frontiers | Research Topics

The impact of global industrial manufacturing and the development strategy of new energy and new technologies under the action of carbon reduction

Edited by
Wen-Tsao Pan, Yiwen Zhang, Weilin Xiao, Chi Lau,
Shan Shan and Keping Yu

Published in
Frontiers in Energy Research

ISSN 1664-8714
ISBN 978-2-8325-4354-2
DOI 10.3389/978-2-8325-4354-2

About Frontiers

Frontiers is more than just an open access publisher of scholarly articles: it is a pioneering approach to the world of academia, radically improving the way scholarly research is managed. The grand vision of Frontiers is a world where all people have an equal opportunity to seek, share and generate knowledge. Frontiers provides immediate and permanent online open access to all its publications, but this alone is not enough to realize our grand goals.

Frontiers journal series

The Frontiers journal series is a multi-tier and interdisciplinary set of open-access, online journals, promising a paradigm shift from the current review, selection and dissemination processes in academic publishing. All Frontiers journals are driven by researchers for researchers; therefore, they constitute a service to the scholarly community. At the same time, the *Frontiers journal series* operates on a revolutionary invention, the tiered publishing system, initially addressing specific communities of scholars, and gradually climbing up to broader public understanding, thus serving the interests of the lay society, too.

Dedication to quality

Each Frontiers article is a landmark of the highest quality, thanks to genuinely collaborative interactions between authors and review editors, who include some of the world's best academicians. Research must be certified by peers before entering a stream of knowledge that may eventually reach the public - and shape society; therefore, Frontiers only applies the most rigorous and unbiased reviews. Frontiers revolutionizes research publishing by freely delivering the most outstanding research, evaluated with no bias from both the academic and social point of view. By applying the most advanced information technologies, Frontiers is catapulting scholarly publishing into a new generation.

What are Frontiers Research Topics?

Frontiers Research Topics are very popular trademarks of the *Frontiers journals series*: they are collections of at least ten articles, all centered on a particular subject. With their unique mix of varied contributions from Original Research to Review Articles, Frontiers Research Topics unify the most influential researchers, the latest key findings and historical advances in a hot research area.

Find out more on how to host your own Frontiers Research Topic or contribute to one as an author by contacting the Frontiers editorial office: frontiersin.org/about/contact

The impact of global industrial manufacturing and the development strategy of new energy and new technologies under the action of carbon reduction

Topic editors
Wen-Tsao Pan — Wuyi University, China
Yiwen Zhang — Anhui University, China
Weilin Xiao — Zhejiang University, China
Chi Lau — Teesside University, United Kingdom
Shan Shan — Coventry University, United Kingdom
Keping Yu — Hosei University, Japan

Citation
Pan, W.-T., Zhang, Y., Xiao, W., Lau, C., Shan, S., Yu, K., eds. (2024). *The impact of global industrial manufacturing and the development strategy of new energy and new technologies under the action of carbon reduction*. Lausanne: Frontiers Media SA. doi: 10.3389/978-2-8325-4354-2

Table of contents

frontiers | Frontiers in Energy Research

TYPE Editorial
PUBLISHED 11 January 2024
DOI 10.3389/fenrg.2023.1356863

Check for updates

OPEN ACCESS

EDITED AND REVIEWED BY
Hailong Li,
Central South University, China

*CORRESPONDENCE
Wen-Tsao Pan,
teacherp0162@126.com

RECEIVED 16 December 2023
ACCEPTED 26 December 2023
PUBLISHED 11 January 2024

CITATION
Pan W-T, Xiao W, Yu K, Lau C, Zhang Y and Shan S (2024), Editorial: The impact of global industrial manufacturing and the development strategy of new energy and new technologies under the action of carbon reduction.
Front. Energy Res. 11:1356863.
doi: 10.3389/fenrg.2023.1356863

Editorial: The impact of global industrial manufacturing and the development strategy of new energy and new technologies under the action of carbon reduction

Wen-Tsao Pan[1]*, Weilin Xiao[2], Keping Yu[3], Chi Lau[4], Yiwen Zhang[5] and Shan Shan[6]

[1]School of Business, Wuyi University, Wuyishan, China, [2]School of Management, Zhejiang University, Hangzhou, China, [3]Graduate School of Science and Engineering, Hosei University Chiyoda, Chiyoda, Japan, [4]School of Management, Teesside University Middlesbrough, Middlesbrough, United Kingdom, [5]School of Computer Science and Technology, Anhui University Hefei, Hefei, China, [6]School of Business, Coventry University Coventry, Coventry, United Kingdom

KEYWORDS

new energy, new technologies, carbon reduction, industrial manufacturing, COP28

Editorial on the Research Topic
The impact of global industrial manufacturing and the development strategy of new energy and new technologies under the action of carbon reduction

Introduction

In 2023, the Conference of the Parties (COP28) of the United Nations Framework Convention on Climate Change (UNFCCC) will continue to discuss the issue of carbon emission reduction. The international community expects all parties to effectively fulfill their commitments to reduce carbon emissions and take joint actions to respond effectively to the crisis and challenges posed by climate change. Carbon dioxide will cause the global average temperature to warm up year by year.

The significant factors contributing to global warming are the use of coal, oil, and natural gas, the reduction of plants due to deforestation, and the emission of exhaust gases. Under this circumstance, various countries have joined the carbon emission reduction initiatives one after another. As shown in Figure 1, the carbon emissions of the European Union and the United States have shown a specific downward trend. Japan and Russia have maintained lower carbon emissions, and India's carbon emissions have grown relatively more, yet China has shown a relatively significant increase.

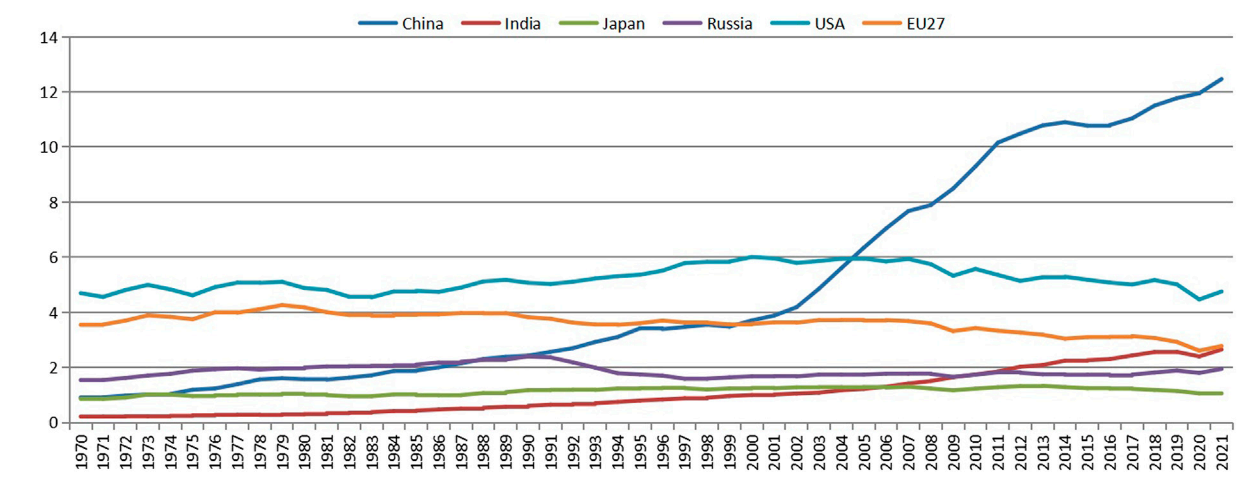


FIGURE 1
World carbon emission trends by country, source: (JRC, 2022).

Main body

Rising temperatures will lead to other changes that will cause sea levels to rise, inundating land and eroding coasts, leaving coastal countries devastated. Moreover, coastal cities and countries are the most economically and socially developed areas of the countries and have a higher concentration of population, which has the most severe impact on the economy and society. A study by Kaur et al. (2023) found a positive correlation between carbon dioxide, methane, and greenhouse gas emissions and the financial expenditures needed to implement climate change mitigation strategies. A study by Liu et al. (2017) showed that China is expected to reach peak carbon emissions around 2030 and reduce per unit of GDP carbon dioxide emissions by 60%–65% compared to 2005. Semenov (2023) analyzed the similarities and differences between the modern long-term trends of atmospheric CO2, CH4, and N2O concentrations and the intra-annual (inter-monthly) fluctuations.

The problem of calculating the enhancement of the anthropogenic greenhouse effect with modern spectral data using a one-dimensional horizontally homogeneous radiation model is discussed. It is shown that the estimation of the greenhouse effect by CO2, CH4, and N2O obtained using the radiative model is different. Mikhaylov et al. (2020) used the energy balance method to simulate the projected trends in greenhouse gas emissions by industries up to 2030. Using sensitivity analyses, we found that reducing anthropogenic CO2 emissions from humans (cars and households) would mitigate the consequences of significant climate change.

To respond effectively to the challenges of global climate change, countries are working together to achieve carbon peaking and carbon neutrality and accelerate the green development of industrial carbon reduction. So far, carbon emissions have peaked in 54 countries around the world. The primary source of carbon emissions in the United States is energy activities. The carbon emissions from the industrial production process is only 5.32%, and after the carbon emissions peaked in 2007, the carbon emissions showed a declining trend in the proportion. When the EU peaked in 1990, the proportion of its industrial production process was 9.24%. From 1990 to 2018, the carbon emissions from the EU's industrial production decreased relatively. Japan's carbon emissions peaked in 2013, with *per capita* carbon emissions below the EU *per capita* level of 8.66 per cent, and the UK had already achieved peak carbon as early as 1991, with a decline of 42.26 per cent in 2018 compared to 1991. Sikarwar et al. (2021) used a model based on input-output table data that includes energy consumption and related industrial production to analyse anthropogenic carbon emissions and their drivers.

The United States, the 28 member states of the European Union (EU), China, and India, which contribute nearly 60 per cent of total anthropogenic carbon emissions, are considered benchmarks for assessing global impacts, from which corresponding trends are derived. Wang et al. (2023) find that, under a formal environmental management system, the impact of foreign direct investment (FDI) on industrial carbon emissions in China is not apparent. This implies that individual cities' standard environmental management systems could be more efficient in formulating or implementing policies. Li et al. (2019) found that energy intensity, economic output effect, and energy consumption structure are the main influencing factors through regression analysis of the factors affecting carbon emissions from electricity and heat supply industries. In various scenarios, we also predicted the carbon emissions of the power and heat supply industry and estimated their reduction possibilities. Xu et al. (2017) argued that the only way to achieve carbon emissions in the region is by adjusting the industrial structure and the energy structure, reducing energy consumption, and optimizing the industrial structure.

Contribution of the study

This Research Topic main contribution is exploring the business transition to low carbon after COP26. In particular, it is hoped that the paper will focus on the unique national circumstances of each country and examine how to optimize each country's own industrial manufacturing, transport, agricultural production, and renewable energy application efforts and business to reduce carbon emissions in the context of multilateral cooperation between governments. Xie points out that businesses are wasting a lot of energy in their production and operations and producing a large amount of CO. The large amount of emissions is different from the economic benefits of the enterprise. Therefore, the immediate task of the enterprise is to use energy scientifically and reasonably and significantly improve the energy efficiency of the enterprise rate, thus reducing the excessive consumption of energy by the firms. Jiang selects firms from the financial point of view. Performance indicators were analyzed to help enterprises save energy in a low-carbon economy.

Wan and Yu used ten financial warning indicators to construct a risk prediction model from four aspects: financing risk, investment risk, capital operation risk, and growth risk and included "low carbon" in the financial risk warning indicator system, which is expected to provide reference and reference to the financial risks faced by the low-carbon economy. Zhu et al. proposed that the fuzzy control evaluation algorithm of a regional economy based on the SDM model can better predict the economic growth of Beijing-Tianjin-Hebei. They proposed the low-carbon development strategy of Beijing-Tianjin-Hebei, and the economic integration further promotes the integration of the development of Beijing-Tianjin-Hebei and promotes China's economy to optimize its structure. These papers are of contribution and reference value in analyzing the impact of carbon emission reduction on industrial production and economic development from different perspectives.

Author contributions

W-TP: Conceptualization, Formal Analysis, Supervision, Writing–original draft, Writing–review and editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

JRC (2022). "CO2 emissions of all world countries", in EDGAR - Emissions Database for Global Atmospheric Research. Available at: https://edgar.jrc.ec.europa.eu/report_2022#Fossil%20CO2%20Emissions%20by%20Country.

Kaur, A., Tanwar, A., Kaur, H., and Singh, J. (2023). A study on linkage between global warming indicators and climate change expenditure. *IOP Conf. Ser. Earth Environ. Sci.* 1110, 012059. doi:10.1088/1755-1315/1110/1/012059

Li, W., Liu, L., Wang, X., Quan, C., Zhang, S., and Yu, H. (2019). The analysis of CO_2 emissions and reduction potential in China's production and supply of electric and heat power industry: a case study based on the LMDI method. *Environ. Prog. Sustain. Energy* 38. doi:10.1002/ep.13192

Liu, Q., Chen, Y., Teng, F., Tian, C., Zheng, X., and Zhao, X. (2017). Pathway and policy analysis to China's deep decarbonization. *Chin. J. Popul. Resour. Environ.* 15 (1), 39–49. doi:10.1080/10042857.2017.1286753

Mikhaylov, A.Y., Moiseev, N., Aleshin, K., and Burkhardt, T. (2020). Global climate change and greenhouse effect. *Entrepreneursh. Sustain. Issues* 7 (4), 2897–2913. doi:10.9770/jesi.2020.7.4(21)

Semenov, S. M. (2023). Effective land management strategies can help climate mitigation in China. *Nat. Clim. Chang.* 12, 789–790. doi:10.1038/s41558-022-01440-3

Sikarwar, V. S., Reichert, A., Jeremias, M., and Manovic, V. (2021). COVID-19 pandemic and global carbon dioxide emissions: a first assessment. *Sci. Total Environ.* 794, 148770. doi:10.1016/j.scitotenv.2021.148770

Wang, C., Liu, T., Zhu, Y., Wang, H., Zhao, S., and Liu, N. (2023). The impact of foreign direct investment on China's industrial carbon emissions based on the threshold model. *Environ. Sci. Pollut. Res.* 30, 65086–65101. doi:10.1007/s11356-023-26803-x

Xu, X., Yang, G., Tan, Y., Zhuang, Q., Tang, X., Zhao, K., et al. (2017). Factors influencing industrial carbon emissions and strategies for carbon mitigation in the Yangtze River Delta of China. *J. Clean. Prod.* 142, 3607–3616. doi:10.1016/j.jclepro.2016.10.107

frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 04 January 2023
DOI 10.3389/fenrg.2022.1087526

OPEN ACCESS

EDITED BY
Wen-Tsao Pan,
Hwa Hsia University of Technology,
Taiwan

REVIEWED BY
Zhe Song,
Yantai University, China
Kunni Han,
Qingdao University, China
Youwen Ma,
Shanghai Jiao Tong University, China

*CORRESPONDENCE
Baochun Yu,
2100037@gnnu.edu.cn

SPECIALTY SECTION
This article was submitted to Carbon Capture, Utilization and Storage, a section of the journal Frontiers in Energy Research

RECEIVED 02 November 2022
ACCEPTED 16 December 2022
PUBLISHED 04 January 2023

CITATION
Wan J and Yu B (2023), Early warning of enterprise financial risk based on improved BP neural network model in low-carbon economy.
Front. Energy Res. 10:1087526.
doi: 10.3389/fenrg.2022.1087526

Early warning of enterprise financial risk based on improved BP neural network model in low-carbon economy

Jie Wan[1] and Baochun Yu[2]*

[1]Department of Culture Management, Shanghai Publishing and Printing College, Shanghai, China,
[2]School of Economics and Management, Gannan Normal University, Ganzhou Jiangxi, China

The concept of low-carbon economic development has led to changes in the business environment and financial environment of enterprises, leading to increased financial risks faced by enterprises. How to help enterprises better warn, prevent and control financial risks from the perspective of low-carbon economy has become a hot issue worth studying. Based on this, this paper is based on the perspective of low carbon economy, on the basis of analyzing the financing risk, investment risk, capital operation risk and growth risk faced by enterprises under the requirements of low carbon economy development. A set of financial risk management framework with clear hierarchy and strict vertical logic has been constructed. Ten financial early-warning indicators are constructed from four aspects. The risk prediction model of the indicator system is established using the research method of BPNN (Back Propagation Neural Network). The model is trained and simulated through the MATLAB neural network toolbox. After 10 indicators passed Bartlett's correlation test, the BPNN financial early warning model was programmed using MATLAB software. The accuracy rate was 84.3%. The neural network training results show that when the layer node is 8, the best correct recognition rate can be obtained. Incorporate "low carbon" into the financial risk early warning indicator system that meets the requirements of low carbon economic development in the design of enterprise financial risk early warning indicators. This paper is expected to provide reference and reference for low-carbon economy enterprises to deal with financial risks under the new situation.

KEYWORDS

back propagation neural network, financial risk, enterprise, early warning model, low-carbon economy

1 Introduction

The core feature of developing a low-carbon economy is low carbon emissions. The so-called low carbon economy is an economic model based on low energy consumption, low pollution and low emissions, which corresponds to the high carbon economy characterized by high energy consumption, high pollution and high emissions. The essence of low carbon economy is to maintain economic and social development while realizing efficient utilization of resources and low-carbon or carbon free development of energy. Under the advocacy of green environmental protection and low-carbon development, all economic entities around the world actively assume environmental responsibility to promote low-carbon development. The financial market plays an important role in promoting the transition to a low-carbon economy. Low carbon green development will play a key role in helping the financial market in the process of transition to a low carbon economy (Louche et al., 2019). Under the impact of "economic globalization", the market competition is intensifying, and enterprises are facing enormous pressure for survival and development. Among them, there are many cases of mismanagement caused by the financial crisis, which directly put these companies in trouble, or even led to their bankruptcy. Therefore, it is very practical to establish a scientific data model to analyze and forecast the financial data of enterprises. It can not only monitor the financial situation of enterprises in real time, but also play an effective role in financial early warning (Kuang et al., 2022). Several indicators and single variable ratios can be used to measure the robustness reflected in the company's balance sheet (leverage, profitability, liquidity ratio, etc.). However, each indicator cannot measure the overall financial risk or financial distress level of a company separately (Colak, 2021). The combination of quantitative financial indicators with macroeconomic variables, industry factors and corporate non-financial standards can be used for robust and balanced risk analysis. Based on enterprise risk management (ERM) theory, it can be used as an important aspect of risk management to analyze the possibility of company failure (Tan et al., 2022). In a normal economic environment, the main predictor of financial failure is to distinguish between healthy and failed SMEs. Autonomous ratio, interest and sales, asset turnover, days of accounts receivable and period of accounts payable are variables that increase the probability of financial failure, while repayment ability and return on assets reduce the probability of failure (Zizi et al., 2020). The transition to a low-carbon economy will lead to large-scale structural changes. Some industries will have to expand their relative economic weight, while others, especially those directly related to fossil fuel production and consumption, will have to decline. This systemic change may have a significant impact on the stability of the financial system, including sudden asset revaluation, debt default and foam in emerging industries (Semieniuk et al., 2021). Traditional machine learning needs data representing feature target relationship, and relies on the development, maintenance and modification of handmade features, which are usually costly. Therefore, modeling highly variable heterogeneous patterns is a challenge. Deep learning is expected to remedy. The hierarchical and distributed representation of data is learned automatically, which reveals the generation features that determine the target, avoids artificial feature engineering, and is more robust to changes (Kim et al., 2020). The SEM model results show that risk management and tenure of CEO have a significant positive impact on financial performance and corporate capital. Through risk management,

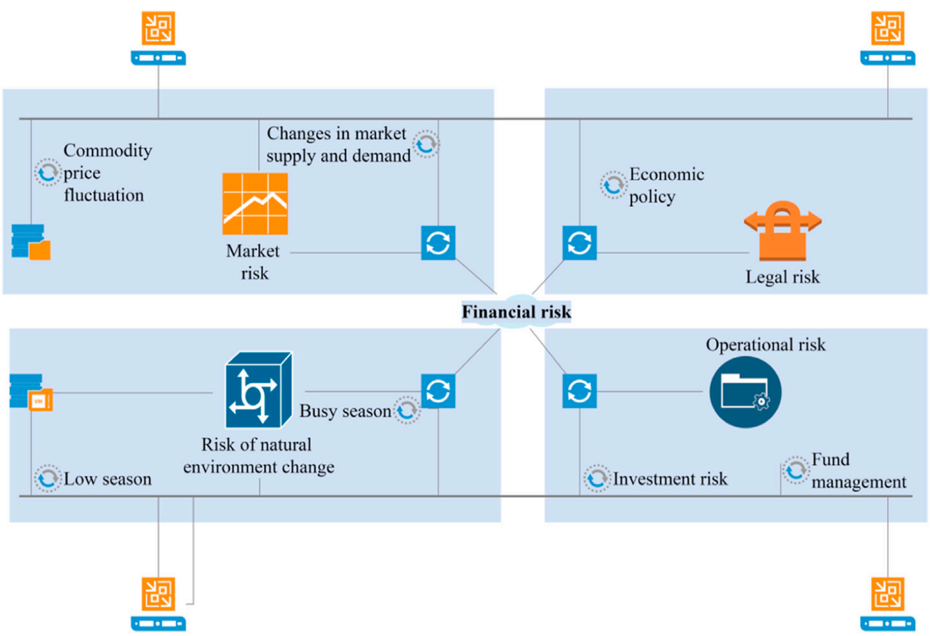


FIGURE 1
Types of corporate financial risks.

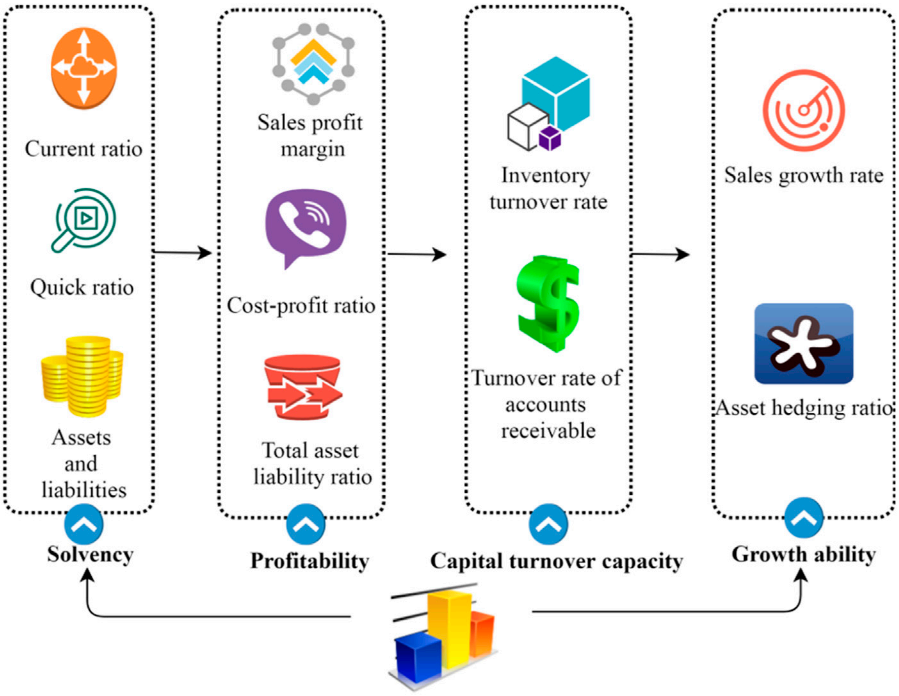


FIGURE 2
Financial risk early warning indicator system.

CEO duality and board size have a significant positive impact on financial performance (Hamid and Purbawangsa, 2022). We will actively fulfill our social responsibilities by establishing a low-carbon and environment-friendly business model, and build the green core competitiveness of enterprises.

Financing risk analysis of enterprises from the perspective of low-carbon economy financing risk refers to the lack of sufficient cash flow to pay the principal and interest, which makes enterprises suffer losses. During the financial crisis, the prediction ability of all traditional financial distress prediction models will decline. Therefore, it is necessary to develop a model by identifying variables that have a greater impact on the financial distress of companies operating in developed and developing markets (Ashraf et al., 2019). From the perspective of low-carbon economy, the impact on corporate financing risk is mainly manifested in two aspects: on the one hand, in order to respond to the requirements of national environmental protection policies, enterprises must update or even discard traditional high energy consumption and high pollution equipment or technologies. Traditional econometric models in economic forecasting mainly have the problem of understanding the model and using deviation. At present, there are many estimation methods in econometric modeling, especially under the guidance of machine learning ideas, new AI research has obtained more estimation methods. However, most of the errors caused by these algorithms and random interference errors are uncontrollable. The use and purchase of new environmental protection equipment forced the total debt of enterprises to increase, and the increase in the amount of financing naturally increased the risk and pressure of enterprise debt repayment. In order to detect and deal with the systematic risk of the increasing amount of data generated in financial markets and systems, many researchers have increasingly adopted machine learning methods. Machine learning methods are used to study the outbreak and contagion mechanism of systemic risks in financial networks and improve the supervision of current financial markets and industries (Kou et al., 2019). On the other hand, corporate debt is mainly used for energy-saving and environmental protection equipment or technology research and development, which cannot directly improve the economic benefits of enterprises. It also increases the operating costs of enterprises. Force the fund supplier to raise the enterprise financing threshold or financing cost under the influence of green credit. This also increases the constraints and difficulties of enterprise financing. To sum up, the environmental requirements of low-carbon economy on enterprises have increased the pressure on enterprises to raise funds and financial burden. The principle of financial risk control of small and medium-sized enterprises needs to conform to the general objective of the enterprise. The general objective of an enterprise is the starting point and destination of all business

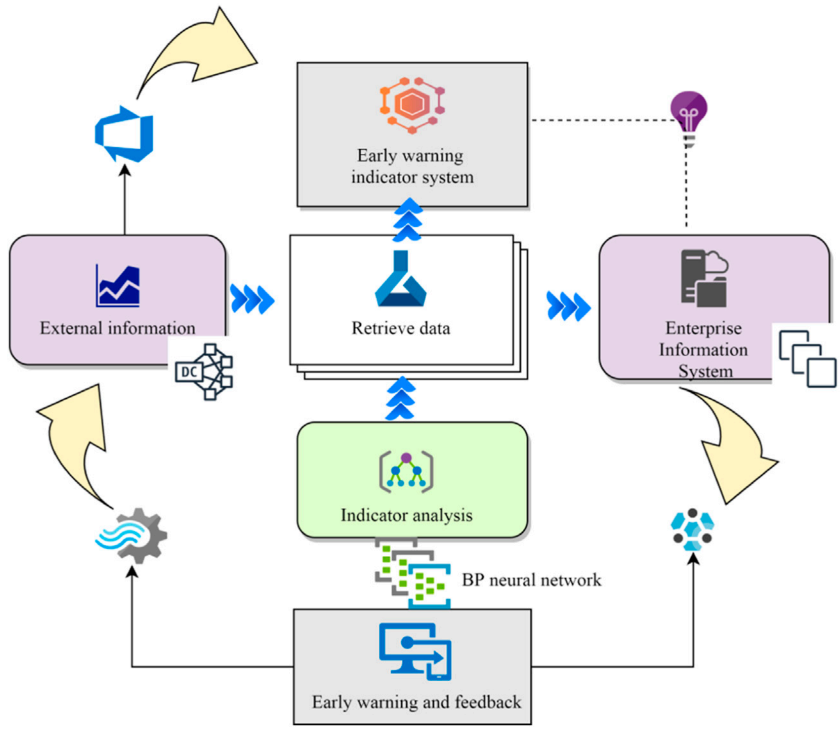


FIGURE 3
Basic process of financial early warning model based on BPNN.

activities of the enterprise. The principle of combining local risk with overall risk prevention and control. The business results of an enterprise are the result of a number of interrelated business activities. Therefore, under the original financing risk management, enterprises should also focus on indicators such as carbon asset liability ratio and carbon current liability ratio, and timely reveal the financial risks related to carbon assets and liabilities. Establish a financial risk monitoring and prediction index system. It has a standardized, comprehensive, sensitive, complementary and operable financial risk monitoring and early warning indicator system. There should also be indicators reflecting changes in the financial system and the external environment of the region. Some financial relative quantity estimation indicators closely related to economic operation and reflecting changes in the financial system should be set.

Because the neural network method can enable the model to have the self-learning ability with the changing complex environment, the BP neural network model is widely used to make the enterprise financial dynamic early warning possible. The basic idea of establishing the financial crisis early warning model with BP neural network is to take the financial evaluation index as the input value, and first give a weight. The output value is transferred to the output value through the hidden layer, and the output value after the function operation is compared with the expected value. If the error is large, the error will return along the original path in reverse, and the weight of each layer node will be modified for iterative calculation. After each operation, the weight distribution of the sample data is updated according to the error structure. After several iterations. When the error accuracy requirements are met, a group of optimal weights will be obtained, which are the parameters of the prediction model. In this paper, BP neural network is used as the financial early warning model, and the improved indicators are used as input variables. Compared with the traditional financial indicators as input variables, the low error rate shows that the improved input variables are more effective.

This paper first analyzes the types of enterprise risks, and then constructs an enterprise early warning model based on the basic principles of BPNN. Secondly, it points out the advantages of using BPNN to take advantage of enterprise financial risk early warning. The author believes that the biggest feature of early warning is pre control and quantitative management, and from the perspective of quantitative management, enterprise risk is more quantified from the perspective of financial risk. The enterprise dynamically monitors the important factors that affect the enterprise's finance, makes statistical analysis of financial data, and through data statistics and analysis, reasonably and scientifically evaluates the company's financial situation, and timely reflects the risks found. It can quickly respond to the operating conditions of the enterprise,

TABLE 1 Corresponding indicators of the input layer.

Output layer	Name of financial indicators
Node 1	Net profit rate of total assets
Node 2	Current ratio
Node 3	Inventory turnover rate
Node 4	Turnover rate of fixed assets
Node 5	Growth rate of total assets
Node 6	Equity ratio
Node 7	Net profit Net cash content

especially the hidden risks of the enterprise. It is helpful for enterprise managers to allocate resources and analyze the causes of enterprise risks in combination with enterprise financial data. According to the early warning indicator system, obtain relevant data from the company's external and enterprise information systems. The data are processed and condensed into independent principal component factors, which are used as input values of BPNN, and then used for early warning. Finally, according to the early warning results, send an alarm, return it to the enterprise information system, link it with the management procedures, analyze the reasons of the financial crisis, and propose control strategies for the financial crisis.

The contributions of this research and innovation are as follows:

1 The definition of rating results can reflect the financial situation of the institution more comprehensively and truly, and can improve the accuracy of the early warning model. Avoid blind low-carbon investment and reduce the economic benefits of enterprises.
2 Collect data in various ways and verify each other. The lost data shall be processed at different levels to ensure that the data can be mutually verified, so as to minimize information distortion.
3 Include non-financial indicators closely related to the financial status of green low-carbon enterprises into the selection range. So that the indicator system can more accurately reflect the actual financial situation of enterprises. It effectively warns against the investment risks brought by blind low-carbon investment.

This article is divided into six sections from the organizational structure.

The first section is the introduction. Firstly, it introduces the research background and significance of financial risk research. Secondly, it introduces the research status, the organizational structure and main content of this paper. It summarizes the research results from the perspective of financial early warning, and then puts forward the innovation in this research. The second section mainly introduce the research on financial management in various countries and the existing deficiencies. The third section introduces the types of enterprise financial risks and the functions of early warning system in detail, and the basic process of the financial early warning model based on BPNN. The fourth section introduces the algorithm. The fifth section is application of model design. The sixth section is the conclusion, which summarizes the results of the full text.

2 Related work

Traditional investment risk refers to the uncertainty of future investment income in the process of investment. The possibility of making enterprises suffer financial losses. From the perspective of low-carbon economy, enterprise investment risk refers to the transformation of enterprises from "high carbon" to "low carbon". The cost of investment reconstruction or re purchase of operating equipment or technology is greater than the economic benefits of low-carbon investment in the future. Due to the large amount of operating funds required for the purchase of low-carbon equipment or newly developed environmental protection technologies by enterprises. And as a fixed asset or intangible asset, it needs to increase the economic benefits of the enterprise through value transfer for a long time in the future. Therefore, enterprises will carry out feasibility demonstration before upgrading or purchasing low-carbon equipment or technology, so as to avoid blind low-carbon investment to reduce the economic benefits of enterprises. That is to evaluate and calculate the initial cost of low-carbon investment and the economic benefits it will bring to the enterprise in the future. In order to effectively warn the investment risks arising from blind low-carbon investment, enterprises need to carry out targeted management of carbon

TABLE 2 Rotated composition matrix.

Variable	Component				
	1	2	3	4	5
Current ratio	0.668	0.117	0.669	0.543	0.458
Quick ratio	0.371	0.104	0.857	0.489	0.676
Asset liability ratio	0.851	0.119	0.227	0.94	0.719
Inventory turnover rate	0.143	0.273	0.149	0.721	0.492
Turnover rate of fixed assets	0.663	0.96	0.128	0.889	0.98
Return on net assets	0.922	0.964	0.49	0.594	0.893
Sales growth rate	0.798	0.127	0.672	0.258	0.302
Cash turnover	0.323	0.319	0.121	0.727	0.414
Turnover rate of total assets	0.977	0.622	0.424	0.118	0.379

TABLE 3 Collinearity diagnosis.

Dimension	Characteristic value	Conditional index
1	7.398	8.19
2	7.293	4.57
3	5.29	7.04
4	4.265	9.15
5	0.715	.27
6	0.571	9.32
7	0.915	10
8	0.406	4.85
9	0.681	9.08
10	0.91	2.14

investment under the original investment risk management. The hidden carbon investment risks of enterprises are revealed by measuring the economic benefits and cost rate of carbon investment in the future. The emergence of financial crisis is a gradual process and the result of deterioration of a series of factors. The reasons are divided into two categories: internal and external, namely, systematic risk and unsystematic risk. It is a common risk that changes in external risk factors of the company cause the uncertainty of the entire financial environment, thus affecting the financial operation of all companies in the whole society. In nature, systematic risk is environmental risk. The main factors that cause systematic risk are economic environment, legal environment and financial environment. The economic environment mainly includes: Economic cycle, economic development level and macroeconomic policies. The legal environment mainly includes: organizational form, relevant provisions of corporate governance and tax regulations; The financial environment is the most important external environmental influence factor of the company. At present, most models generally conduct financial early warning based on single type features, lacking early warning analysis based on multi type features. The accuracy and robustness of early warning of models also need to be further improved. On the premise that financial indicators and non-financial indicators are used to construct multiple types of financial features, Xuefeng et al. (2022) integrates multiple CART trees to construct CFW Boost by combining the causal relationship of features. It is found that CFW Boost has higher accuracy and more stable early warning performance than other models. The demonstration conforms to the market law, which can provide useful reference for enterprises and market supervision departments. Zeng analyzed the traditional financial risk early warning model based on accounting information. Based on this, an enterprise risk early warning model is proposed from the perspective of cash flow, and a financial risk early warning indicator system is established. After preprocessing, the data is input into the model according to the type of financial risk early warning indicators to obtain the company's financial risk prediction results (Zeng, 2022). The concept of low-carbon development involves several interrelated tasks: improving energy efficiency, using renewable energy, etc. Kapitonov used statistical analysis, mathematical modeling and standard

FIGURE 4
Number of training steps and mean squared error.

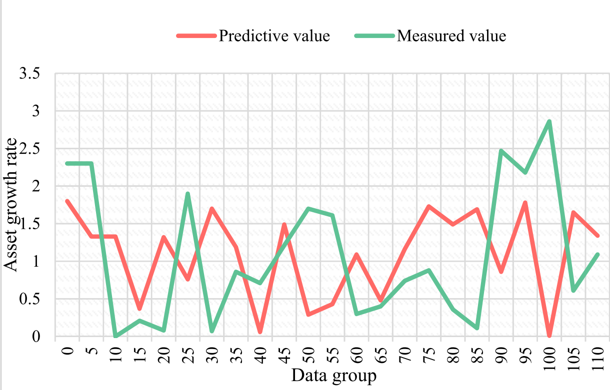


FIGURE 5
The training results of the solvency index.

estimation methods to analyze the most important factors of development. It is the first time to put forward the sustainable development structure of energy security (Kapitonov, 2021). With the intensification of competition among enterprises, investors and enterprises pay more and more attention to the role of financial crisis early warning in enterprise management. Shang et al. (2021) selected multiple financial indicators based on big data mining of the Internet of Things. It is found that the rules among all financial indicators select more representative financial risk indicators. Then, FCM (fuzzy clustering method), parallel rules and parallel mining algorithm are used to determine frequent fuzzy option sets, so as to obtain fuzzy association rules satisfying the minimum fuzzy credibility. The financial risk of listed companies is a problem that needs attention. The financial crisis of e-commerce companies is a complex and gradual process, and its unique reasons may be many. E-commerce companies are facing financial risks or difficulties, and bankruptcy and liquidation are also increasing. Cao et al. (2022) studied from the perspective of establishing a financial early warning model based on deep learning and building an early warning mechanism for financial risks of e-commerce companies, and analyzed and predicted the financial risks of listed companies. Through the construction of the financial security early warning system, crisis signals can be diagnosed as early as possible, and crisis signals can be timely and effectively prevented and resolved. The traditional financial risk assessment is inaccurate, and the adaptive assessment ability is low. To solve this problem, Kang proposed a financial risk assessment model based on big data. The adaptive fuzzy weighted control method is used to fuse the information of financial risk assessment data and big data classification, and the asset return control and innovation assessment model are used to carry out linear programming and square fitting for financial risk. Based on the intervention factors of financial market participants, a quantitative regression analysis was conducted. According to the economic game theory, we have conducted big data analysis and prediction on financial risk assessment through regression analysis (Kang, 2019). The SME sector plays a crucial role in promoting economic growth in emerging countries. Buchdadi et al. (2020) tested the determinants of SME performance, namely the financial literacy of managers. Use financial product access and financial risk attitude as intermediary variables. Such studies use quantitative methods and use structural equation modeling (SEM) to analyze data. Through multiple regression analysis, Valaskova et al. (2018) determined significant predictive factors under specific

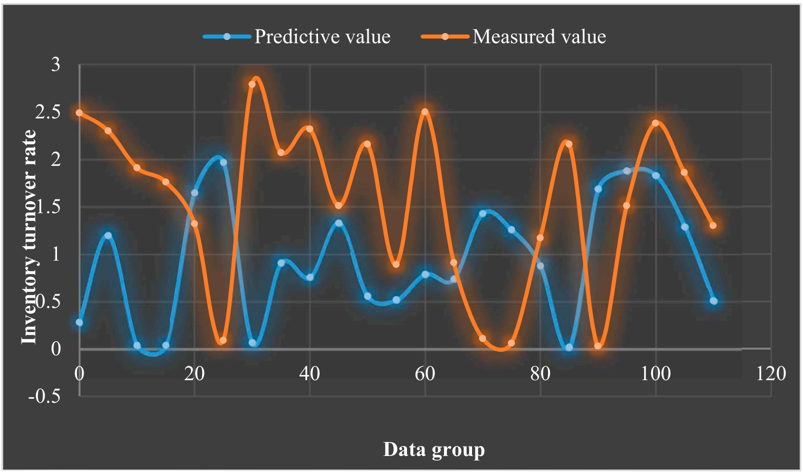


FIGURE 6
Training results of operational capability indicators.

