0.1694	0.6177	1.0638	0.2656	0.3829	0.7881	0.2094	0.4148	0.9781	0.1694
2021	0.5294	1.1524	0.1797	0.6420	1.0411	0.2849	0.4665	0.8768	0.1889	0.4482	1.1524	0.1797
Year							PP					
2011	6.5707	8.2028	4.2384	6.7866	8.2028	5.2339	6.5824	8.1821	4.2384	6.2507	7.8273	4.2999
2012	6.5828	8.2023	3.9966	6.7740	7.8767	5.2312	6.6375	8.2023	5.2468	6.2447	7.8445	3.9966
2013	6.5609	7.9232	4.3221	6.7259	7.8809	5.2353	6.6343	7.9232	5.2584	6.2365	7.8832	4.3221
2014	6.5582	8.1731	4.0135	6.7195	7.8859	5.2419	6.6330	8.1731	5.2703	6.2373	7.8928	4.0135
2015	6.5484	8.2313	4.0287	6.7052	7.8908	5.2514	6.6254	8.2313	5.2477	6.2310	7.6752	4.0287
2016	6.4927	8.7608	2.5734	6.6736	7.8957	4.9821	6.5053	8.7608	2.5734	6.2213	7.3968	4.0438
2017	6.4599	9.1052	2.5738	6.6096	7.9006	2.5845	6.4934	9.1052	2.5738	6.2066	7.0096	4.0585
2018	6.4393	9.3609	2.5740	6.5996	7.9054	2.5751	6.4639	9.3609	2.5740	6.1822	7.0079	4.0731
2019	6.3780	9.5643	2.5767	6.5733	7.9103	2.5800	6.3790	9.5643	2.5767	6.1005	7.1162	4.0875
2020	6.3382	9.7333	2.5739	6.5256	7.9151	2.5743	6.3620	9.7333	2.5739	6.0436	7.2138	2.5747
2021	6.3252	9.8778	2.5744	6.5277	7.9199	2.5756	6.3259	9.8778	2.5744	6.0382	7.3028	2.5888
Year							FDI					
2011	0.0082	0.0442	0.0003	0.0103	0.0257	0.0008	0.0100	0.0442	0.0018	0.0032	0.0137	0.0003
2012	0.0087	0.0430	0.0004	0.0112	0.0250	0.0013	0.0102	0.0430	0.0020	0.0034	0.0150	0.0004
2013	0.0088	0.0457	0.0004	0.0108	0.0283	0.0015	0.0106	0.0457	0.0021	0.0036	0.0173	0.0004
2014	0.0083	0.0477	0.0001	0.0099	0.0322	0.0015	0.0105	0.0477	0.0023	0.0032	0.0120	0.0001
2015	0.0077	0.0421	0.0001	0.0093	0.0312	0.0009	0.0099	0.0421	0.0022	0.0027	0.0089	0.0001
2016	0.0075	0.0419	0.0001	0.0090	0.0309	0.0012	0.0103	0.0419	0.0013	0.0018	0.0077	0.0001
2017	0.0071	0.0423	0.0001	0.0086	0.0285	0.0012	0.0098	0.0423	0.0005	0.0016	0.0091	0.0001
2018	0.0070	0.0424	0.0001	0.0082	0.0313	0.0011	0.0097	0.0424	0.0004	0.0018	0.0010	0.0001
2019	0.0065	0.0364	0.0001	0.0074	0.0285	0.0011	0.0091	0.0364	0.0004	0.0019	0.0175	0.0001
2020	0.0069	0.0374	0.0001	0.0076	0.0341	0.0001	0.0097	0.0374	0.0001	0.0025	0.0324	0.0001
2021	0.0068	0.0445	0.0001	0.0073	0.0359	0.0001	0.0093	0.0342	0.0001	0.0029	0.0445	0.0001
Year							IS					
2011	0.8657	0.9775	0.6887	0.8839	0.9775	0.7256	0.8713	0.9731	0.7238	0.8330	0.9539	0.6887
2012	0.8661	0.9796	0.6932	0.8813	0.9796	0.7076	0.8778	0.9731	0.7417	0.8301	0.9626	0.6932
2013	0.8755	0.9766	0.7062	0.8747	0.9643	0.7062	0.8961	0.9766	0.8018	0.8511	0.9658	0.7084
2014	0.8767	0.9914	0.7167	0.8772	0.9914	0.7624	0.8967	0.9743	0.7837	0.8510	0.9738	0.7167
2015	0.8791	0.9796	0.7120	0.8802	0.9796	0.7120	0.8990	0.9679	0.7955	0.8517	0.9699	0.7335
2016	0.8833	0.9707	0.7256	0.8825	0.9667	0.7256	0.9043	0.9638	0.8089	0.8583	0.9707	0.7346
2017	0.8901	0.9768	0.6667	0.8839	0.9734	0.6667	0.9085	0.9768	0.6667	0.8762	0.9728	0.7486
2018	0.9006	0.9908	0.7195	0.9011	0.9863	0.7569	0.9171	0.9908	0.7282	0.8793	0.9731	0.7195
2019	0.9049	0.9871	0.7242	0.9161	0.9871	0.8179	0.9184	0.9772	0.8308	0.8723	0.9754	0.7242
2020	0.8824	0.9863	0.6416	0.8962	0.9863	0.6676	0.9044	0.9840	0.8121	0.8357	0.9618	0.6416
2021	0.8315	0.9843	0.5595	0.8740	0.9725	0.7044	0.8933	0.9843	0.7863	0.6946	0.9726	0.5595