FIGURE 7
Profitability index training results.

economic environment conditions to estimate the prosperity and profitability of enterprises. The results obtained in the study are very important for the company itself, as well as its business partners, suppliers and creditors, to eliminate financial and other corporate risks related to the company's unhealthy or adverse financial situation. He and Chen aims to study the application of the construction of the early warning model of the financing and financial risks of animal breeding enterprises in the economic transition period, and is conducive to the early warning of the financial risks of the animal breeding industry in this country in the economic transition period. This experimental study shows that building a financial risk early warning model can make the financing of animal breeding companies more clearly reflected in the economic transition period, and improve the financing probability of enterprises (He and Chen, 2020). Du and Shu proposed a credit scoring model based on deep learning network to solve the systemic risk problem caused by the lack of credit scoring in the existing financial market. Its purpose is to effectively manage the financial market and reduce the risk of financial enterprises. The bionic optimization algorithm is introduced, and an integrated

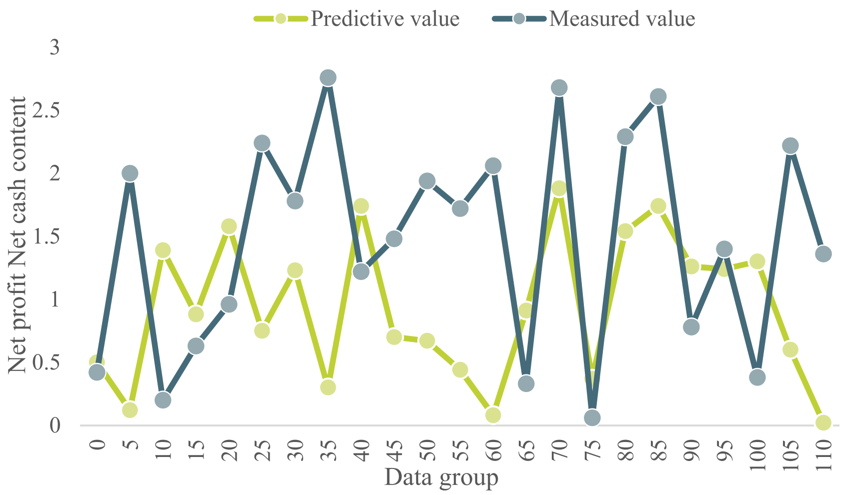


FIGURE 8
Training results of cash flow capability indicators.

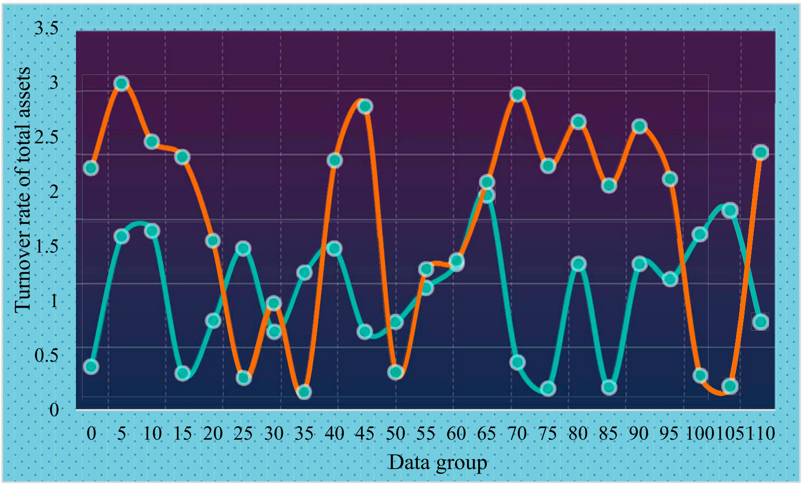


FIGURE 9
Training results of developmental ability indicators.

deep learning model is proposed. Finally, a financial credit risk management system using integrated deep learning model is proposed (Du and Shu, 2022).

From the perspective of low-carbon economy, the growth risk of enterprises mainly refers to that the continuous growth of carbon investment of enterprises fails to effectively promote the growth of economic benefits of enterprises. That is, the growth rate of carbon investment is greater than the growth rate of enterprise economic benefits. This risk reveals that the enterprise carbon investment fails to give full play to its benefits, and there are blind investment and waste of investment. From the current research results, the selection of early warning indicators and early warning theory are still not perfect. Moreover, at present, there are few classified models for the same industry in China. Due to the different characteristics among industries, the factors affecting the formation of financial crisis are also different. Therefore, we need to design and establish a financial management model from a new perspective, and use new methods and means to improve the rationality and accuracy of financial management. For example, the combination of statistical methods and computer software, and the combination of statistical models and artificial neural networks can complement each other.

3 Types of enterprise financial risks and functions of early warning system

From the perspective of financial management, small and medium-sized enterprises can interpret the causes of bankruptcy or failure of small and medium-sized enterprises in two aspects: First, the operating income of enterprises is decreasing until losses occur. Secondly, the enterprise is short of funds and cannot effectively pay off the due debts. This is also the realistic background of the research on the financial risk prediction of SMEs. A sound and efficient financial early warning system can help small and medium-sized business owners to understand the changes in the business operation and financial situation, predict the risk of business failure, and leave time and space for small and medium-sized business owners to deal with this crisis. The integrity principle means that the indicators designed should cover all risk early warning financial indicators related to low-carbon economy. We should not only consider the actual economic indicators of enterprises, but also consider the resources that may be wasted in economic activities and the damage to the ecological environment after wasting resources. The principle of comparability means that the expected users can use these financial early warning indicators to compare with the financial information of other enterprises. That is, the indicator design cannot only consider the low-carbon economy. It is also necessary to consider the financial situation of the enterprise, so as to achieve the comparison with the financial statements when the low carbon indicators were not designed before. Business risk mainly refers to the possibility of adverse impact on the Company's objectives due to production and operation reasons. For example, the supply risks caused by the changes in the political and economic conditions of the raw material supply place, the emergence of new materials and other factors. Production risks caused by unreasonable production organization. Sales risks caused by sales decision-making mistakes. If a company's equity capital is insufficient, or it blindly pursues economies of scale and financial leverage benefits and becomes excessively indebted, it will increase its burden of repaying debt principal and interest. At the same time, the owners and creditors of the company will demand to increase the distribution of investment income and increase the interest rate due to the increased investment risk, which will further increase the financial burden. The solvency was further reduced. If the structure of the company's assets or liabilities is unreasonable and the cash flow is poor, which causes difficulties in short-term debt repayment or turnover, it will also lead to financial crisis. Modern enterprises are faced with the various business pressures and risks, the inconsistency between owners and operators and asymmetric information. In addition, we are faced with the ever-changing market and the ever-changing international and environment. Coupled with a series of changes in politics, economy and society, risks are inevitable. Financial risk is the final embodiment of many risks. Early warning system can help enterprises to prevent crises and carry out strategic management. The main financial risks faced by the company can be splited into the following categories (Figure 1).

3.1 Market risk

Enterprises may involve a variety of commodities. The prices of these commodities fluctuate with the fluctuation of market prices, and their uncertain changes make enterprises face the uncertainty of losses.

3.2 Legal risks

China's macro-economic policies often change, and the pressure of inflation makes the price rise, the project cost increase, and also brings risks to the company's operation. In addition, the relevant regulations formulated by state institutions or industry organizations to regulate the financial behavior of enterprises and coordinate the financial relations between different financial entities will also implicate enterprises.

3.3 Operational risk

The company faced problems in planning and managing the operation of investment projects, which led to the return rate of investment funds being far lower than the borrowing rate, and even brought debt problems to institutions.

3.4 Risk of natural environment change

The nature is always in a kind of movement and change, which often has a certain impact on economic activities. Seasonal changes will produce "off season" and "peak season" of commodity sales, while natural disasters often have a destructive impact on the normal operation of enterprises, which will ultimately be reflected in the financial results of enterprises.

The establishment of the index system is the most important link in the whole financial risk early warning system. Early warning indicators should be the most representative financial indicators. They should not be too many and should comprehensively reflect the financial situation and operating results of the enterprise, so they should not be less. Select indicators that are highly related to risk early warning to form an indicator system. The index diagnosis for all aspects of the enterprise mainly includes the following contents: business diagnosis, production diagnosis, organizational diagnosis, and technical diagnosis. In order to help find or judge the main problems and causes in enterprise management, propose targeted measures to improve the level of enterprise management. The indicator system should not only consider the particularity of each enterprise, but also be designed in combination with the different characteristics of modern enterprises. In terms of the selection of specific indicators, considering that the indicators should complement each other without duplication and give expression to the financial situation of the company as comprehensively and comprehensively as possible, each early warning module takes several representative indicators. Figure 2 shows the warning indicator system studied in this paper.

BPNN has excellent error correction ability and learning ability. It play a significant role to apply it to enterprise financial early warning. Its basic principle is that the input layer is responsible for importing data samples and sending sample data to the hidden layer. Secondly, the hidden layer processes data in real time according to the activation function, and transfers the calculation results to the next layer. Finally, the output layer is responsible for output. After training, the network deviation gradually reduces to achieve the desired value. Therefore, we can establish an expectation function, put all indicators into the function, and use the discriminant method to score and classify. Figure 3 shows the basic process of the financial early warning model based on BPNN.

The establishment steps are as follows: 1) Select an appropriate analysis mode. To establish a financial early warning model, the most fundamental thing is to choose an appropriate analysis mode, that is, first analyze and judge whether the research object is suitable for single variable model or multi variable model. 2) Determine the appropriate sample for analysis. For a discriminant function, it is very important to focus the discriminant values on two or more intervals to achieve the effect of discrimination. This requires starting from the analysis of samples and dividing them into several obvious categories. 3) Design and further screen out appropriate financial indicators or financial indicator combinations. 4) Use the analysis software to calculate the model parameters (assuming SPSS system is selected to complete the analysis model). 5) Results inspection. There are two main aspects to test the results: One is the accuracy test, the other is the predictive test.

The implementation steps of the financial early-warning comprehensive index measurement system. The implementation steps of the financial early-warning comprehensive index measurement system are generally as follows: 1) Design the core indicators and auxiliary indicators that should be monitored in the financial early-warning comprehensive index; 2) Measure the "early warning critical indicator value" of various financial monitoring indicators; 3) Measure the "actual index value" of various financial monitoring indicators; 4) According to the "early warning critical value" and "actual indicator value" of each financial monitoring indicator, measure the early warning composite index of each financial monitoring indicator and predict the warning degree; 5) Analyze and evaluate the financial early-warning comprehensive index. The efficiency coefficient method refers to comparing each index to be evaluated with its own standard according to the principle of multi-objective planning, and according to the weight of each index. The power function is transformed into measurable evaluation scores, and then the individual index scores of each index are summed up to obtain the comprehensive evaluation scores. The efficiency coefficient method is used to convert financial indicators into single efficiency coefficients. In fact, the influencing factors of different industries have been removed, which should improve the risk prediction.

4 Optimization of back propagation neural network model

The first step is to set variables and parameters. Assuming that the number of input and output neurons is M and N.

$$\alpha = \frac{M+N}{2} \le L \le (M+N) + 10 = b \tag{1}$$

Standardization before data input can effectively improve the convergence speed and effect. This paper analyzes some of the motivations. If our activation function is sigmoid or TAH, the maximum gradient interval is around 0. When the input value is large or small, the change of sigmoid or TAH is basically flat. That is to say, the gradient tends to zero while the optimization speed is very slow. The simplest and most useful method is to carry out z-score, PCA whitening and other standardization methods, scaling the input to 0 mean and standard variance.

Because of the non-linear dynamics of neural networks, it is difficult to obtain a simple and general formula to identify hidden layer units in theory. However, some qualitative conclusions obtained through extensive and long-term application process will help to reasonably arrange the number of hidden layer units. Therefore, the number of hidden layer units can be determined by referring to the following formula.

$$L = \sqrt{n_1 + m} \times a \tag{2}$$

Among them, L is the number of hidden layer nodes, m is the number of input layer nodes, n_1 is the number of output layer nodes, and a is a constant between 1 and 10. Therefore, the number of hidden layer nodes is determined to be 6.

The second step is to initialize the connection right and threshold value.

After the training, use the test sample to test the network accuracy, compare the actual output with the expected output of the test sample, and select the number of hidden layer nodes with the highest alert accuracy as the final number of hidden layer nodes of the alert model in this paper. If the set accuracy requirements are met, that is, the error is within the allowable range, the algorithm is terminated and the BPNN model is obtained. If the error fluctuation exceeds the limited range, assess the error of the hidden layer node, calculate the error gradient, adjust the weight and threshold, and adjust the relevant parameters if essential until the error meets the set standard.

$$E_p = \frac{1}{2}\sum_{i=1}^{m}(t_i - y_i)^2 \tag{3}$$

The output curve of Sigmoid function is relatively flat at both ends, with sharp changes in the middle part, which is closer to the signal output form of biological neurons. Generally, the differentiated S-ray function is continuously defined as the activation function in the hidden layer node, namely:

$$f(x) = \frac{1}{1+\exp(-x)} \tag{4}$$

In the reverse iteration process of error, determine whether the adjacent calculation cells need to be iterated in the orthogonal direction, which will lead to zigzag jump near the extreme value. Although this can reduce the value of the network performance function as quickly as possible, it slows down the convergence calculation of the network and makes the calculation result easy to approach the local minimum.

$$w_{ij} = w(t) + \eta\delta_{pi}\rho_{pj} \tag{5}$$

For the input layer neurons of the model, the input and output are the same. The calculation rules for the neurons of the middle hidden layer and the output layer are as follows:

$$Y_{kj} = f_w\left(\sum_{i=1}^{n}(k \cdot \alpha - 1)\right) \cdot \lambda_k \tag{6}$$

In the above formula, f is the sigmoid function.

The output value at the n-th iteration is:

$$y(n) = f\left[\sum_{i=1}^{n} w(n)x_i + \phi(n)\right] \tag{7}$$

The actual output value in the n-th iteration is:

$$z(n) = f\left[\sum v(n) y_i(n) + r\right] \tag{8}$$

In order to save the time of training network, partial connection mode can be used to obtain better accuracy in a reasonable time, the update amount Δw_{ij} of w_{ij} is expressed by the following formula:

$$\Delta w_{ij} = -\mu \frac{\partial E}{\partial w_i} \tag{9}$$

$$N(t) = \sum_{i=1}^{k} n_k + N_o + N_p \tag{10}$$

N_0 and N_p represent the number of neurons. These $N(t)$ excited neurons form the excitation path and realize the functional distribution. The model is further validated by the following formula:

$$RE = \sqrt{\frac{1}{n} \times \sum_{i=1}^{n} a\left(\frac{p_{1-}p_0}{\delta}\right)^2} \tag{11}$$

$$N_{pj} = \sum_{i=1}^{n} Q_{ij} F_{pi} \tag{12}$$

Take the probability analysis method to measure the degree of investment risk. The probability analysis method calculates the standard deviation according to the probability rate of return, expected rate of return and probability analysis of the investment scheme under various economic conditions. The standard deviation refers to the deviation degree between the expected yield rate and the yield rate. The standard deviation formula is:

$$\varpi = \sqrt{\sum_{i=1}^{n} (X_i - \bar{X})^2 p_i} \tag{13}$$

Among them, X_i is the yield rate, $\bar{X}$ is the expected yield rate, and p_i is the probability. During the comprehensive evaluation of the financial situation, due to the different types of financial indicator data, there is no comparability between indicators. Before building a model for comprehensive evaluation, these indicators must be normalized according to a specific formula. For benefit type indicators, the larger the indicator value, the better, so that:

$$y_{ij} = \frac{x_{ij} - b_j}{a_i - b_j} \tag{14}$$

For cost index, that is, the smaller the index value, the better, let:

$$P_{ij} = \frac{a_j - x_{ij}}{a_j - b_j} \tag{15}$$

Moderate indicators require that the indicator value is determined to be a fixed value as the best, so that:

$$R_{ij} = \frac{1}{1 + t - x_{ij}} \tag{16}$$

5 Analysis of training results of neural network model

The purpose of back propagation is to achieve optimization without repeating derivative steps. It refers to a multilayer neural network that uses error back propagation (BP algorithm for short) to solve the weight correction problem in the training of artificial neural network. An algorithm for training some given feedforward neural networks for a given input pattern when the classification is known. When each segment of the sample set is displayed to the network, the network will see its output response to the sample input mode. Then, the measurement output response is compared with the expected output and the error value. Then, we adjust the connection weight according to the measured error value. In order to train the BP neural network, it is necessary to calculate the weighted input vector, network output and error vector of the network, and then calculate the sum of squares of the errors. When the sum of error squares of the training vector is less than the error target, the training stops. In this paper, by increasing the training times and observing the simulation results to find the best training times, the network has the best generalization ability. According to the above research results, it can be seen that the early warning of enterprise financial risk under the low-carbon perspective has certain particularity, and the principles, indicator setting and weight of each indicator must be considered when establishing. Therefore, this paper proposes the following suggestions for establishing a low carbon economy enterprise financial risk early warning system. First, multiple principles should be considered in the design. When designing the financial risk early warning system, enterprises should consider the principles of integrity, comparability and systematization; Scientific principle, etc. as shown in Table 1.

This paper determines the weight of financial risk early warning indicators. In the criteria layer, the carbon profitability index has the highest weight, followed by the carbon debt repayment index, carbon development index and carbon operation index. It shows that experts believe that under the perspective of low-carbon economy, enterprises still aim to make profits, that is, to make profits by using carbon equipment, carbon inventory, etc. The important indicator of bank loans to enterprises is the debt repayment indicator, so we should still pay attention to the carbon debt repayment indicator when developing the carbon economy, that is, the indicator is still important. However, the ultimate goal of carbon development indicators and carbon operation indicators is to promote the rise of carbon profitability indicators, which may be the reason why experts give a lower score. Among the financial factors of an enterprise, profitability and solvency have the greatest impact on the financial crisis in, while growth ability, capital structure and operating ability and non-financial factors have relatively little impact. In the final analysis, profitability and solvency are the ability of enterprises to obtain funds. It is the blood of a capital enterprise, and the profitability is an important factor to determine whether the capital is sufficient. The business activities of an enterprise cannot be separated from financial support, just as the human body cannot live without blood. But practice shows that the lack of funds has become an important factor hindering the survival and development of enterprises.

The samples selected in this paper are manufacturing companies listed in Shenzhen and Shanghai stock exchanges, and the original data are all from Huatai Securities website www.htzq.com cm. Among them, Bankruptcy companies selected refer to those specially treated by the stock market in 2017 (There are 27 ST companies in total. The base date is the earliest occurrence date of financial anomalies. The financial statement data of these companies before the base date are selected. In this paper, the same company in different years is also considered as different companies. After removing the companies with missing financial data, the total number of samples used in the final empirical analysis is 138. Among them, the total number of training samples is 10, and the total number of generalized tests is 56. For the selected sample data, the equal scale example is used to reduce In this way, the financial data can fall into the range [0, 1], so that the neural network can process the data. K-S test is adopted to test the normality of basic financial early-warning indicators. S-W inspection and K-S inspection: S-W inspection is recommended for small samples (less than 50), and K-S inspection is recommended for large samples (more than 50). It will be used when using software to solve statistical problems. If the financial early warning indicators meet the normal distribution, perform a *t*-test on the selected basic financial early warning indicators. If the financial early warning indicators do not meet the normal distribution, Kruskal Wallis non-parametric test is performed on the selected basic financial early warning indicators to obtain the component matrix in Table 2.

Through the significance test of the initial variables, we know that 10 indicators such as the cash recovery rate of assets have obvious correlation with the financial situation of the enterprise. However, some of these indicators have strong collinearity and contain repeated information, which will have a certain impact on the accuracy of the experiment. Therefore, continue to use factor analysis to screen the 10 indicators for the second time to eliminate the collinearity between indicators, as shown in Table 3.

From the results of collinearity diagnosis, the eigenvalues of the first few principal components are larger, while the latter ones are smaller. At the same time, the conditional index of the latter principal components far exceeds 8, which also indicates that there is serious multicollinearity among these variables. We need to filter the independent variables.

Use the weight of financial risk early warning indicators of low-carbon economy enterprises studied in this paper. This paper uses AHP method to calculate the weight of financial risk early warning indicators. Among them, collect the survey results of each respondent, and finally take the comprehensive results of three opinions to scale the importance. It can be seen that this weight is very effective, so it is recommended that enterprises use this financial risk early warning indicator weight to warn their financial risks. At the same time, the consistency check table of financial risk early warning indicators from the perspective of low-carbon economy also shows that the weights designed in this paper are appropriate. In addition, the smaller the final comprehensive weight value of the research setting, the smaller the contribution to the enterprise. The weight reflects the importance of each early warning indicator to the overall evaluation target. The determination of index weight is an important link in the early warning of SMEs' financial risk. It can be said that the determination of indicator weight can affect the effective play of early warning system functions to some extent. Comparing 100 randomly selected test results, it is found that the simulation error of .9984 using the optimized weight and threshold is far less than the simulation error of 2.13 using the random weight and threshold (Figure 4).

A single-layer neural network has no hidden layer (input directly maps to output). For the output layer, which is also different from other layers in the neural network, neurons in the output layer generally do not have an activation function (or they can be considered as having a linear equivalent activation function). This is because the final output layer is mostly used to represent the classification score value, so it is a real number of any value. Compared with a single hidden layer, neural network training with two hidden layers does not help to improve the accuracy of prediction. This has actually given us a basic principle for designing BP neural network. The improvement of error accuracy can also be achieved by increasing the number of neurons in the hidden layer, and the training effect is easier to observe and adjust than increasing the number of layers. Therefore, in general, using a single hidden layer can meet the research needs, and the key consideration is to determine the number of neurons in the hidden layer. The most important input mode should be determined from a large number of raw test data. If the two inputs have strong correlation, just take one of them as the input, which requires statistical analysis of the original data, test the correlation between them, carry out correlation analysis, and find out the most important quantity as the input.

The critical value of early warning indicators includes the determination of satisfactory value, impermissible value and upper and lower limit value. 1) Positive type variable. The average value of the industry is selected as the satisfaction value, but the selection of values is not allowed to be different. 2) Inverse variable. Its standard value is determined in the opposite way to the positive variable. The satisfactory value is 0, and the disallowed value is .3. 3) Stable variable. Add 10 percentage points above the average value of the industry as the satisfaction value, and take - times and half of the satisfaction value as the upper and lower limit of the unacceptable value. 4) Moderately optimal variable. According to the industry average value of the ratio, the increase and decrease of 10 percentage points on the basis of the average value is taken as the upper and lower limit of the satisfactory range of the ratio. The upper and lower limits of the disallowed range are doubled and halved on the average value. Establish an early warning indicator system that can reflect the risk characteristics of the enterprise, including indicators reflecting five dimensions of debt repayment, operation, development, profitability and cash flow. In order to improve the convergence speed and stability of the model, SPSS25.0 is used to conduct factor analysis on these five dimensions, select financial indicators that meet the requirements of the model, and take the extracted main factors as the input data of the model.

It can be seen from Figures 5, 6, 7, 8, 9 that the model has a good prediction result on the operating capacity index, with the average prediction error less than 3%, the average prediction error on the solvency index between 5% and 10%, and the average prediction error on the crude fatty acid value of soybeans between 1.3% and 2.9%. Since the training data of the model comes from the same enterprise, and each indicator factor has a similar change law, the prediction error of the five dimensions of the model is reduced by 12.8%, 6.4%, 8.4%, 8.0%, and 8.1% respectively, and the prediction effect is better. The ideal situation is that the network output is equal to the expected output. Generally speaking, the R value is above .9, which indicates that the BPNN has good performance. The solid line in the figure is the actual fitting situation, while the dotted line is the ideal fitting situation. It can be seen that the neural network is very close to the ideal fitting condition.

Through repeated experiments, it is proved that when the number of hidden nodes is small, the network has poor ability to obtain knowledge from the samples, and cannot quickly find the internal laws in the samples, resulting in slow convergence speed and low accuracy of the model. Increasing the number of hidden nodes can speed up the convergence of the model and improve the accuracy of the model. When the number of hidden layer nodes is 8, the optimal correct recognition rate can be achieved. After 10 indicators passed the KMO and Bartlett correlation test, MATLAB software was used to program and establish the BPNN financial early warning model. The accuracy rate was 84.3% after verification.

6 Conclusion

Enterprises should pay attention to carbon profitability indicators and carbon debt repayment indicators when conducting low carbon financial early warning. It is found that the carbon profitability index has the highest weight in the criteria layer, followed by the carbon debt repayment index, carbon development index and carbon operation index. It can be seen that experts believe that under the perspective of low-carbon economy, enterprises are still for profit, that is, to use carbon equipment, carbon inventory, etc. to make profits for enterprises. The important indicator of bank loans to enterprises is the debt repayment indicator, so we should still pay attention to the carbon debt repayment indicator when developing the carbon economy. This paper constructs 10 financial early warning indicators from four aspects, uses the research method of BPNN to complete the establishment of the risk prediction model of the indicator system, and conducts training and simulation experiments on the established model through the MATLAB neural network toolbox. The results show that the early warning management of enterprise financial risk is conducive to strengthening the internal control level of enterprises, helping enterprises to solve the problems in management, thereby promoting the development of enterprises and enhancing their competitiveness. As the lifeblood of enterprise development, financial management directly determines the future development trend of the enterprise. How to improve the sustainable development ability of the enterprise based on meeting both the economic development and the enterprise's own development is what the current workers need to pay attention to. Therefore, business operators need to change their core concepts and improve the working level and efficiency of financial personnel. However, the study lacks correlation analysis of the original variables. The correlation coefficient matrix between calculated variables needs to be statistically tested. Further analysis is needed in future research. However, the analysis of differences in asset structure, business characteristics and human capital level in this paper is insufficient. BP neural network has no strict requirements on data distribution. Therefore, further analysis is needed in the future research.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JW wrote the manuscript, BY contributed to manuscript revision. They contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Ashraf, S., Gs Félix, E., and Serrasqueiro, Z. (2019). Do traditional financial distress prediction models predict the early warning signs of financial distress?[J]. *J. Risk Financial Manag.* 12 (2), 55. doi:10.3390/jrfm12020055

Buchdadi, A. D., Sholeha, A., and Ahmad, G. N. (2020). The influence of financial literacy on SMEs performance through access to finance and financial risk attitude as mediation variables[J]. *Acad. Account. Financial Stud. J.* 24 (5), 1–15.

Cao, Y., Shao, Y., and Zhang, H. (2022). Study on early warning of E-commerce enterprise financial risk based on deep learning algorithm. *Electron. Commer. Res.* 22 (1), 21–36. doi:10.1007/s10660-020-09454-9

Colak, M. S. (2021). A new multivariate approach for assessing corporate financial risk using balance sheets. *Borsa İstanbul Rev.* 21 (3), 239–255. doi:10.1016/j.bir.2020.10.007

Du, P., and Shu, H. (2022). Exploration of financial market credit scoring and risk management and prediction using deep learning and bionic algorithm[J]. *J. Glob. Inf. Manag. (JGIM)* 30 (9), 1–29. doi:10.4018/jgim.293286

Hamid, N., and Purbawangsa, I. B. A. (2022). Impact of the board of directors on financial performance and company capital: Risk management as an intervening variable. *J. Co-op. Organ. Manag.* 10 (2), 100164. doi:10.1016/j.jcom.2021.100164

He, H., and Chen, X. (2020). Animal Farming Enterprise Financing and Financial Risk Early Warning Model Construction in Economic Transition Period[J]. *Rev. Científica Fac. Ciencias Veterinarias* 30 (2), 992–1003.

Kang, Q. (2019). Financial risk assessment model based on big data. *Int. J. Model. Simul. Sci. Comput.* 10 (04), 1950021. doi:10.1142/s1793962319500211

Kapitonov, I. A. (2021). Development of low-carbon economy as the base of sustainable improvement of energy security. *J]. Environ. Dev. Sustain.* 23 (3), 3077–3096. doi:10.1007/s10668-020-00706-0

Kim, A., Yang, Y., Lessmann, S., Ma, T., Sung, M. C., and Johnson, J. E. (2020). Can deep learning predict risky retail investors? A case study in financial risk behavior forecasting[J]. *Eur. J. Operational Res.* 283 (1), 217–234. doi:10.1016/j.ejor.2019.11.007

Kou, G., Chao, X., Peng, Y., Alsaadi, F. E., and Herrera, V. E. (2019). Machine learning methods for systemic risk analysis in financial sectors[J]. *Technol. Econ. Dev. Econ.* 25 (5), 716–742. doi:10.3846/tede.2019.8740

Kuang, J., Chang, T. C., and Chu, C. W. (2022). Research on Financial Early Warning Based on Combination Forecasting Model. *Sustainability* 14 (19), 12046. doi:10.3390/su141912046

Louche, C., Busch, T., Crifo, P., and Marcus, A. (2019). Financial Markets and the Transition to a Low-Carbon Economy: Challenging the Dominant Logics. *Organ. Environ.* 32 (1), 3–17. doi:10.1177/1086026619831516

Semieniuk, G., Campiglio, E., Mercure, J. F., Volz, U., and Edwards, N. R. (2021). Low-carbon transition risks for finance. *Wiley Interdiscip. Rev. Clim. Change* 12 (1), e678. doi:10.1002/wcc.678

Shang, H., Lu, D., and Zhou, Q. (2021). Early warning of enterprise finance risk of big data mining in internet of things based on fuzzy association rules. *Neural Comput. Appl.* 33 (9), 3901–3909. doi:10.1007/s00521-020-05510-5

Tan, M. M., Xu, D. L., and Yang, J. B. (2022). Corporate Failure Risk Assessment for Knowledge-Intensive Services Using the Evidential Reasoning Approach. *J. Risk Financial Manag.* 15 (3), 131. doi:10.3390/jrfm15030131

Valaskova, K., Kliestik, T., Svabova, L., and Adamko, P. (2018). Financial Risk Measurement and Prediction Modelling for Sustainable Development of Business Entities Using Regression Analysis. *Sustainability* 10 (7), 2144. doi:10.3390/su10072144

Xuefeng, Z. A. O., Weiwei, W. U., Xu, G. U. O., and Huining, S. H. I. (2022). CFW-Boost Model for Cause-and-effect Analysis in Enterprise Financial Risk Warning[J]. *J. Syst. Manag.* 31 (2), 317.

Zeng, H. (2022). Influences of mobile edge computing-based service preloading on the early-warning of financial risks. *J. Supercomput.* 78 (9), 11621–11639. doi:10.1007/s11227-022-04329-2

Zizi, Y., Oudgou, M., and El Moudden, A. (2020). Determinants and predictors of smes' financial failure: A logistic regression approach. *J. Risks* 8 (4), 107. doi:10.3390/risks8040107

TYPE Original Research
PUBLISHED 05 January 2023
DOI 10.3389/fenrg.2022.1094440

OPEN ACCESS

EDITED BY
Wen-Tsao Pan,
Hwa Hsia University of Technology,
Taiwan

REVIEWED BY
Sa Li,
Pingdingshan University, China
Yifan Wang,
Southeast University, China
Hui Dong,
Tangshan Normal University, China

*CORRESPONDENCE
Jie Xie,
xiejie@hnuit.edu.cn

SPECIALTY SECTION
This article was submitted to Carbon Capture, Utilization and Storage, a section of the journal Frontiers in Energy Research

RECEIVED 10 November 2022
ACCEPTED 19 December 2022
PUBLISHED 05 January 2023

CITATION
Xie J (2023), Analysis on the digital transformation index system of enterprise's low carbon business performance based on AHP-DEA. *Front. Energy Res.* 10:1094440.
doi: 10.3389/fenrg.2022.1094440

Analysis on the digital transformation index system of enterprise's low carbon business performance based on AHP-DEA

Jie Xie*

School of Management, Hunan University of Information Technology, Changsha, Hunan, China

With the arrival of the low carbon era, enterprises, as the main body of the market economy, must take the road of low carbon operation whether to fulfill their social responsibilities or to seek enterprise development. However, Chinese enterprises started late to understand the low-carbon economy. So far, except for a few state-owned enterprises, some leading private enterprises and foreign-funded enterprises, they have made remarkable achievements in low-carbon emission reduction. Most enterprises in China have not realized the importance of low carbon emission reduction. In order to step out of the "high carbon" era and coordinate economic development and environmental protection, China must solve the problem of low-carbon transformation of small and medium-sized manufacturing enterprises. How to measure the degree of low carbon transformation, and how the government objectively evaluates the degree of low carbon economic development of enterprises, with a view to formulating corresponding standard incentives and punishment measures for them. It is urgent to establish a sound, reasonable and feasible low carbon operation management indicator system, and comprehensively evaluate the information related to low carbon operation of SMEs through reasonable selection of indicators. According to the connotation of low-carbon enterprises, the economic benefits of enterprises are closely combined with environmental benefits. A set of low carbon operation performance evaluation index system including economy, technology and environment has been constructed. The AHP index weight is calculated by establishing the AHP model and the Data Envelopment Analysis (DEA) index weight is calculated by establishing the DEA model. On this basis, the grey relational evaluation model based on AHP-DEA is established. Then the paper evaluates the performance of representative enterprises' low carbon operation. Propose corresponding improvement suggestions for the problems reflected in the low carbon operation performance ranking of enterprises and the scoring of various indicators. The research results show that the algorithm has high efficiency and the accuracy of model evaluation is 95.51%. To a certain extent, this study makes up for the research results of the impact of digital transformation on corporate strategic performance, and also provides ideas for the research of corporate financial performance evaluation.

KEYWORDS

AHP-DEA, internal control, digital transformation, enterprise performance assessment, low-carbon economy

1 Introduction

Under the low-carbon economy, for Chinese enterprises, it means more investment. Unqualified enterprises may be eliminated, but it also contains endless business opportunities, which will promote the better development of enterprises. Therefore, enterprises need to establish an enterprise performance evaluation index system based on low-carbon economy to help enterprises develop in the long run. Under low carbon, performance evaluation must be multi-dimensional and comprehensive (Pflaum and Golzer, 2018). At present, there are no uniform standards and suggestions on how to create an enterprise performance evaluation index system based on a low-carbon economy. And it is not advisable to blindly imitate enterprises in other countries or domestic well-known enterprises. Efforts should be made to build an enterprise performance evaluation index system that takes into account both the situation of the enterprise and low carbon factors (Andriole, 2020). While evaluating the profit of the enterprise, we should take into account the customer, internal operation and employee training, especially the impact of fossil energy consumed by the enterprise to obtain economic benefits on the ecological environment. In the era of low-carbon economy, the traditional enterprise performance evaluation index system must be rebuil. According to the specific situation of each enterprise, in addition to financial indicators, customer indicators, internal business indicators and employee growth indicators, low-carbon environmental indicators must also be added. For example, low carbon economic quality indicators, low carbon economic governance indicators, low carbon policy implementation evaluation indicators and low carbon technology innovation indicators urge enterprises to take the responsibility of environmental protection while pursuing economic interests (Rocha et al., 2021). Enterprises have played a positive role in accumulating social wealth, enriching the market, solving employment, technological innovation, etc. At the same time, due to the low production level, backward equipment, excessive exploitation of resources, serious waste and imperfect management, the production and operation activities of enterprises have become a major factor affecting the environment. In order to step out of the "high carbon" era and coordinate economic development and environmental protection, China must solve the problem of low-carbon transformation of small and medium-sized manufacturing enterprises (Wetering et al., 2021). Then, enterprises should measure the extent of their low-carbon transformation. The government should objectively evaluate the degree of low carbon economic development of enterprises, with a view to formulating corresponding standard incentives and punishment measures for them. Based on this, it is very important to establish a sound, reasonable and feasible low-carbon operation management indicator system (Zhu and Song, 2021). Through reasonable selection of indicators, comprehensively evaluate the information related to low-carbon operation of SMEs, and correctly measure the degree of low-carbon operation of enterprises. The government can effectively control and supervise the low-carbon operation of small and medium-sized enterprises, and help enterprises self check and self reform. It is imperative and urgent to improve the efficiency of government monitoring and evaluation.

Looking at the research on "low carbon," it is found that most scholars focus on the impact of low carbon economy on the national economy, the importance of developing low carbon economy, and the way to develop low carbon economy. The evaluation of enterprise performance in the low carbon economy is in its infancy. Under the low-carbon economy, enterprises can not unilaterally ignore the economic performance of enterprises in order to reduce carbon dioxide emissions (Bhaskar et al., 2019). We should not just focus on the economic benefits of enterprises for the purpose of making profits and ignore the impact of enterprises on the environment. Enterprises need to improve their economic efficiency on the basis of energy conservation and emission reduction, adjust their energy structure and improve energy efficiency. Therefore, this paper will take small and medium-sized enterprises as the research object, and select the main indicators reflecting the low carbon operation results of enterprises. Build a low carbon operation evaluation index system for enterprises (Ramay et al., 2019). Then, based on the Analytic Hierarchy Process (AHP) model, each indicator of the enterprise's low-carbon operation performance is processed to obtain the weight of each evaluation element. On this basis, use the gray correlation evaluation model of AHP-DEA to rank enterprises from the perspective of low carbon operation performance, and then put forward the direction that should be improved in the process of low carbon operation.

From the perspective of technology, today's digital transformation is a transition from industrial civilization to information civilization. The application of these good technologies can change, subvert, or optimize everything we do now. Once the enterprise has mastered the application of new technologies, it will gradually form an acceleration. Strictly speaking, digital transformation has three perspectives. The first is the technical perspective, which is dominated by CIOs or CTOs. The second is the business perspective, which is dominated by business line leaders such as the marketing manager and the manager in charge of R&D. The third perspective is the enterprise perspective, that is, the digital transformation of the enterprise as a whole, which mainly guides entrepreneurs to lead. This paper briefly discusses the impact of digital technology from the three levels of enterprise, enterprise and industry. 1) Business. Digital technology empowers employees and redefines work, and people and machines work together. The machines mentioned here are not only machines and equipment that we can see, but also digital platforms and software applications such as various APPs. 2) Enterprise. All industries will be led by smart enterprises with exponential learning ability. 3) Industry. The business ecology, which takes the platform as the carrier and replaces property rights with digital, will rise in an all-round way. Under the background of digital transformation, the internal control of enterprises faces unprecedented opportunities and challenges. At present, the impact of digital transformation of enterprises on performance is still unclear. More importantly, at present, there are still some problems in the research of digital transformation of enterprises, such as the disunity of theoretical concepts and the incomplete selection of indicators, which also makes the research in this field insufficient (Chen et al., 2019). Good financial condition is the material basis of enterprise operation, and the foundation of sustainable and vigorous growth of enterprises. Therefore, financial performance has always been the focus of research in the field of enterprise performance. The financial performance of an enterprise is an intuitive and comprehensive reflection of its operating results, which is concerned by all stakeholders inside and outside the enterprise. The financial performance level of an enterprise will have a direct or indirect impact on investors' investment, bank loans, commercial credit of suppliers and customers and even the market share of the enterprise.

The contribution of research and innovation lies in:

1) Build a set of enterprise low carbon business performance evaluation index system. The grey relational evaluation model based on AHP-DEA is established. Then it evaluates the low carbon business performance of representative SMEs.
2) Studied the enterprise digitalization, internal control and financial performance evaluation, and discussed their mechanisms. At the same time, it puts forward the path of strengthening the digitalization of enterprise internal control in the current era.
3) The traditional DEA analysis method is easy to produce deviation and cannot reflect the preference of decision-makers. The grey relational evaluation model of AHP-DEA is adopted to effectively solve the problem that AHP method is easily affected by individual factors of experts. At the same time, according to the problems reflected by the ranking of low carbon business performance and the scoring of various indicators, the paper puts forward the direction for enterprises to improve low carbon business.

The first section of the study elaborates that enterprises should measure the development background of their low-carbon transformation. We should not only focus on the economic benefits of enterprises for the purpose of making profits, but also ignore the impact of enterprises on the environment. Section 2 refers to the technologies that relevant enterprises can use, such as artificial intelligence and the Internet of Things. Further improve the digitalization level of enterprise internal control. Section 3 discusses the content of enterprise digital control performance in low-carbon economy. It is analyzed that the AHP-DEA method of performance appraisal is to improve the performance of each employee, and constantly develop the potential of individuals and teams, so as to improve the performance of enterprises and make them successful. After that, the enterprise performance evaluation based on AHP-DEA model is carried out. Section 4 discusses the conclusion. Section 5 summarizes the full text. The results show that the method in this paper is also conducive to comprehensive analysis and evaluation of the overall comprehensive performance of enterprises, and can truly reflect the actual operation of enterprises. It provides a theoretical reference for enterprises to evaluate the performance of their operating systems, and enables enterprises to continuously improve and develop.