4. Empirical results and analysis

4.1. Analysis of CEE measurement results

Figure 1 plots the average annual trend of CEE of YREB. It shows that the total CEE of YREB fluctuates upward. Additionally, it is observed that the CEE in the lower, middle, and upper reaches of YREB are showing a fluctuating upward trend. Specifically, the CEE of the lower reaches of YREB has been smaller than the CEE of the total YREB from 2011 to 2021. The CEE of the middle reaches of YREB has been larger than the CEE of the total YREB in 2011-2016 and 2018 and smaller than the CEE of the total YREB in 2017 and 2019-2021. The CEE of the upper reaches of YREB has been larger than the CEE of the total YREB.

4.2. Benchmark model results

From **Table 5**, it is found that the synergy between GF and DF contributes to the enhancement of CEE. This is because, first, the synergy between GF and DF can more efficiently channel various factors of production to low-carbon projects (Shi and Yang, 2024). This enables a more efficient allocation of resources that help to drive the low-carbon transition of industries, which in turn enhances CEE. Second, the synergy between GF and DF can accelerate the application of technological innovation in the low-carbon fields (Yin *et al.* 2024). Relevant departments can monitor and manage carbon emissions more accurately with the help of fintech tools, thus promoting the R&D of green production technologies. This will encourage enterprises in YREB to actively introduce low-carbon technologies and equipment, and improve production processes, thus reducing carbon emissions in YREB and consequently improving CEE. Third, the synergy between GF and DF can help raise the public's awareness of carbon reduction and promote the spread of the green consumption concept (Mirza *et al.* 2023). This can prompt consumers to change their consumption behaviors and focus more on energy-saving and emission reduction when choosing products and services, thus contributing to reducing carbon emission intensity and improving CEE.

Table 5. The impact of synergy between GF and DF on the CEE of YREB

Variables	(1)	(2)
	LCEE	LCEE
SGD	0.7858*	1.0370**
	(0.4721)	(0.4409)
HR		-2.1897***
		(0.1787)
ED		0.0603
		(0.0429)
FD		-0.2214**
		(0.1028)
PP		-0.0041
		(0.0185)
FDI		-2.3957
		(2.8775)
IS		-0.6840***
		(0.2076)
_cons	-1.5793***	-1.2084**
	(0.2886)	(0.5496)
City	Yes	Yes
Year	Yes	Yes
N	1166	1166
R^2	0.6456	0.6976

*Note: *, **, *** mean significant at the level of 10%, 5%, and 1%, respectively.*

Table 6. Robustness test

Variables	(1)	(2)	(3)	(4)	(5)
	LCEE(New)	LCEE	LCEE	LCEE	LCEE
SGD	0.6468***		0.6902***	0.8121***	2.8420***
	(0.2030)		(0.1594)	(0.0996)	(0.7155)
SGD(New)		0.0464**			
		(0.0185)			
ER					-0.1714*
					(0.1004)
TE					2.0310
					(4.7288)
TR					0.0341
					(0.0235)
Control	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
N	1166	1166	1166	954	1166
R^2	0.1355	0.6978	0.7844	0.7970	0.7024