2 Related work

The early definition of enterprise economy is mostly centered on economic benefits and aimed at reducing costs. Economic growth mainly depends on the massive consumption of resources, lacking comprehensive consideration of environmental and social benefits. With the proposal of "low carbon economy," the early supply chain will inevitably develop into a low carbon supply chain. Low carbon supply chain is a new economic form and development mode. Through technological innovation, institutional innovation, new energy development and other means, we can reduce the consumption of high carbon energy such as coal and oil as much as possible and reduce greenhouse gas emissions. The development of low-carbon supply chain is a global revolution involving production mode, lifestyle, values, national rights and interests and human destiny. On the one hand, enterprises should actively assume the responsibility of environmental protection and meet the requirements of national energy conservation and consumption reduction targets. On the other hand, enterprises should adjust their economic structure, improve energy efficiency, develop emerging industries, and build a low-carbon industrial system. This is a realistic way to abandon the previous development model of "pollution first, treatment later, low-end first, high-end first, extensive first and intensive second," and is an inevitable choice to achieve win-win economic development and resource and environment protection. It is of great theoretical and practical significance to fully explore and identify the influencing factors and their transmission paths in the low carbon transformation of enterprises, so as to truly implement them and promote enterprise performance. At present, many scholars have discussed this problem. The research of Hu F et al. shows that the higher the degree of low carbon, the higher the level of financial performance (Hu and Yang, 2020). At the same time, internal control plays an intermediary role between enterprise digitalization and financial performance. Christof E and others pointed out that enterprises can use artificial intelligence and the Internet of Things and other technologies to achieve online supervision functions such as real-time monitoring, automatic early warning, supervision and evaluation of internal control systems, and further improve the digitalization level of enterprise internal control (Christof and Duarte, 2018). Kauffman and Weber (2018) believed that in the context of the gradual expansion of the enterprise's development scale, the importance of its internal control work has become increasingly prominent, and the transformation and upgrading of internal control has become an inevitable trend. Taking the relationship between internal control and performance appraisal as a starting point, Doukidis et al. (2020) deeply analyzed the underlying causes of the enterprise's development dilemma and put forward relevant suggestions. It provides a good environment for improving performance appraisal. Bhadoria et al. (2017) pointed out that the effectiveness of performance appraisal is affected by internal control to some extent, and performance appraisal can directly affect the implementation of internal control (Kim and Kim, 2017). Zeebaree et al. (2019) examined the impact of performance evaluation purpose on miners' organizational citizenship behavior. The survey data of miners were analyzed by multiple regression and bootstrap sampling. The results show that both the development purpose and the evaluation purpose of performance evaluation have a positive impact on the overall OCB and its four dimensions through organizational identity. In addition, the relationship between the development purpose of performance evaluation and the overall OCB and its four dimensions is stronger than that of performance evaluation. Enterprises spend a lot of manpower and material resources to establish internal control and performance appraisal, but the main reason for the ineffectiveness is that they ignore the relationship between the two. Therefore, the effective combination of internal control and performance appraisal is particularly important. Harp et al. designed appropriate assessment indicators from the four levels of customer, finance, learning and growth, and internal business in combination with the actual situation; At the same time, through the comprehensive use of AHP method to empower and optimize the indicators of the performance appraisal model, laying the foundation for further performance appraisal (Harp and Barnes, 2018). Although academia is interested in performance management as a key determinant of the effectiveness of enterprise process improvement methods such as Total Quality Management (TQM) and its derivatives, few empirical studies explicitly explore the practice of performance management systems in organizations with a focus on TQM. Soltani and Wilkinson described how organizational and management forces led to the performance management system being unable to accept the core principles of process improvement methods such as TQM (Soltani and Wilkinson, 2020). Huang et al. (2019) conducted a performance evaluation on an enterprise, and linked the problems and causes in the process of enterprise growth in the evaluation process, thus establishing an enterprise performance evaluation index system. Elshaer et al. (2021) bridged the knowledge gap and examined the direct impact of GHRM on the environmental performance of small tourism enterprises and the indirect impact through the environmental friendly behavior of employees. GHRM has an indirect, positive and significant impact on environmental performance through task related and positive environmental behaviors. This reflects the value and important role of employee environmental friendly behaviors in the relationship between GHRM and environmental performance of small tourism enterprises. It provides a new idea for Chinese enterprises to establish a scientific and reasonable performance appraisal index system. Khan et al. (2017) collected the financial data of more than 100 listed companies before and after M&A, and selected more than ten financial indicators for empirical analysis using factor analysis. Gu et al. (2020) found that in the process of performance evaluation, there were significant differences in the perception of organizational justice. To a certain extent, these differences can be explained by the changes in the impact of relationships on executive decision-making. This, in turn, is related to differences in organizational goals between banks and differences within organizations at the departmental level (Gu et al., 2020). Digital dynamic capability and digital innovation are of great significance for textile enterprises to achieve digital transformation performance. Shen et al. (2022) has developed a conceptual model based on the resource capability performance framework to test how the adoption of digital technology, digital dynamic capabilities and digital innovation orientation affect the digital transformation performance of enterprises. The results show that the positive relationship between digital technology adoption and digital transformation performance is not significant; This path is fully realized through digital dynamic capabilities. The digital transformation of enterprises not only reshapes the business model and industrial boundaries, but also boosts the high-quality development of China's economy. Zhang et al. (2022) reviewed the existing literature and found that digital technology can improve the production efficiency of enterprises by reducing costs, improving efficiency and innovation. Bastari et al. (2020) aimed to examine the impact of transformational leadership on employee performance, with employee motivation as the intermediary variable. The results show that transformational leadership has a significant impact on employees' job performance, and job motivation is an intervention variable. Employees' work motivation also has a significant impact on their work performance. The digital business transformation plan is failing due to the gap in understanding the mechanism for enterprises to obtain business value from technology. Organizational readiness is not only the technology, but also the reason for the success of digital transformation. Organizational readiness refers to the ability to use and coordinate core organizational capabilities. Based on the research on the rapid development of digital technology and the advantages of information system discipline in this field, Pappas et al conceptualized the big data and business analysis ecosystem and proposed a model to describe how the big data and business analysis ecosystem paved the way for digital transformation andsustainable society, that is, the digital transformation and sustainable development (DTS) model (Pappas et al., 2018).

This paper takes low-carbon economy and enterprise digital reform as the indicators of reform. Customer satisfaction and residents' low carbon concept are taken as indicators of social indicator factor layer. Establish a set of performance evaluation index system of low-carbon supply chain with reasonable design and strong operability to provide a strong basis for the development and research of low-carbon supply chain. By analyzing the current situation and existing problems of enterprise performance evaluation system, a set of enterprise financial performance evaluation system is systematically and comprehensively constructed. At the same time, it analyzes the performance evaluation methods of enterprises, and constructs the enterprise performance evaluation model based on AHP-DEA method. Through this model, we can evaluate the financial performance of enterprises, find out deficiencies and put forward suggestions, so as to support enterprises to maintain industrial competitiveness, and also provide ideas for the research of financial performance evaluation.

3 Methodology

3.1 Discussion on digital control performance of enterprises in low carbon economy

Low carbon enterprises refer to enterprises that adjust their energy structure and improve energy efficiency while improving economic returns. In the process of production and operation, reduce the carbon emissions of enterprises as much as possible. Increase the whole industry's investment in low-carbon technology research and development, create more low-carbon environment-friendly products, and improve the low-carbon competitiveness of enterprises. Reduce the impact of enterprises on the environment, and realize the sustainable development of enterprises and the whole society. It has been 10 years since the low carbon economy was put forward, but the research on low carbon economy mostly focuses on the relationship between energy consumption, economic growth and carbon emissions, lacking systematic analysis of low carbon economy. There are few studies on the evaluation index system and evaluation methods for the low carbon economy system, which makes the concept and policy lack of a bridge to guide the practice of low carbon economy. This paper makes a systematic analysis on various factors involved in the development level of low-carbon economy, aiming to build a performance evaluation system suitable for enterprises in the perspective of low-carbon economy. Carry out comprehensive evaluation and comparison, and propose targeted and clear enterprise development direction (Gu et al., 2020). Therefore, the establishment of this system can provide evaluation basis for the development of low-carbon economy in China in the future, and is conducive to guiding the low-carbon and sustainable development of enterprises.

The design principles of enterprise performance evaluation under the low-carbon economy: 1) Systematic principle. The enterprise performance evaluation under the perspective of low-carbon

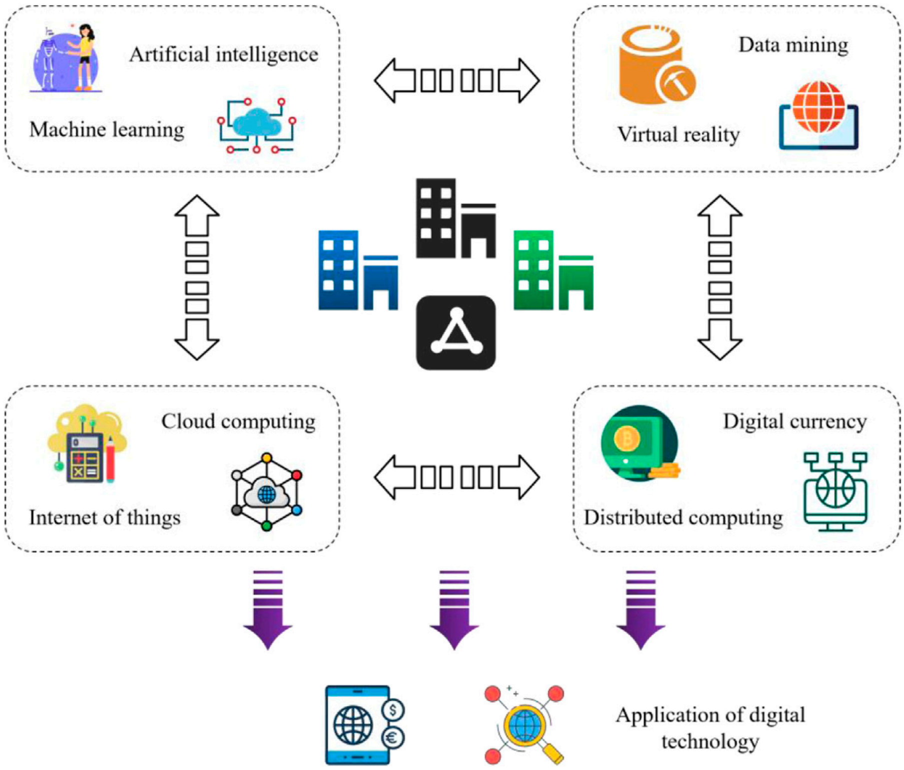


FIGURE 1
The underlying technology and practical application based on enterprise digital transformation.

economy must be comprehensive. Therefore, in terms of index design, comprehensive evaluation of enterprise performance should be made from different perspectives. Among them, basic indicators and evaluation indicators, quantitative indicators and qualitative indicators must be interrelated and mutually restricted to form an organic whole. 2) Principle of goal consistency. The performance evaluation system should be consistent with the enterprise's development strategy, that is, the medium and long-term goals to be achieved by the enterprise. Only in this way can we correctly play the guiding role of performance evaluation and serve the development of enterprises. The data required for various indicators of enterprise performance evaluation shall be easy to collect and process, that is, the data can be obtained directly or indirectly from the enterprise statistical statements, accounting statements and relevant data reports, so as to reduce the enterprise management costs. 4) The principle of giving consideration to both financial indicators and non-financial indicators. Under the low-carbon economy, the main content of enterprise performance evaluation still needs to be financial performance. However, only setting financial indicators is easy to weaken the pursuit of long-term goals of enterprises, and non-financial evaluation indicators are easy to timely and continuously track enterprise goals. In particular, the introduction of innovation, environment and other factors into the evaluation system is conducive to the optimization of enterprise business processes and the realization of development goals.

Digital transformation, as a transformation mode at the forefront of the digital economy era, has a great demand for technological innovation. Digital transformation strengthens the ability of enterprises to mine and integrate internal and external information, and it will have a higher sensitivity to forward-looking technology, thus helping to grasp the direction of technological innovation and reducing innovation risks. The integration with digital internal control will strengthen the internal control system's control of business processes and the identification and prevention of risks. In addition, the internal control of enterprises should take into account the operational efficiency while improving the security and reducing the risk of operation and management, otherwise, the internal control will become the fetter of enterprise development. Figure 1 shows the underlying technology and practical application based on enterprise digital transformation.

In the actual business operation, we are exposed to various information such as voice, image, video, document, etc. The information is structured into orders through human intervention, and the work order data enters the IT system one by one. That is, the transformation of unstructured information in the real world, and the realization of structured data that can be understood by IT systems. With various ubiquitous terminals and intelligent applications, the problem of diversification and real-time of data acquisition is really solved. It reduces manual secondary processing and conversion. When enterprises have truly formed such real-time and diverse data resources, they can talk about further value-added applications such as big data storage, big data processing and analysis.

Under the background of digital transformation, enterprises have established corresponding information systems in business fields such as safety management, financial management, marketing, production and operation, human resource management and party building management. Enterprises actively promoting the implementation of digitalization will have an impact on their own organization and management. The implementation of digitalization will bring about changes in enterprise management mode and relationships in organizations. At the same time, the promotion of digitalization will significantly improve the performance level of entity enterprises. The application of digital technology in the internal control system of enterprises strengthens the supervision, control and prediction of production and sales, thus improving the reasonable compliance and efficiency of enterprise operation. At the same time, the internal control system of digital enterprises can find, prevent, reduce or eliminate risks in time, thus improving the financial performance of enterprises. The application of information technology can not only greatly improve the management level of enterprises, but also optimize the internal control effect. If we want to improve the internal environment of enterprises, we must first improve the internal control consciousness of the top management of enterprises. Only the managers of enterprises pay enough attention to internal control, and play an exemplary role, and drive the employees of the whole enterprise with their own fine style, so as to promote the long-term and healthy growth of enterprises. At the same time, enterprises should increase the investment in digitalization and informatization, strengthen the training of digitalization-related talents, integrate internal information systems and platforms, and build several system platforms with mature applications, advanced concepts and perfect functions. Integrate the requirements of internal control into the system platform to improve the digitalization, informationization and systematization level of internal control management.

3.2 AHP-DEA method

According to the analytic hierarchy process, we can get the importance of different indicators of the scheme level to the target level—enterprise performance evaluation. In the standard layer, profitability has the largest weight and the largest impact on financial performance evaluation. The weight of operation capacity is the smallest; In the scheme layer, the current ratio has the largest weight, the largest impact on financial performance evaluation, and the cost of sales ratio has the smallest weight. Therefore, it is feasible to adopt AHP-DEA financial performance evaluation model. Performance appraisal is to improve the performance of each employee, and constantly develop the potential of individuals and teams, so as to improve the performance of enterprises and make them succeed. Essentially, both of them are effective integration of enterprise resources, and their ultimate goal is the realization of enterprise strategic goals. Choosing the appropriate performance assessment method is the premise of the effective growth of enterprise performance assessment, and it is also the effective guarantee to reduce the error of performance assessment results. The enterprise development strategy made by managers is closely related to the results of performance assessment. DEA is an effective efficiency assessment method. DEA method can be used to deal with the problems of multi-input and multi-output comparison with the same decision-making unit, and the judgment of the relative effectiveness of the decision-making unit can be solved by mathematical methods. DEA is used to express the efficiency of an enterprise by the ratio of various outputs to inputs. This calculation method can effectively ignore the influence of standard cost on different indicators, and it can be used to evaluate the performance of comparable departments or enterprises.

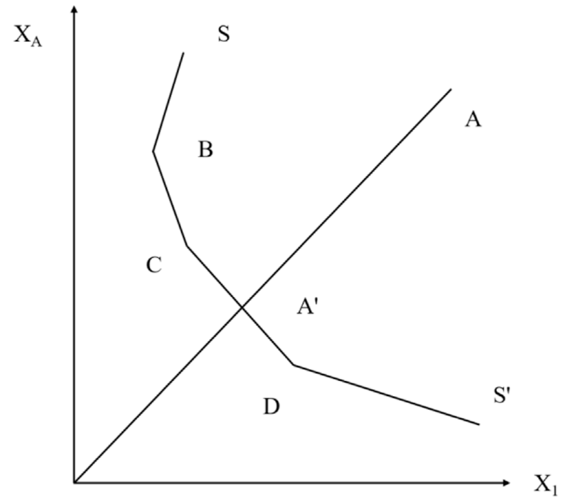


FIGURE 2
Basic idea diagram of DEA method.

DEA only depends on the data of input index and output index, and evaluates each decision-making unit from the perspective of relative effectiveness. It does not depend on the specific form of production function, especially it can effectively deal with the assessment problems of multiple inputs and multiple output indicators. DEA model can be used to evaluate a certain economic benefit index and social benefit index, and it is also a good analytical tool to evaluate the business situation of enterprises. Assume that the input of a certain operating system is two configurations of X_1 and X_A, and it is generated as A. SS' is the equal-volume combination line, which is the production frontier, and B, C and D are located on the production frontier. Figure 2 depicts the basic idea of the DEA method.

AHP is a model method that combines qualitative indicators with quantitative indicators to study unstructured decision-making strategies. The main core process of this method is to establish a multi-level hierarchical structure model, and its essence is a method of systematic comprehensive research by determining the target weight relationship. The basic method is to construct a judgment matrix through pairwise comparison, and then sort the factors at all levels through consistency test. The specific calculation process of AHP can be described as the following three steps: 1) Establishing hierarchical structure. 2) Construct judgment matrix. 3) Ranking and consistency inspection of criteria layer. In this paper, AHP is used to determine the weight of each dimension and each index of the balanced scorecard. Through

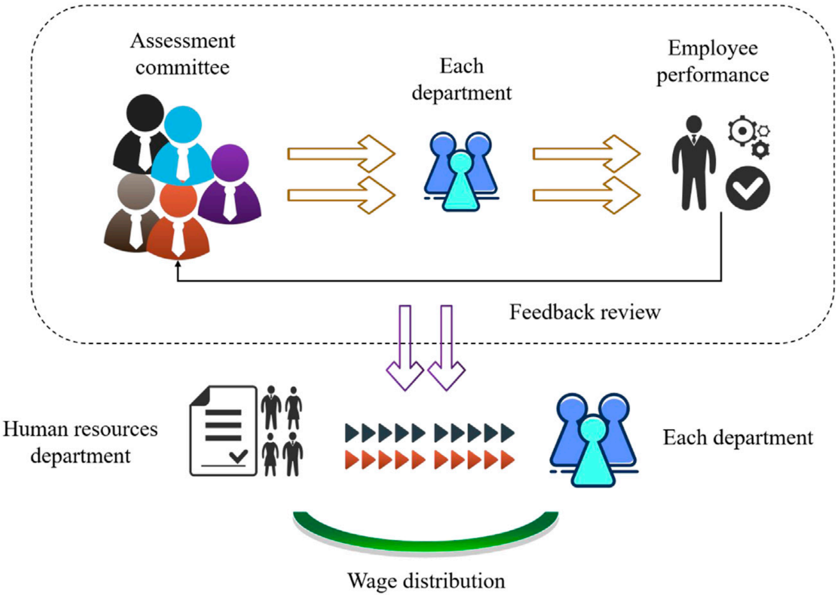


FIGURE 3
Enterprise performance assessment process.

TABLE 1 AHP assessment index of enterprise performance.

Performance assessment index	Primary index	Secondary index
	Solvency	Liquidity ratio
		Net value ratio
		Reserve ratio
		Fixed capital ratio
	Profitability	Business profit margin
		Business yield
		Return on net assets
		Return on total assets
	Operating efficiency	Loss ratio
		Cost rate
		Total asset turnover
	Growth ability	Asset growth rate
		Price growth rate

AHP, complex problems can be divided into different levels, and the problems can be simplified. The enterprise performance assessment process is shown in Figure 3.

Hierarchical structure model is mainly composed of three parts: Scheme layer, criterion layer and target layer. The scheme layer refers to the evaluated schemes and measures, etc. Level is the multi-level assessment standard of the scheme; The goal layer is divided into two types: The overall goal and the sub-goal. AHP and DEA are the main components of operational research assessment methods. In order to maintain the objective evaluation of experts on the importance of indicators in AHP method, and integrate the advantages of DEA method on the selection of optimal decision-making scheme. This paper will choose the linear weighting method to obtain the comprehensive weight of the indicators. A preference parameter needs to be introduced here θ ($0 \le \theta \le 1$), as the proportion of expert opinions. The application of operational research assessment method can effectively avoid the influence of subjective factors on financial performance assessment results, and the algorithm of operational research method can be realized by program, which is practical. Therefore, in order not to affect the

TABLE 2 Random consistency index.

n	RI
1	0
2	0
3	.58
4	.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

managers' correct judgment of the enterprise's operating conditions, through research and analysis, this paper uses AHP-DEA method to evaluate the financial performance of enterprises.

3.3 Enterprise performance assessment based on AHP-DEA model

The so-called performance assessment is to analyze the input and output of an enterprise in the process of operation, and evaluate the operation of the enterprise. To evaluate the performance of enterprises, it is necessary to use appropriate methods and strategies to study the data of enterprises, so that enterprises can obtain the maximum input-output ratio. In this paper, the performance assessment indexes are selected reasonably, and the weights of each index are set by AHP, so as to construct a performance assessment system, and explore the effect and path of digital transformation on the strategic performance of enterprises. The principle of systematicness is that the selected assessment indexes should be comprehensive, holistic, relevant and hierarchical, which is the first principle to establish the assessment index system. The assessment index system should include many factors that affect enterprise performance. The AHP assessment index of enterprise performance in this paper is shown in Table 1.

When evaluating financial performance, the economic status of a certain level of an enterprise can be reflected by its corresponding financial indicators. Generally speaking, enterprise performance includes four aspects: asset operation, financial income, debt paying ability and development ability. Considering the characteristics of enterprises, this paper evaluates the performance level of enterprises in terms of solvency, profitability, operating ability, growth ability and investment yield. Because when constructing the matrix, the quantitative values between the two indicators are obtained by issuing questionnaires. Therefore, in order to avoid the influence of objective factors on the judgment of the importance degree of the two factors, this paper judges whether the assignment of the two indicators is reasonable through consistency test, that is, the method of setting CI. At the same time, the result of AHP needs consistency test to test its rationality. Namely:

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{1}$$

Among them, the greater the CI value, the greater the deviation of the judgment matrix. Secondly, calculate the consistency ratio CR:

$$CR = \frac{CI}{RI} \tag{2}$$

Where RI refers to the random consistency index value. Table 2 is random consistency index.

Usually, when $CR > 0.1$, It means that the judgment matrix needs to be modified until the test conditions are met for the next stage of work. In this paper, small enterprises are taken as the research object. According to the connotation of low-carbon enterprises, economic benefits of enterprises are closely combined with environmental benefits. Use AHP to sort the enterprise performance evaluation indicators, and follow the basic principles of constructing the low carbon operation performance evaluation indicator system. A set of low carbon operation performance evaluation index system for small and medium-sized enterprises including economy, technology, energy, facilities, environment and other dimensions has been constructed.

In the assessment of enterprise performance, two enterprises are arbitrarily selected: A and B, and their relative performance values E_{AB} and E_{BA} are calculated respectively. The solution process is as follows:

$$E_{AB} = \max\sum_{r=1}^{s} u_r y_{rA} \tag{3}$$

$$s.t.\sum_{i=1}^{m} v_i x_{iA} = 1 \tag{4}$$

$$\sum_{r=1}^{s} u_r y_{rA} \leq 1 \tag{5}$$

$$\sum_{r=1}^{m} u_r y_{rB} - \sum_{i=1}^{m} v_i x_{iB} \leq 0 \tag{6}$$

$$E_{BA} = \max\sum_{r=1}^{s} u_r y_{rB} \tag{7}$$

$$s.t.\sum_{i=1}^{m} v_i x_{iB} = 1 \tag{8}$$

$$\sum_{r=1}^{s} u_r y_{rB} \leq 1 \tag{9}$$

$$\sum_{r=1}^{s} u_r y_{rA} - \sum_{i=1}^{m} v_i x_{iA} \leq 0 \tag{10}$$

$$u_r \geq 0,\ \ r = 1,2,3,\ldots,s\ \ v_i \geq 0,\ \ i = 1,2,3,\ldots,m \tag{11}$$

Among them, x_{iA} represents the i-th input value of A corporate performance; y_{rA} represents the r-th output value of A corporate performance; x_{iB} represents the i-th input value of B corporate performance; y_{rB} represents the r-th output value of B corporate performance value. The comprehensive assessment function is expressed as follows:

$$f(y) = \sum_{i=1}^{n} b_i y_i' \tag{12}$$

Total rank random consistency ratio is as follows:

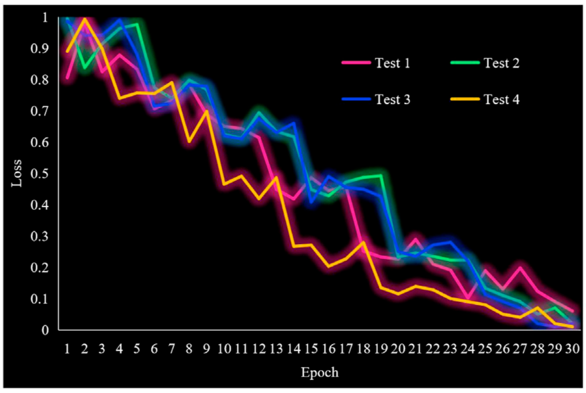


FIGURE 4
Training results of the algorithm.

$$CR < 0.1\left(CR = \sum_{j=1}^{n} a_j CI_j \Big/ \sum_{j=1}^{n} a_j RI_j\right) \tag{13}$$

At this time, it is considered that the results of hierarchical total sorting have satisfactory consistency. Make a pairwise comparison between each index, use c_{ij} to represent the importance comparison value of factor i to factor j, and use 1-9 and its reciprocal as the comparison scale to score and sort each assessment index, thus constructing Get the judgment matrix:

$$C_{ij} = \frac{1}{c_{ij}} \tag{14}$$

Let X be the original data set with the same basic measurement unit, and Y be the standardized data set. The normalization processing principle can be used to convert the original data into a number between 0 and 1. Calculated as follows:

$$Y = 0.1 + 0.9 \times \frac{X - X_{\min}}{X_{\max} - X_{\min}} \tag{15}$$

Among them, $X_{\max}$ is the maximum value in the collected sample; $X_{\min}$ represents the minimum value in the collected sample.

4 Result analysis and discussion

Low carbon enterprises refer to enterprises that adjust their energy structure and improve energy efficiency while improving economic benefits. In the process of production and operation, reduce the carbon emissions of enterprises as much as possible. Increase enterprises' investment in low-carbon technology research and development, create more low-carbon environment-friendly products, and improve enterprises' low-carbon competitiveness. Reduce the impact of enterprises on the environment, and realize the sustainable development of enterprises and the whole society. Therefore, this paper takes small and medium-sized enterprises as the research object. According to the connotation of low-carbon enterprises, the economic benefits of enterprises are closely combined with environmental benefits. Fully absorb and use for reference the advanced theoretical achievements related to the construction of low carbon evaluation system. Following the basic principles of the construction of low carbon operation performance evaluation index system, a set of low carbon operation performance evaluation index system including enterprises is constructed.

This paper systematically and comprehensively constructs a set of enterprise financial performance assessment system, and builds an enterprise performance assessment model based on AHP-DEA method. In this section, the model algorithm is tested experimentally to verify its effectiveness. According to AHP method, dividing enterprise performance assessment indexes plays a guiding role in the process of enterprise performance assessment. The finer the quantitative indicators are, the more obvious the effect on enterprise performance assessment will be, and the better the operation status of the evaluated enterprise can be observed. DEA method requires the number of sample decision-making units, which is too small to meet the calculation requirements.

In this paper, after consulting the literature on environmental performance audit, it is sorted out and summarized. Taking iron and steel enterprises as an example, nearly 60 items in four categories were finally selected. A Iron and Steel Enterprises closely focus on the company's core values, develop efficient business policies and strategies and effectively implement them. By improving the production efficiency, strengthening the staff's working ability and improving the company's management level, we are gradually approaching the strategic goal of "becoming the most competitive steel enterprise in the world." As far as 2013 is concerned, the overall operation of the company is good and the sales performance is satisfactory, which has occupied a strong leading position in the steel industry. The total operating income of the company in that year was up to 19,003 billion yuan, and the total profit obtained was 8.01 billion yuan, which is very gratifying. Therefore, this paper selects the financial data of Company A from 2010 to 2019. The original data comes from the annual financial report of Company A, and the financial statement of each year is regarded as a DMU. At the same time, this paper also collected a large number of relevant information about A company, such as announcements, news about the company, official website of the company, etc., and integrated the collected relevant information to extract the relevant data that may be used in this paper. Four test sets are used to normalize the data, and then DEAP software is used to calculate and analyze the evaluation results. Figure 4 shows the training results of the algorithm.

Because the collected raw data has negative numbers, there will be some incompatible problems when importing the input-output model, so it is necessary to preprocess the data. After pretreatment, many experiments were carried out. The experimental results of MSE (Mean squared error), RMSE (Root mean square error) and MAE (Mean absolute error) are drawn into a table, as shown in Table 3.

TABLE 3 Index experimental results.

Algorithm	MSE	RMSE	MAE
AHP	5.15	.605	1.95
DEA	6.34	.624	1.92
AHP-DEA	4.17	.502	1.31

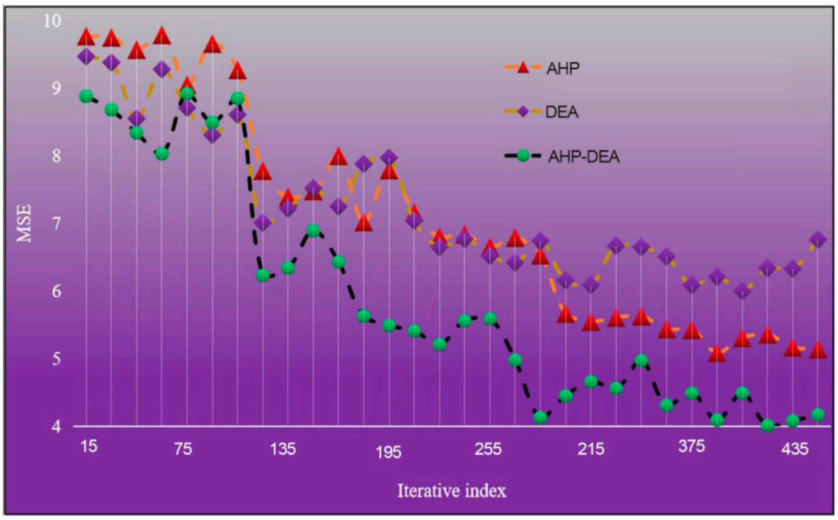


FIGURE 5
MSE experimental results.

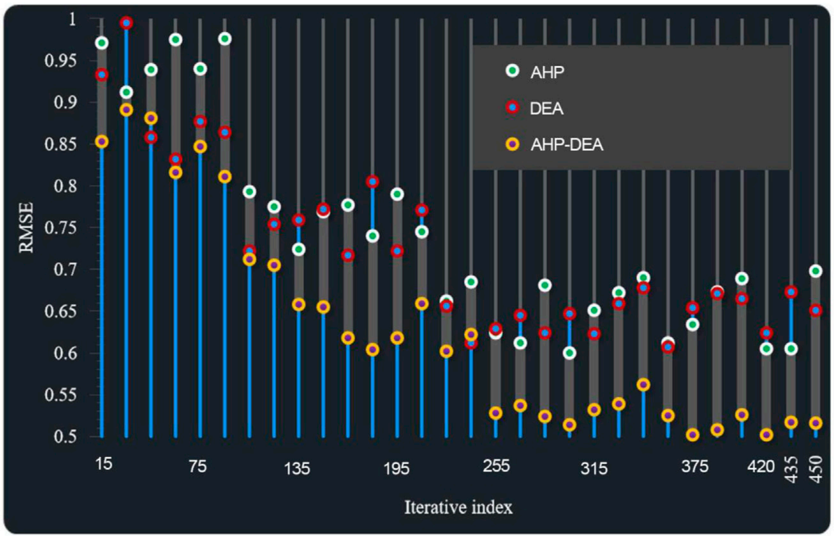


FIGURE 6
RMSE experimental results.

The experimental results of MSE are shown in Figure 5. The experimental results of RMSE are shown in Figure 6. The experimental results of MAE are shown in Figure 7.

From the analysis of the above experimental results, it can be concluded that the MSE, RMSE and MAE values of this method are lower than those of the comparison algorithm.

Firstly, this paper makes it clear whether the model is based on input or output, and when choosing it, it should be controllable and treatable according to the indicators. That is to say, the input or output indicators can be controlled to the maximum extent. In this paper, the input indicators are net fixed assets, main business costs and the number of employees, which are controllable and manageable. Therefore, the model based on input index is adopted in this paper. Figure 8 shows the efficiency of the model. Figure 9 shows the assessment accuracy of the model.

In this section, after data collection, index comparison and analysis, the validity of AHP-DEA model is tested, and finally the results are analyzed. This document determines whether the model is based on input or output. When selecting the model, it should be controlled and processed according to the indicators. Figure 9 shows the evaluation accuracy of the model. The maximum calculated value is 95.51%. Based on the principle and model of AHP-DEA and the establishment of enterprise performance assessment index system, this paper gives the corresponding comprehensive assessment index and calculation method, which is helpful to quantify enterprise performance assessment index. At the same time, the methods in

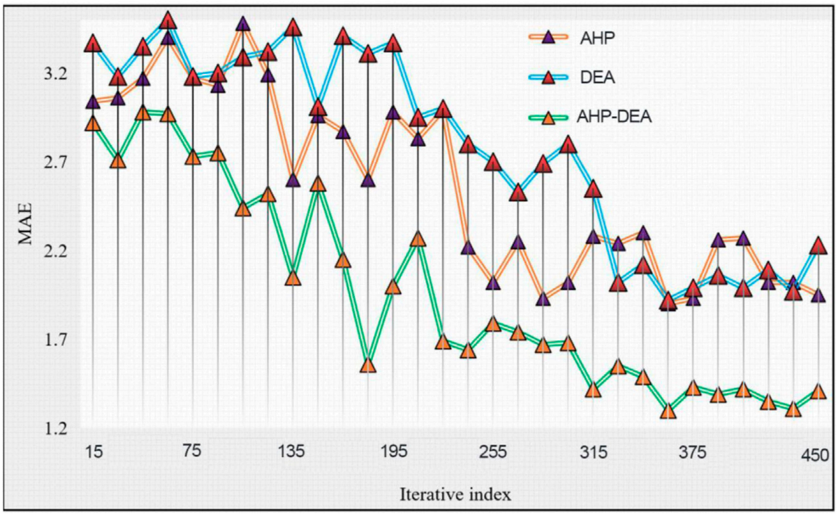


FIGURE 7
MAE experimental results.

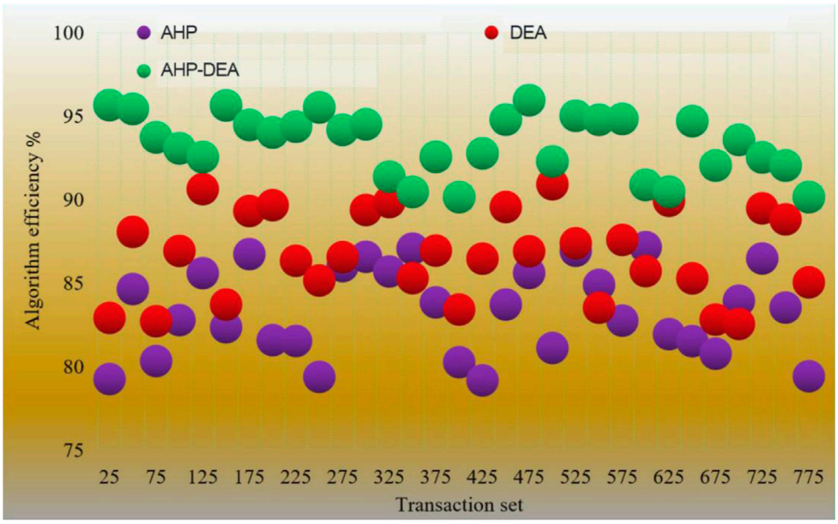


FIGURE 8
Efficiency of the model.

this paper are also conducive to comprehensively analyzing and evaluating the overall comprehensive performance of enterprises, which can truly reflect the actual operation situation of enterprises, and provide theoretical reference for enterprises to evaluate the performance of their operating systems, so that enterprises can continuously improve and develop.

With the continuous growth of China's economy, the ecological environment has been seriously damaged, which has brought varying degrees of impact on human survival and development. Low carbon economy has become an innovative economic development model proposed by countries around the world to cope with the current environmental situation. As the main body of economic activities, enterprises play an important role in the development of low-carbon economy. In the process of long-term operation and development of enterprises, the level of operation is mainly reflected by the performance evaluation system, which has exposed a series of problems and deficiencies. It is urgent to innovate and improve the enterprise performance evaluation system. Therefore, this paper mainly designs the enterprise performance evaluation system from the perspective of low carbon economy. Based on the economic performance system, it proposes reasonable improvement measures for the existing problems. A scientific and reasonable enterprise performance evaluation system is designed by integrating

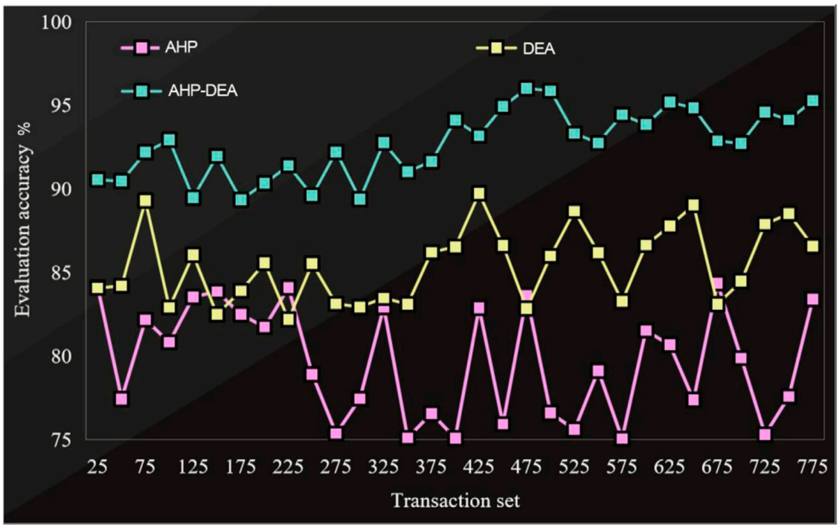


FIGURE 9
Assessment accuracy of the model.

various influencing factors, so that the business activities of enterprises can be followed by rules and contribute to the cause of environmental protection.

In the process of production and operation, enterprises have caused a great waste of energy and carbon dioxide emissions that are disproportionate to their economic performance. Therefore, the top priority of the company is to use energy scientifically and reasonably, greatly improve the energy efficiency of the enterprise, so as to reduce the excessive consumption of energy by the enterprise. This can not only implement the national policy requirements for energy conservation and emission reduction of enterprises, but also promote the improvement of economic benefits of enterprises to a certain extent. Enterprises should abandon high pollution and low efficiency energy and use sustainable low-carbon and renewable energy technologies and innovative clean energy technologies instead. So as to effectively reduce greenhouse gas emissions. Enterprises should also improve employees' low carbon awareness and attach importance to and strengthen the training of employees' skills. Reasonably allocate the human resources of enterprises, so as to improve the labor productivity of enterprises. And then effectively improve the scores of enterprise carbon productivity, energy output elasticity index and other indicators.

5 Conclusion

This paper takes small and medium-sized enterprises as the research object, and closely combines economic benefits with environmental benefits according to the connotation of low-carbon enterprises. A set of low-carbon operation performance evaluation index system for SMEs has been established, which includes five dimensions of economy, technology, energy, facilities and environment. According to the judgment matrix, calculate the maximum eigenvalue and its corresponding eigenvector, and use AHP-DEA method to rank the enterprise performance according to the eigenvector. The experimental results show that the algorithm has high efficiency, and the accuracy of model evaluation is 95.51%. To some extent, this study makes up for the research results of the impact of digital transformation on enterprise strategic performance in the low-carbon economy. By combining the characteristics of AHP model and DEA model, a gray correlation evaluation model based on AHP-DEA is established. Then evaluate the low-carbon operation performance of five representative SMEs. Through empirical analysis, it is found that the grey relational evaluation model of AH-DEA is used in this paper to effectively solve the problem that AHP method is easy to be affected by experts' personal factors and cause bias. And the traditional DEA analysis method can not reflect the preference of decision makers. At the same time, this paper puts forward the direction that enterprises should improve their low-carbon operation based on the problems reflected by the ranking of enterprises' low-carbon operation performance and the scoring of various indicators.

The study has some limitations, and this study lacks more case studies. In the future, the evaluation results of different enterprises will be compared through research on local SMEs. Reduce the corresponding score of cost indicators such as enterprise production energy intensity, enterprise non-productive building carbon emissions, and *per capita* carbon emissions.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

Funding

This work was supported by Subject of Hunan social science achievements Review Committee: Research on the digital transformation path of Hunan small and medium-sized micro enterprises under the action background of "Migrating to Cloud, Using Digital Tools and Enabling Intelligence" (No. XSP22YBC595).

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Andriole, S. J. (2020). Innovation, emerging technology, and digital transformation. *IT Prof.* 22 (4), 69–72. doi:10.1109/mitp.2020.2985491

Bastari, A., Eliyana, A., and Wijayanti, T. (2020). Effects of transformational leadership styles on job performance with job motivation as mediation: A study in a state-owned enterprise. *Manag. Sci. Lett.* 10 (12), 2883–2888. doi:10.5267/j.msl.2020.4.019

Bhadoria, R. S., Chaudhari, N. S., and Tomar, G. S. (2017). The Performance Metric for Enterprise Service Bus (ESB) in SOA system: Theoretical underpinnings and empirical illustrations for information processing. *Inf. Syst.* 65 (4), 158–171. doi:10.1016/j.is.2016.12.005

Bhaskar, L. S., Schroeder, J. H., and Shepardson, M. L. (2019). Integration of internal control and financial statement audits: Are two audits better than one? *Account. Rev.* 94 (2), 53–81. doi:10.2308/accr-52197

Chen, Y., Wang, J., Zhu, J., Sherman, H. D., and Chou, S. Y. (2019). How the great recession affects performance: A case of Pennsylvania hospitals using DEA. *Ann. Operations Res.* 278 (1-2), 77–99. doi:10.1007/s10479-017-2516-1

Christof, E., and Duarte, C. (2018). Digital transformation. *IEEE Softw.* 35 (4), 16–21. doi:10.1109/ms.2018.2801537

Doukidis, G., Spinellis, D., and Ebert, C. (2020). Digital transformation?A primer for practitioners. *IEEE Softw.* 37 (5), 13–21. doi:10.1109/ms.2020.2999969

Elshaer, I. A., Sobaih, A. E. E., Aliedan, M., and Azazz, A. M. (2021). The effect of green human resource management on environmental performance in small tourism enterprises: Mediating role of pro-environmental behaviors. *Sustainability* 13 (4), 1956. doi:10.3390/su13041956

Gu, F., Nolan, J., and Rowley, C. (2020). Organizational justice in Chinese banks: Understanding the variable influence of guanxi on perceptions of fairness in performance appraisal. *Asia Pac. Bus. Rev.* 26 (2), 169–189. doi:10.1080/13602381.2019.1700622

Harp, N. L., and Barnes, B. G. (2018). Internal control weaknesses and acquisition performance. *Account. Rev.* 93 (1), 235–258. doi:10.2308/accr-51780

Hu, F., and Yang, J. (2020). A fuzzy performance evaluation model for government websites based on language property and balanced score card. *Int. J. Enterp. Inf. Syst.* 16 (2), 148–163. doi:10.4018/ijeis.2020040109

Huang, X. L., Chen, G. T., and Lee, E. H. (2019). The moderating effect of internal control on performance of cross-border M&A under the uncertainty of economic policy: Evidence from China. *J. Korea Trade* 23 (7), 128–146. doi:10.35611/jkt.2019.23.7.128

Kauffman, R. J., and Weber, T. A. (2018). Special section: The digital transformation of vertical organizational relationships. *J. Manag. Inf. Syst.* 35 (3), 837–839. doi:10.1080/07421222.2018.1481646

Khan, S., Dong, Q., and Zhang, Y. (2017). The impact of green supply chain on enterprise performance: In the perspective of China. *J. Adv. Manuf. Syst.* 16 (03), 263–273. doi:10.1142/s0219686717500160

Kim, H-D., and Kim, Y. (2017). Corporate social responsibility and internal control effectiveness. *Asia-Pacific J. financial Stud.* 46 (2), 341–372. doi:10.1111/ajfs.12172

Pappas, I. O., Mikalef, P., Giannakos, M. N., Krogstie, J., and Lekakos, G. (2018). Big data and business analytics ecosystems: paving the way towards digital transformation and sustainable societies. *Information Systems and e-Business Management* 16 (3), 479–491. doi:10.1007/s10257-018-0377-z

Pflaum, A. A., and Golzer, P. (2018). The IoT and digital transformation: Toward the data-driven enterprise. *IEEE Pervasive Comput.* 17 (1), 87–91. doi:10.1109/mprv.2018.011591066

Ramay, W. Y., Xu, C. Y., and Illahi, I. (2019). Keyword extraction from social media via AHP. *Hum. Syst. Manag.* 37 (4), 463–468. doi:10.3233/hsm-180344

Rocha, C., Quandt, C., Deschamps, F., Philbin, S., and Cruzara, G. (2021). Collaborations for digital transformation: Case studies of industry 4.0 in Brazil. *IEEE Trans. Eng. Manag.* 2021 (99), 1–15. doi:10.1109/tem.2021.3061396

Shen, L., Zhang, X., and Liu, H. (2022). Digital technology adoption, digital dynamic capability, and digital transformation performance of textile industry: Moderating role of digital innovation orientation. *Manag. Decis. Econ.* 43 (6), 2038–2054. doi:10.1002/mde.3507

Soltani, E., and Wilkinson, A. (2020). TQM and performance appraisal: Complementary or incompatible? *Eur. Manag. Rev.* 17 (1), 57–82. doi:10.1111/emre.12317

Wetering, R., Kurnia, S., and Kotusev, S. (2021). The role of enterprise architecture for digital transformations. *Sustainability* 13 (2237), 1–5. doi:10.3390/su13042237

Zeebaree, S. R. M., Shukur, H. M., and Hussan, B. K. (2019). Human resource management systems for enterprise organizations: A review. *Periodicals Eng. Nat. Sci. (PEN)* 7 (2), 660–669. doi:10.21533/pen.v7i2.428

Zhang, T., Shi, Z. Z., Shi, Y. R., and Chen, N. J. (2022). Enterprise digital transformation and production efficiency: Mechanism analysis and empirical research. *Econ. Research-Ekonomska Istraživanja* 35 (1), 2781–2792. doi:10.1080/1331677x.2021.1980731

Zhu, P., and Song, J. (2021). The role of internal control in firms' coping with the impact of the COVID-19 pandemic: Evidence from China. *Sustainability* 13 (11), 6294. doi:10.3390/su13116294

frontiers | Frontiers in Energy Research

TYPE Brief Research Report
PUBLISHED 05 January 2023
DOI 10.3389/fenrg.2022.1080230

Check for updates

OPEN ACCESS

EDITED BY
Chi Lau,
Teesside University, United Kingdom

REVIEWED BY
Jia Shuaishuai,
Guangzhou University, China
Cheng Jin,
Shaoxing University, China

*CORRESPONDENCE
Fangbin Qian,
✉ 20152015@zyufl.edu.cn

SPECIALTY SECTION
This article was submitted to Carbon Capture, Utilization and Storage, a section of the journal Frontiers in Energy Research

RECEIVED 26 October 2022
ACCEPTED 16 December 2022
PUBLISHED 05 January 2023

CITATION
Zhang J and Qian F (2023), Digital economy enables common prosperity: Analysis of mediating and moderating effects based on green finance and environmental pollution.
Front. Energy Res. 10:1080230.
doi: 10.3389/fenrg.2022.1080230

Digital economy enables common prosperity: Analysis of mediating and moderating effects based on green finance and environmental pollution

Jie Zhang[1] and Fangbin Qian[2]*

[1]Department of Economics and Management, Zhejiang University of Science and Technology, Hangzhou, Zhejiang, China, [2]School of Hospitality Administration, Zhejiang Yuexiu University of Foreign Languages, Shaoxing, China

This study aims to explore the impact of the digital economy on common prosperity. For this reason, a bidirectional fixed effect model based on panel data of 30 provinces (cities and autonomous regions) in China is empirically tested. The results show that the digital economy can significantly improve the level of common prosperity, and has a positive impact on green and sustainable economic activities such as promoting environmental improvement, coping with climate change and resource conservation and efficient utilization, which is still valid after a series of robustness tests. It also demonstrates the role of green finance as a partial intermediary in the process of shared prosperity and as a negative regulator of environmental pollution. Analysis of regional heterogeneity shows that the enabling effect of the digital economy on common prosperity is more significant in eastern and central provinces, but not significant in western provinces. The results of this study have some reference significance for some countries, where the gap between rich and poor has widened during the epidemic, to narrow the income gap and provide ideas for the parties that made commitments at the Glasgow Climate Summit (COP26) to curb warming and reduce CO_2 emissions. That is, continuous improvement of digital infrastructure; emphasis on the intermediary role of green finance and the negative regulating role of local environmental pollution levels; following the relative comparative advantages of regions and formulating differentiated policies for the development of the digital economy, etc.

KEYWORDS

digital economy, common prosperity, green finance, environmental pollution, carbon emission reduction, COP26

1 Introduction

"Narrowing the gap between rich and poor and promoting common prosperity" is the essential demand of people all over the world. Since 2020, the world has been severely impacted by the COVID-19 epidemic, the economic situation and structure have become chaotic and complex, the income gap of people at all levels has further widened, and the distribution of social welfare has been uneven for a long time (Binns and Low, 2021). How to improve social welfare and promote equitable social distribution has become an urgent issue for governments around the world. Since the reform and opening-up, China's national policy has shifted from the traditional simultaneous prosperity to a part of getting rich first, while driving common prosperity. In terms of policy orientation, it is "Efficiency First, Consideration to Fairness." As a result, China's economy has grown rapidly. Meanwhile, the gap between the rich and the poor in China continues to widen with a Gini coefficient of about .45, which measures the gap between the rich and the poor, exceeding the United Nations' warning line of .40. The income gap between different groups exists for a long time and is at a high level, and there is a risk of falling into the "middle-income trap" (Liu et al., 2022). In recent years, China has gradually entered the era of digital economy. The concept of "Common Prosperity" and a series of measures to narrow the gap between rich and poor has been formally proposed to promote equitable distribution. Even under the influence of the epidemic, these policies have also achieved remarkable results. Therefore, the various measures and experiences of the Chinese government on how to guide the healthy development of the domestic economy and promote the process of common prosperity are undoubtedly worth learning from all countries in the world.

In 2021, President Xi Jinping, as China's most authoritative leader, once again emphasized the urgency of achieving common prosperity and the importance of finance as the core of the modern economy at the Central Finance and Economics Commission. The Central Finance and Economics Committee is known to be an important institutional arrangement for the Chinese Party Central Committee to lead the economic work and has important guidance on the direction and policies of economic development, and the themes of the meetings have basically become the focus of subsequent economic work. As an extension and breakthrough of the traditional financial system, the digital economy has effectively alleviated the shortcomings and drawbacks of the traditional Chinese financial system and has become an important part of the modern financial system. The White Paper on Digital Ecological Industry Boosting the Development of Common Prosperity pointed out that "developing digital economy is a feasible path to achieve common prosperity." China's entry into the stage of common prosperity coincides with the era of the digital economy (Xia and Liu, 2021). The innovation effect, spillover effect, synergy effect, and inclusive effect caused by the digital economy provide a sharing mechanism for balanced development and promote the whole society to share the dividend of the digital economy (Rihui, 2022). It can be seen that the digital economy provides a feasible way to transform the national economic structure, and it is considered an important basis for achieving the goal of common prosperity. In this context, an in-depth exploration of the impact of China's digital economy development on common prosperity and related issues will not only help to deeply tap the value and potential of the digital economy in the process of promoting common prosperity, and promote the high-quality development of the digital economy but also have an important reference significance for countries around the world that have been widening the gap between rich and poor in the epidemic to narrow the income gap and achieve common prosperity for all.

2 Literature review

In recent years, the digital economy, including AI, Quantum Information, Blockchain, IoT, and 5G mobile network, has played an increasingly important role in the national economy with the development of the Internet. The continuous integration of digital technology and the real economy has spawned many new models, but also led to the upgrading of the industrial structure (Su, et al., 2021) and the transformation of the economic development mode (Ahn, 2020). Numerous studies have conducted relevant research mainly in the following directions: first, in economic finance, Wang and Zhang (2022) used a mediating effects model, a threshold regression model and a spatial Durbin model to demonstrate that the digital economy is an important path for environmental regulation to strengthen the high-quality development of the economy, and the two together promote high-quality economic development. Xu et al. (2022) argued that the synergistic development of manufacturing and information and communication services has a significant positive impact on economic resilience. Wang et al. (2022)'s study is based on panel data of 121 countries from 2003 to 2019, and the results show that financial risk has a significant negative impact on the digital economy. Secondly, in energy research, Qu and Hao (2022) found that the digital economy has a significant mitigating effect on energy poverty, and there are regional differences, with the mitigation effect being more pronounced at high levels of digital economy development. Again, in terms of curbing climate warming, the carbon reduction effects of the digital economy and renewable energy have been confirmed by many studies (Chen, 2021; Li Z et al., 2021; Shang et al., 2022), especially in the context of climate warming and the recent signing of the Glasgow Climate Convention. Finally, the poverty reduction effect of the digital economy has also attracted a lot of attention. On the one hand, using digital information technology can enhance social capital from social networks, social participation, and social trust, and provide diversified financial services, thus reducing multidimensional poverty (Liu et al., 2021). On the other hand, the digital economy provides financial services for different groups at affordable costs, which improves the willingness of long-tail customers to use finance, making vulnerable groups benefit from it, thus alleviating poverty (Huang et al., 2019a).

Meanwhile, many studies have focused on common prosperity. For example, Li et al. (2022) built a measurement index system of the digital economy and shared prosperity, and demonstrated the coordination between the digital economy and shared prosperity through empirical research, which is of great significance for narrowing the regional economic gap. Zhang et al. (2022) constructed a micro common prosperity index from the three dimensions of material wealth, spiritual wealth, and social sharing, and found that digital economy and inclusive finance are important ways to narrow the gap between urban and rural areas and promote common prosperity by using the two-way fixed effect model. Based on the new economic geography perspective, Zhou (2022) included the digital economy in the core marginal model. His research shows that the digital economy provides solutions to alleviate the imbalance and disharmony of regional development, and promotes the process of common prosperity to a certain extent.

It can be seen from the above that the development of the digital economy plays an important role in achieving common prosperity. Firstly, the digital economy itself reflects a strong growth potential. The integrated application of digital technology, the promotion of digital industrialization, and industrial digitalization have become important guarantees for achieving the accumulation of material wealth for common prosperity. The digital economy with AI, Big Data, Cloud Computing, Blockchain, etc. as its core has spawned a large number of new industries and new models (Hukal et al., 2020), and is increasingly becoming a new engine for economic growth (Hjort and Poulsen, 2019; Yang, 2022). According to the data in the White Paper on China's Digital Economy Development (2021), China's digital economy will reach 39.2 trillion yuan in 2020, accounting for 38.6% of GDP, and still maintain a high growth rate of 9.7% under the impact of the epidemic. Secondly, the development of the digital economy is playing a huge role in resource allocation, employment, income distribution, urban-rural gap, public services, and many other aspects, involving the increase of social wealth, improvement of social welfare, fair distribution of society and many other fields (Zhou et al., 2021), and directly related to the benefits of reform and development achievements to most people. In short, the digital economy provides a new driving force and a feasible path for achieving common prosperity.

Since the concept of common prosperity was first proposed by China, Chinese scholars pay more attention to its conceptual analysis, influential effects, and measurement of common prosperity indicators, while scholars from other countries focus more on the role of the digital economy in poverty alleviation, resource allocation, employment, and income distribution. To sum up, although the existing literature has made relatively rich research results, there are still areas to be expanded: First, the current literature is more unilateral research on the digital economy or common prosperity, and there is no good unified framework; Second, as the second largest economy in the world, China's experience in narrowing the income gap and promoting common prosperity can be used for reference by other countries, especially developing countries. However, at present, there are few empirical studies on the development of China's digital economy and the level of common prosperity, mainly focusing on theoretical analysis, lacking sufficient credibility, and unable to accurately describe the specific role of the digital economy in promoting common prosperity; Third, since the 2021 Glasgow Climate Conference (COP26), the concepts related to green development have gradually come into the public's view. The question of whether green finance and the level of environmental pollution play a certain role in the impact path of digital economy enabling common prosperity and what role they play is one of the fields rarely covered by scholars at present.

Based on this, this paper establishes an empirical model based on China's provincial panel data to specifically explore the impact between the digital economy and common prosperity. The possible marginal contributions are as follows: ① Based on the development level of the digital economy, this paper constructs an impact model of China's digital economy on the level of common prosperity from a more comprehensive perspective, expands existing research, and provides some ideas and methods for other countries to promote social equity and narrow the gap between rich and poor. ② This paper confirms the positive role of digital economy in green economic activities of environmental improvement, climate change response and resource conservation and efficient utilization, analyzes the impact of the digital economy on promoting common prosperity, and uses its green characteristics, discusses the intermediary role of green finance as a variable and the regulatory role of local environmental pollution level, and uses empirical analysis to verify it, deepening the existing literature. ③ Based on the geographical location, this paper explores the heterogeneous effect of China's digital economy on common prosperity. ④ Digital economy, common prosperity, green finance, and environmental pollution are placed in the same framework in this paper, referring to the methods of other scholars, starting from the mathematical model, and using comparative analysis to deduce and verify their relationship.

3 Theoretical mechanism analysis

3.1 Digital economy enables common prosperity

First of all, the integrated application of digital technology has greatly liberated and developed productivity, provided new impetus for regional economic growth and high-quality economic development (Yang, 2022), and digital platforms have provided great potential for the global economy and society (Bonina et al., 2021). At the same time, digital governance escorts the economic model of the new digital industry (Hukal et al., 2020), so as to consolidate the foundation of common prosperity. However, the deep integration of the digital economy and the real economy has not only promoted general macroeconomic growth but also significantly improved the quality of economic development (Shen et al., 2022), which means that there is strong momentum support for achieving common prosperity. In addition, the digital economy has inherent advantages and essential characteristics of increasing marginal revenue, high innovation, high growth, strong diffusion, wide coverage, and low cost, etc. (Rihui, 2022), which have an all-round and subversive impact on the economy and society. Compared with the traditional agricultural economy and industrial economy, the digital economy can release more economic development dividends, showing a strong "making bigger cakes" dynamic mechanism.

Secondly, with the popularization of digital technology and the expansion of application scenarios, the inclusiveness of the digital economy is gradually revealed, and digital dividends benefit most people and help achieve balanced growth. Additionally, the digital economy is the endogenous power to achieve inclusive growth and regional coordinated development. The spillover effect and synergy effect of digital economy development have significant income growth effect and poverty reduction effect (Ai and Tian, 2022; Lechman and Popowska, 2022), which has a negative direct effect on the regional gap and greatly reduces the urban-rural development gap (Chen and Wu, 2021). Therefore, the development of the digital economy helps to solve the problem of unbalanced development and promotes equal development opportunities in different dimensions such as regions, people, and urban-rural areas, which has a sharing mechanism of "dividing the cake" (Xiang et al., 2022).

3.2 Mediating effect of green finance

Green finance refers to economic activities that can promote environmental improvement, cope with climate change and save and use resources efficiently, which can also be understood as financial services provided for projects in the fields of environmental protection, energy conservation, clean energy, green transportation, green architecture, carbon emission reduction, etc. Common prosperity is an ideal state in which social wealth generally increases, the gap between rich and poor continues to narrow, and all people share the achievements of development.

Green finance refers to economic activities that can promote environmental improvement, cope with climate change and save and use resources efficiently, which can also be understood as financial services provided for projects in the fields of environmental protection, energy conservation, clean energy, green transportation, green architecture, etc. Common prosperity is an ideal state in which social wealth generally increases, the gap between rich and poor continues to narrow, and all people share the achievements of development. The basic premise for green finance to promote common prosperity includes three aspects: ①green finance can improve productivity and promote income level; ②green finance is inclusive and friendly to underdeveloped regions and low-and-moderate-income groups, thus narrowing the gap between rich and poor; ③green finance is conducive to all people sharing the achievements of development. Zheng et al. (2022) summarized the mechanism of green finance to improve the level of common prosperity: On the premise of comprehensive consideration of the impact and role of government regulation and market resource allocation, the subjective initiative of the participants is fully exerted through the division of division effect, distribution effect of green elements, green technology effect, employment effect, and inclusion effect, so as to realize the expansion of the green financial market scale, improve the productivity level, promote the income level, narrow the gap between the rich and the poor, share the development achievements, and ultimately achieve common prosperity. Among them, the role of government regulation is embodied in an environmental regulation system, green assessment mechanism, green fiscal and tax policies, income distribution system, etc.; The role of market resource allocation is reflected in the competition mechanism and price mechanisms, such as affecting the energy consumption and carbon emission reduction of enterprises through the carbon trading mechanism, optimize the production and manufacturing process, and explore the feasible path of low-carbon transformation of enterprises (Xuan et al., 2020). Therefore, as one of the important branches of the digital economy, it is assumed that green finance has undertaken some mediating effects in the process of promoting common prosperity, which will be verified in the next part.

3.3 Moderating effect of environmental pollution level

For a long time, most literature has paid more attention to the relationship between environmental pollution and economic growth, mainly focusing on the study of the Environmental Kuznets Curve (Rao and Yan, 2020). In the early stage of economic development, pollution has risen rapidly; When the economic growth crosses a certain point, the environmental pollution shows a downward trend. However, with the improvement of residents' income levels and the widening gap between the rich and the poor, the relationship between pollution and the income gap has also come into everyone's sight. Most scholars believe that the greater the income gap, the less conducive to environmental protection. The widening income gap in a country is generally not conducive to the improvement of environmental quality. Some scholars believe that the level of common prosperity is related to the "inverted N" of industrial wastewater, carbon dioxide emissions, smoke, and dust emissions. In the process of moving towards high income, the widening of the income gap is not conducive to environmental protection and pollution control (Wang and Zhang, 2021). Moreover, the income gap between urban and rural areas has a negative externality of malignant cumulative effect. The larger the income gap, the greater the impact of environmental pollution on common prosperity (Lan et al., 2021). For example, Huang and Ye (2022) used panel data from 30 provinces in the Chinese Mainland from 2002 to 2019 to prove that environmental pollution has a significant negative impact on the income gap and common prosperity. In addition, there is no doubt that the digital economy can improve the level of environmental pollution (Deng and Zhang, 2022; Li and Zhou, 2021; Li Y et al., 2021). To sum up, there is reason to speculate that the variable of environmental pollution level may play a moderating role in the process of the digital economy boosting common prosperity, and specific research will be shown in the next part.

4 Model construction, indicator selection, and data source

4.1 Model specification

Considering the availability of data, this paper uses panel data of 30 provinces in China (excluding Hong Kong, Macao, Taiwan, and Tibet) from 2011 to 2019 as samples to build a bidirectional fixed effect model to examine the impact of digital economy development on the level of common prosperity. This model is mainly used for panel data analysis, in which bidirectional fixation refers to the simultaneous control of time and provinces to reduce the impact of relevant missing variables or other factors on the study, making the results of this paper more reliable and robust. The mathematical model is as follows:

$$cp_{it} = \alpha + \alpha_1 de_{it} + \alpha_2 control_{it} + \mu_i + \varphi_t + \varepsilon_{it} \quad (1)$$

Here, ***i*** represents the Province, ***t*** represents the Year, ***cp*** represents the Common Prosperity Level, and ***control*** represents a set of control variables in the equation, which includes foreign direct investment (FDI), opening level (open), financial development level (finance), human capital level (redu), and innovation capability (innovation). In addition, in order to alleviate the endogenous problem of missing variables, this paper uses $\boldsymbol{\mu_i}$, $\boldsymbol{\varphi_t}$ to control the fixed effect of province and year, and $\boldsymbol{\varepsilon_{it}}$ is the random error.

In order to test the mediating effect of green finance (green), referring to the method proposed by Wen and Ye, 2014, Eqs. 2, 3 on the basis of Eq. 1 have been constructed to test the mediating effect, as follows:

$$green_{it} = \beta + \beta_1 de_{it} + \beta_2 control_{it} + \mu_i + \varphi_t + \varepsilon_{it} \quad (2)$$

$$cp_{it} = \gamma + \gamma_1 de_{it} + \gamma_2 green_{it} + \gamma_3 control_{it} + \mu_i + \varphi_t + \varepsilon_{it} \quad (3)$$

According to the test method of Wen and Ye (2014), $\boldsymbol{\alpha_1}$ represents the total effect of the digital economy enabling common prosperity. In Eqs. 2, 3, $\boldsymbol{\beta_1}$ and $\boldsymbol{\gamma_2}$ represent the mediating effect of green finance. $\boldsymbol{\gamma_1}$ represents the direct impact of the digital economy on common prosperity in the dimension of green finance. Based on the significance of $\boldsymbol{\alpha_1}$, if $\boldsymbol{\beta_1}$ and $\boldsymbol{\gamma_2}$ are significant, then when $\boldsymbol{\gamma_1}$ is significant, it is considered that green finance has a partial mediating effect; if $\boldsymbol{\gamma_1}$ is not significant, it is a complete mediating effect. If at least one of $\boldsymbol{\beta_1}$ or $\boldsymbol{\gamma_2}$ is not significant, the Bootstrap test is performed, and if the test passes, it indicates that partial mediating effects exist.

At the same time, in order to test the moderating effect played by the environmental pollution level (poll), an interactive term (de * poll) between the environmental pollution level and the digital economy has been constructed. Through the significance of interaction items to verify whether there is a regulatory effect, this study will further establish the following moderating effect Eq. 4:

$$cp_{it} = \eta_0 + \eta_1 de_{it} + \eta_2 poll_t + \eta_3 de_{it}{}^{*} poll_{it} + \eta_4 control_{it} + \mu_i + \varphi_t + \varepsilon_{it} \quad (4)$$

TABLE 1 System of common prosperity indicators.

Index	Sub-index	Weights	Attributes
Common prosperity level	Urban *per capita* disposable income (Yuan)	0.22	+
	Rural *per capita* disposable income (Yuan)	0.25	+
	Per Capita GDP (Yuan/person)	0.27	+
	Average wage of urban unit employees (Yuan/person)	0.26	+

TABLE 2 System of digital economy development level indicator.

Index	Sub-index	Description	Attributes
Digital economy development level	Internet penetration rate	Number of Internet broadband access users among 100 people	+
	Information on internet-related practitioners	The proportion of employees in the computer service and software industry in urban units	+
	Internet-related outputs	The total amount of telecommunications services *per capita*	+
	Mobile phone penetration	Number of mobile phone users among 100 people	+
	Development of digital inclusive finance	China digital inclusive finance index	+

4.2 Variable measure and description

4.2.1 Explained variable

Common prosperity level (cp). Starting from the connotation of common prosperity, based on the conclusions published by Zheng in 2022, combined with the availability of provincial-level data, a common prosperity evaluation index system, which conforms to China's actual situation, has been constructed as shown in Table 1.

4.2.2 Core explanatory variable

Digital economy development level (de). There is no unified approach to measure the level of digital economy development at the provincial level. Considering the availability of data and drawing on the views of Zhao et al. (2020), this paper measures the level of the digital economy in each province from the aspects of Internet development and digital inclusive finance. For the measurement of Internet development, refer to the method of Huang et al. (2019b), four indicators have been adopted: Internet penetration rate, information on Internet-related practitioners, Internet-related outputs, and mobile phone penetration. The actual contents of these four indicators are the number of Internet broadband access users among 100 people, the proportion of employees in the computer service and software industry in urban units, the total amount of telecommunications services *per capita*, and the number of mobile phone users among 100 people. For measuring the development of digital inclusive finance, China Digital Inclusive Finance Index is adopted, which is jointly prepared by the Digital Finance Research Center of Peking University and Ant Financial Services Group (Guo et al., 2020). Individual missing values are supplemented by linear interpolation, and the data of the above five indicators are standardized and reduced by principal component analysis to obtain the development level of the digital economy. The weights of principal components at all levels are listed in descending order, which is 0.713, 0.139, 0.090, 0.046, and 0.012 (Table 2).

4.2.3 Mediating variable

Green financial level (green). In the current literature, there are generally two kinds of methods to measure green finance: the comprehensive indicator system and the capital allocation indicator, both of which have advantages and disadvantages. In theory, the comprehensive indicator system can more comprehensively measure the development of green finance, but the construction of the indicator system itself has the uncertainty of weight measurement and the risk of missing sub-indicators, which is difficult to support effective econometric analysis. The capital allocation index can better overcome the problem of insufficient sample size, and in many theoretical models, it can keep consistent with the theoretical connotation of the core variables of the model, but this indicator inevitably gives up the comprehensiveness of the green financial measurement (Wen et al., 2022). Considering all factors comprehensively, this paper refers to the method proposed by Dong in 2020, and constructs a more reasonable green financial indicator system from the perspective of credit, investment, insurance, and government intervention (Table 3). For some missing values, the 5-years average method is used to calculate.

4.2.4 Moderating variable

Environmental pollution index (poll). In recent years, China's rapid economic development has caused certain damage to the ecological environment. Based on the actual situation and taking full account of the availability of information and data on various environmental pollutants, this paper quotes the calculation results published by Fu and Peng (2020) as the moderating variable, which selects five kinds of pollutant indicators: total wastewater, chemical

TABLE 3 System of green financial indicator.

Index	Sub-index	Description	Attributes
Green finance	Green credit	Interest expenditure of six high-energy-consuming industries/Total industrial interest expenditure	−
	Green investment	Investment in environmental pollution control/GDP	+
	Green insurance	Agricultural insurance income/Total agricultural output value	+
	Government support	Financial expenditure on environmental protection/General budget expenditure	−

oxygen demand in wastewater, sulfur dioxide, smoke and dust, and solid waste. The comprehensive index of environmental pollution is constructed by the entropy method. The larger the index value is, the worse the environmental quality is; On the contrary, the better the environmental quality is.

4.2.5 Control variables

In order to more comprehensively explore the impact of digital economy development enabling common prosperity, this paper refers to the ideas and principles for selecting control variables such as Kakwani et al. (2022); Zha and Fang (2022); Zhu et al. (2022), and then selects the following control variables: 1) Foreign direct investment (FDI), measured by the total investment of foreign-invested enterprises registered at the end of the year; 2) Openness index (open), measured by the ratio of the total import and export volume of foreign trade to the GDP of the year; 3) Financial development level (finance), measured by the ratio of the loan balance of financial institutions to GDP of the year; 4) Human capital level (redu), measured by the average years of education *per capita* in each province; 5) Innovation ability (innovation), measured by the ratio of internal expenditure of research and experimental development (R&D) funds of each province to the GDP of the year.

4.3 Data source and description

Based on the data of the China Statistical Yearbook, China Statistical Yearbook on Environment, China Statistical Yearbook on Science and Technology, Yearbook of China's Insurance, the website of the National Bureau of Statistics, statistical yearbooks of each province, China Stock Market and Accounting Research Database (CSMAR), and relevant reports on digital economy development over the years, the panel data of 30 provinces, cities and autonomous regions (excluding Tibet, Hong Kong, Macao, and Taiwan) in China has been collated and calculated and taken as statistical samples. Among them, individual missing values are supplemented by the advanced interpolation method; At the same time, in order to mitigate the heteroscedastic interference caused by data fluctuations, some data are processed by logarithmization. Some missing values are supplemented by linear interpolation; At the same time, in order to mitigate the heteroscedastic interference caused by data fluctuations, some data are logarithmized. In addition, in order to avoid pseudo regression between variables due to correlation, the variance inflation factor (VIF) was tested. The test result shows that the mean value was 5.14, which can be considered that there is no serious multicollinearity in the selected indicator data. Descriptive statistics of variables are shown in Table 4:

TABLE 4 Descriptive statistics of variables.

Variable	Obs	Mean	Std. Dev.	Min	Max
Cp	270	0.313	0.123	0.133	0.846
De	270	0.750	1.155	−1.027	6.614
Green	270	0.185	0.108	0.062	0.793
de* poll	270	0.191	0.339	−.535	2.187
Lnfdi	270	6.570	1.366	3.432	9.777
Open	270	0.270	0.304	0.013	1.548
finance	270	3.139	1.071	1.568	7.607
Redu	270	9.172	.893	7.474	12.782
innovation	270	1.636	1.116	0.411	6.315

5 Empirical test

5.1 Benchmark regression

The benchmark regression results of digital economy development enabling common prosperity are shown in Table 5. Column (1) shows the direct impact of digital economy development on common prosperity without adding control variables and fixed effects. The regression coefficient is positive, and it has passed the significance level test of 1%, indicating that digital economy development can promote common prosperity. Columns (2) and (3) are the results of gradually controlling the fixed effects of time and province after adding control variables. The R-squared values are higher than that in column (1), and the regression coefficient is still significantly positive at the level of 1%, which indicates that the digital economy has a significant positive effect on common prosperity when considering the differences in the impact of innovation capacity, financial development, openness index, and other factors in different provinces. In general, for every unit of increase in the development level of the digital economy, China's level of common prosperity will increase by 0.043 units.

It can be seen from the value in column (3) that, in terms of control variables, the coefficient of FDI is significantly negative, which may be the "U" relationship proposed by Nie and Zhe (2020), that is, in the initial stage of FDI inflow, the regional income gap continues to expand due to the location choice and industrial choice of FDI, and the demand for skills of the labor force increases with the gradual improvement of the inflow quality of FDI, so the urban-rural income gap has been further expanded. The coefficient of the openness index is significantly negative, which may be because foreign trade is mainly concentrated in developed regions, and the

TABLE 5 Benchmark regression of digital economy and common prosperity.

	(1)	(2)	(3)
	cp	cp	cp
de	0.094*** (0.002)	0.064*** (0.007)	0.043*** (0.008)
Lnfdi		−0.003 (0.004)	−.017*** (0.005)
open		−0.100*** (0.013)	−0.161*** (0.015)
finance		−0.013*** (0.004)	−0.016*** (0.004)
redu		0.023*** (0.006)	0.017*** (0.006)
innovation		0.043*** (0.007)	0.033*** (0.007)
_cons	0.242*** (0.009)	0.045 (0.056)	0.223*** (0.063)
Provincial fixed effect	No	No	Yes
Year fixed effect	No	Yes	Yes
Observations	270	270	270
R-squared	0.910	0.968	0.972

Standard errors are in parentheses ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

"polarization effect" attracts labor from backward regions to gather in cities, which is not conducive to promoting common prosperity. The coefficient value of the financial development level is significantly negative, indicating that it has aggravated social inequality to a certain extent (Brei et al., 2018; Zhang, 2021). The coefficient of human capital level is significantly positive, indicating that the higher the level of education, the more conducive to improving the income level, increasing the proportion of middle-income groups, and promoting common prosperity. The coefficient of innovation capability is significantly positive at the level of 1%, indicating that technological innovation has improved total factor productivity and is conducive to improving income levels, and its diffusion effect and scope economy effect are conducive to the sharing of development achievements by all people.

5.2 Analysis of mediating effect and moderating effect

5.2.1 Mediating effect

In this section, green finance is used as a mediator between the digital economy and common prosperity to establish a mediating effect model, and the regression results are shown in Table 6 with reference to the stepwise test method of Wen and Ye, (2014):

Step 1. Test the total effect of the digital economy on common prosperity by using the Eq. 1. The results are shown in Column (1) of Table 6, that the higher the level of the digital economy, the higher the level of common prosperity of the province, which is significantly positively correlated, and $\boldsymbol{\alpha_1} = \boldsymbol{0.043}$ is the total effect of the independent variable on the dependent variable.

Step 2. Use Eq. 2 to test whether the digital economy has a significant impact on green finance. As shown in column (2) of Table 6, $\boldsymbol{\beta_1} = \boldsymbol{0.033}$ is at the level of 1%, which shows that the development of the digital economy in each province has a significant role in promoting green finance, and has a positive impact on green economic activities such as controlling carbon dioxide emissions, promoting energy transformation and curbing climate warming. This result is the same as that of Tian et al. (2022). They discussed the impact of the digital economy on the efficiency of green financial investment in China and found that its application in green finance can reduce the imbalance of regional economic development.

Step 3. Since the coefficient has been verified in the first two steps that both α_1 and β_1 are significant, the independent variable and the mediator are put into Eq. 3 to test whether their influence on the dependent variable is significant and analyze whether the mediating variable has completely or partially mediating effect. As shown in Column (3) of Table 6, the digital economy and green finance are both at the level of 1% and significantly positively correlated with the level of common prosperity, indicating that green finance has played a partial mediating effect in the process of enabling the digital economy to achieve common prosperity, and its value is the product of $\boldsymbol{\beta_1}$ and $\boldsymbol{\gamma_2}$ (0.033 * 0.481 = 0.016). $\boldsymbol{\gamma_1} = \boldsymbol{0.027}$ represents that under the dimension of green finance, the direct impact of the digital economy on common prosperity decreases by 0.016 compared with the total effect of 0.043, which is the same as the intermediary effect results calculated earlier, which again shows the correctness of the model.

TABLE 6 Regression results of mediating effect and moderating effect model.

	(1)	(2)	(3)	(4)
	cp	green	cp	cp
de	0.043*** (0.008)	0.033*** (0.009)	0.027*** (0.007)	0.040*** (0.008)
green			0.481*** (0.052)	
de*poll				−0.025*** (0.006)
poll				0.024 (0.023)
Control variable	Yes	Yse	Yes	Yes
Provincial fixed effect	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes
Observations	270	270	270	270
R-squared	0.972	0.849	0.979	0.974

Standard errors are in parentheses ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

TABLE 7 Robustness test.

	(1)	(2)	(3)	(4)	(5)	(6)
	cp	cp	cp	cp	cp	cp
dige	0.976*** (0.086)	0.453*** (0.076)				
de			0.085*** (0.008)	0.034*** (0.008)	0.074*** (0.014)	0.044*** (0.011)
_cons	0.079*** (0.012)	0.140** (0.063)	0.234*** (0.004)	0.196*** (0.062)	0.234*** (0.005)	0.230*** (0.075)
Control variable	No	Yes	No	Yes	No	Yes
Provincial fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Observations	270	270	270	270	180	180
R-squared	0.946	0.972	0.950	0.972	0.923	0.955

Standard errors are in parentheses *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

5.2.2 Moderating effect

Further analysis shows the regression results of the mathematical model with the environmental pollution level as the moderating variable in Column (4) of Table 6. Both the digital economy (de) and the interaction of the digital economy and environmental pollution index (de * poll) have a significant impact on the level of common prosperity at the level of 1%. The coefficient of the former is positive, while the coefficient of the latter is negative, indicating that environmental pollution has a negative regulatory effect on the development of common prosperity, which is similar to the research results of He et al. (2022). They found that there is a strong spatial correlation between the ecological environment level and the relatively poor areas, and formulating effective environmental protection policies is the key to controlling climate change、promoting green development and common prosperity.

5.3 Robustness test

5.3.1 Replace core explanatory variables

Zhao et al. (2020) used the principal component analysis method to calculate the weight of the digital economy indicators in the previous section, but now, using Miao et al., 2022 method for reference, the entropy weight method is used to calculate the digital economy level (dige) and then conduct regression. As shown in Column (1) and Column (2) of Table 7, the results are significant at the level of 1% regardless of whether control variables are added, which is basically consistent with the benchmark regression results.

5.3.2 Winsorize

In order to eliminate the adverse effects of abnormal values and non-randomness on the measurement results, the variables in the model (1) above were winsorized by 1% up and down and then regressed again. As shown in Columns (3) and (4) of Table 7, whether control variables are added or not, the regression results are significant at the level of 1%, fully verifying the robustness of the empirical study.

5.3.3 Shorten sample cycle

In order to investigate whether the impact of the development level of the digital economy on common prosperity is affected by the duration of the study, referring to the method of Luo and Liu (2022), the sample interval has been shortened to 2013–2018 and then regresses again. Therefore, the total number of samples is reduced from 270 to 180. As shown in Columns (5) and (6) of Table 7, the regression results are still significant at the level of 1%, which shows the reliability and preciseness of this study.

5.4 Endogenetic treatment

Although the bidirectional fixed effect model adopted in this paper can effectively solve the endogenous problems caused by missing individual changes or time changes, it cannot effectively solve the endogenous problems caused by causality. Therefore, the instrumental variable method will be adopted to conduct the endogenetic test, using the lag term of the development level of the digital economy and the interaction term of the number of fixed phones per hundred people in each region in 1984 and the number of Internet users in the previous year is taken as the instrumental variables of the development level of the digital economy in each region, and the two-stage least square method (2SLS) is used to conduct the test. Columns (1) and (2) of Table 8 report the regression results of two tool variables in detail, showing that the promotion effect of the digital economy on common prosperity is significant at the level of 1%, indicating that the basic conclusion is still stable after considering endogenous issues. In addition, the p values corresponding to the LM statistics of Kleibergen Paap rk are .000 and .006 respectively, significantly rejecting the original hypothesis, indicating that there is no problem of insufficient identification of tool variables. At the same time, Cragg Donald's Wald F statistics are greater than the critical value (16.380) of the Stock-Yogo weak identification test at the 10% level, indicating that it is reasonable to select the lag term of the development level of the digital economy, the interaction term between the number of fixed phones per 100 people in 1984 and the number of Internet users in the previous year as the tool variable.

TABLE 8 Two-stage least squares (2SLS) regression.