4.3. Robustness test

First, the paper re-measures the CEE of YREB cities using the standard efficiency SBM model instead, and then logs the results to obtain LCEE(New). Second, the interaction term is the product between two or more variables, commonly used in statistics to indicate the interaction between variables and measure the level of synergy between variables. Therefore, the paper uses the interaction term between GF and DF to re-measure the explanatory variables, thus obtaining SGD(New). Third, to prevent individual outliers in the sample from having a large impact on the regression results, the paper winsorizes the data by about 3%. Fourth, the COVID-19 outbreak caused remarkable changes in the patterns of economic activity, transport, and industrial production within the YREB. These changes may lead to unusual fluctuations in the data sampled in 2020 and 2021. Accordingly, the data for these two years is deleted. Fifth, given that the omission of variables may affect the accuracy of the empirical results, the paper adds control variables such as environmental regulation (ER), scientific and technological development (TE), and trade openness (TR) to the original model for re-regression. Among them, ER=GDP/industrial sulfur dioxide, wastewater, and soot emissions. TE=total science and technology expenditure/GDP. TR=total trade import and export/GDP. The results obtained from the above five methods of re-regression are listed in **Table 6**. The coefficients of SGD and SGD(New) are all significantly positive, which suggests that the synergy between GF and DF indeed contributes to increasing CEE.

Table 7. Endogeneity test

Variables	2SLS					
	First	**Second**	**First**	**Second**	**First**	**Second**
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
	LCEE	LCEE	LCEE	LCEE	LCEE	LCEE
IPR	0.0314^{***}					
	(0.0027)					
MPR			0.0448^{***}			
			(0.0036)			
L.GF					0.2432^{***}	
					(0.0148)	
SGD		3.2188^{**}		2.7131^{***}		2.2465^{***}
		(0.8137)		(0.4558)		(0.3950)
Control	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Kleibergen-Paap rk LM statistic	122.835^{***}	71.318^{***}	235.079^{***}			
Cragg-Donald Wald F statistic	135.180	74.792	269.869			
N	1166	1166	1166	1166	1060	1060
R^2	0.8127	0.0939	0.4466	0.0318	0.7860	0.6934

Table 8. Mechanism test

Variables	**(1)**	**(2)**	**(3)**	**(4)**
	GT	**LCEE**	**CEI**	**LCEE**
SGD	6.1358^{***}		-0.0439^{*}	
	(0.4423)		(0.0236)	
GT		0.0398^{***}		
		(0.0147)		
CEI				-0.2566^{***}
				(0.0235)
Control	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
N	1166	1166	1166	1166
R^2	0.7528	0.2792	0.6127	0.6986

4.4. Endogeneity test

The paper adopts the instrumental variable method to mitigate the endogeneity problem. First, the Internet penetration rate (IPR) is chosen as an instrumental variable for SGD. This is because the synergy between GF and DF is highly reliant on the Internet infrastructure, and an increase in IPR can promote the integration of GF and DF. Moreover, the impact of IPR on CEE is mainly achieved indirectly by playing the synergistic effect of GF and DF. IPR is expressed using the logarithm of the number of international Internet users. Second, the mobile phone penetration rate (MPR) is selected as an instrumental variable for SGD. This is because DF relies on IT infrastructure, and an increase in MPR means wider communication network coverage and easier information interaction, which can provide the basis for DF development. In turn, it can directly promote the synergy between GF and DF in information sharing, business innovation, and so on. Furthermore, MPR only affects the synergistic development of GF and DF indirectly by influencing DF, and it has no direct causal relationship with CEE. MPR is denoted by the logarithm of the number of mobile phone subscribers. Third, the one-period lagged GF index (L.GF) is chosen as the instrumental variable for SGD. This is because GF is persistent, and L.GF is significantly associated with the level of GF development in the current period, which can directly influence the level of synergy between GF and DF. Additionally, due to its temporal separation, L.GF can reduce the interference of contemporaneous confounders with other variables such as CEE and DF in the current period, and it is more likely to act only indirectly on CEE by affecting the ability of GF and DF to integrate in the current period. The above variables all comply with the two basic principles of "correlation" and "exogeneity" of instrumental variables. Notably, the paper also conducts the unidentifiable test and the weak instrumental variable test. **Table 7** presents the results of the endogeneity test (using two-stage least squares (2SLS)). The results suggest that the instrumental variables selected are reasonable, and the synergy between GF and DF can actually improve the CEE of YREB.