	(1)	(2)
	cp	cp
de	0.046*** (0.017)	0.259*** (0.065)
Control variable Provincial fixed effect Year fixed effect	Yes Yes Yes	Yes Yes Yes
Kleibergen-Paap rk LM Statistics	29.642 (0.000)	7.478 (0.006)
Cragg-Donald Wald F Statistics	167.42 {16.380}	20.482 {16.380}
Observations	240	270
R-squared	0.966	0.879

Note: Values in ( ) are p values, and values in { } are critical values at the 10% level of the Stock-Yogo weak identification test.

TABLE 9 Heterogeneity analysis.

	(1)	(2)	(3)
	Eastern	Central	Western
	Cp	cp	Cp
de	0.066*** (0.013)	0.031** (0.012)	0.001 (0.006)
_cons	0.571*** (0.150)	0.150** (0.064)	0.178*** (0.033)
Control variable	Yes	Yes	Yes
Provincial fixed effect	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes
Observations	99	72	99
R-squared	0.981	0.993	0.996

Standard errors are in parentheses $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

5.5 Heterogeneity analysis

There are obvious regional differences in the development degree and policy support of the digital economy and common prosperity in different regions of China. Therefore, in order to further explore whether there is regional heterogeneity in the promotion effect of the digital economy on common prosperity, the sample will be divided into eastern, central, and western regions for re-testing. As shown in Table 9, the regression coefficient of the digital economy in the central and eastern regions is significantly positive, indicating that the development of the digital economy has significantly promoted the process of common prosperity in this region, but not in the western regions. At the same time, the spillover effect intensity of the digital economy shows "East > Central > West". It can be concluded that the impact of China's digital economy on common prosperity has regional heterogeneity. The digital economy in the eastern region plays a stronger role in promoting common prosperity, followed by the central region, and the western region is the weakest. The reason for this difference may be that compared with the western region, the eastern region has an earlier and higher level of digital economy development, and the dividend of digital inclusive finance is more fully released; However, due to the constraints of traditional financial foundation, resource talent and ideas, the application level of digital technology and financial services in the central and western regions is relatively low, resulting in the inability to fully release the dividend of the digital economy in the western regions.

6 Conclusion and recommendations

6.1 Conclusion

Since 2020, the world has been severely impacted by the COVID-19. The economic situation and structure have become chaotic and complex. The income gap of people at all levels has further expanded. The distribution of social welfare has been uneven for a long time. How to improve social welfare and promote social fair distribution has become an urgent problem for governments around the world. In this context, based on China's provincial panel data in 2011–2019, this paper conducts an empirical study on the impact mechanism of the digital economy enabling common prosperity through the panel fixed effect model, mediating effect model, moderating effect model, and other methods. The main conclusions are as follows:

First, the basic facts show that the development of the digital economy has obviously promoted the level of common prosperity in China, not only playing a role in "making the cake bigger" on the overall level but also playing a role in "dividing the cake better" in terms of distribution. The regression coefficients passed the 1% significance test before and after adding the control variables and bidirectional fixed effects on time and provinces. In general, the level of common prosperity in China will increase by 0.043 units every time the level of digital economy development increases by one unit. The results of endogenous and robust tests show that this result is highly reliable.

Second, the result of intermediary effect shows that the development of digital economy has a significant role in promoting green finance, and it is significant at the level of 1%. It has a positive impact on green economic activities such as controlling carbon dioxide emissions, promoting energy transformation and curbing climate warming.

Third, the analysis of the transmission mechanism shows that the digital economy not only has a direct promoting effect on common prosperity but also can have a significant positive impact through green finance, that is, the digital economy can indirectly promote social fair distribution and narrow the gap between rich and poor by promoting green finance. At the same time, the level of local environmental pollution will have a negative regulating effect on the process of common prosperity.

Fourth, the contribution of the digital economy to shared prosperity is more pronounced in central and eastern China, significant at the 5% and 1% levels respectively, but not in the western provinces, reflecting some regional heterogeneity.

6.2 Recommendations

The above research conclusion have important reference significance for some countries that have widened the gap between the rich and the poor during the epidemic to narrow the income gap, promote fair distribution, achieve common prosperity for all, and provide empirical evidence for governments to give full play to the dividend advantage of digital economy enabling common prosperity. It also provides some ideas for relevant parties who made commitments at the Glasgow Climate Summit (COP26) to curb climate warming and reduce CO_2 emissions. Based on this, we propose the following recommendations:

(1) Continue to develop the digital economy, improve the digital infrastructure, focus on expanding the coverage of digital inclusive finance, and give play to the carbon emission reduction effect of digital finance. The main crux of the significant differences in the development of the digital economy among regions is the uneven infrastructure. Therefore, the deep integration and development of digital technology and the real economy should be paid attention to, so as to improve the level of the digital economy and narrow the gap between rich and poor.

(2) Attach importance to the mediating role of green finance to promote common prosperity with "green development". Especially at the moment of officially signing the Glasgow Climate Convention, the inclusive nature of the digital economy should be active to promote green and sustainable development and steadily advance the process of common prosperity. At the same time, the negative adjustment of the local environmental pollution level should be fully considered, so as to strengthen environmental governance, balance the environmental pollution costs borne by residents of all levels, and reduce the negative impact on the environment. As a result, the ecological compensation mechanism and environmental protection laws and regulations will be improved according to the idea of "whoever pollutes shall govern, whomever gains shall compensate."

(3) Follow the regional comparative advantages and formulate differentiated digital economy development policies. The digital economy empowering common prosperity has significant regional heterogeneity, and the digital economy empowering effect in the central and eastern regions is more significant. Therefore, while improving the digital infrastructure, the central and eastern regions should focus on the layout of digital industries to avoid convergence and low-level duplication of construction; Give full play to the leading edge of digital technology, focus on breaking through the research and development of core and key digital technologies and pay attention to the integration of digital resources. In the relatively backward regions of various countries, the government should actively popularize the inclusiveness of the digital economy, promote residents to adapt to digital financial services, narrow the digital gap between regions, and promote the realization of the goal of the common prosperity of the country.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by JZ. The first draft of the manuscript was written by JZ and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Ahn, J. S. (2020). The politics of social pacts on income security in digital economies: Is government's role significant? *Korean J. Soc. Sci.* 39 (1), 233–267. doi:10.18284/jss.2020.04.39.1.233

Ai, X., and Tian, Y. (2022). The poverty reduction effect of the digital economy. *J. Huan Univ. Soc. Sci.* 36 (1), 50–56. doi:10.16339/j.cnki.hdxbskb.2022.01.007

Binns, C., and Low, W. Y. (2021). The rich get richer and the poor get poorer: The inequality of COVID-19. *Asia Pac. J. Public Health* 33 (2-3), 185–187. doi:10.1177/10105395211001662

Bonina, C., Koskinen, K., Eaton, B., and Gawer, A. (2021). Digital platforms for development: Foundations and research agenda. *Inf. Syst. J.* 31 (6), 869–902. doi:10.1111/isj.12326

Brei, M., Ferri, G., and Gambacorta, L. (2018). Financial structure and income inequality. *Available at SSRN 3290522*.

Chen, L. (2021). How CO2 emissions respond to changes in government size and level of digitalization? Evidence from the BRICS countries. *Environ. Sci. Pollut. Res.* 29, 457–467. doi:10.1007/s11356-021-15693-6

Chen, W., and Wu, Y. (2021). The development of digital economy, the digital divide and the income gap between urban and rural residents. *South China J. Econ.* (11), 1–17. doi:10.19592/j.cnki.scje.390621

Deng, R., and Zhang, A. (2022). Research on the impact and mechanism of urban digital economy development on environmental pollution in China. *South China J. Econ.* (2), 18–37. doi:10.19592/j.cnki.scje.390724

Fu, Y., and Peng, Z. (2020). Green financial development, R&D investment and regional economic growth: An empirical study based on the provincial panel threshold model. *Statistics Decis.* 36 (21), 120–124. doi:10.13546/j.cnki.tjyjc.2020.21.024

Guo, F., Wang, J., Wang, F., Kong, T., Zhang, X., and Cheng, Z. (2020). Measuring China's digital inclusive financial development: Index compilation and spatial characteristics. *China Econ. Q.* 19 (04), 1401–1418. doi:10.13821/j.cnki.ceq.2020.03.12

He, X., Li, A., Li, J., and Zhuang, Y. (2022). Conservation and development: Spatial identification of relative poverty areas affected by protected areas in China and its spatiotemporal evolutionary characteristics. *Land* 11 (7), 1048. doi:10.3390/LAND11071048

Hjort, J., and Poulsen, J. (2019). The arrival of fast internet and employment in Africa. *Am. Econ. Rev.* 109 (3), 1032–1079. doi:10.1257/aer.20161385

Huang, B., and Ye, Q. (2022). Environmental pollution, residents' health and urban-rural income gap: Impact mechanism and empirical test. *J. Henan Univ. Animal Husb. Econ.* 35 (03), 23–30.

Huang, Q., Li, Z., and Xiong, D. (2019a). The poverty reduction effect of digital inclusive finance and its transmission mechanism. *Reform* 309 (11), 90–101.

Huang, Q., Yu, Y., and Zhang, S. (2019b). Internet development and manufacturing productivity improvement: Internal mechanism and China's experience. *China Ind. Econ.* (08), 5–23. doi:10.19581/j.cnki.ciejournal.2019.08.001

Hukal, P., Henfridsson, O., Shaikh, M., and Parker, G. (2020). Platform signaling for generating platform content. *Mis Q.* 44 (3), 1177–1205. doi:10.25300/misq/2020/15190/

Kakwani, N., Wang, X., Xue, N., and Zhan, P. (2022). Growth and common prosperity in China. *China & World Econ.* 30 (1), 28–57. doi:10.1111/CWE.12401

Lan, G., Wu, Y., Kuang, X., and Lv, Y. (2021). Effect of environmental pollution on urban-rural income gap. *J. Beijing Univ. Aeronautics Astronautics Soc. Sci. Ed.* 34 (3), 105–112. doi:10.13766/j.bhsk.1008-2204.2020.0093

Lechman, E., and Popowska, M. (2022). Harnessing digital technologies for poverty reduction. Evidence for low-income and lower-middle income countries. *Telecommun. Policy* 46 (6), 102313. doi:10.1016/j.telpol.2022.102313

Li, G., Zhou, X., and Lu, J. (2021). No adequate evidence indicating hypertension as an independent risk factor for COVID-19 severity. *Macroeconomics* 110 (7), 146–147. doi:10.1007/s00392-020-01653-6

Li, Y., Hu, M., and Zhao, Y. (2022). Research on coordination of digital economy and common prosperity in Zhejiang Province based on entropy weight TOPSIS and coupling mechanism. *Acad. J. Bus. Manag.* 4. doi:10.25236/AJBM.2022.040711

Li, Y., Yang, X., Ran, Q., Wu, H., Irfan, M., and Ahmad, M. (2021). Energy structure, digital economy, and carbon emissions: Evidence from China. *Environ. Sci. Pollut. Res.* 28, 64606–64629. doi:10.1007/s11356-021-15304-4

Li, Z, Z., Li, N., and Wen, H. (2021). Digital economy and environmental quality: Evidence from 217 cities in China. *Sustainability* 13 (14), 8058. doi:10.3390/su13148058

Liu, X., Huang, Y., and Huang, S. (2022). Digital inclusive finance and common prosperity: Theoretical mechanism and empirical facts. *Financial Econ. Res.* 37 (1), 135–149.

Liu, Z., Wei, Y., Li, Q., and Lan, J. (2021). The mediating role of social capital in digital information technology poverty reduction an empirical study in urban and rural China. *Land* 10 (6), 634. doi:10.3390/land10060634

Luo, B., and Liu, Y. (2022). Tax preference, innovation investment, and high-quality development of enterprises. *Tax Econ. Res.* 25 (04), 13–21. doi:10.16340/j.cnki.ssjjyj.2020.04.003

Miao, L., Chen, J., Fan, T., and Lv, Y. (2022). Impact of digital economy development on carbon emission - based on panel data analysis of 278 prefecture-level cities. *South China Finance* (02), 45–57.

Nie, X., and Zhe, G. (2020). *The impact of foreign direct investment on the income gap between urban and rural areas in China – a case study of Guangdong province*. Beijing: China Economic & Trade Herald, 21–24.

Qu, J., and Hao, X. (2022). Digital economy, financial development, and energy poverty based on mediating effects and a spatial autocorrelation model. *Sustainability* 14 (15), 9206. doi:10.3390/SU14159206

Rao, C., and Yan, B. (2020). Study on the interactive influence between economic growth and environmental pollution. *Environ. Sci. Pollut. Res.* 27 (31), 39442–39465. doi:10.1007/s11356-020-10017-6

Rihui, O. U. Y. A. N. G. (2022). Logic, mechanism and path in the promotion of collective prosperity by digital economy. *J. Chang'an Univ. Soc. Sci. Ed.* 24 (1), 1–15.

Shang, Y., Razzaq, A., Chupradit, S., Binh-An, N., and Abdul-Samad, Z. (2022). The role of renewable energy consumption and health expenditures in improving load capacity factor in ASEAN countries: Exploring new paradigm using advance panel models. *Renew. Energy* 191, 715–722. doi:10.1016/j.renene.2022.04.013

Shen, W., Xia, W., and Li, S. (2022). Dynamic coupling trajectory and spatial-temporal characteristics of high-quality economic development and the digital economy. *Sustainability* 14 (8), 4543. doi:10.3390/su14084543

Su, J., Su, K., and Wang, S. (2021). Does the digital economy promote industrial structural upgrading? — a test of mediating effects based on heterogeneous technological innovation. *Sustainability* 13 (18), 10105. doi:10.3390/su131810105

Tian, X., Zhang, Y., and Qu, G. (2022). The impact of digital economy on the efficiency of green financial investment in China's provinces. *Int. J. Environ. Res. Public Health* 19 (14), 8884. doi:10.3390/IJERPH19148884

Wang, J., and Zhang, G. (2022). Can environmental regulation improve high-quality economic development in China? The mediating effects of digital economy. *Sustainability* 14 (19), 12143. doi:10.3390/SU141912143

Wang, J., Zhao, J., Dong, K., and Dong, X. (2022). Is financial risk A stumbling block to the development of digital economy? A global case. *Emerg. Mark. Finance Trade* 58, 4261–4270. doi:10.1080/1540496X.2022.2066995

Wang, L., and Zhang, M. (2021). Exploring the impact of narrowing urban-rural income gap on carbon emission reduction and pollution control. *Plos One* 16 (11), e0259390. doi:10.1371/journal.pone.0259390

Wen, S., Shi, H., and Guo, J. (2022). Research on emission reduction effect of green finance from the perspective of general equilibrium theory: Modeling and empirical test. *Chin. J. Manag. Sci.*, 1–14. doi:10.16381/j.cnki.issn1003-207x.2021.2630

Wen, Z., and Ye, B. (2014). Analyses of mediating effects: The development of methods and models. *Adv. Psychol. Sci.* 22 (5), 731–745. doi:10.3724/SP.J.1042.2014.00731

Xia, J., and Liu, C. (2021). Digital economy enabling common prosperity: Function path and policy design. *Res. Econ. Manag.* 42 (9), 3–13. doi:10.13502/j.cnki.issn1000-7636.2021.09.001

Xiang, Y., Lu, Q., and Li, Z. (2022). The development of digital economy enables common prosperity: Effect and mechanism. *Secur. Mark. Her.* (5), 2–13.

Xu, Y., Li, J., Yan, Y., Gao, P., and Xie, H. (2022). Can coordinated development of manufacturing and information communication service industries boost economic resilience? An empirical study based on China's provinces. *Sustainability* 14 (17), 10758. doi:10.3390/SU141710758

Xuan, D., Ma, X., and Shang, Y. (2020). Can China's policy of carbon emission trading promote carbon emission reduction? *J. Clean. Prod.* 270, 122383. doi:10.1016/j.jclepro.2020.122383

Yang, W., Chen, X., Zhou, Y., Tang, X., Sun, Y., Dong, Y., et al. (2022). Digital economy promotes high-quality development: Production efficiency improvement and consumption expansion. *J. Shanghai Univ. Finance Econ.* 24 (1), 1–16. doi:10.1017/cjn.2022.336

Zha, H., and Fang, J. (2022). Research on the measurement of common prosperity level and regional Differentiation in China. *Int. J. Soc. Sci. Educ. Res.* 5 (8), 568–578. doi:10.6918/IJOSSER.202208_5(8).0081

Zhang, J., Dong, X., and Li, J. (2022). Can digital inclusive finance promote common prosperity? An empirical study based on micro household data. *J. Finance Econ.* 48 (07), 4–17. doi:10.16538/j.cnki.jfe.20220316.101

Zhang, X. (2021). *Financial development and common prosperity: A research framework*. Beijing: Economic Perspectives.

Zhao, T., Zhang, Z., and Liang, S. (2020). Digital economy, entrepreneurial activity and high-quality development: Empirical evidence from Chinese cities. *J. Manag. World* 36 (10), 65–76. doi:10.19744/j.cnki.11-1235/f.2020.0154

Zheng, S., Zou, K., and Li, H. (2022). Green development promotes common prosperity: Theoretical interpretation and empirical research. *CASS J. Political Sci.* (2), 52–65+168169.

Zhou, J., Fan, X., Chen, Y. J., and Tang, C. S. (2021). Information provision and farmer welfare in developing economies. *Manuf. Serv. Operations Manag.* 23 (1), 230–245. doi:10.1287/msom.2019.0831

Zhou, M. (2022). The digital economy and the regional economic gap: An inverted U-shaped relationship. *Front. Comput. Intelligent Syst.* 1 (1), 53–61. doi:10.54097/fcis.v1i1.1462

Zhu, Z., Chen, Y., and Wei, T. (2022). The function mechanism and realization path of corporate social responsibility driving common prosperity. *Int. Core J. Eng.* 8 (8), 111–119. doi:10.6919/ICJE.202208_8(8).0015

frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 20 January 2023
DOI 10.3389/fenrg.2022.1080595

Check for updates

OPEN ACCESS

EDITED BY
Wen-Tsao Pan,
Hwa Hsia University of Technology,
Taiwan

REVIEWED BY
Shuo Xing,
Hunan University, China
Wantian Cui,
Liaoning University, China
Lichun Zhou,
Shangqiu Normal University, China

*CORRESPONDENCE
Honglan Jiang,
199014@mtc.edu.cn

SPECIALTY SECTION
This article was submitted to Carbon Capture, Utilization and Storage, a section of the journal Frontiers in Energy Research

RECEIVED 26 October 2022
ACCEPTED 29 November 2022
PUBLISHED 20 January 2023

CITATION
Jiang H (2023), Discussion on key technologies of big data in financial budget performance management in low-carbon economy.
Front. Energy Res. 10:1080595.
doi: 10.3389/fenrg.2022.1080595

Discussion on key technologies of big data in financial budget performance management in low-carbon economy

Honglan Jiang*

School of Economics and Management of Mianyang Teachers' College, Mianyang, Sichuan, China

Reducing energy consumption, pollution and waste emissions are the basic elements of the concept of low-carbon economy. There is an inseparable link between low-carbon economy and financial work in enterprises. In terms of financial work, it is an indispensable element in the development of enterprises. In order to help enterprises improve their financial performance with pertinence, comparability and applicability, this paper selects clear enterprise performance evaluation indicators for analysis from the financial perspective. It aims to help enterprises save energy in a low-carbon economic environment. In this study, the performance evaluation system and financial allocation method of Anhui enterprises' financial expenditure are studied. In the empirical analysis, 10 ordinary enterprise undergraduate colleges in Anhui Province are selected as samples. This model covers the performance evaluation scope of most financial expenditures of general enterprises in Anhui Province, and is analyzed in the process of DEA model analysis. In the process of DEA model analysis, it can better explain the input-output performance of Anhui enterprises. In this paper, financial expenditure performance evaluation indicators designed based on principal component analysis, data envelopment analysis and other analysis methods can focus on reflecting the input and output of enterprises. It can realize the standardization of evaluation results and better compare the efficiency of financial capital expenditure between enterprises. In other words, the concept of low carbon in enterprises has given a certain standard for the development of financial work. The financial department of the enterprise must fully implement the concept of low carbon during the budget period. Only in this way can we effectively promote the development of enterprises towards low-carbon and environmental protection. Finally, it will lay a solid foundation for the sustainable development of the enterprise.

KEYWORDS

fiscal expenditure, performance evaluation, financial allocation method, data envelopment analysis, low-carbon economy

Introduction

In order to improve the development benefits under the low-carbon economy, enterprises should implement the concept of low-carbon economy on the basis of environmental protection and emission reduction, so as to promote the innovative development of financial management. Environmental quality will affect the promotion of local government officials, which is more prominent in low-carbon pilot cities, while political promotion incentives will significantly improve the carbon reduction performance of enterprises (Chen et al., 2022). The basic concept of low-carbon economy At present, one of the most critical development paths in the process of developing our country's socio-economic model is low-carbon economy. Climate change mitigation measures directly affect most sustainable development goals and objectives, mainly through common interests. Improving energy efficiency, reducing the demand for energy services and shifting to renewable energy provide the greatest common economic benefits (Iacobuţă et al., 2021). Through the innovation of the development structure of the supplier, the industry will be promoted to complete the transformation of the integrated mode, and the energy consumption and the emission of pollutants will be reduced. Although climate change has brought huge economic consequences, the current climate response is still dominated by economic logic, which is the reason for taking limited action. In addition, although accounting technology has great potential, it is not widely used in the design of stimulus plans. Clearly integrate accounting techniques into the design, delivery and review of the stimulus package to achieve economic growth and social equity while responding to the crisis (Bui and de Villiers, 2021). The main idea of low carbon economy is to realize the peaceful coexistence of man and nature. This concept brings new high standard requirements for the current form of economic development. During operation, major enterprises should not only focus on the immediate economic benefits, but also ignore energy conservation and environmental protection. For a sustainable future, green certification, e-commerce and environmental education can promote a low-carbon economy by reducing carbon emissions, but there is little research on hotels and other enterprises (Chen, 2019). Especially since 2020, the interference brought by the greenhouse effect has been increasing, and more and more countries attach importance to the development benefits and value of low-carbon economy. Therefore, enterprises in our country should constantly add the concept of low-carbon economy to promote the unified development of social economy and natural ecology.

Low carbon economy has brought changes in consumption concept to enterprise investment. From the perspective of marketing, the profit opportunities of enterprises are all based on consumer demand. Therefore, the change of consumption content affects the direction of enterprise investment. Low carbon economy effectively supports the development of energy-saving and emission reduction SMEs. The Bank gives priority to supporting customers' green credit projects in the fields of new energy, energy conservation, environmental protection and comprehensive utilization of resources. Obviously, the future financial resources will focus on enterprises that actively develop low-carbon economy. The government is brewing and formulating a series of policy tools to promote the development of low carbon economy in China and even the world. These tools include: formulation of emission reduction targets, issuance of emission reduction instructions to enterprises, imposition of carbon taxes, etc. In the process of capital raising by enterprises, the interference brought by low-carbon economy mainly includes two aspects. First, it will improve the difficulty of raising funds for enterprises, and may not be able to prepare sufficient funds for the work when carrying out low-carbon transformation (Semieniuk et al., 2021). This is mainly due to the moderate improvement and supplement of the original credit system by the government under the influence of the development of low-carbon economy. Then the new policy of green credit was formed, which led to the restriction of the financing work in enterprises and had an impact on the initial financing situation of enterprises. Second, the amount of funds that enterprises need to raise on a low-carbon basis is increasing, which to some extent increases the high-risk of debt repayment. In detail, in order to reach the standard of low-carbon economy, some enterprises must improve the intensity of capital investment in the application of low-carbon facilities and technologies (Louche et al., 2019). At this time, the amount of capital that the enterprise needs to prepare will also increase, which indirectly increases the risk of the enterprise in repaying its debts.

The concept of "performance evaluation" in Western countries originated from the civil service system in the United Kingdom, and then it was widely applied to business management with the development of society. Evidence supports more and more practical literature, emphasizing the transformation risk of financial markets. This suggests that policy intervention may be required to address market failures and related potential risk pricing errors (Thomä and Chenet, 2017). In the late 1970s, the concept of "performance evaluation" was introduced into the functional management of government departments in order to improve government management and enhance the efficiency of government management and service level. Since the 1980s, the "New Public Management Movement" has been launched in Western countries such as the United Kingdom, the United States, Australia and New Zealand, whose main content is to adopt theories, methods and techniques of business management (Baranova and Paterson, 2017), introduce market competition mechanisms, and improve the level of public management and the quality of public services by taking the performance of inputs and outputs as the guide. In the field of fiscal expenditure, the establishment of "fiscal expenditure performance evaluation" has played a very important role in the efficiency of the use of government funds, the optimization of the structure of fiscal expenditure and the allocation of resources (Zhu et al., 2019). In China, with the establishment and development of the market economy system, the scale of fiscal revenue and expenditure has been maintaining a stable and rapid growth, but there is a limit to the fiscal revenue, and if the fiscal expenditure is not managed reasonably and effectively, its demand will be unlimited. Therefore, the performance evaluation of fiscal expenditures and the effective improvement of the efficiency of the limited fiscal funds have become the key to improve the current situation of fiscal expenditures (Tong et al., 2019). In recent years, China has been paying attention to the performance evaluation of fiscal expenditures and performance appropriation methods, and has repeatedly and explicitly proposed to establish a performance evaluation system and optimize the budget allocation mode. Report and performance evaluation report, performance evaluation results and their application, etc. The introduction of this measure has provided a useful guarantee to standardize the behavior of financial expenditure performance evaluation, establish a scientific and reasonable performance evaluation management system, and improve the efficiency of financial funds use (Ho, 2018).

The innovative contribution of this paper lies in the design of new financial expenditure performance evaluation indicators, which can focus on reflecting the input and output of enterprises. It can standardize the evaluation results and better compare the efficiency of financial capital expenditure between enterprises. In other words, the low carbon concept of enterprises provides a certain standard for the development of financial work. The results of this empirical study reflect the differences between enterprises in the implementation of education costs, transfer payment and reward and punishment mechanisms. From the perspective of performance allocation, for enterprises with large business scale but still able to meet the basic needs of enterprise project expenditure, the purpose of deducting some funds is to improve the efficiency of fund use, clarify the performance orientation and gradually improve the management level from the perspective of financial expenditure optimization. Reflected on the past financing management mode, innovated and reformed the new financial financing management mode. Ensure the liquidity of funds, improve the anti risk ability of enterprises and promote the sustainable development of enterprises.

The first section introduces the research background and main structure of this paper. It shows that there is an inseparable relationship between low carbon economy and enterprise financial work. The second section introduces the research status of relevant fields at home and abroad, citing the theoretical research of different researchers in performance evaluation indicators. The third section introduces the construction of financial expenditure performance evaluation standard system and financial allocation model through theoretical research. This paper studies the performance of university financial expenditure by using principal component analysis (PCA) and data envelopment analysis (DEA), and explores a new performance allocation model on this basis. This paper puts forward the principles of the enterprise financial expenditure performance evaluation system, and selects the relevant indicators. The fourth section tests and analyzes the scheme proposed in this paper. The fifth section summarizes the research content of this paper and looks forward to the future research direction. The financial department of the enterprise must fully implement the low-carbon concept within the budget period. Only in this way can we effectively promote the development of enterprises towards low-carbon and environmental protection. Finally, it will lay a solid foundation for the sustainable development of enterprises.

Related work

The risk of investment return has been improved, which is the most direct and critical impact of low-carbon economy on major enterprises. Based on the low-carbon economic development model, enterprises need to gradually improve from the initial high carbon to low carbon. To achieve this goal, major enterprises will invest a lot of money in low-carbon facilities and technologies. When the government creates state-owned enterprises (SOEs), one of the main purposes is to reduce their financial burden in the long run, also known as financial sustainability. The relationship between the financial sustainability of state-owned enterprises and government intervention. Lee et al. (2022) has taken a novel approach, using equity to measure government intervention. The results show that only when the government ownership is lower than the threshold, the state-owned enterprises in emerging economies can achieve financial sustainability. No matter where the enterprise invests its capital, it must get a return. All major enterprises are analyzing and exploring whether low carbon can be integrated into enterprise development. Due to unreasonable investment research, insufficient real-time information and data, it is easy for enterprises to blindly invest in developing low-carbon projects. In turn, this has greatly reduced the return on investment of enterprises and hidden greater capital risk for enterprises. Hsu et al. (2021) research shows that green financing reduces short-term loans, thus limiting the over investment in clean energy, while long-term loans have little impact on the over investment in renewable energy, and the intermediate effect is unsustainable. At the same time, the growth of green finance will reduce excessive investment in renewable energy to a certain extent, and improve the productivity of renewable energy investment. In terms of theoretical research, system and appropriation design of performance evaluation indexes, Heinicke pointed out that in the design of performance evaluation system, the administrators of all levels of government and enterprise in the United States should jointly develop performance evaluation reports, so that the design of performance evaluation system of fund expenditures will produce real and reliable results, and the specific assessment indexes should be more inclined to measurable quantitative indexes, too many qualitative indicators will affect the authenticity of the final appraisal. It aims to provide a comprehensive insight into the research of performance measurement system (PMS) for SMEs. Therefore, a systematic literature review of management accounting, small and medium-sized enterprises and general management is conducted to build existing knowledge (Heinicke, 2018). Nazari et al. (2020) determines the university's priorities through importance performance analysis (IPA) to improve performance and policy formulation. Therefore, in order to achieve educational income, the growth of the number of students should be regarded as one of the most important stages in improving university performance in the future. In addition, guidelines for universities and higher education institutions were proposed to identify key factors for implementation and improvement of performance.

Grossi et al. (2019) combines previous accounting, performance measurement (PM) and accountability studies on the emerging field of knowledge intensive public organizations (KIPO). It reviews the academic analysis and insights on changes in accounting, PM and accountability in enterprises, and paves the way for future research in this field. The domestic research on the performance evaluation of financial expenditures and reform of budget management methods in enterprise started late, and it is mainly attributed to the following aspects: First, the research on the performance evaluation index system of enterprise. Levytska et al. (2020) believes that financial performance analysis can find opportunities to improve the financial situation of enterprises. Effectively control the income and expenditure indicators, and make economic and reasonable decisions based on the calculation results. The characteristics of profit generation and accounting profit are different, and these characteristics should be taken into account when analyzing the financial performance of business entities that do not always ensure the accuracy of information. New public management initiatives have prompted municipalities to evaluate SOEs based on multidimensional performance reports. However, little is known about the pre decision information search and weighing process between different performance dimensions when decision-makers evaluate the performance of state-owned enterprises. When Lindermüller et al. (2022) assessed the allocation budget of state-owned enterprises, participants considered multiple performance dimensions and focused on financial and customer performance information. The results show that when municipal financial resources are scarce, participants will devote more energy to the performance evaluation process. Islami et al. (2018) pointed out the importance of target management in enterprise performance budget. And on this basis, the paper discusses the importance of applying MBO as a performance assessment (PA) method in improving employee efficiency. Econometric results show that with the improvement of staff efficiency, MBO method should be used as a performance appraisal method. In addition, the research results show that the evaluation of employees' individual performance and the clear definition of results are the largest parameters in all other activities of the MBO method. Jiang et al. (2018) examined the impact of positive corporate environmental responsibility on the financial performance of Chinese energy industry enterprises through panel data multivariable regression analysis. The results show that positive corporate environmental responsibility has a positive impact on the financial performance of enterprises that pass the endogenous test. The results also show that private ownership has a stronger role in promoting the relationship between positive corporate environmental responsibility and corporate financial performance. This study will help to increase the knowledge of corporate environmental responsibility in emerging economies, and provide insights into corporate environmental responsibility practices and government environmental regulation and policies.

A study of previous literature reveals that the research on the performance evaluation system of financial expenditures is in continuous progress, with a variety of research directions and methods, and many high-quality research results have been applied in the practical work of the performance evaluation system. However, the following problems still exist in the relevant work: first, the performance evaluation indexes lack purpose. Secondly, the status of performance evaluation is too high. Third, the performance evaluation of financial expenditures should be linked with performance appropriation and performance budget.

Design of enterprise financial system and financial allocation under the background of low-carbon economy

The goal of enterprise financial management directly determines the basic direction and purpose of enterprise management. From the historical experience of financial management, we can see that the development of financial management objectives has also gone through several specific stages. So far, the most widely accepted goal is to maximize the value of enterprises. Under the traditional economic conditions, the actual responsibilities undertaken by enterprises are all economic responsibilities, not social responsibilities, which means that investors themselves really need to make rational choices. However, under the condition of low-carbon economy, China has different responsibilities. To be specific, the enterprise bears more than economic responsibility. To a greater extent, it is social responsibility. This means that the disclosure of financial

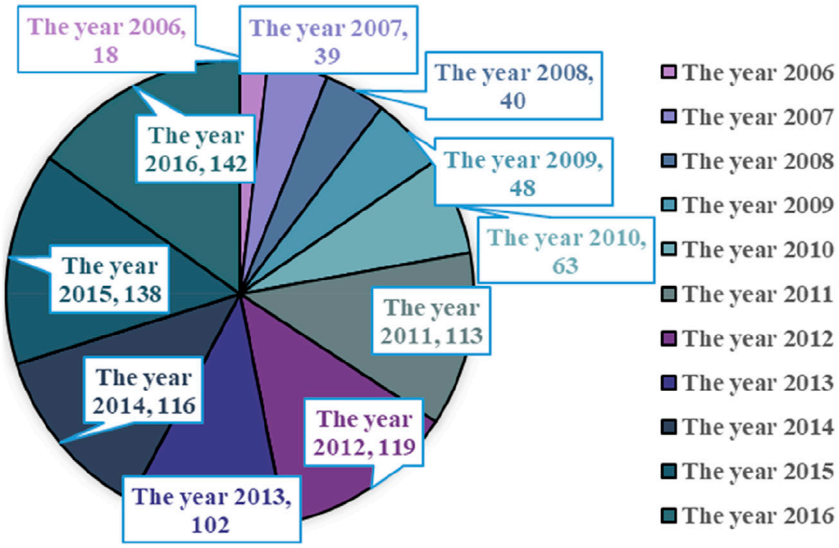


FIGURE 1
Financial education expenditure (billion yuan).

management is no longer limited to financial information, but also includes resource and environmental information.

From the perspective of low-carbon economy, the internal control mechanism of major enterprises plays a key role in the operation and supervision. Therefore, enterprises must attach importance to the efficiency of internal control mechanism to fully improve the high quality and high level of enterprise supervision, and China can also effectively improve the speed and quality of enterprise development. On the contrary, if an effective internal control mechanism is not developed, it will easily lead to various adverse problems, such as unclear distribution of department responsibilities, low work efficiency, and unreasonable internal supervision of enterprises. Under the influence of these problems, the financial management crisis in enterprises will be enhanced under the background of low-carbon economy. Therefore, it can be concluded that from the perspective of low-carbon economy, the efficiency of enterprise internal control mechanism must be improved. In view of various serious problems arising during the operation of the enterprise, we must fully follow the relevant norms of internal control system to better rectify them. And then fully prevent the emergence of strategic mistakes and various undesirable problems. As the scale of enterprise is expanding, the demand for funding is increasing, and the government's financial spending capacity is limited, China's enterprise is facing a shortage of funding, therefore, China has started to explore the diversification of enterprise investment bodies to change the situation of a single source of enterprise funding structure in China. However, due to the real situation, the government financial allocation still accounts for the main source of enterprise funding. In Anhui Province, the basic situation of enterprise funding shows that financial allocation is absolutely dominant, business income is supplementary and other channels are complementary. From the data of 2016, the state financial education funding accounted for 66.34% of the total education funding income of general enterprise in that year, the career income accounted for 30.01% of the total income, and the percentage of other income was only 3.65%.

The amount of government financial investment into enterprise will directly affect the operation efficiency of colleges and universities, thus affecting the quality of talent cultivation and the sustainable development of society, Anhui Province also recognizes the importance of developing enterprise and keeps increasing the volume of financial expenditure on enterprise. During this period, the annual financial expenditure on education has maintained a continuous growth momentum, with the most significant growth rate in 2016. The relative scale of enterprise expenditure in Anhui province can be seen from the proportion of enterprise expenditure to GDP as shown in Figure 1.

From the above data, it can be seen that the demand for enterprise funds in Anhui Province is increasing as the popularization and massization of enterprise continues to deepen, but the contradiction between the demand and supply of enterprise funds in enterprise is very acute due to the limited support of government financial expenditures to enterprise. Therefore, to change this situation, it is necessary to improve the efficiency of the use of enterprise financial funds, reduce the waste of educational resources, and optimize the allocation of resources, thus it is urgent to improve the financial expenditure of enterprise to implement the reform of performance evaluation system and implement the performance-oriented financial allocation.

DEA was proposed by three American statisticians and operational research researchers. It mainly solves the specific technical efficiency problems of input and output through the non-parametric technical efficiency method. Technical efficiency mainly solves the problem of calculating the technical efficiency in actual production by measuring the output index when the input is known. On the micro level, the DEA model mainly analyzes the ratio of each output to each input of the decision-making unit (DMU). The input and output indicators multiplied by a certain weight can reflect the comprehensive technical efficiency and scale technical efficiency.

CCR model is the first input-output model in the development history of DEA. It is a DEA model that calculates the technical efficiency of the decision-making unit of the target unit through objective data analysis under the condition that the return on scale remains unchanged. It can evaluate the technical efficiency of any decision-making unit with input and output. The technical efficiency of any decision-making unit with input and output can be evaluated. In a large number of experiments, the most prominent applications are military, medical and educational undertakings.

Suppose, according to the CCR output-oriented model, the number of decision-making units (DUMs) to be calculated is n, each $DMU_z\,(z = 1, 2, \ldots, n)$ has different inputs x_i (i = 1, 2, . . . , m), and its input weights are represented by w_i (i = 1, 2, . . . , m) and the weight coefficients ≥, and each DMU has different outputs y_j (j = 1, 2, . . . , s), and its output weights are represented by t_j (j = 1, 2, . . . , s) and the weight coefficients ≥, in the model, the number of DUMs to be calculated for a given The technical efficiency of all DMUs must not exceed 1. The currently calculated DMU is denoted as DMU_k. The specific formula is as follows:

$$\mathrm{DMU}_k = \begin{cases} \max \dfrac{\sum_{j=1}^{m} t_j y_{jk}}{\sum_{i=1}^{m} w_i x_{ik}} \\ \text{s.t. } \dfrac{\sum_{j=1}^{s} t_j y_{jz}}{\sum_{i=1}^{m} w_i x_{iz}} \le 1 \\ w \ge 0, t \ge 0 \\ i = 1, 2, \ldots, u;\ j = 1, 2, \ldots v;\ z = 1, 2, \ldots n \end{cases} \tag{1}$$

Since $\sum_{i=1}^{m} w_k x_{iz} \ge 0$, the above model can be equivalently transformed to a linear programming model, such that

$$T = \frac{1}{\sum_{i=1}^{m} w_i x_{ik}}, u = Tt, v = Tw \tag{2}$$

Then the new equivalence planning model is:

$$P = \begin{cases} \max \sum_{j=1}^{s} u_j y_{jk} \\ \text{s.t. } \sum_{j=1}^{s} u_j y_{jz} - \sum_{i=1}^{v} v_i x_{iz} \le 1 \\ \sum_{i=1}^{m} v_i x_{ik} = 1 \\ v \ge 0; u \ge 0 \\ i = 1, 2, \ldots, u;\ j = 1, 2, \ldots v;\ z = 1, 2, \ldots n \end{cases} \tag{3}$$

The integrated combination coefficient of the linearity of the pairwise model DMU is expressed as φ, and the solution value of the model α^r, which is the optimal solution, ranges between $(0, 1]$, and the relevant conclusions can be drawn according to the optimal solution of the pairwise model.

When $\alpha^r \le 1$, it means that the current evaluated DMU is technically inefficient, and the value of the marginal maximum limit of input reduction is $(1 - \alpha^r)$, which means that in the current technically efficient situation, the inputs can be decreased in a linear and equal proportion without reducing the output.

When $\alpha^r = 1$, it means that the evaluated decision unit DMU is in the best technically efficient state, and the indicators of each input are in the optimal state without reducing the output, and there is no need to reduce the input.

The output-oriented CCR model is the minimum efficiency model calculated by the output-oriented model, and the optimal solution of the output model is defined as β, and the model is mainly as follows:

$$P2 = \begin{cases} \max \sum_{i=1}^{m} v_i x_{ik} \\ \text{s.t. } \sum_{j=1}^{s} u_j y_{jz} - \sum_{i=1}^{v} v_i x_{iz} \le 1 \\ \sum_{j=1}^{s} u_i y_{iz} = 1 \\ v \ge 0; u \ge 0 \\ i = 1, 2, \ldots, u;\ j = 1, 2, \ldots v;\ z = 1, 2, \ldots n \end{cases} \tag{4}$$

In the CCR input and output model, the calculation of the combined efficiency of inputs and outputs becomes possible, and the redundancy analysis of input or output indexes can be performed according to the DEA model, which provides the direction to suggest the optimization of each input or output.

Suppose, according to the CCR output-oriented model to calculate the target decision unit, the number of decision units (DUM) is n, $DMU_z\,(z = 1, 2, \ldots, n)$ each DMU will have a variety of inputs x_i (i = 1, 2, . . . , m), its input weights are represented by w_i (i = 1, 2, . . . , m) and weight coefficients ≥ 0, at the same time, each DMU will have a variety of outputs y_j (j = 1, 2, . . . , s), its output weights are represented by t_j (j = 1, 2, . . . , s) and weight coefficients ≥ 0, in the model to be given DMU all technical efficiency must not exceed 1, the current calculation of DMU is denoted as DMU. The specific BCC model is as follows:

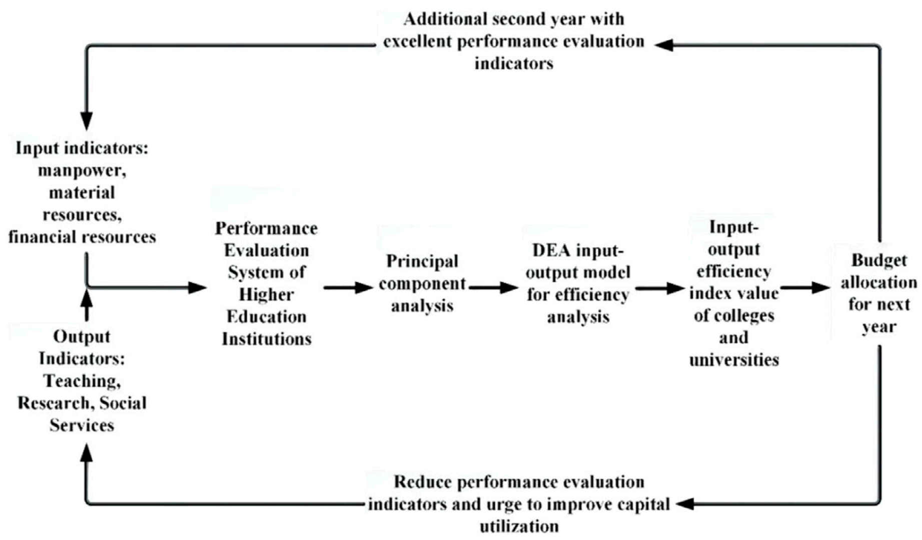


FIGURE 2
Flow chart of financial expenditure evaluation system of enterprise.

Input model BCC model:

$$D = \begin{cases} \min \alpha \\ \text{s.t.} \sum_{z=1}^{n} \varphi_z x_{iz} \leq \alpha x_{ik} \\ \sum_{z=1}^{n} \varphi_z y_{jz} \geq y_{jk} \\ \sum_{z=1}^{n} \varphi_z = 1 \\ \varphi \geq 0 \\ i = 1, 2, \ldots, m;\ j = 1, 2, \ldots s;\ z = 1, 2, \ldots n \end{cases} \tag{5}$$

As a model with variable returns to scale BCC, the new effective DMU generated production frontier curve will replace the production frontier with constant returns to scale, so that the projection points from other DEA analysis cannot be projected onto the production frontier with constant returns to scale, thus the new set of DMUs under the premise of variable returns to scale, excluding a portion of DMUs that need to improve returns to scale reflecting pure technical efficiency. At the same time, the constraints, as shown in Eq. 6, provide the possibility to calculate the scale efficiency.

$$\sum_{m=1}^{v} \varphi_m = 1\,(\varphi \geq 0) \tag{6}$$

The input of enterprise can be considered from "human, financial and material," and the output can be considered from "teaching, scientific research and social service," because the input and output of enterprise have a certain periodicity, especially scientific research, from the establishment of projects, funds to the output of scientific research. The results of financial performance evaluation are very unstable, and the specific indicators should be selected in 3 years or more to analyze the effectiveness of the use of funds in enterprise on a rolling basis. The specific process of performance evaluation work and performance appropriation work can be shown in Figure 2.

The input of enterprise in Anhui Province is diversified and complex, and the evaluation system of financial expenditure of enterprise is based on the principles of index design and the inherent requirements of performance appropriation, the design of input indexes should conform to the principles of clarity, comparability, importance and economic availability, and the efficiency can be calculated in detail to provide a basis for the next year's appropriation. In the "input-output" model, input indicators are generally set with X as the variable. The relevant indicators are shown in Figure 3.

From the viewpoint of economic units, the economic activities of enterprise are complex, and there are multiple inputs and multiple outputs, such as input and output for comparison, and there is ambiguity in their input weights and output weights. In the performance evaluation system of enterprise, there are analysis methods such as Deffel method and hierarchical analysis method. The analysis is carried out by the experience and subjective judgment of relevant experts, and the judgment results are often subjective. To address this problem, the use of objective analysis methods in the field of statistics can often solve this problem, so that the final evaluation results can be standardized and the inputs and outputs of enterprise can be treated objectively.

Financial performance indicators provide investors with data information for investment decisions. However, there are many indicators reflecting financial performance, so it is necessary to

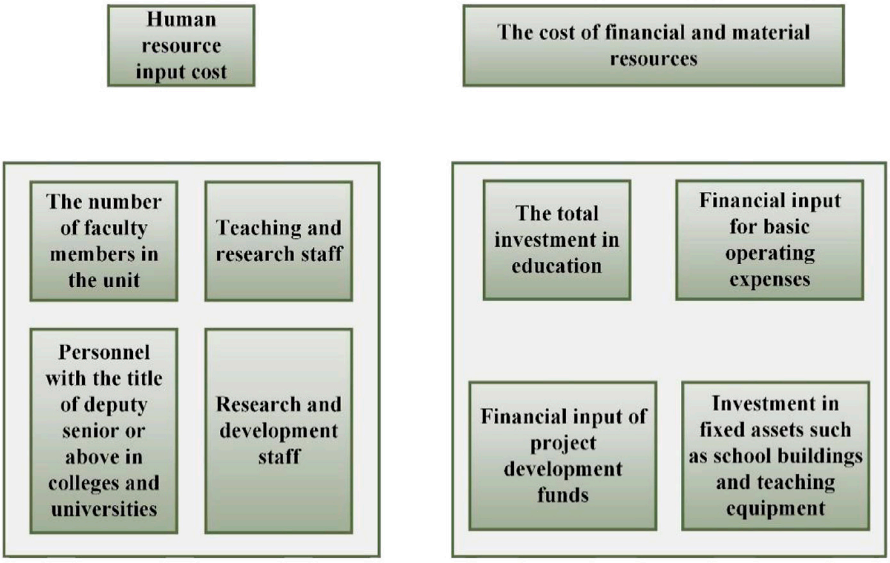


FIGURE 3
The investment system of financial expenditure performance evaluation of colleges and universities in Anhui Province.

find a few indicators that can reflect many indicators. Using the principal component analysis method, the empirical analysis of the financial performance indicators of listed companies from the aspects of profitability, operating capacity, solvency and development capacity has certain advantages. Principal component analysis is used to reduce the dimensionality of input indicators and output indicators established in the financial fund performance evaluation index system of enterprise. The purpose of data dimensionality reduction is to find out the indicators with higher substitution to explain the other indicators based on the understanding of the correlation of indicator data. The substitution indicators can be used to obtain the comprehensive evaluation score of principal components with the standardized data and variance contribution rate, and replace more original variables with a small number of variables. The main steps of the principal component analysis method are as follows.

(1) It is assumed that there are $a\,(\mathrm{i} = 1, 2, \ldots, a)$ samples of input category in this financial evaluation system of Anhui enterprise, and there are $b\,(j = 1, 2, \ldots, b)$ indicators of evaluation category, and the mathematical matrix of $c = (c_{ij})_{ab}$ is set.

$$C = \begin{pmatrix} c_{11}, c_{12} & \ldots & c_{1b} \\ \vdots & \ddots & \vdots \\ c_{a1}, c_{a2} & \cdots & c_{ab} \end{pmatrix} \tag{7}$$

(2) Since the unit of measurement of each index is different from the extraction standard, it is not possible to compare them, so the mean of the calculated sample should be standardized by Z. The main method of standardization is to transform the ratio between the mean and the variance to obtain the standardized matrix, where S_j is the mean of the sample index and $\bar{c}_j$ is the standard deviation of the sample, and the main formula is as follows:

$$Z_{\mathrm{ij}} = \frac{\left(c_{ij} - \bar{c}_j\right)}{S_j} \tag{8}$$

(3) Based on the correlation coefficients of the indicators j, the correlation coefficients of the correlation coefficient matrix of the indicators were calculated as:

$$R = \begin{pmatrix} r_{11}, r_{12} & \ldots & r_{1b} \\ \vdots & \ddots & \vdots \\ r_{a1}, r_{a2} & \cdots & r_{ab} \end{pmatrix} \tag{9}$$

$$r_{kj} = \frac{\sum_{k=1}^{a} (x_{ki} - \bar{x}_i)\left(x_{ki} - \bar{x}_j\right)}{\sqrt{\sum_{k=1}^{a} (x_{ki} - \bar{x}_i)^2 \times \sum_{k=1}^{a} \left(x_{kj} - \bar{x}_j\right)^2}} \tag{10}$$

(4) Based on the equation $|\lambda_{jb} - R| = 0$, the eigenroots of the matrix R are solved λ_b, the eigenvectors $P\,(i = 1, 2, \ldots, b)$ are calculated and ranked according to the magnitude of each eigenvalue, whose ranking size reflects the role played by the magnitude of the other variables explained.
(5) The main idea of principal component analysis is to reflect the original large number of original variables with fewer variables, therefore, it is necessary to calculate the cumulative

contribution of the variance of a few variables, let the variance calculated contribution is G, the contribution of the variance of the principal component should be greater than 80%, the cumulative contribution of the variance is calculated by the formula

$$G = \frac{\sum_{j=1}^{k} \lambda_j}{\sum_{j=1}^{b} \lambda_j} \geq 80\% \tag{11}$$

(6) Based on the eigenvectors and eigenvalues, the loadings of each principal component can be calculated, which reflect the correlation between the principal components and the original variables and are calculated as follows:

$$L_{ij} = \sqrt{\lambda_i} P_{ij} \left(i = 1, 2, \ldots a; j = 1, 2, \ldots b\right) \tag{12}$$

(7) The principal component scores can be converted based on the eigenvectors and the standardized indicator variables.

$$F_i = P_{11} Z_1 + P_{12} Z_2 + \ldots + P_{ab} Z_b \left(i = 1, 2, \ldots a; j = 1, 2, \ldots b\right) \tag{13}$$

(8) Based on the final scores of the principal components, the overall score H of the principal component analysis can be converted according to the weighted average of their contributions.

$$H = \frac{\sum_{i=1}^{b} G_i F_i}{\sum_{i=1}^{b} G_i} \tag{14}$$

After the indicator classification and dimensionality reduction analysis of PCA, the values of the original higher school performance evaluation indicators can be reduced from the initial 15 indicators to 4 indicators, which has a greater advantage for the substitution of input and output models, so that the input model of the BCC model with actual data substituted into the input-output has a better explanation for the input and output of specific indicators.

Input BCC model

$$BCC = \begin{cases} \max \sum_{j=1}^{s} u_j y_{jk} + u_0 \\ s.t. \sum_{j=1}^{s} u_j y_{jz} - \sum_{i=1}^{m} v_i x_{iz} - u_0 \leq 1 \\ \sum_{i=1}^{m} v_i x_{ik} = 1 \\ v \geq 0; u \geq 0; u_0 \text{ free} \\ i = 1, 2, \ldots, m; j = 1, 2, \ldots s; z = 1, 2, \ldots n \end{cases} \tag{15}$$

In the performance evaluation system of financial expenditures of enterprise, the technically effective analysis and several chirping analysis of DEA are used to find out the problems of comprehensive evaluation and technical efficiency. According to the performance evaluation report, the final evaluation results can be applied to the final financial allocation.

Let the sample of participating enterprise be $n(j = 1, 2, \ldots, n)$, the total financial project expenditure allocation for the current year be C, the input-output factor of $A_{ij} (i = 1, 2, \ldots m; j = 1, 2 \ldots n)$ in the principal component analysis of schools, the overall technical efficiency and pure technical efficiency in the performance assessment be X and Y respectively, and the financial budget project expenditure allocation for the next year be F, which can be converted by the following formula.

$$F = C \times \frac{\sum_{i=1}^{m} A_i}{\sum_{j=1}^{n} A_{ij}} \times \frac{X + Y}{2} \tag{16}$$

The above formula can only convert the actual allocation of enterprise for the current year, but cannot reward enterprise with good performance evaluation. After converting the actual project expenditure allocation of each enterprise institution in the above formula, the sum of X and Y must be less than 2. The conversion formula is based on the financial allocation factor, and the incentive performance funding is G. The formula is as follows:

$$G = f \times \frac{\sum_{i=1}^{m} A_i}{\sum_{j=1}^{n} A_{ij}} \tag{17}$$

Effective performance appraisal will play a good role in promoting enterprise performance. It will effectively improve the positive performance of each employee, enable the strong to win higher status and interests, enable the weak to have pressure and upward momentum, and ultimately promote the realization of enterprise goals. For enterprises, the growth of talents is an indispensable part of enterprises. The ultimate goal of the performance test is to promote the common growth of enterprises and employees. Through the continuous discovery and improvement of problems in the assessment process, we can promote the improvement to achieve a win-win situation for individuals and enterprises.

Analysis of simulation results

In view of the new environmental situation of low-carbon economy, this paper proposes the following financial management measures for enterprises through full understanding and experience of its characteristics and opportunities. In order to play a due role in the actual application process. During the operation period, enterprises must give higher support to low-carbon projects. For those safe and reliable low-carbon projects, more efforts can be made in the investment of funds to promote the full operation of the project. In addition, we should also build a reasonable regulatory mechanism according to the actual situation, so that the operation of low-carbon projects has corresponding pillars. Second, when carrying out low-carbon projects, people first must be taken as the basic concept, so human resources can be put in the first place in the allocation work. The authority and effectiveness of each link must be well demonstrated. Under the influence of the current low-carbon economy, the benefits brought by human resources to enterprises are continuously improving. Therefore, the human resources work must be well handled to ensure that the allocation of benefits can meet the actual requirements.

Through theoretical thinking on the performance evaluation system, performance allocation and performance budget management, this research constructs the financial expenditure performance evaluation system of Anhui Province's colleges and universities. Collect quantifiable actual input and output indicators of colleges and universities, and convert the data into the input-output model to calculate the actual performance score through the dimension reduction idea of principal component analysis. On this basis, we will explore the fund allocation mode of Anhui Province's higher education projects. Through the empirical research of colleges and universities in Anhui Province, the correctness and operability of the ideas are tested, so as to provide a way of thinking for the connection between performance appraisal and budget allocation. In this study, as a research on the financial expenditure performance evaluation system and financial allocation method of enterprise in Anhui Province, 10 general enterprise undergraduate institutions in Anhui Province were selected as samples in the empirical analysis, accounting for 84.61% of the total number of general undergraduate enterprise in Anhui Province, which covers the performance evaluation scope of most of the financial expenditures of general enterprise in Anhui Province, and in the process of DEA model analysis. In the process of DEA model analysis, it can best explain the performance of input-output of Anhui enterprise.

In order to maintain the homogeneity of DMU in the reference set, this paper classifies DMU before DEA evaluation. The existing researches either only give abstract solutions or only solve some problems. In order to get a more comprehensive solution, a qualitative and quantitative classification method for DMU is proposed according to the evaluation purpose. The applicability of qualitative and quantitative classification methods is also given. The selection of the sample in this study was based on the following considerations.

Selection of DMU samples

In this study, the principle of comparability was considered in the design of the performance evaluation system, and for the sample selection of DMU, the "inputs" and "outputs" of the analyzed indicators are highly comparable. The consistency of performance evaluation indexes of enterprise can be a basic guarantee from the perspective of performance evaluation and improving the efficiency of financial resources. In this study, the 10 enterprise in Anhui Province are all undergraduate colleges and universities, and some of them have been deleted, as follows: First, the average *per capita* allocation of undergraduate colleges and universities in Anhui Province from 2013 to 2015 has reached RMB 12,000, while the average *per capita* allocation of enterprise is only RMB 0.8 million. The "input" is not in the same standard. Secondly, four medical schools and art colleges in Anhui Province were deleted from the sample. Anhui Medical University, Anhui University of Traditional Chinese Medicine, Wannan Medical College and Bengbu Medical College not only include the *per capita* allocation of enterprise, but also include the presence of hospitals and other institutions in the form of per bed allocation, which is completely different in terms of allocation and volume. In terms of output, the social service functions of medical schools include not only the output of enterprise in terms of teaching, research and conversion of research results, but also the related contribution to the provision of medical services and the improvement of local medical standards. The output of art institutions includes compositions and works, which are also deleted because of the inconsistent assessment index system. The financial expenditure performance evaluation index of colleges and universities should have a clear direction. In ¨ Input production ˆ This model considers the use efficiency of financial expenditure funds of colleges and universities. To put it simply, it is how to get a higher output when the current year's input is fixed, and how to evaluate the performance. The results of performance evaluation will be used as the basis for performance fund allocation in the next year. Units with good evaluation results will receive more financial support. Units with poor evaluation results will continue to provide financial support in the previous year. Improve the quantity and quality of various indicators in the output, and improve the overall score of performance evaluation.

The selection of DMU sample data year

Teaching output, scientific research output and social services of enterprise are cyclical, especially in scientific research, a subject often has a long annual cycle from the establishment to the end of the project, and there are not many scientific research projects that obtain scientific research papers and technical results by making human and financial investment in the same year, and the use of input and output data of a certain year to assess enterprise lacks fairness. 2014, the Ministry of Finance in the institutions The reform of the budgeting system of institutions proposed to prepare budgets in the form of three-year rolling budget for provincial and municipal institutions, which strengthened the medium and

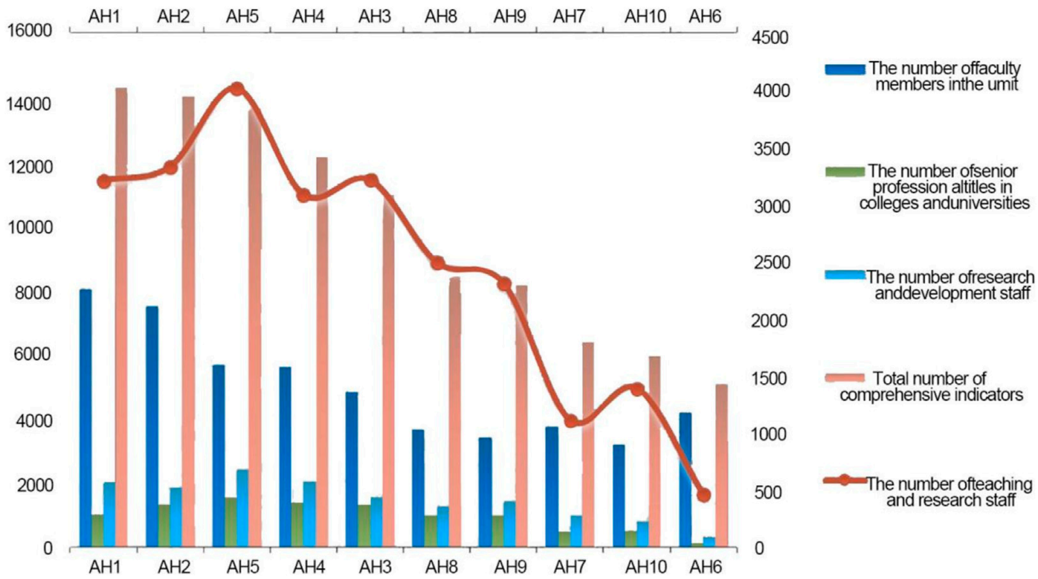


FIGURE 4
Human resource input cost indicators for financial expenditure performance evaluation.

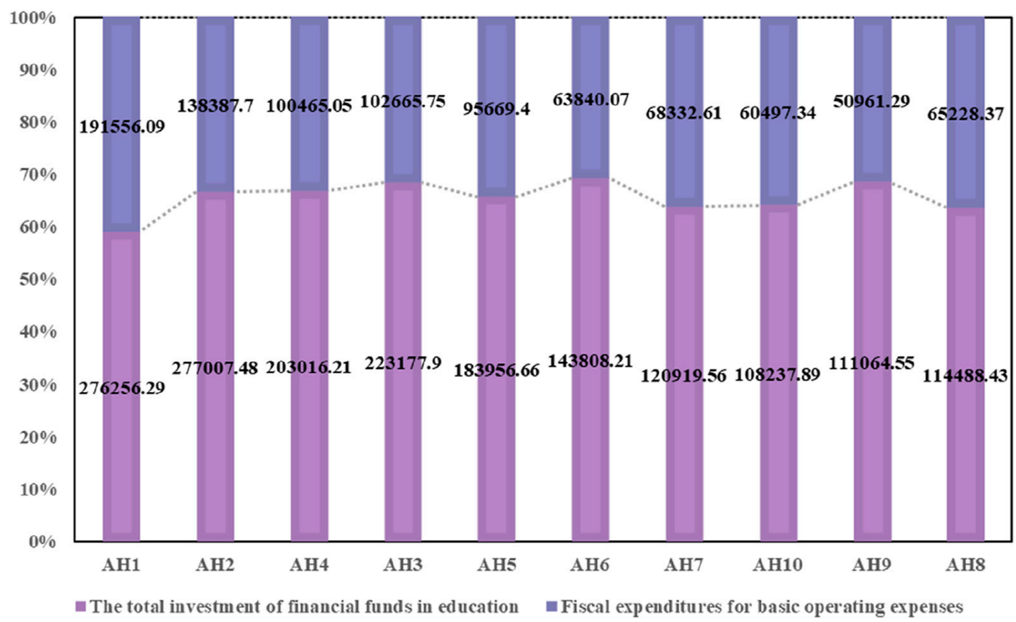


FIGURE 5
Financial and material resources input cost indicators for financial expenditure performance evaluation.

long-term role of budget control, while some national and provincial projects were also established in the context of three-year rolling budgeting in terms of annual allocation and annual output. Under the specification of performance assessment and evaluation system of enterprise, 3 years of data from 10 provincial undergraduate institutions in Anhui Province were selected for analysis, and the data index data were taken as the sum of 3 years to reflect the actual performance of the use of

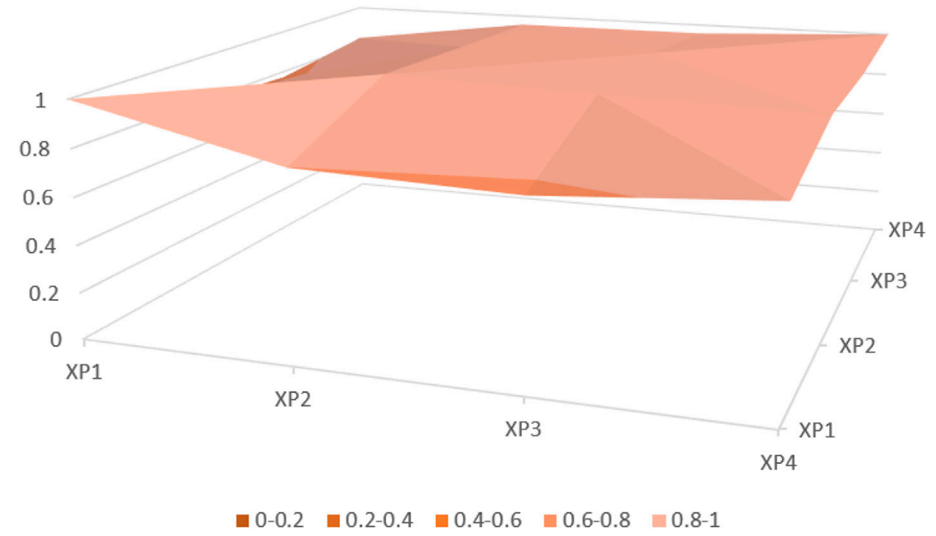


FIGURE 6
Matrix after dimension reduction.

funds in enterprise. In the process of data collection, due to the recent years, only some of the "input" data are available for 2016–2017 in 10 Anhui undergraduate institutions, and most of the "output" data are being counted by national departments and institutions of enterprise. In this study, some data of 2016–2017 were used for reference.

From the data of the 10 undergraduate institutions selected in Figure 4, the combined indexes of the number of faculty members in AH1, AH2, AH3, AH4 and AH5 are all above 10,000 in Anhui enterprise, and the number of faculty members and research and development personnel is also relatively high, and the scale of faculty members is in the first echelon of universities in Anhui province.

From the data of 10 undergraduate institutions selected in Figure 5, the total combined indexes of AH1 and AH2 financial and material resources input costs among Anhui enterprise are above 10 billion RMB, and the total combined indexes of financial and material resources input costs are in the first echelon of Anhui enterprise.

The currently evaluated DMU is the case of low technical efficiency, which is represented by the marginal maximum limit value of input reduction. That is, under the current technical efficiency, without reducing the output, the input can be reduced in a linear and equal proportion. When the evaluated DMU is in the best technical effective state, the indicators of each input are in the best state without reducing the output, so there is no need to reduce the input. According to the research of this actual data, a total of 15 indicators were selected to reflect the financial performance evaluation of enterprise well. In the process of actual DEA model analysis, since the number of DMUs in this study has been determined as 22, if the number is less than the overall converted indicators, it is very easy to have the result that all DMUs are valid, which makes the final performance appraisal model distorted. Therefore, the selected indicators must be processed for dimensionality reduction. In this empirical study, PCA is used, and SPSSV22 software is applied to reduce the correlation between the data, and the most representative indicators are selected for analysis, among which: 4 indicators of human cost input, 5 indicators of financial capital input, 3 indicators of teaching category output and 3 indicators of research category output.

From the Figure 6, the number of unit faculty members (XP1), the number of teaching and research staff (XP2), the number of senior titles in the institution (XP3), and the number of research and development staff (XP4) have relatively close correlation coefficients, and are suitable for the principal component analysis method.

Using the data standardization method and principal component analysis method in SPSS, the "total variance of interpretation" and "component matrix" are obtained. It can be seen from the test results that, at the level of significance α If it is 0.05, the sample p-value is 0, obviously less than 0.05, so the sample data is suitable for principal component analysis. From Figure 7, it is observed that the cumulative percentage of variance of the first three components has reached at least 91.308%, and the general standard is more than 85%, so it is appropriate to extract the first three principal components here. The cumulative index of eigenvalue is greater than 1, and the contribution of variance should be greater than 80%. The extracted sum of squares is loaded with 3.652 indicators. This better reflects the overall variable information, and the other four repeated partial variables can be replaced.

In this paper, the input-output factors of 10 undergraduate institutions in Anhui standardized after data dimensionality

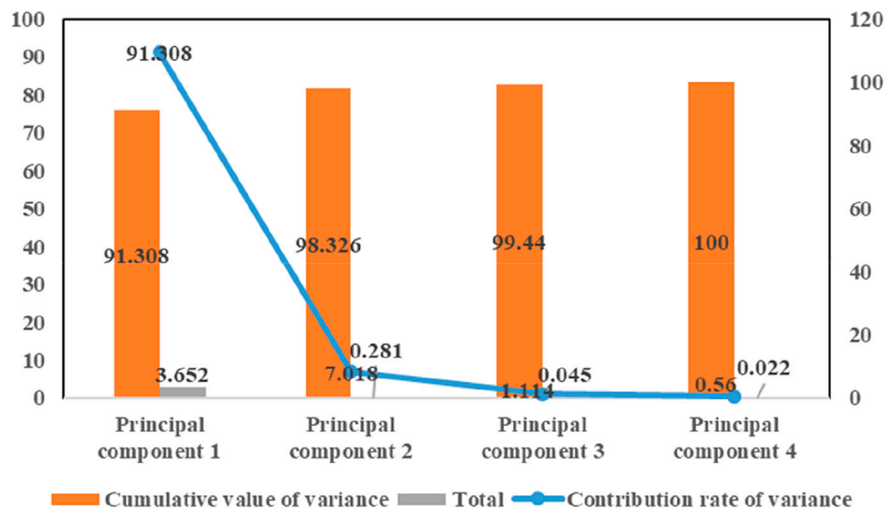


FIGURE 7
Total variance of the principal components.

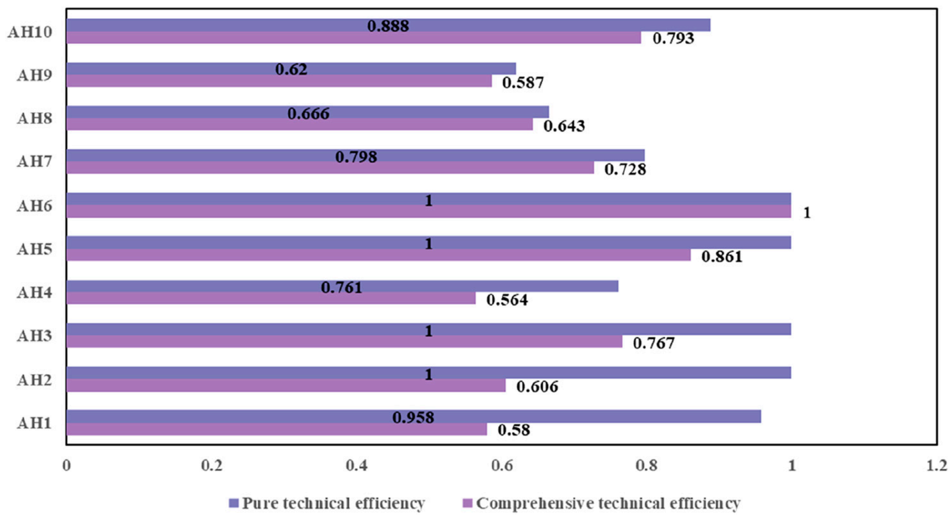


FIGURE 8
Input-output scores of enterprise in Anhui Province.

reduction are substituted into DEA input-output model using MAXDEAbasic software, where: DMU = 22, input indicators are X1 and X2, output indicators are Y1 and Y2, and the analysis results of input-oriented BCC model are selected as shown in Figure 8.

Based on the component factors and performance evaluation indicators, the projected appropriation of $2.1 billion for the 2016 budgeted financial allocation for project expenditures, the actual appropriation for each university can be calculated, taking AH1 as an example, and setting the actual appropriation for AH1 in 2016 as C. The appropriation for AH1 in 2016 is as follows

$$C = 21 \times \frac{3.562}{33.423} \times \frac{0.580 + 0.958}{2} = 1.448 \tag{18}$$

According to the financial allocation factor and performance, the allocation of Anhui provincial institutions is shown in Figure 9.

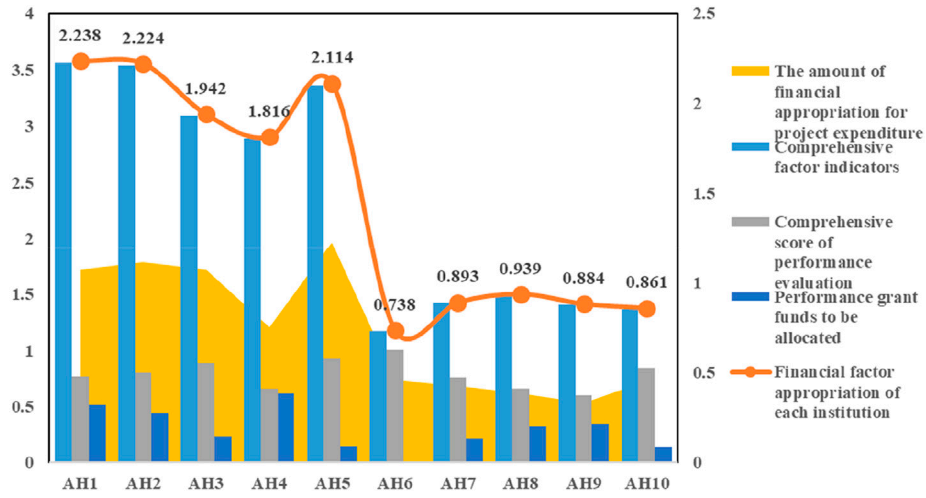


FIGURE 9
Performance Appropriation funds for provincial institutions of higher learning in Anhui province.

In summary, the results of this empirical study reflect the differences in the cost of schooling among enterprise, the realization of transfer payments, and the implementation of reward and punishment mechanisms. Anhui provincial enterprise have great differences in the combined volume of teachers' resources, financial capital investment, teaching and research output, and reflecting the indicators by comprehensive factor indicators can well solve the inconsistency of data. From the perspective of performance appropriation, deducting part of the funds for enterprise with larger scale of operation but still meeting the basic needs of project expenditures of enterprise is to promote them to improve the efficiency of fund use, clarify the performance orientation and gradually improve the management level from the perspective of financial expenditure optimization. At the same time, from the perspective of rewarding performance appropriation, enterprise with excellent performance can get rewarding funds, and institutions with large comprehensive volume get more performance appropriation, more investment and wider range of financial expenditure, which can promote further development of enterprise with excellent performance appropriation.

Extensive financial management mode has caused resource waste and environmental pollution. In order to change this situation, enterprises must establish the concept of low-carbon economic development and build a new model of financial management. However, the overall implementation is very difficult, so enterprises must eliminate some outdated technologies and outdated equipment. Formulate a scientific and modern financial management system for low-carbon economy to enable enterprises to effectively adapt to the development requirements of low-carbon economy and achieve high-quality and comprehensive development. In recent years, China has attached great importance to environmental protection and has been promoting the low carbon economy development model. However, the actual effect has not reached the expected goal, one of which is financing management. To implement the low-carbon economic model, enterprises need to seriously study this issue. At the same time, reflect on the past financing management model, and innovate and reform the new financial financing management model. To ensure the liquidity of funds and improve the anti risk ability of enterprises, so as to promote the continuous development of enterprises.

In view of the new environmental situation of low carbon economy, this paper fully understands its characteristics and opportunities. The following financial management measures are proposed to play a due role in the actual application process. (1) People first is the most fundamental condition for any work. The same is true in financial management. Therefore, under the general situation of low-carbon economy, the primary task is to improve the professional quality and professional quality of relevant managers, and gradually form a good green corporate culture in the enterprise. (2) Innovate the content of financial management. It mainly means that the green financing plan should be formulated accordingly when financing. The formulation and implementation of this plan is to pave the way for the funds needed to protect the environment in the follow-up work. To avoid greater risks to itself due to insufficient or idle funds. (3) Establish green management system. The enterprise shall establish a set of green management system, and the provisions of this system shall be stipulated according to the relevant regulations in the national financial management system and the industrial financial management system. And specifically formulate the governance and protection measures that the enterprise needs to take against the ecological environment problems.

Summary and outlook

Under the background of low carbon economy, enterprises can achieve better and long-term development only by quickly adapting to the current policy environment. The performance evaluation of financial expenditures of enterprise and the change of performance appropriation method are the most concerned issues for financial departments, education authorities and decision makers of enterprise. From the grand strategy of national economic system reform, the appropriation of financial funds will gradually change from increasing the input of total amount of funds to increasing the evaluation of the effectiveness of using funds. From the actual situation of financial expenditure performance evaluation in Anhui enterprise, the performance evaluation of financial funds is still in the initial stage, and there is no mature theoretical system and outstanding excellent working effect.

This study constructs the financial expenditure performance evaluation system of enterprise in Anhui Province through theoretical consideration of performance evaluation system, performance appropriation and performance budget management. The actual input and output indicators that can be quantified by each enterprise institution are collected, and the actual performance scores are converted by substituting the data into the input-output model through the dimensionality reduction idea of principal component analysis, and this is used as a basis to explore the project expenditure fund allocation model of enterprise in Anhui Province. Through the empirical study of 10 institutions of enterprise in Anhui Province, we test the correctness and operability of the idea, and provide an idea to link performance evaluation and budget allocation. At present, the reform of financial management under the low-carbon economy is still a relatively new theoretical concept. That is to say, its progress and development are still at a basic stage, lacking not only the necessary theoretical support, but also the support of practical experience. However, This paper takes the total number of enterprise teachers in Anhui Province as an example. This is not a good representative of all low-carbon enterprises, so it has certain limitations. It is also necessary to expand the data surface for analysis. After all, financial management under the low-carbon economy is a scientific and sustainable concept, which aims to improve the living environment, that is, to lay the foundation for the harmonious coexistence of human and nature, which is an inevitable choice after our economic development to a certain extent. In the future, we have every reason to believe that with the continuous development and exploration of science and technology and the continuous progress of the times, the financial management under the low-carbon economy will be further developed and optimized. This will greatly help enterprises to improve their green competitiveness, and will make great contributions to their own scientific and sustainable development.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

HLJ wrote the manuscript and approved its submission to Frontiers in Psychology.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Baranova, P., and Paterson, F. (2017). Environmental capabilities of small and medium sized enterprises: Towards transition to a low carbon economy in the East Midlands. *Local Econ.* 32 (8), 835–853. doi:10.1177/0269094217744494

Bui, B., and de Villiers, C. (2021). Recovery from covid-19 towards a low-carbon economy: A role for accounting technologies in designing, implementing and assessing stimulus packages. *Account. Finance* 61 (3), 4789–4831. doi:10.1111/acfi.12746

Chen, L. F. (2019). Green certification, e-commerce, and low-carbon economy for international tourist hotels. *Environ. Sci. Pollut. Res.* 26 (18), 17965–17973. doi:10.1007/s11356-018-2161-5

Chen, S., Mao, H., and Sun, J. (2022). Low-carbon city construction and corporate carbon reduction performance: Evidence from a quasi-natural experiment in China. *J. Bus. Ethics* 180 (1), 125–143. doi:10.1007/s10551-021-04886-1

Grossi, G., Kallio, K. M., Sargiacomo, M., and Skoog, M. (2019). Accounting, performance management systems and accountability changes in knowledge-intensive public organizations: A literature review and research agenda. *Account. Auditing Account. J.* 33 (1), 256–280. doi:10.1108/aaaj-02-2019-3869

Heinicke, A. (2018). Performance measurement systems in small and medium-sized enterprises and family firms: A systematic literature review. *J. Manag. Control* 28 (4), 457–502. doi:10.1007/s00187-017-0254-9

Ho, A. T. K. (2018). From performance budgeting to performance budget management: Theory and practice. *Public Adm. Rev.* 78 (5), 748–758. doi:10.1111/puar.12915

Hsu, C. C., Quang-Thanh, N., Chien, F. S., Li, L., and Mohsin, M. (2021). Evaluating green innovation and performance of financial development: Mediating concerns of environmental regulation. *Environ. Sci. Pollut. Res.* 28 (40), 57386–57397. doi:10.1007/s11356-021-14499-w

Iacobuţă, G. I., Höhne, N., Van, S. H. L., and Leemans, R. (2021). Transitioning to low-carbon economies under the 2030 agenda: Minimizing trade-offs and enhancing co-benefits of climate-change action for the sdgs. *Sustainability* 13 (19), 10774. doi:10.3390/su131910774

Islami, X., Mulolli, E., and Mustafa, N. (2018). Using Management by Objectives as a performance appraisal tool for employee satisfaction. *Future Bus. J.* 4 (1), 94–108. doi:10.1016/j.fbj.2018.01.001

Jiang, Y., Xue, X., and Xue, W. (2018). Proactive corporate environmental responsibility and financial performance: Evidence from Chinese energy enterprises. *Sustainability* 10 (4), 964. doi:10.3390/su10040964

Lee, C. L., Ahmad, R., Lee, W. S., Khalid, N., and Karim, Z. A. (2022). The financial sustainability of state-owned enterprises in an emerging economy. *Economies* 10 (10), 233. doi:10.3390/economies10100233

Levytska, S., Akimova, L., Zaiachkivska, O., Karpa, M., and Gupta, S. K. (2020). Modern analytical instruments for controlling the enterprise financial performance. *Financial credit activity problems theory Pract.* 2 (33), 314–323.