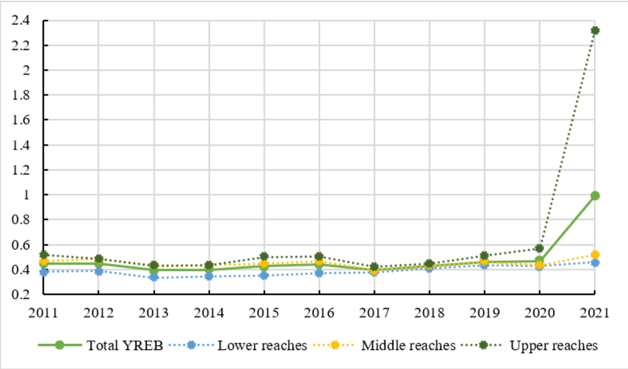


Figure 1. Graph of average annual trends for the CEE

4.5. Mechanism test

What is the impact mechanism of synergy between GF and DF to improve the CEE of YREB? This part constructs equations (9)-(10) to conduct the mechanism test.

$$GT_{it}\left(CEI_{it}\right) = \mu_4 + \delta_1 SGD_{it} + \varphi_4 Control_{it} + \sigma_i + \sigma_t + \varepsilon_{it} \quad (9)$$

$$LCEE_{it} = \mu_5 + \varepsilon_1 GT_{it}\left(CEI_{it}\right) + \varphi_5 Control_{it} + \sigma_i + \sigma_t + \varepsilon_{it} \quad (10)$$

Among them, GT_{it} denotes green technological innovation, which is represented by the logarithm of the total number of green patents granted. CEI_{it} means carbon emission intensity, which is calculated by using carbon emissions per unit of output.

Table 9. Heterogeneity test for regions

Variables	(1)	(2)	(3)
	Lower reaches	**Middle reaches**	**Upper reaches**
	LCEE	**LCEE**	**LCEE**
SGD	0.2340	0.9265	1.9828**
	(0.6702)	(0.7733)	(0.8458)
Control	Yes	Yes	Yes
City	Yes	Yes	Yes
Year	Yes	Yes	Yes
N	451	396	319
R^2	0.7847	0.8667	0.6044

Table 10. Heterogeneity test for population density

Variables	(1)	(2)
	High	**Low**
	LCEE	***LCEE***
SGD	1.1850***	0.2433*
	(0.2381)	(0.1301)
Control	Yes	Yes
City	Yes	Yes
Year	Yes	Yes
N	578	588
R^2	0.6999	0.9025

Table 11. Heterogeneity test for green innovation capacity

Variables	(1)	(2)
	Low	**High**
	LCEE	**LCEE**
SGD	0.4143***	2.6958***
	(0.1283)	(0.6006)
Control	Yes	Yes
City	Yes	Yes
Year	Yes	Yes
N	638	528
R^2	0.8173	0.7248

From columns (1)-(2) of **Table 8**, the coefficients of SGD and GT are significantly positive. This means that promoting green innovation is a channel through which the synergy between GF and DF enhances CEE in YREB cities. This is because the synergy of GF and DF can better provide financial support and risk management services for green technology innovation, which is beneficial to accelerate the transformation of green technology products. This can have a favorable impact on many fields, such as energy use, cleaner production, pollution control, etc., which contributes to improving the CEE of YREB.

From columns (3)-(4) of **Table 8**, the coefficients of SGD and GEI are all significantly negative. This demonstrates that reducing carbon intensity is a channel through which the synergy of GF and DF enhances CEE in YREB cities. This is because the synergy between GF and DF can help resources to be more precisely allocated to low-carbon fields. It improves the allocated and utilized efficiency of resources (Zhou *et al.* 2022), and it can also trigger technological advancement, upgrading of industrial structure, etc., which lowers the difficulty of carbon reduction. Ultimately, it can contribute to the growth of CEE in YREB.

4.6. Heterogeneity test

4.6.1. Geographic location

Different regions of YREB differ in economic structure, technological development, resource utilization, industrial layout, and financial development (Liu *et al.* 2024a). Among them, the upper reaches of the YREB are rich in ecological resources but relatively economically lagging behind, and the development base of GF and DF is weak. The positive impact of the synergy of GF and DF on carbon emission reduction may be limited by imperfect infrastructures, undeveloped industrial support, immature ways of utilizing the resources, and so on. However, to a certain extent, it also means that this region has a high potential for financial development and low-carbon development. The middle reaches of the YREB are characterized by high pressure on the low-carbon transition of traditional industries, and the synergy between GF and DF on CEE may be more dependent on industrial restructuring. The lower reaches of the YREB are featured by the developed economy, financial resources concentration, better development of high-tech industries, etc. The synergy between GF and DF is more likely to improve CEE in this region through the formation of a closed loop of "resource aggregation-technology empowerment-scenario landing", but the implicit carbon problem of high-value-added industries may weaken the effect of carbon mitigation. Consequently, the paper divides the full sample of YREB into three sub-samples, lower, middle, and upper reaches, for regression analyzes to study whether the impact of the synergy between GF and DF on the CEE of YREB has regional heterogeneity.

From **Table 9**, the synergy between GF and DF contributes most to CEE in the cities in the upper reaches of the YREB, and it does not contribute significantly to CEE in the cities in the lower and middle reaches of the YREB. The upper reaches of YREB's cities often face greater environmental pressure (Liu *et al.* 2024a) and higher demands for structural transformation and upgrading during low-carbon development. The synergy between GF and DF can provide them with more precise and efficient financial support and technical services for their low-carbon development, thus pushing their CEE to achieve the most rapid growth. The cities in the lower and middle reaches of the YREB have certain advantages in DF infrastructure development, GF product and service innovation, rationalization of market mechanisms, industrial layout, policy and institutional support, and regional competition and cooperation (Li *et al.* 2024). These cities usually have a stronger ability to integrate the development of GF and DF and higher carbon reduction efficiency. It leads to a smaller space for carbon reduction in these cities, thus triggering a limited positive effect on CEE from the synergy of GF and DF.

4.6.2. Population density

Population density is the basis for the scale effect of GF and DF. YREB cities have different population densities, which causes distinctions in resource utilization, energy consumption, environmental governance capacity, and carbon emission factors. In general, regions with high population densities tend to have concentrated urbanization, dense industries, and significant economic agglomeration effects, which may make it easier to synergize the development of GF and DF to improve CEE. Regions with low population densities may have inadequate infrastructure, uneven distribution of resources, and obvious industrial fragmentation, which may result in poor carbon abatement effects from the synergistic development of GF and DF. The paper measures population density by population per square kilometer, and uses the median of the measurement results as the cut-off point to classify the 106 cities in YREB into two groups of "high population density" and "low population density".

From **Table 10**, the synergy between GF and DF has a more pronounced positive impact on CEE in cities with high YREB population density compared to cities with low YREB population density. Cities with high YREB population density usually have a higher intensity of economic activities and resource demand (Qin *et al.* 2024) due to high population and economic activities. And the residents of this area also have a stronger demand for digital facility construction and GF products. Consequently, these cities also have relatively higher carbon emissions. The synergy between GF and DF can reduce the scale of carbon emissions in these cities more effectively by improving resource allocation efficiency, increasing energy utilization (Ran and Zhang, 2023), and enhancing public awareness and participation in improving environmental quality (Guo *et al.* 2023). Thereby, CEE can be improved.

4.6.3. Green innovation capacity

Green innovation can help drive the greening of digital technologies and better stimulate the low-carbon application potential of GF and DF (Zhou *et al.* 2022). Differences in urban green innovation capacity may bring about differentiation in the development level of GF and DF, thus affecting the effectiveness of carbon emission reduction. In general, subjects with high green innovation capacity can transform financial support into emission reduction outcomes more effectively (e.g., faster promotion of clean energy technologies, faster expansion of green credit scale, etc.). Subjects with low green innovation capacity may have difficulty in fully unleashing the synergistic effects of GF and DF due to insufficient technology absorption capacity, thus limiting the promotion of CEE. The paper estimates the green innovation capacity by the total number of green patents granted, and based on the median value of this measure as the cut-off point, the 106 cities in YREB are grouped into two groups: "low green innovation capacity" and "high green innovation capacity".