Lindermüller, D., Sohn, M., and Hirsch, B. (2022). Trading off financial and non-financial performance information to evaluate state-owned enterprise performance–a process tracing-experiment. *Int. Public Manag. J.* 25 (5), 639–659. doi:10.1080/10967494.2020.1799888

Louche, C., Busch, T., Crifo, P., and Marcus, A. (2019). Financial markets and the transition to a low-carbon economy: Challenging the dominant logics. *Organ. Environ.* 32 (1), 3–17. doi:10.1177/1086026619831516

Nazari, S. S., Mousakhani, S., Tavakoli, M., Dalvand, M. R., Šaparauskas, J., and Antuchevičienė, J. (2020). Importance-performance analysis based balanced scorecard for performance evaluation in higher education institutions: An integrated fuzzy approach. *J. Bus. Econ. Manag.* 21 (3), 647–678. doi:10.3846/jbem.2020.11940

Semieniuk, G., Campiglio, E., Mercure, J. F., Volz, U., and Edwards, N. R. (2021). Low-carbon transition risks for finance. *WIREs Clim. Change* 12 (1), e678. doi:10.1002/wcc.678

Thomä, J., and Chenet, H. (2017). Transition risks and market failure: A theoretical discourse on why financial models and economic agents may misprice risk related to the transition to a low-carbon economy. *J. Sustain. Finance Invest.* 7 (1), 82–98. doi:10.1080/20430795.2016.1204847

Tong, P., Zhao, C., and Wang, H. (2019). Research on the survival and sustainable development of small and medium-sized enterprises in China under the background of low-carbon economy. *Sustainability* 11 (5), 1221. doi:10.3390/su11051221

Zhu, Y., Zhu, B., and Lang, J. (2019). An empirical study on financial performance evaluation of Chinese A and H cross-listed companies. *Int. J. Bus. Perform. Manag.* 20 (3), 229–246. doi:10.1504/ijbpm.2019.10023530

frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 24 January 2023
DOI 10.3389/fenrg.2023.1113295

OPEN ACCESS

EDITED BY
Wen-Tsao Pan,
Hwa Hsia University of Technology,
Taiwan

REVIEWED BY
Nie Chen,
Zhejiang Business Technology Institute,
China
Da Meng,
Shenzhen Technology University, China
Yi Cao,
Hebei Finance University, China

*CORRESPONDENCE
Hua Wu,
wuhua@sias.edu.cn

SPECIALTY SECTION
This article was submitted to Carbon Capture, Utilization and Storage, a section of the journal Frontiers in Energy Research

RECEIVED 01 December 2022
ACCEPTED 16 January 2023
PUBLISHED 24 January 2023

CITATION
Zhu L, Wu H and Xu Y (2023), Modeling and analysis of factors affecting the integration of Beijing Tianjin Hebei low carbon economy based on SDM model.
Front. Energy Res. 11:1113295.
doi: 10.3389/fenrg.2023.1113295

Modeling and analysis of factors affecting the integration of Beijing Tianjin Hebei low carbon economy based on SDM model

Lin Zhu[1], Hua Wu[1]* and Ying Xu[2]

[1]College of Business, Sias University, Zhengzhou, China, [2]College of Finance and Information, Ningbo University of Finance and Economics, Ningbo, China

Background: Under the guidance of carbon peak and carbon neutral targets, China's economic development is facing unprecedented challenges. It is of great strategic significance and value to study the integrated development of regional low-carbon economy. The harmonious development of Beijing-Tianjin-Hebei (Beijing-Tianjin-Hebei) has become a national strategy, and its importance is prominent.

Objective: To promote the regional economic integration of Beijing-Tianjin-Hebei is the top priority of promoting the development of Beijing-Tianjin-Hebei integration at present, and is the key to achieving the coordinated development and mutual benefit of Beijing-Tianjin-Hebei.

Methods: In this context, this paper studies the fuzzy control evaluation algorithm of regional economy based on SDM model. Realized the prediction of the expansion of the low-carbon economy in Beijing-Tianjin-Hebei, and put forward the development strategy of the economic integration of Beijing-Tianjin-Hebei. The ranking of regional competitiveness of fuzzy control evaluation method is in line with the reality of today's economic expansion. The application of fuzzy rules improves the speed, accuracy and objectivity of evaluation.

Results: The final experiment shows that the accuracy of the algorithm is very high, reaching 95.14%. In addition, the algorithm has higher efficiency and better performance. The fuzzy control evaluation algorithm of regional economy can better predict the economic growth of Beijing, Tianjin and Hebei.

Conclusion: Propose the development strategy of Beijing-Tianjin-Hebei low-carbon economic integration to further promote the development of Beijing-Tianjin-Hebei integration and promote the adjustment and optimization of China's economic structure.

KEYWORDS

SDM model, Beijing Tianjin Ji region, low carbon economic, regional economic integration, fuzzy control evaluation algorithm

1 Introduction

Based on the connotation and characteristics of regional low-carbon economic integration, the strategic implications of regional low-carbon economic integration development are summarized. It mainly includes the strategic choice of regional energy transformation, the strategic innovation of regional system integration, the strategic measures of regional economic development mode transformation and the strategic guarantee of regional new business model construction. By doing a good job in top-level design, accelerating the development of new energy industry, building a new industrial development mode, and giving play to the effect of maintaining and increasing the value of carbon assets. Build carbon neutral demonstration parks and promote diversified cooperation among regions, promote coordinated regional development and high-quality industrial development, promote the construction of a beautiful China, and help achieve the goals of carbon peak and carbon neutrality. Decades of development have greatly improved China's economic and social outlook. However, it is precisely because of the rapid economic expansion that the inherent differences in transportation, resources, culture and economic base among regions have been further enlarged, and the imbalance of regional economic expansion has become more and more prominent. Located in the heart of the Bohai Rim in China area of Northeast Asia, Jing-Jin-Ji is the largest and most dynamic area in northern China, attracting more and more attention from China and even the whole world. Chai et al. measured the carbon entropy and carbon emission efficiency of 25 industries in Beijing Tianjin Hebei region from 2000 to 2015 by building a carbon entropy model and a total factor industrial carbon emission efficiency evaluation model. The research shows that: (a) The priority industries in Beijing Tianjin Hebei region are expanding, the regional competitiveness of moderately developed industries is improving, and the proportion of industries that restrict development is significantly decreasing. (b) The spatial distribution of the three types of industries presents a concentric ring pattern, with priority industries as the core, moderate industries as the main, followed by industries with limited development. (c) The situation of medium and efficient industries has improved, while that of inefficient industries has declined (Chai et al., 2021). In order to further study the current situation and development trend of low carbon construction in Beijing, Tianjin and Hebei, in the absence of direct data on carbon emissions. The research team searched the China Statistical Yearbook, and then converted the final energy consumption data into GDP, population carbon emissions and living consumption of the three major industries in Beijing, Tianjin and Hebei from 2005 to 2015. On this basis, Zhang et al. analyzed the change trend of carbon emissions in Beijing Tianjin Hebei region and put forward some problems. Finally, the corresponding suggestions, solutions and countermeasures are put forward for the existing problems (Zhang et al., 2018a). Xue et al.'s improvement of carbon emission efficiency (CEE) will promote the development of green low-carbon economy in Beijing Tianjin Hebei region of China. This paper uses the unexpected output EBM model to measure the city level CEE in BTH from 2007 to 2016. This paper analyzes the spatial distribution characteristics and evolution laws of Central and Eastern Europe from the overall and local aspects, and verifies the influencing factors of Central and Eastern Europe by using the spatial quantile regression model (Xue et al., 2022). Therefore, it is need to grasp the present situation of industrial development in Jing-Jin-Ji, and to understand the development trend of leading industries in Jing-Jin-Ji and the interrelated results.

China will vigorously support green and low-carbon energy development in developing countries. Achieving carbon peaking and carbon neutralization is an inherent requirement of China's high-quality development, a strategic choice to practice the idea of ecological civilization, and a broad and profound economic and social systematic change. China is faced with the huge challenge of carbon emission reduction. It is necessary to explore a new mode and path for the integrated development of regional low-carbon economy, enhance the systematicness, integrity and synergy of carbon emission reduction, and accelerate the in-depth emission reduction. With the transformation of China's economic development model, various industries in Beijing Tianjin Hebei (BTH) region have put forward the requirement of high energy conservation and emission reduction (ECER). However, as an important indicator of achieving sustainable low-carbon development, the rebound effect of energy consumption has not been fully investigated in industrial enterprises in this field. Li et al. (2018) uses an alternative estimation model based on the neoclassical economic theory to measure the energy rebound effect of industrial enterprises in BTH. Carbon dioxide mainly comes from industrial economic activities. Industrial structure optimization is an effective way to reduce carbon dioxide emissions. Gu et al. uses the panel data of 13 cities in Beijing Tianjin Hebei urban agglomeration from 2006 to 2019 to calculate the industrial structure rationalization index using the Theil index. Use the proportion of industrial added value to calculate the industrial structure upgrading index. Through the construction of STIRPAT model, this paper quantitatively analyzes the impact of industrial structure rationalization and upgrading on carbon emissions (Gu et al., 2022). Regional economic integration refers to the elimination of trade barriers by different spatial entities, and the realization of free flow, cooperation and complementarity in space, industry and market. It is the unity of state and process, means and purpose. Under the guidance of regional strategy, regional coordination is strengthened through regional planning and policies, and the spatial pattern of social and economic activities is optimized (Rahul, 2016). On a larger scale, regional economic integration is no longer limited to the union between regions or cities within a country (Yu, 2020). Regional economic integration is one of the remarkable characteristics of current economic expansion, and the construction of regional metropolitan areas represented by Jing-Jin-Ji has great influence on international metropolitan areas. Therefore, this article will model and analyze the influencing factors of Jing-Jing-Ji cluster on regional economic integration, which has certain practical significance.

Hu et al. studied the different impacts of coordinated development of Beijing Tianjin Hebei region on industrial energy and pollution intensity based on the difference method (DID) and quantile DID method. The panel data covers the industrial energy consumption and three kinds of wastes, namely industrial wastewater, sulfur dioxide and dust emissions, in all 13 cities in BTH and 17 cities in Henan Province from 2007 to 2017. The research results show that, in addition to the dust pollution caused by the traffic integration in BTH, China should pay more attention to the green industrial relocation from Beijing to Hebei, and strengthen the coordinated environmental supervision while maintaining the interests of enterprises (Hu et al., 2020). Liu et al. used principal component analysis, entropy evaluation method and coupling coordination model (CCDM) to assess the coordination level between carbon and air quality mitigation in 34 low carbon pilot cities in China. We also use three case studies to illustrate the formation of mechanisms and policies that lead to different coupling patterns at the local level. We found that most pilot cities showed a moderate degree of coupling and coordination between low-carbon development and air quality. The results show that most low carbon pilot cities have relatively high scores in low carbon development (Liu et al., 2021). Due to the special conditions of geographical proximity, the economy of Jing-Jin-Ji is inextricably linked, and this inherent permeability and interdependent economic relationship has incomparable advantages in improving foreign competitiveness. The economic development characteristics of Beijing Tianjin Hebei region: the economic core areas with different levels have been formed with Beijing as the center. The economic development of the Beijing Tianjin Hebei Economic Zone has maintained a relatively high speed, but there are large differences between different regions. Taking the county economy of Beijing Tianjin Hebei as the research unit, this paper attempts to explore the time concentration distribution characteristics and spatial correlation of the county economic development of Beijing Tianjin Hebei under the background of the coordinated development of Beijing Tianjin Hebei, and reveals the gap between Hebei Province and Beijing Tianjin.

In the current context, Beijing Tianjin Hebei regional integration should not only accelerate the pace of regional coordinated development, but also re-examine itself and recognize its advantages and disadvantages. This paper analyzes the reality and feasibility of Beijing Tianjin Hebei integration, mainly discusses the influencing factors of Beijing Tianjin Hebei cluster on regional economic integration based on SDM model, and carries out modeling and analysis. The main contributions are as follows:

1. Construct a regional economic competitiveness index system with dual spatial integration characteristics. A workable regional economic evaluation system has been formed.
2. Propose the economic integration strategy of Beijing Tianjin Hebei region. It not only makes the basic data accurate and complete, but also makes the relevant models easy to systematize. It provides a way for the study of other regional economic integration.
3. The experimental results show that the fuzzy control evaluation algorithm of regional economy can better predict the economic growth of Beijing, Tianjin and Hebei. The study is expected to further promote the integrated development of Beijing, Tianjin and Hebei, and promote the adjustment and optimization of China's economic structure.

This paper studies the fuzzy control evaluation algorithm of regional economy based on SDM model, realizes the prediction of low carbon economic expansion in Beijing Tianjin Hebei, and puts forward the development strategy of economic integration in Beijing Tianjin Hebei. Section 1 describes the connotation and characteristics of regional low-carbon economic integration, and summarizes the strategic significance of regional low-carbon integration development. Section 2 analyzes the existing research results of regional economic integration and low-carbon economy. The influence of industrial agglomeration on regional economic integration is obtained. Section 3 analyzes the economic conditions and environment of the Beijing Tianjin Hebei region, which is also an important embodiment of the diversity and unity of the construction of ecological civilization and the construction of a beautiful China. The fuzzy evaluation model of regional economy is analyzed. Section 4 forecasts and simulates the regional economic expansion of Beijing Tianjin Hebei. In this part, the fuzzy evaluation model of regional economy is used to predict the economic growth of Beijing Tianjin Hebei, and the effectiveness of the algorithm proposed in this paper is verified. Section 5 summarizes the full text. The results show that the fuzzy control evaluation algorithm of regional economy can better predict the economic growth of Beijing, Tianjin and Hebei. This study is expected to further promote the integration of Beijing, Tianjin and Hebei, and promote the adjustment and optimization of China's economic structure.

2 Related work

The integrated development of regional low-carbon economy has rich connotation, as well as regional, systematic and collaborative characteristics. Based on the existing research results of regional economic integration and low carbon economy, this paper defines regional low carbon economic integration as a new regional development model integrating multiple (carbon technology integration, system integration, management integration, etc.) with low carbon economy as the development direction in a specific regional space. Improve energy utilization efficiency, strengthen regional coordinated emission reduction, and promote regional low-carbon zero carbon development and sustainable development. The integrated development of regional low-carbon economy is conducive to adjusting the energy consumption structure, significantly reducing carbon emissions, giving play to the role of market integration and regional coordinated emission reduction, promoting regional coordinated development, promoting high-quality industrial development, and helping build a beautiful China.

Regional ecological coordinated development is a new form of regional coordinated development aimed at building ecological civilization in the "new normal" period. The coordinated ecological development of Beijing Tianjin Hebei (BTH) region is particularly important because it is leading China's overall coordinated development and reform. Based on the complex system theory, synergetics and the concept of ecological civilization and green development in the "new normal" period, Zhao and Zhang built a regional ecological synergy measurement model, which scientifically evaluated the dynamic evolution of BTH's ecological synergy level from 2006 to 2018. Using econometric models, we also analyzed the welfare effect and regional heterogeneity of ecological synergy in regional development (Zhao and Zhang, 2021). Gao and Li (2021) calculated the level of industrial agglomeration by using the relevant industrial agglomeration index, and measured the regional economic integration index of the Yangtze River Delta by comprehensive assessment method. In order to better reflect the level of urbanization, the panel entropy weight method is used to weight the population, industry and area factors. Wang et al. constructs a comprehensive indicator of urbanization. The panel regression between the composite index and the average nighttime light after fusion showed a strong correlation. The accuracy test shows that the estimated value of the fusion average light calculated by the urbanization level estimation model fully represents the urbanization level (Wang et al., 2021). Jeff (2014) improved SOM algorithm and applied it to pattern classification of regional economic assessment. Li et al. established a logarithmic average divisor index model to decompose the total carbon emission increment. The carbon finance effect is divided into green credit effect and carbon trading effect, and the impact of carbon finance

10.3389/fenrg.2023.1113295

on carbon emissions is analyzed (Li et al., 2019). Xiao et al. discussed the environmental effect and mechanism of coordinated development of urban agglomeration. The results show that the coordinated development of Beijing, Tianjin and Hebei has a significant and sustained impact on the convergence of PM2.5 to the low level. The further mechanism identification results show that the air joint defense rules and policies in the process of Beijing Tianjin Hebei coordinated development mainly promote the convergence of PM2.5 through population and economic scale effects, structural effects and technological effects, and promote the convergence of PM2.5 to a lower direction by reducing the economic growth scale of the city itself. It is suggested to further promote the formation and development of Beijing Tianjin Hebei integration, strengthen cross regional environmental governance cooperation between local governments, and promote green growth and coordinated development of urban agglomeration (Xiao et al., 2022). The rapid economic growth in China's megalopolis is characterized by rapid urbanization, accompanied by a series of environmental problems, ranging from extensive soil pollution to groundwater depletion. Tian et al. analyzed the interaction between urbanization and ecosystem, and reviewed the existing urban and ecosystem analysis framework. Taking the Beijing Tianjin Hebei region as an example, this paper introduces a conceptual framework to analyze the megacity region, and applies the simulation model to predict the possible interaction between urbanization and the ecological environment (Tian et al., 2019). Climate change and rapid urbanization have brought natural and human genetic interference to urban ecosystems, and damaged the sustainability and resilience of cities. The assessment of urban ecological resilience and the study of its impact mechanism are of great significance for sustainable urban management. Taking the Beijing Tianjin Hebei Urban Agglomeration (BTHUA) region of China as the research area, Shi et al. constructed an evaluation index to evaluate the urban ecological resilience and its spatial pattern by using the resilience substitutes of net primary productivity from 2000 to 2020. The evaluation index is constructed from two dimensions, including the sensitivity and adaptability of urban ecosystem, to capture the two key mechanisms of resilience, namely resistance and resilience (Shi et al., 2022). Cui and Wang (2021) put forward countermeasures and feasible suggestions for promoting the growth of Jing-Jin-Ji cooperation and regional economic integration by analyzing the current situation of Jing-Jin-Ji low carbon economic cooperation and the problems existing in regional economic integration. Li (2014) pointed out that high economic expansion should not simply pursue economic aggregate and growth rate, but should pay more attention to the harmonious growth of economy, society and environment. Hussain et al. (2022) found that the consumer price index (CPI) factors that lead to the decline of Jing-Jin-Ji market integration development level are mainly housing, clothing, transportation and communication.

On the basis of summarizing the existing research results, this article studies a fuzzy control assessment algorithm of regional economy combined with SDM model, realizes the prediction of Jing-Jin-Ji low carbon economic expansion, and then puts forward the development strategy of Jing-Jin-Ji low carbon economic integration. In order to further promote the integrated growth of Jing-Jin-Ji and promote the adjustment and optimization of China's economic structure.

3 Methodology

3.1 Analysis of regional economic conditions and environment in Jing-Jin-Ji

Different regions have different resource endowments and regional characteristics. The difference of resource endowment and location determines that different regions have different industrial structure, industrial layout and development space. Secondly, the difference in economic infrastructure and infrastructure between regions is an important factor affecting the development of low-carbon economy. If a region has a good economic foundation and complete infrastructure, it can better promote the development of low-carbon economy and be conducive to the construction of ecological civilization. Thirdly, there are differences in human environment between regions. This requires selecting appropriate low-carbon economic development path according to different cultural characteristics. Regionality is a prerequisite and basic guarantee for the differentiated development of low-carbon economy in different regions, and also an important embodiment of the diversity and unity of ecological civilization construction and the construction of a beautiful China.

The Beijing Tianjin Hebei region has great potential for emission reduction. It is particularly important to finance energy conservation and emission reduction through technological innovation and optimization transformation of the real economy. Therefore, we should seize the opportunity to vigorously develop carbon finance, establish carbon finance innovation system and mechanism, and cultivate a multi-level carbon trading market system. Carry out the innovation of financial activities of low-carbon financial derivatives such as low-carbon swaps, forwards, futures trading, low-carbon securities, low-carbon futures, funds, etc. It has become the most important work of the carbon market in the process of Beijing Tianjin Hebei integration. With the acceleration of global economic process, regional economic integration has become the leading force to promote regional economic expansion. Regional economic integration refers to the stage of market integration between different spatial economic entities in order to obtain benefits such as production, consumption and trade (Ye, 2014). Including the gradual evolution from product market and factor markets to the unification of economic policies. Jing-Jin-Ji is the heart of the northern region, and its regional economic expansion is the core of China's northern economy. The regional economic integration of Jing-Jin-Ji can not only promote the economic growth of Beijing, Tianjin, Hebei and other provinces and cities, but also reflect the significance in guiding the future economic growth of surrounding areas and even enhancing the overall national strength of the whole country (Liu and Wang, 2016). Compared with the divergent and uniform distribution pattern of the Yangtze River Delta and the Pearl River Delta, Beijing and Tianjin are located in the hinterland and edge of Hebei Province respectively. Geographically, this kind of mega-city exists in one region at the same time in three provinces and cities, and it is rare even in the history of regional economy in the world. From the perspective of actual economic expansion, only GDP, total retail sales of social consumer goods and total investment in fixed assets of Jing-Jing-Ji cluster are close to the "Pearl River Delta" and lag behind the "Yangtze River Delta". The total import and export volume and the actual utilized foreign capital account for 13% and 18% of the national proportion, and the total volume is less than half of the Yangtze River

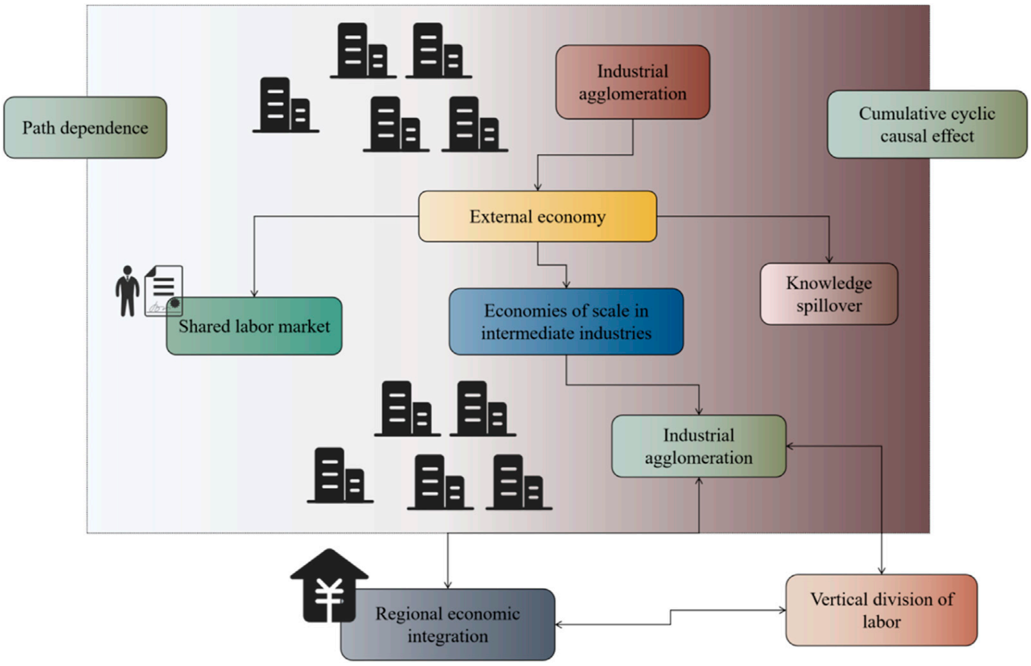


FIGURE 1
The mechanism of industrial agglomeration's influence on regional economic integration.

Delta and Pearl River Delta. The influence mechanism of industrial agglomeration on regional economic integration is shown in Figure 1.

The growth of Jing-Jin-Ji low carbon economic integration is not only related to the long-term growth of its own economy, but also of great significance for promoting the harmonious growth of the whole country and improving the regional economic integration mechanism of China (Zhang et al., 2018b). Among them, the gathering of high-tech industries plays a more and more important role in improving industrial structure, coordinating industrial cooperation and development, and improving regional innovation power. All regions regard the growth of high-tech industries as the primary task, and in the final analysis, it is to develop the economy. Beijing is the national political center, cultural center and the engine of knowledge economy development; Tianjin is an important industrial and commodity base; Hebei province has unique natural resources and a relatively complete industrial system, and has the most complete natural endowment and economic foundation for developing regional economic integration. No matter from the scope of regional cooperation or the rational allocation of resources and production factors, the formulation of Jing-Jin-Ji integration is more appropriate. In the Jing-Jin-Ji, the coordinated economic growth of the Bohai Rim region has become increasingly prominent. It is need to strengthen the communication and convergence of coordinated development in strategic planning, industrial development, policies and regulations, deepen, infiltrate and integrate regional industrial specialization, and promote the formation of high-end, high-quality and high-tech industrial structures. However, there are still some problems to be solved in the stage of regional economic integration in Jing-Jin-Ji: obvious differences in regional economic expansion in Jing-Jin-Ji, lack of industrial division and cooperation, irrational industrial structure, lagging growth of regional factor markets, and market barriers still exists. Therefore, a correct understanding of the present situation of regional economic integration in Jing-Jin-Ji is of great significance for promoting the growth of Jing-Jin-Ji integration (Lin and Meng, 2020). It is obviously not scientific to evaluate the level of economic expansion in a historical period only based on the clustering results of a certain time. To seek further development and coordinate regional imbalances, China should also learn from past experience. In addition, Jing-Jin-Ji is connected by mountains and rivers, and there is also a foundation for integrated development inside. Therefore, it can be said that the harmonious growth of Jing-Jin-Ji integration has both external impetus and internal motive force.

3.2 Fuzzy assessment model of regional economy

To evaluate the coordinated development system of Beijing Tianjin Hebei region, the focus is to extract specific manifestations from the complex relationship. That is to find the main factors influencing the statistical monitoring of the coordinated development of Beijing, Tianjin and Hebei. In addition, it is necessary to take full account of the independence of each factor and maintain a clear hierarchy and interdependence of each factor. Because the coordinated development of regional systems is not only an economic problem, but also a deep-seated social and ecological problem. Therefore, the target level is the level of regional coordinated development, and the criterion level is composed of economic subsystem, social subsystem and ecological subsystem. The economic subsystem is mainly reflected in three aspects: economic level, economic structure and economic extroversion: the social subsystem is measured in terms of population development, science and education level and infrastructure construction; the ecological subsystem is measured in terms of resource utilization and environmental protection. On the basis of the principle of operability, the indicator layer selects some relatively typical eigenvalues that can cover the indicator system and strives to reflect the degree and problems of the collaborative development process. The systematicness of the integrated development of regional low-carbon economy mainly refers to the integration of technology, system and management, and the deep integration of each other, which constitutes a unique spatial ecosystem. First, technological innovation is the basis and premise for the integrated development of low-carbon economy, and also the basis for achieving carbon peak and carbon neutralization. Only technological innovation can bring about new ways of production and life, and promote the fundamental change of production relations. The economic growth of a region can not be separated from the support of industry. How to promote the harmonious growth of Jing-Jin-Ji industries and improve the industrial integration level of Jing-Jin-Ji is of great significance to promote the regional economic integration of Jing-Jin-Ji. In fact, the inter-regional input-output technology reflect the significance in analyzing the input-output relationship among different regions, but it needs a large amount of survey data and systematic estimation, and its analysis results are mostly not ideal because of its big assumptions. This article studies the regional economic integration of Jing-Jin-Ji, so it is need to study Jing-Jin-Ji as a whole region.

SDM (Supervised Descent Method) is a Supervised Descent method, which is a Method to solve non-linear Least Squares (NLS) problems. The gradient descent direction is learned from the training data and the corresponding regression model is established, and then the gradient direction is estimated using the obtained model. Fuzzy cluster analysis is a mathematical method to classify things fuzzy according to certain requirements when the boundaries between things that need to be classified in mathematical analysis are blurred. Let the set of n samples be:

$$\mathrm{x} = \{\mathrm{x}_1, \mathrm{x}_2, \mathrm{x}_3, \ldots, \mathrm{x}_n\} \tag{1}$$

The characteristic data of each sample is expressed as:

$$(\mathrm{x}_{i1}, \mathrm{x}_{i2}, \mathrm{x}_{i3}, \ldots, \mathrm{x}_{in}) \quad \mathrm{i} = 1, 2, 3, \ldots, \mathrm{n} \tag{2}$$

The fuzzy relationship between samples can be established by calculating the similarity coefficient, correlation coefficient, distance or other quantities representing similarity between samples, and written in matrix form. Namely:

$$R = \begin{bmatrix} \mathrm{x}_{11} & \mathrm{x}_{12} & \mathrm{x}_{13} & \ldots & \mathrm{x}_{1n} \\ \mathrm{x}_{21} & \mathrm{x}_{22} & \mathrm{x}_{23} & \ldots & \mathrm{x}_{2n} \\ \ldots & & \ldots & & \ldots \\ \mathrm{x}_{n1} & \mathrm{x}_{n2} & \mathrm{x}_{n3} & \ldots & \mathrm{x}_{nn} \end{bmatrix}_{n\times n} \tag{3}$$

This fuzzy relationship is reflexive ($\gamma_{ii} = 1$) and symmetric ($\gamma_{ij} = \gamma_{j1}$), but generally not transitive.

According to the fuzzy comprehensive assessment and regional competitiveness assessment index system, the assessment model is established. In order to obtain an optimal fuzzy classification, a classification criterion is needed, the objective function is defined as the weighted distance between the sample and the cluster center, and the weighting coefficient is the q power of the membership function of the sample. Therefore, the fuzzy clustering problem can be described as the following optimization problem:

$$\min J(U, V) = \sum_{k=1}^{n}\sum_{i=1}^{c}\left(u_{ik}^{q}(d_{ik})^2\right) \tag{4}$$

$$s.t.\sum_{i=1}^{c} u_{ik} = 1\,(k = 1, 2, 3, \ldots, n) \quad 0 \le u_{ik} \le 1 \tag{5}$$

Among them, u_{ik} is the membership degree of the sample belonging to the i class; V is the set of C cluster centers. When $q = 1$, fuzzy clustering degenerates into hard C-means clustering. d_{ik} represents the distance between the sample x_k and the i cluster center, which is defined as:

$$d_{ik} = \|x_k - v_i\|_A^2 = (x_k - v_i)^T A (x_k - v_i) \tag{6}$$

Where A is the positive definite matrix of $P \times P$. When $A = I$, it is the euclidean distance. Figure 2 shows the assessment map of Jing-Jin-Ji low carbon economic integration.

Industrial agglomeration, industrial division of labor and economies of scale are the dynamic effects of regional economic integration. New spatial economics, new international trade theory and industrial agglomeration theory show that the free flow of factors caused by regional economic integration plays a key role in forming industrial agglomeration and improving regional competitiveness. After establishing the scope of index screening, the principle of index screening should be considered. Due to the complexity and diversity of socio-economic indicators, the following principles must be followed when selecting indicators: (1) Objectivity. (2) representativeness. (3) Comprehensiveness. (4) Independence. (5) Comparability. (6) Availability. (7) Scientific. Because the core elements of regional competitiveness should be based on regional specialization economy and learning effect, the core elements of regional competitiveness can be decomposed into three secondary indicators: trading awareness, trading behavior and trading means. The auxiliary elements of regional competitiveness are divided into three indicators: government management ability, the relationship between government and enterprises, and the degree of regional openness. Through the analysis of the history and general situation of the transformation of labor employment structure in Jing-Jin-Ji, and the relationship between labor employment growth and economic growth, this article finds that from the long-term trend, with the growth of economy, the labor force in the primary industry will continue to decline. The labor force in the secondary and tertiary industries is constantly rising; The structure of the labor force gradually tends to be reasonable. In this article, the "time distance" between the two places is used to replace the economic distance between cities in Jing-Jin-Ji urban agglomeration, that is, the time it takes for the two cities to travel in a normal way. Therefore, the function used to express the "economic distance" between cities in Jing-Jin-Ji is as follows:

$$F_{ij} = \alpha * H + \beta * G \tag{7}$$

Among them, the "economic distance" between Jing-Jin-Ji cities is represented by F_{ij}; The time it takes for the railway to travel between two cities is expressed as H; The time required by the road between two cities is G; α represents the weight of the transportation volume of the railway transportation mode; β indicates the weight of freight volume transported by road transportation. Among them:

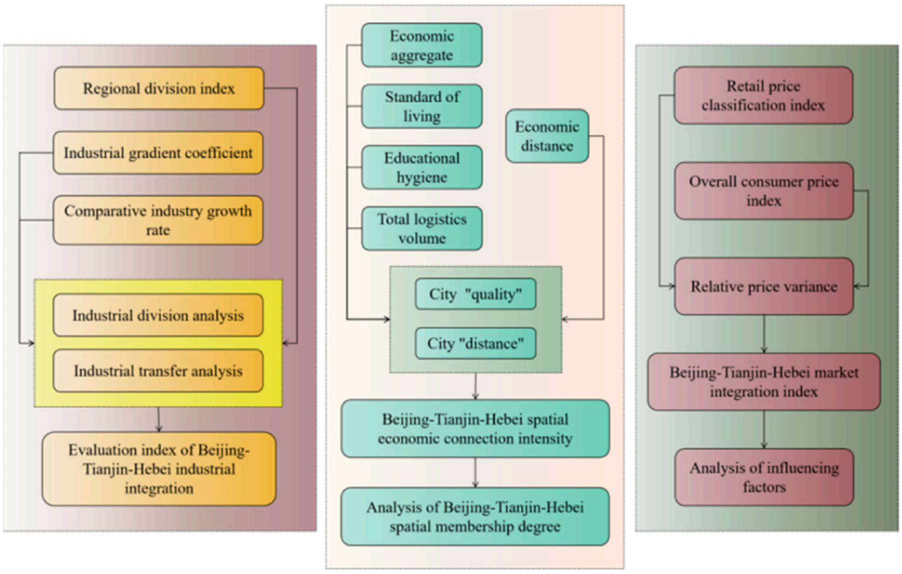


FIGURE 2
Assessment map of Jing-Jin-Ji low carbon economic integration.

$$\alpha + \beta = 1 \tag{8}$$

Two groups of deviation variables d_j^+ and d_j^- are introduced, which respectively represent the positive and negative deviation between the j-th target value and its expected target value. The objective function of the objective programming is to find the sum of absolute values of errors, namely:

$$e = \min \sum_{j=1}^{K} \left(d_j^+ + d_j^-\right) \tag{9}$$

If the meaning of the error of each objective of the original problem is different, then the linear weighted sum of the absolute value of the error can be found, that is:

$$E = \min \sum_{j=1}^{K} \lambda_i \left(d_j^+ + d_j^-\right) \tag{10}$$

Where λ_i is the weight coefficient of the j target. To use the sum of absolute errors as the objective function, the following constraints should be considered:

$$f_j(X) + d_j^- = d_j^+ + f_j^* \quad d_j^+ \geq 0 \quad d_j^- \geq 0 \tag{11}$$

The weighted mathematical model of goal programming is:

$$\min_{X \in R} \sum_{j=1}^{K} \left(d_j^- + d_j^-\right) \tag{12}$$

$$s.t. \begin{cases} f_j(X) - d_j^+ + d_j^- = f_j^* \\ d_j^+, d_j^-, X \geq 0 \end{cases} \quad j = 1, 2, 3, \ldots, k \tag{13}$$

For the missing index values, this article considers the cluster analysis of the complete index data of other provinces and cities first, and then classifies them into the nearest category by the nearest neighbor discriminant method according to the indexes that are not missing. In this article, a wide range of assessment indexes: MSE (Mean squared error), RMSE (Root mean square error) and MAE (Mean absolute error) are used to test and analyze the algorithm. Here are the specific formulas of these four indicators:

$$MSE = \frac{1}{n} \sum_{k=1}^{n} \left(y_k - \hat{y}_k\right)^2 \tag{14}$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{k=1}^{n} \left(\left|y_k - \hat{y}_k\right|\right)^2} \tag{15}$$

$$MAE = \frac{1}{n} \sum_{k=1}^{n} \left|y_k - \hat{y}_k\right| \tag{16}$$

Where y_k is the actual value and $\hat{y}_k$ is the output value. In order to adapt to different expected output modes, different network structures are selected in the specific implementation stage of the algorithm, and the corresponding training results are obtained by training them respectively. Then, different training results are analyzed and compared, and the most appropriate training result is selected as the output result of pattern classification.

4 Result analysis and discussion

4.1 Prediction and simulation of regional economic expansion in Jing-Jin-Ji

With the help of Kernel density estimation and exploratory spatial data analysis, this paper discusses the space-time characteristics and evolution trend of *per capita* GDP in 157 counties in Beijing Tianjin Hebei region from 2010 to 2017. If enterprises want to achieve sustainable development under the rigid constraints of carbon peaking and carbon neutralization, they must meet the latest

TABLE 1 Errors of the algorithm.

Algorithm	MSE	RMSE	MAE
Qualitative Evaluation	5.04	0.612	2.13
Quantitative Evaluation	6.07	0.637	1.94
Fuzzy control evaluation	4.64	0.513	1.29

requirements of carbon emission reduction and improve the value of carbon assets. Thirdly, institutions of higher learning and scientific research institutions have the advantages of talents and technology to provide technical support and intelligent support for the integrated development of regional low-carbon economy; Financial institutions can give play to the financial attribute of carbon, expand the scale of investment and financing, and promote the coordinated development of their industries. The continuous expansion of population will exert great pressure on the growth of the whole society and even the whole regional economy, directly affecting the sustainable growth of population and economy, and thus related to the implementation of the strategy of taking the lead in realizing modernization. Therefore, accurately predicting the population size of Jing-Jin-Ji in the next few years can provide a scientific basis for regional economic expansion decisions and accelerate the growth of regional economy. In addition, the CPI is an economic index that reflects the change of a country's consumer level, and it can indirectly reflect the price change of

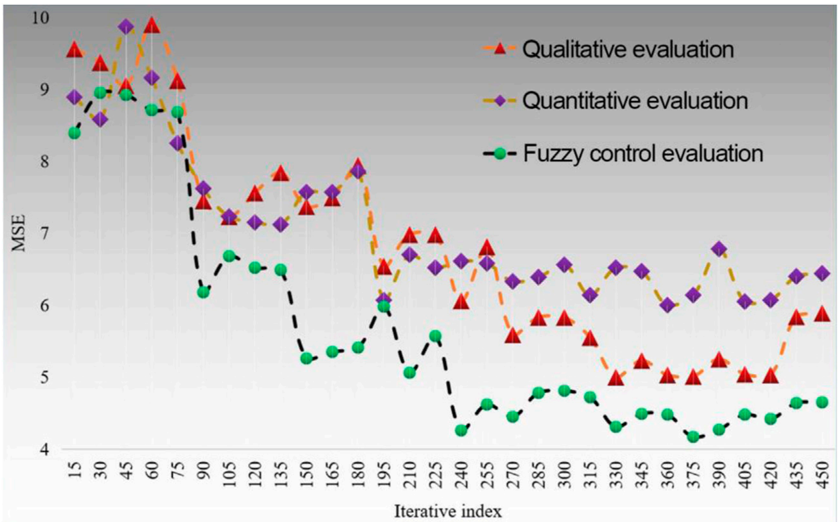


FIGURE 3
MSE experimental results.

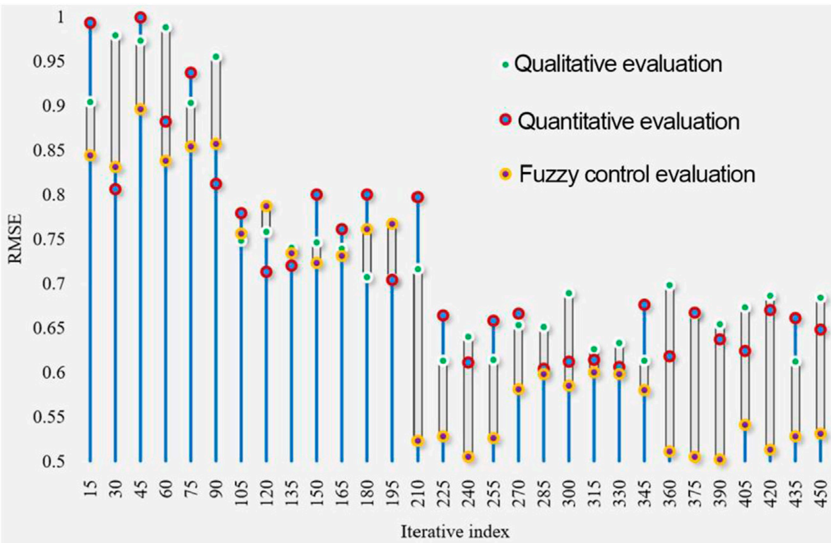


FIGURE 4
RMSE experimental results.