From **Table 11**, the synergy between GF and DF has a greater impact on CEE in cities with high YREB green innovation capacity than in cities with low YREB green innovation capacity. Cities with high YREB green innovation capacity usually have stronger technological R&D and application capabilities, and they can more effectively utilize the financial and technical support provided by DF and GF. Therefore, these cities have better prospects for low-carbon development, and they can optimize and upgrade their industrial and energy structures more quickly. This will reduce the difficulty of carbon reduction (Gong *et al.* 2024) and increase carbon productivity and CEE.

Table 12. Threshold effect test

Variables	Threshold	Fstat	Prob	Bootstrap
SGD	Single	38.22	0.0067***	300
	Double	14.46	0.1033	300

Table 13. Threshold estimation

Variable	Type	Value	Confidence interval (95%)
SGD	First threshold	0.6659	[0.6607, 0.6674]

Table 14. Panel threshold regression results

Variables	(1)
	LCEE
SGD1	SGD≤0.6659
	0.3904***
	(0.1269)
SGD2	SGD>0.6659
	0.5678***
	(0.1173)
Control	Yes
City	Yes
Year	Yes
N	1166
R^2	0.5109

4.7. Panel threshold model results

To study whether the synergy of GF and DF has a threshold effect on the CEE of YREB, the paper uses SGD as the threshold variable and conducts a threshold effect test. From **Table 12**, the p-value for the single threshold is significant, while the p-value for the double threshold fails to pass the test of significance, so its threshold number is set to 1. This suggests that there is a threshold effect of the synergy between GF and DF on the CEE of YREB.

After identifying the number of thresholds, further finding of the threshold values is required. From **Table 13**, the first threshold value for SGD is 0.6659 and falls within the confidence interval of [0.6607, 0.6674].

Table 14 reports the panel threshold regression results. As the level of synergistic development of GF and DF increases, the coefficients of SGD exhibit a gradually larger trend. When SGD>0.6659, it makes the synergy of GF and DF exert the maximum positive influence on the CEE of YREB. This is because, in the early stages of developing GF and DF, market acceptance and awareness of GF and DF are relatively low. In this case, the integrated development of GF and DF may lead to wastage of resources, lower marginal effects of technological and service innovations, and more difficulty in risk management and control (Yin *et al.* 2024). This may make it hard for GF and DF to develop synergistically, resulting in a limited positive effect on the CEE of YREB. However, when the synergistic development capability of GF and DF crosses the threshold value of 0.6659, DF can allocate resources more efficiently, which contributes to the promotion of technological innovation in the field of GF, the improvement of service quality and efficiency of GF, and the safeguarding of the stable development of GF. This prompts GF and DF to form a more effective synergy, thus helping to reduce the difficulty of carbon reduction in YREB, and consequently improving the CEE of YREB.

4.8. Spatial econometric regression results

Before the SDM regression, the paper performs the global Moran index test for CEE. From **Table 15**, most of the global Moran indexes of CEE from 2011 to 2021 are significantly negative, suggesting the existence of a negative spatial correlation. This is because there are large dissimilarities among YREB cities in economic structure, technological level, policy environment and regulation, and regional interactions, thus making CEE exhibit a negative spatial correlation.

Next, the paper examines the spatial spillover effect of the synergy of GF and DF on the CEE of YREB. From **Table 16**, the coefficients of SGD and W × SGD are both significantly positive, which suggests that the synergy between GF and DF has a positive spatial spillover effect on the CEE of YREB. This is because financial resources have high liquidity, and DF's technological advantages and GF's environmental orientation can promote faster cross-regional transfer and allocation of financial resources (Liu *et al.* 2024b). It can promote the dissemination of advanced low-carbon technologies, industrial greening development experience, and carbon reduction management experience among the cities in YREB. Thus, the synergy between GF and DF can exert green spillover effects.

Finally, the paper decomposes the spatial spillover effect. From **Table 17**, the results reveal that while the synergy of GF and DF contributes to the CEE of YREB local cities, it also enhances the CEE of YREB neighboring cities. The synergy between GF and DF has created a significant spatial spillover effect in promoting CEE in YREB local cities by optimizing industrial structure, improving energy utilization, spreading green consumption concepts, and promoting energy-saving and carbon-reducing technological reforms. This effect enables the neighboring cities of YREB to learn and absorb the carbon emission reduction experience and technological achievements of the local cities of YREB. This accelerates the green development process of neighboring cities and improves CEE (Li and Xu, 2024b).

Table 15. Global Moran's Index

Year	I	Z	P-value
2011	-0.1111	-2.1409	0.0323**
2012	-0.0972	-1.8537	0.0638*
2013	-0.1059	-2.0335	0.0420**
2014	-0.0906	-1.7142	0.0865*
2015	-0.0921	-1.7454	0.0809*
2016	-0.0413	-4.8914	0.0000***
2017	-0.0051	0.6882	0.4913
2018	-0.0038	0.8772	0.3804
2019	-0.0473	-2.1853	0.0289**
2020	-0.0297	-3.1012	0.0019**
2021	-0.0283	-3.2957	0.0010**

Table 16. The SDM model regression results

Variables	(1)
	LCEE
SGD	1.2777***
	(0.4352)
W × SGD	11.8140**
	(5.6757)
rho	-0.7864***
	(0.2777)
sigma2_e	0.0790***
	(0.0033)
Control	Yes
W × Control	Yes
City	Yes
Year	Yes
N	1166
R^2	0.0525

Table 17. Decomposition results for the spatial spillover effect

Variables	(1)	(2)	(3)
	Direct	Indirect	Total
	LCEE	LCEE	LCEE
SGD	1.2172***	6.5669*	7.7841**
	(0.4403)	(3.6855)	(3.8248)
Control	Yes	Yes	Yes

5. Conclusions and implications

5.1. Conclusions

First, the CEE of YREB cities in total, lower, middle, and upper reaches show an increasing trend from 2011 to 2021. The order of subregional changes is Upper reaches > Lower reaches > Middle reaches. Second, the synergy between GF and DF can help promote the growth of YREB's urban CEE, and the synergy between GF and DF can help improve YREB's CEE by promoting green technology innovation and reducing carbon emission intensity. Third, the contribution of the synergy between GF and DF to the CEE of YREB can be heterogeneous depending on geographic location, population density, and green innovation capacity. Fourth, there is a single threshold effect of the synergy of GF and DF on the CEE of YREB. As the level of GF and DF synergy development increases, its positive impact on the CEE of YREB tends to be larger. Particularly, when the collaborative development capacity of GF and DF crosses the threshold value, it will make its positive impact on the CEE of YREB even greater. Fifth, the synergy between GF and DF has a positive spatial spillover effect on the CEE of YREB, and it can simultaneously enhance the CEE of the local and neighboring cities of YREB.

5.2. Implications

First, relevant authorities should continuously promote the integration and development of GF and DF, and hasten the digital transition of GF, so that GF and DF can play a synergistic role in driving the low-carbon development of YREB. For instance, they can utilize digital technologies for identifying and assessing the environmental risks of loan projects, record and recognize the sources of low-carbon projects, and promote enterprises to increase factor inputs for low-carbon technological reforms.

Second, relevant authorities should implement targeted GF, DF, and low-carbon development strategies by considering the development of different cities in YREB to narrow the development gaps among cities in YREB. For example, they can accelerate the balancing of factor input levels, technological innovation and transformation capabilities, digital infrastructure development, financial service efficiency, and carbon reduction capabilities of different cities.

Third, relevant authorities should scientifically guide the development of GF and keep the level of DF development within a reasonable range, so that the synergy between DF and GF can maximize the effect of promoting the growth of CEE in YREB. For instance, they can strengthen policy guidance and supervision, enhance talent training and introduction, improve the DF resource sharing mechanism, and facilitate digital technology innovation and application.

Fourth, relevant authorities should reinforce virtuous cooperation and exchanges among YREB cities in the fields of finance, carbon reduction, environmental protection, innovation, entrepreneurship, etc., to avoid vicious competition among cities. For example, they can keep expanding the space for factor mobility, further synergize the pollution and carbon reduction schemes among cities, and strengthen the flow of DF and GF innovation achievements across cities.

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