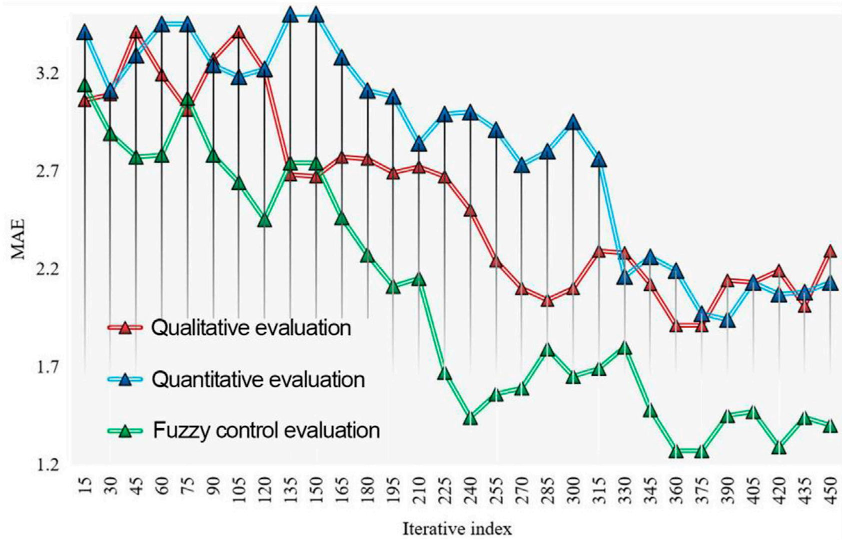


FIGURE 5
MAE experimental results.

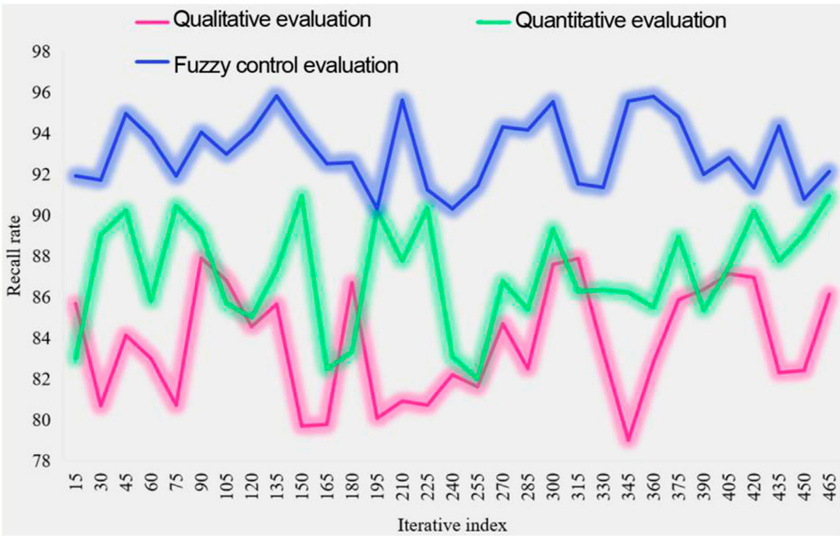


FIGURE 6
Comparison of recall rates of different models.

consumer goods purchased by households in China. In this section, the fuzzy assessment model of regional economy is used to predict the growth of Jing-Jin-Ji economy, and the effectiveness of the algorithm proposed in this article is verified. The errors of this algorithm are shown in Table 1.

The development samples of Beijing Tianjin Hebei region were sampled by random sampling without duplicate samples. Now the algorithm in this article is compared with other algorithms, and the error of the algorithm is analyzed. Firstly, 450 samples were randomly selected, and several error indexes of different algorithms were drawn respectively. The MSE comparison of different algorithms is shown in Figure 3. RMSE comparison of different algorithms is shown in Figure 4. The MAE comparison of different algorithms is shown in Figure 5.

From the data analysis in Figures 3–5, this paper studies the results of regional economic evaluation using SDM model. The analysis results of SDM model show that economy and energy are the causes of environment. Economic development has its own inertia, and energy drives economic development; economic, energy and environmental variables are interrelated in space. It is necessary to properly handle the solid waste in time and be alert to the pollution caused by waste gas and water. Compared with other algorithms, the data results of MSE, RMSE and MAE of this algorithm are impressive. The algorithm has small error and good performance.

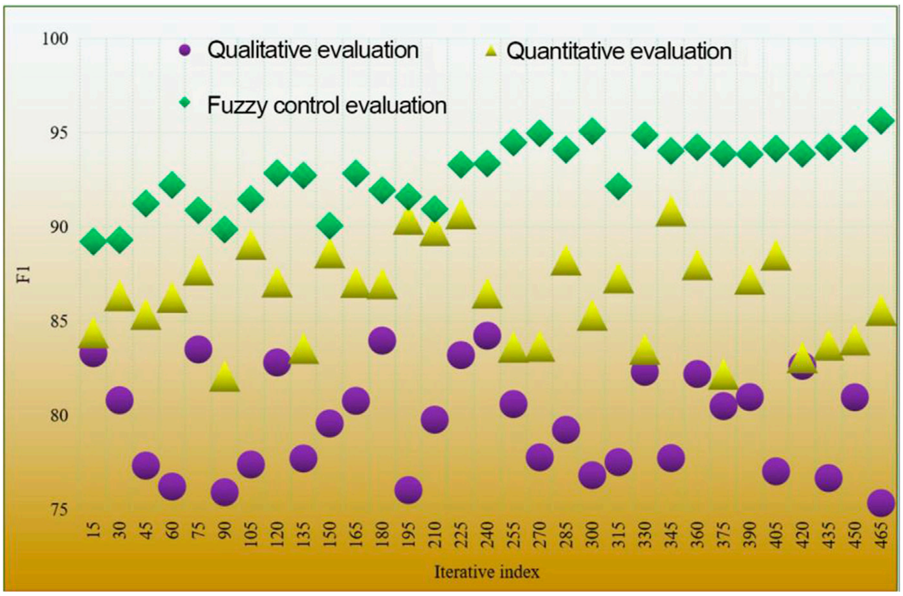


FIGURE 7
Comparison of F1 values of different models.

TABLE 2 Accuracy of the model.

Iterative index	Accuracy
350	87.655
375	86.915
400	88.046
425	83.958
450	85.527
475	87.761
500	91.811
525	91.966
550	91.734
575	95.694

In this article, in order to eliminate the error of distance measurement caused by index correlation, several irrelevant factors must be summarized from the data, which requires factor analysis of the data. Before factor analysis, the data should be standardized to eliminate the influence of index dimension and magnitude. In this article, the standard score method is selected to standardize the data. After the experiment, the recall rates of different models are compared as shown in Figure 6. Comparison of F1 values of different models is shown in Figure 7.

In this article, the input-output model can be used to make various investment-related calculations, simulate investment policies, and provide scientific basis for formulating investment policies. The fund occupancy matrix table and the fund occupancy coefficient need to be solved. When building a dynamic input-output model, the fund occupancy matrix and fund occupancy coefficient are another important tool to establish the dynamic relationship between investment and total output. A dynamic input-output model can also be established to directly link investment with production. This requires the model to have certain accuracy. Table 2 and Figure 8 show the comparison of accuracy of different models.

According to the above analysis results, when the training times are reached, the training is terminated. It is found that the accuracy of this algorithm is higher than other algorithms. In fact, fuzzy control rules are a set of multi-conditional statements, which can be expressed as fuzzy relations from the input variable Universe to the output Universe. The fuzzy control rules in this article consist of 28 sentences, which express the fuzzy relationship between core competitiveness elements and auxiliary competitiveness elements to regional competitiveness. The fuzzy control assessment of regional economy is applicable to the assessment of regional economic growth of various economic regions, provinces and cities with rapid growth of network economy. The running efficiency of different algorithms is shown in Table 3 and Figure 9.

In order to verify the reliability of the method, many experiments are carried out in this section. The final experiment shows that the accuracy of the proposed algorithm is high, reaching 95.14%. Moreover, the algorithm has higher efficiency and better performance. The results show that the fuzzy control assessment algorithm of regional economy can well predict the growth of Jing-Jin-Ji economy.

On the whole, the commonness is that the spatial distribution of *per capita* GDP in the counties of Beijing, Tianjin and Hebei shows a high concentration with Beijing, Tianjin, Tangshan and Langfang as the core. The county economic growth in the Beijing Tianjin Tangshan region is still dominant, and the spatial pattern has not changed for many years. And the counties with high and low concentration are mostly distributed around the Beijing Tianjin Tangshan area, showing a typical "center periphery" spatial structure. The spatial agglomeration pattern of most counties in central and southern

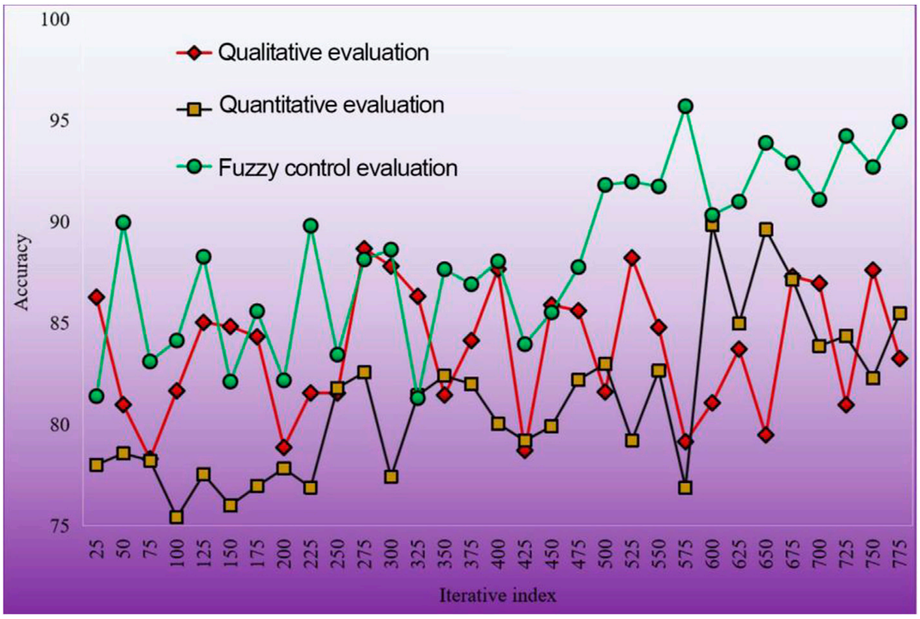


FIGURE 8
Accuracy of different models.

TABLE 3 Operating efficiency of the algorithm.

Transaction set	Operational efficiency
350	0.259
375	0.269
400	0.268
425	0.253
450	0.244
475	0.285
500	0.28
525	0.317
550	0.39
575	0.335

Hebei is not significant, and the radiation and driving role of Shijiazhuang as the provincial capital city is not significant. The economic growth pole that radiates the central and southern Hebei has not been formed, and the positive spatial spillover effect on the surrounding areas is not significant. The spatial pattern of low and low concentration areas is relatively stable. On the one hand, it is affected by its own economic foundation, resource endowment, location conditions and other factors. On the other hand, it is also related to the rapid development of the surrounding county economy. In general, the economic growth among counties in Beijing, Tianjin and Hebei is still uneven, and the gap between counties in Hebei Province and Beijing and Tianjin is still large. The spatial spillover pattern with Beijing Tianjin Tangshan region as the core and spreading to the periphery still appears. As the provincial capital, Shijiazhuang has not yet formed a space spillover to the surrounding areas, and it still needs a long way to become the third pole of economic growth in Beijing, Tianjin and Hebei.

4.2 Jing-Jin-Ji low carbon economic integration strategy

Technological innovation is the forerunner and prerequisite for the integrated development of regional low-carbon economy, among which regional system integration is one of its development trends. On the basis of technological innovation, based on the innovation and breakthrough of single carbon emission reduction technology, such as carbon capture technology, carbon utilization technology, etc., regional system integration of multiple technologies is gradually developed, which provides the basic conditions for the integrated development of regional low-carbon economy. While forming technology integration, it also forms system integration, management integration, etc. to realize the integrated development of regional low-carbon economy. After the overall regional planning forecast is completed, the specific implementation is the problem of regional coordinated development. Regional coordinated development is a complex social system engineering. On the basis that all parties in the region have the same Scientific Outlook on Development, it is the primary task of regional coordinated development to determine the development countermeasures. How to base on the actual situation of Jing-Jin-Ji, focus on the requirements of future development, and realize coordinated development in all aspects of spatial integration, industrial integration and market integration is an important breakthrough for Jing-Jin-Ji to upgrade its development level and level in the future. The experimental results in the previous section show that the fuzzy control assessment algorithm of regional economy proposed in this article can well

10.3389/fenrg.2023.1113295

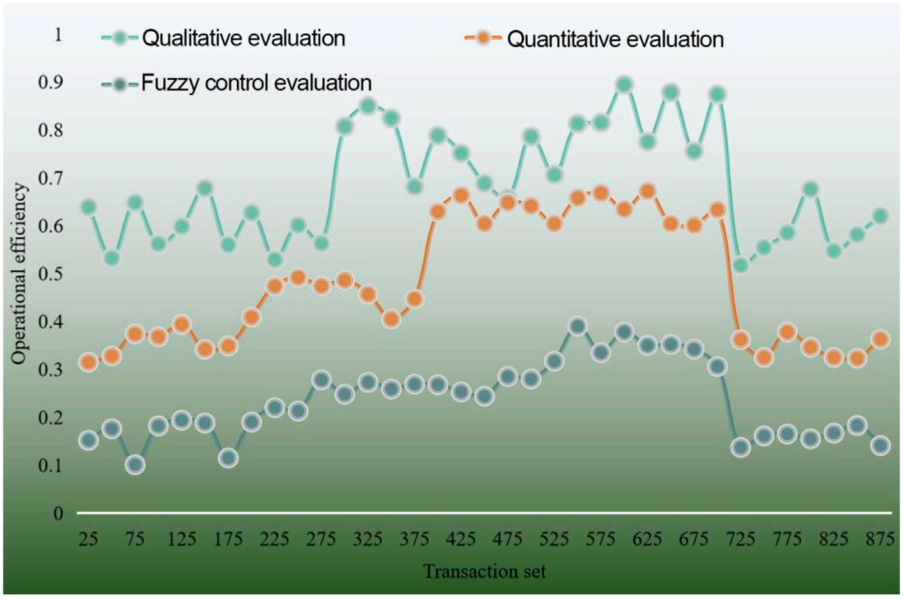


FIGURE 9
Running efficiency of different algorithms.

predict the growth of Jing-Jin-Ji economy. Based on the results of the model's prediction and simulation of Jing-Jin-Ji low carbon economic expansion, this section puts forward some suggestions on the development strategy of Jing-Jin-Ji low carbon economic integration, as follows:

(1) Jing-Jin-Ji is a community of interests, and it was formed under the conscious and organized guidance of the governments of the three places. Therefore, it is necessary for the three governments to make unified planning and deployment for the future growth of Jing-Jin-Ji. The specific planning will play a positive role in promoting the regional economic growth of Jing-Jin-Ji because of the implementation and formulation of the strategy, which is the need of enriching the people and strengthening the region, the major problem facing Jing-Jin-Ji, and the need of ensuring the rapid growth of the region.
(2) To realize regional economic integration, it is need to integrate the development goals of each region and form a consensus on the goals. The goal is to realize the equalization of basic public services in Jing-Jin-Ji, and pursue social equity. Among them, improving the consciousness of changing the appearance of economically backward areas is the foothold to solve the problem of unbalanced regional economic expansion; Strengthening opening to the outside world is an important way to solve the problem of regional economic imbalance; Strengthening the economic exchanges among different regions is the catalyst to realize the coordinated development among regions.
(3) We must fundamentally solve the contradiction between economic expansion and ecological environment, realize the ecological transformation of economic expansion, and change the mode of economic expansion is the key. In addition, in order to break the geographical division, it is need to establish a unified and open human resources market and an open human resources market system in Jing-Jin-Ji.
(4) The economic growth of Jing-Jin-Ji should also be included in the long-term planning of national economic expansion, and this area should be considered as an economic whole. Although the effect of economic expansion will not be too obvious in a short period of time, its development direction should at least meet the general requirements of "Theory of Three Represents" and building a well-off society in an all-round way, and promote multi-level alliance to seek common development.
(5) Finally, in order to adapt the informatization construction to the economic expansion, the state needs to actively adjust the informatization development strategy; Increase investment, improve policy guarantee and other measures, promote the "leap-forward" growth of informatization, and promote the growth of regional economic integration in Jing-Jin-Ji.
(6) According to the requirements of the state, the development differences of cities in the Jing-Jin-Ji should be clearly defined, and the advantages of cities in each region should be complementary, mutually beneficial and win-win and coordinated. Give full play to the advantages of capital resources and talent information; Plus Tianjin's port advantages and industrial development advantages; Combining with the own conditions of manufacturing industry and labor force in Hebei Province, we should form a reasonable division of labor, define the development orientation of the three places, and form a complete economic expansion zone.

The carbon emissions of energy consumption in Beijing, Tianjin and Hebei have continued to increase with the expansion of economic scale, and they have not yet been completely decoupled. Hebei's higher carbon emission growth rate than Beijing and Tianjin hinders the rise of the level of coordinated regulation. Energy intensity and industrial structure upgrading synergy both curb carbon emissions in Beijing, Tianjin and Hebei. Capital efficiency promotes carbon emissions in Beijing,

10.3389/fenrg.2023.1113295

while curbing carbon emissions in Tianjin and Hebei. In addition, labor productivity is an important intermediary factor in Beijing and Hebei, and economic growth is an important intermediary factor in Tianjin. This shows that the supply factors in Beijing, Tianjin and Hebei indirectly affect carbon emissions mainly by affecting labor productivity and *per capita* GDP. The rapid growth of labor productivity is not conducive to controlling the peak time of Beijing Tianjin Hebei. Regulating the rise of capital efficiency is an important path to improve the level of coordinated emission reduction in Beijing Tianjin Hebei. It is not only conducive to reducing carbon emissions in the three regions, but also can fill the gap in emission reduction. The need to improve energy efficiency and adjust the scale and flow of capital is an important path for Beijing and Hebei to achieve high-quality carbon peak.

5 Conclusion

The comprehensive growth of Jing-Jin-Ji urban agglomeration has become a national strategy, and its importance is self-evident. At present, the most important thing to promote the integrated growth of Jing-Jin-Ji is to promote the regional economic integration of Jing-Jin-Ji. Based on this, this article studies a fuzzy control assessment algorithm of regional economy combined with SDM model, and analyzes the influencing factors of Jing-Jing-Ji cluster on regional economic integration. Moreover, this article constructs a new index system of regional economic competitiveness with dual spatial integration characteristics, and gives a fuzzy assessment method and control rules after widely collecting statistical data and soliciting expert opinions, thus forming an operational regional economic assessment system. With this model, the regional economic expansion forecast of Jing-Jin-Ji is realized, and then the regional economic integration strategy of Jing-Jin-Ji is put forward. The establishment and application of Jing-Jin-Ji low carbon economic integration model is a scientific exploration. It not only makes the basic data accurate and complete, but also makes the relevant models easy to systematize, and enables scientific methods to be based on reliable data. It ensures the advanced research methods and the feasibility of the research results, and provides a way for the research of other regional economic integration. The final experiment shows that the accuracy of the proposed algorithm is high, reaching 95.14%. Moreover, the algorithm has higher efficiency and better performance. The results show that the fuzzy control assessment algorithm of regional economy can well predict the growth of Jing-Jin-Ji economy. This study is expected to further promote the integrated growth of Jing-Jin-Ji and promote the adjustment and optimization of China's economic structure. It is believed that with the strengthening of Beijing's urban functions, the further construction of Tianjin Free Trade Zone and the expansion of the new district, Jing-Jin-Ji urban agglomeration is expected to become a brand-new high-quality economic growth pole in the north.

The system proposed in this paper still needs to be improved step by step, and is subject to the continuous test of regional economic practice. Although the evaluation time of each batch of fuzzy control is only a few seconds, more decision groups are still needed to realize it. The direction to be improved in the future mainly includes: the realization of online evaluation and the realization of group decision support system. Expansion of evaluation and weighting method library. Construction of template library; How to realize automatic knowledge acquisition. For example, using artificial neural network, genetic algorithm support vector machine and other methods.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

LZ performed the data analysis, HW performed the formal analysis and the validation, YX wrote the manuscript. All authors approved its submission to the journal.

Funding

This work was supported by MOE (Ministry of Education in China) Project of Humanities and Social Sciences: Research on the Organization Mode and Governance Mechanism of Shared Recycling Recreation (No. 20YJC630241); The Natural Science Foundation of Zhejiang Province: Research on Organization Model and Support System of Supply and Demand Network for Recycling and Remanufacturing (No. LY20G030025); National Social Science Foundation of China: Research on Recycling and Remanufacturing Network Organization and its Governance under Sharing Economy (No. 18BGL184).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Chai, Y., Lin, X., and Wang, D. (2021). Industrial structure transformation and layout optimization of beijing-tianjin-hebei region under carbon emission constraints. *Sustainability* 13 (2), 643. doi:10.3390/su13020643

Cui, W. T., and Wang, S. W. (2021). Analysis on the strength of regional economic ties and network structure of Jing-Jin-Ji. *Res. Technol. Econ. Manag.* 2021 (004), 117–121.

Gao, D., and Li, S. (2021). A study on the coupling coordination between forestry production efficiency and regional economic development in China. *For. Prod. J.* 71 (1), 11–19. doi:10.13073/fpj-d-20-00045

Gu, R., Li, C., Li, D., Yang, Y., and Gu, S. (2022). The impact of rationalization and upgrading of industrial structure on carbon emissions in the Beijing-Tianjin-Hebei urban agglomeration. *Int. J. Environ. Res. Public Health* 19 (13), 7997. doi:10.3390/ijerph19137997

Hu, C., Hu, B., Shi, X., and Wu, Y. (2020). The roles of Beijing-Tianjin-Hebei coordinated development strategy in industrial energy and related pollutant emission intensities. *Sustainability* 12 (19), 7973. doi:10.3390/su12197973

Hussain, Z., Khan, M. K., and Shaheen, W. A. (2022). Efect of economic expansion, income inequality, transportation, and environmental expenditures on transport emissions: Evidence from OECD countries. *Environ. Sci. Pollut. Res.* 2022 (37), 29.

Jeff, Neilson (2014). Regional dynamics in a decentralised Indonesia edited by HalHill (ed.) ISEAS publishing, Singapore, 2014 Pp. 538. ISBN 978 9814 45985 3. *Asian-Pacific Econ. Lit.* 28 (2), 105–107. doi:10.1111/apel.12080

Li, G., Sun, J., and Wang, Z. (2018). Exploring the energy consumption rebound effect of industrial enterprises in the Beijing–Tianjin–Hebei region. *Energy Effic.* 12 (4), 1007–1026. doi:10.1007/s12053-018-9743-4

Li, L., Liu, D., Hou, J., Xu, D., and Chao, W. (2019). The study of the impact of carbon finance effect on carbon emissions in beijing-tianjin-hebei region—based on logarithmic mean divisia index decomposition analysis. *Sustainability* 11 (5), 1465. doi:10.3390/su11051465

Li, W. Z. (2014). Research on the coordination mechanism of harmonious growth of regional economy and finance in Jing-Jin-Ji. *Qiuzhi* 2014 (6), 3.

Lin, P., and Meng, N. N. (2020). Quality measurement and dynamic deconstruction of Jing-Jin-Ji economic expansion under environmental constraints-based on the perspective of green total factor productivity. *Econ. Geogr.* 40 (9), 10.

Liu, H. Z., and Wang, L. N. (2016). The impact of labor mobility on the regional economic expansion gap between Beijing and Tianjin. *Popul. Econ.* 2016 (2), 11.

Liu, T. L., Song, Q. J., Jiaqi, L. U., and Qi, Y. (2021). An integrated approach to evaluating the coupling coordination degree between low-carbon development and air quality in Chinese cities. *Adv. Clim. Change Res.* 12 (5), 710–722. doi:10.1016/j.accre.2021.08.001

Rahul, Sen (2016). China's rise and regional integration in east Asia: Hegemony or community? *Asian-Pacific Econ. Lit.* 30 (1), 153–154. doi:10.1111/apel.12144

Shi, C., Zhu, X., Wu, H., and Li, Z. (2022). Assessment of urban ecological resilience and its influencing factors: A case study of the beijing-tianjin-hebei urban agglomeration of China. *Land* 11 (6), 921. doi:10.3390/land11060921

Tian, L., Xu, G., Fan, C., Zhang, Y., Gu, C., and Zhang, Y. (2019). Analyzing mega city-regions through integrating urbanization and eco-environment systems: A case study of the beijing-tianjin-hebei region. *Int. J. Environ. Res. public health* 16 (1), 114. doi:10.3390/ijerph16010114

Wang, J., Liu, H., Liu, H., and Huang, H. (2021). Spatiotemporal evolution of multiscale urbanization level in the Beijing-Tianjin-Hebei Region using the integration of DMSP/OLS and NPP/VIIRS night light datasets. *Sustainability* 13 (4), 2000. doi:10.3390/su13042000

Xiao, Z., Li, H., and Gao, Y. (2022). Analysis of the impact of the Beijing-Tianjin-Hebei coordinated development on environmental pollution and its mechanism. *Environ. Monit. Assess.* 194 (2), 91. doi:10.1007/s10661-021-09720-9

Xue, L. M., Zheng, Z. X., Meng, S., Li, M., Li, H., and Chen, J. M. (2022). Carbon emission efficiency and spatio-temporal dynamic evolution of the cities in Beijing-Tianjin-Hebei Region, China. *Dev. Sustain.* 24 (6), 7640–7664. doi:10.1007/s10668-021-01751-z

Ye, T. L. (2014). Research on jing-jin-ji economic development strategy in the new era. *Reg. Econ. Rev.* 2014 (001), 138–141.

Yu, M. (2020). Comments on A Framework for regional banking regulation in ASEAN. *Asian Econ. Pap.* 19 (3), 126–127.

Zhang, X. B., Yu, W., Zhang, Y. L., Song, J. P., and Wang, Z. B. (2018). Spatio-temporal differentiation and influencing factors of economic growth in Jing-Jin-Ji. *J. Geogr.* 73 (10), 16.

Zhang, Y., Liu, L., Hu, D., and Zhang, J. (2018). Research on the current situation and countermeasures of carbon emission under the beijing-tianjin-hebei integration—based on the investigation of the current status of carbon emission in beijing-tianjin-hebei region. *J. Low Carbon Econ.* 7 (1), 24–34. doi:10.12677/jlce.2018.71003

Zhao, L., and Zhang, G. (2021). Evaluation and welfare effect of coordinated ecological development of the Beijing–Tianjin–Hebei region. *Chin. J. Popul. Resour. Environ.* 19 (3), 283–290. doi:10.1016/j.cjpre.2021.12.031

frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 03 February 2023
DOI 10.3389/fenrg.2023.1119738

Check for updates

OPEN ACCESS

EDITED BY
Wen-Tsao Pan,
Hwa Hsia University of Technology,
Taiwan

REVIEWED BY
XiaoRan Sun,
Hebei Finance University, China
Zhengmin Li,
Wuhan University, China
Zhongfang Tu,
Hainan Normal University, China

*CORRESPONDENCE
Guan Feng,
20150201017@cqu.edu.cn

SPECIALTY SECTION
This article was submitted to Carbon Capture, Utilization and Storage, a section of the journal Frontiers in Energy Research

RECEIVED 09 December 2022
ACCEPTED 23 January 2023
PUBLISHED 03 February 2023

CITATION
Zhou X, Feng G and Ren Y (2023), Analysis of TMT heterogeneity and IPO underpricing of listed companies in the low carbon economy sector: Evidence from China's stock market.
Front. Energy Res. 11:1119738.
doi: 10.3389/fenrg.2023.1119738

Analysis of TMT heterogeneity and IPO underpricing of listed companies in the low carbon economy sector: Evidence from China's stock market

Xiaohua Zhou[1], Guan Feng[1]* and Yong Ren[2]

[1]School of Economics and Business Administration, Chongqing University, Chongqing, China, [2]Administrative Committee of Chongqing Economic and Technological Development Zone, Chongqing, China

Introduction: Issuance pricing is an important part of the operation of the securities market. Its pricing is directly related to the interests of issuers, investors and underwriters, as well as the regulatory and resource allocation functions of the securities issuance market. When the industry expectations vary greatly, the company has greater TMT heterogeneity. When the market expectation gap expands, the possibility of risk conversion increases. IPO underpricing occurs in stocks of developed countries, developing countries and emerging countries. Because the issuer and the underwriter investors have different information, for example, the information advantage of the underwriter will bring risks to investors when purchasing IPO shares. IPO underpricing is a compensation for the risks brought by information asymmetry.

Methods: At present, little attention has been paid to how the value of listed companies affects the underpricing of intellectual property. This paper will fill in this gap and empirically study the impact of management ability of senior management team on IPO underpricing. Therefore, starting from the Chinese stock market, this paper studies the evidence of vertical parallel executives, heterogeneity of senior management team and IPO underpricing.

Results: The average values of NCSKEW (C1) and DUVOL (C2) were −0.301 and −0.203, respectively, which were close to the descriptive statistics of the study.

Discussion: The dependent variable data in this paper has certain reliability. The minimum value of NCSKEW is −0.361 and the maximum value is 0.392, indicating that the fragmentation risk of different stocks is relatively high.

KEYWORDS

vertical concurrent executives, TMT heterogeneity, IPO underpricing, low carbon economy, China's stock market

1 Introduction

Whether enterprises can take a low-carbon development path depends mainly on financing guarantee and technology research and development level. Because in the process of economic transformation from "high carbon" to "low carbon," enterprises must eliminate backward equipment and technology and adopt new equipment and technology that meet the requirements of low carbon economy. This requires enterprises to have huge funds as the backing to maintain the continuous capital investment in new equipment and new technology.

How to improve the efficiency of financing in a variety of ways to achieve high output at the lowest possible cost of capital is a practical problem faced by all low-carbon enterprises. China's carbon trading pilot policy is expected to be effective and flexible in reducing carbon emissions by encouraging low-carbon innovation. Based on the sample of selected enterprises, Qi et al. analyzed the impact of this pilot policy on low-carbon innovation using a difference model, and conducted a series of robustness tests to confirm the results. Compared with the traditional and historical intensity distribution methods, the results of this study show that the low-carbon innovation degree is significantly greater when using the benchmark method (Qi et al., 2021). Therefore, the financing efficiency of listed companies in the low-carbon economy sector is a topic worthy of study. Low carbon economy is a new form of economic development, which has been widely recognized. Whether China's economy can successfully transform depends to a large extent on the development of relevant enterprises, and the start of enterprise development is financing. The transition from private ownership to public ownership through listing (i.e., IPO or IPO) has attracted the attention of academia. Because the company faces governance, strategic and financial challenges and changes in obtaining favorable valuations from the stock market. This is especially true for family businesses, which leads to the growing interest of family business scholars in this topic. Wang et al. systematically reviewed the existing research on family business IPO and evaluated the latest technology in this field (Wang et al., 2022). In the process of economic transformation from "high carbon" to "low carbon," enterprises must abandon outdated equipment and technology and stay with new equipment and technology that meet the requirements of low carbon economy. This process puts forward very high requirements for the amount of capital of enterprises. Financing activities are the starting point of enterprise financial activities. The uncertainty and information asymmetry surrounding the company's initial public offering often make it difficult for potential investors to identify the value of the enterprise, thus leading to the company's initial public offering underpricing. Based on the signal theory, Liu et al. studied the role of organizational reputation in the company's initial underpricing. We analyzed 463 IPO companies in China from 2010 to 2016, and found that the two dimensions of corporate reputation, known for quality and overall popularity, were significantly negatively correlated with the IPO underpricing of companies. In addition, we find that investors' attention plays an intermediary role in the negative relationship between corporate reputation and the company's IPO underpricing (Liu et al., 2020).

The vertical concurrent appointment of executives is a vertical connection between major shareholders and managers, and its influence is mainly manifested in the following two aspects: first, from an agency theory, the vertical part-timers of the company can enhance the major shareholders' confidence in the company. The intensity of supervision makes it difficult to cover up negative information under larger external supervision, thereby reducing the risk of stock prices falling, which is a "supervision effect"; better control of listed companies by shareholders is also beneficial to the private interests of major shareholders, while major shareholders concealing negative information in order to hollow out small shareholders will increase the risk of stock market collapse, which is the "hollowout effect"; of course, it may also be because the major shareholders assign the company's management personnel to the company, so that the interests between the major shareholders and the entrusted company can be more coordinated, so that the hollowing out of the small shareholders can be reduced, which is the so-called "exploitation" Empty Effect". Exactly which effect plays a dominant role is unknown. Differences in TMT background characteristics such as age, tenure, education level, and functional background reflect differences in TMT values, cognitive attitudes, skills, and risk appetite, and ultimately lead to different corporate behaviors and organizational outcomes. From the existing research results, the heterogeneity of TMT background characteristics has an important impact on strategic change, corporate performance, and whether to use corporate venture capital. In the development process of the modern market economy, as an important part of the modern financial system, the capital market is an effective means of resource allocation. China's economic model involves active government intervention in the financial market. Brunnermeier et al. developed a theoretical framework in which intervention measures can prevent market collapse and volatility explosion, because short-term investors are unwilling to trade with noise traders. In the case of information friction, the government can change the market dynamics, because the noise in its intervention plan becomes an additional factor driving asset prices (Brunnermeier et al., 2022). Sreenu et al. studied whether the use of accounting conservatism in India reduced IPO underpricing, which is a concern of stakeholders and regulators. In addition, this study also examined how information asymmetry affects the meaning of IPO accounting conservatism (Sreenu et al., 2022). Therefore, this paper proposes a research on vertical concurrent executives, TMT heterogeneity and IPO underpricing—evidence from China's stock market. It is of practical significance to improve the efficiency of the financial market and its impact on the stock market is also of great research value.

The IPO price is jointly determined by the listed company and the underwriter of the shares. As it is the first public offering of the company, there is no experience of the company's stock issuance and the relevant stock trading price as a reference. Therefore, the determination of IPO price depends on the market forecast of the issuing company and underwriter, as well as the evaluation and judgment of investors. From the practice of issuing in various countries, it is common that the IPO price is moderately lower than the listing price in the secondary market. This is due to the unique information asymmetry in IP0 issuance in the stock market and the uncertainty risk compensation for the issuance waiting period. However, if the difference between the IPO price and the price on the first day of listing in the secondary market is too large, the rationality of IPO pricing is not tenable. A more successful IPO should be priced at the highest price that investors can tolerate. This means that issuing enterprises can raise the maximum required funds through the stock market. If the issue pricing is too low, causing a large issue underpricing, it indicates that the pricing is unsuccessful and unreasonable. In recent years, the government has been working hard to introduce institutional investors. The purpose is to stabilize the market by introducing institutional investors, so that institutional investors can use the large amount of funds in their hands and their professional capabilities to diversify their investments. Compared with individual investors, they have more positive market effects, so the government has formulated a series of policies to create a good investment environment for institutional investors. Hasan et al. evaluated the relationship between accounting conservatism and stock underpricing in a highly asymmetric information environment. The results show that there is no significant relationship between conservatism and no price reduction in the initial and secondary stock issuance. Other research results also show that in the case of asymmetric information, there is a positive relationship between conservatism and underpricing in the initial and secondary issuance (Hasan et al., 2021). The vertical concurrent appointment of the company's top managers is a relationship arrangement, which reflects the vertical connection between the company and the company, and the main problem in corporate governance is the relationship between the major shareholders and the management.

The research innovation contribution lies in the integration of data mining algorithm and regression equation algorithm to determine the heterogeneity of senior management team and IPO underpricing. It verifies the impact of investors in China's secondary market on IPO underpricing. In China, the phenomenon of "underpricing" of new shares is directly caused by the enthusiasm, irrational optimism and speculation of investors. The differences of risk tolerance of senior management team members are analyzed. The results show that, in the case of expectation gap, compared with the executive team with less tenure heterogeneity, the executive team with greater tenure heterogeneity from different perspectives and different perspectives has a deeper understanding of expectation gap. And may deal with the impact of the expected gap more quickly. The more heterogeneous the tenure of the senior management team is, the more likely the enterprise is to quickly take risk change actions to cope with the impact of the expected gap. When faced with expectation gap, companies with large difference in TMT education level are more likely to take risk changes to deal with it.

This paper empirically studies the impact of executive team management ability on IPO underpricing. Section 1 is the introduction. This part mainly expounds the research background and significance of China's stock market, and puts forward the research purpose, method and innovation of this paper. Section 2 mainly summarizes the relevant literature, summarizes the advantages and disadvantages, and puts forward the research ideas of this paper. Section 3 is the method part. Combining scientific algorithms, it focuses on vertical parallel executives, TMT heterogeneity and IPO underpricing. Section 4 is the experimental analysis. In this part, the data set is tested and the research results are analyzed. Section 5, conclusions and prospects. This part mainly reviews the main contents and results of this study, summarizes the research conclusions, and points out the direction of further research.

2 Related work

At present, most of the researches on the financing of listed companies in the low-carbon economy sector are about the financing forms of these enterprises, which are lack of systematicness. Due to the high dependence of low-carbon enterprises on capital, and China's capital market is not strong and effective. Therefore, it is necessary for low-carbon enterprises to spend energy to improve financing efficiency in order to achieve the goal of maximizing enterprise value. From the perspective of resource dependence and upper-level theory, Li examined how TMT's IPO restructuring (i.e., management changes before and after IPO) affected the company's performance in the years after IPO. This point is studied from the perspective of functional complementarity of TMT, that is, the degree of different functional knowledge that the company's TMT has mastered before and after IPO. The study believes that TMT's functional complementarities have a positive impact on the company's performance after IPO. In addition, the administrative discretion positively regulates this relationship through the measurement of CEO duality and TMT's internal board membership (Li, 2022). Heo and Ryoo investigated whether the issuer's accounting reporting attributes would affect the initial return of Korean emerging market bond issuance. The empirical results show that, generally speaking, the initial return of newly issued bonds is often negative (overpriced). More importantly, the degree of over pricing is positively related to the level of conditional accounting conservatism, which indicates that accounting conservatism alleviates information asymmetry in public debt financing (Heo and Ryoo, 2021). At this stage, the underwriter contacts investors who are willing to book new shares without price restrictions to understand their demand plans. They believe that in the pre underwriting stage of this IPO, information that is very important for underwriters to determine the issue price and maximize the overall income of the company can be obtained. The problem is how to encourage those investors who have more and more accurate information to truly reflect in the IP0 promotion stage. In order to avoid free riding, underwriters are likely to allocate shares and finally determine the issue price. Take certain measures to ensure that investors who are willing to truthfully reflect their information can obtain greater expected returns than those who are unwilling to truthfully reflect their information. One of the implicit meanings of this model is that the issue price will certainly be lower than the equilibrium price determined by the total market demand, so as to ensure that those investors who are willing to reflect the real demand information can obtain income.

When the information among investors is asymmetric, the effect of information superposition may occur. In order to avoid encountering the "winner's curse," the uninformed will understand the purchase intention of other investors before subscribing. When the voice of giving up buying is getting louder and louder, people with information will also doubt whether their information is true, and eventually waver. This is the so-called negative information superposition effect. Assume that emotional investors have optimistic beliefs about the future prospects of IP0. For the downward sloping demand curve of emotional investors, the purpose of the issuer is to rescue their consumer surplus as much as possible. The flooding of the stock market will reduce the stock price, so the best strategy involves controlling the total amount of stocks. The purpose is to prevent the stock price from falling. Finally, the real value of the stock will be displayed naturally and the price will return to the basic value. The IPO prospectus is an important document available to investors. It allows investors to understand the company. When the closing price of the initial public offering (IPO) is higher than its issuing price on the first trading day, IPO underpricing will occur. If investors know whether IPOs may be undervalued, they can obtain considerable returns by subscribing to those undervalued IPOs and selling shares on the first trading day (Tsui and Li, 2021). Eugene Y's research shows that such a management and social bond formed by vertical concurrent positions is a kind of social capital for subordinate companies, and this bond can promote information exchange, mutual influence and mutual solidarity (Eugene and Horowitz, 2022). Accounting conservatism (AC) is one of the components of financial reporting, which has been widely studied by academia to determine its impact on information quality. Accounting scholars have begun to explore how AC relates to different basic functional areas of organizations. Bhutta et al. examined 408 AC related index publications. The objectives of this work include identifying the main authors, literatures and journals, analyzing the regional distribution, scale and evolution of the knowledge base, exploring the current literature and academic structure, and highlighting contemporary trends (Bhutta et al., 2021). Lee et al. examined the relationship between the heterogeneity of TMT composition and corporate performance. Tissue relaxation is regarded as a regulatory variable affecting the above mediation relationship. Based on the CSR report data of Taiwan listed companies, we find that the heterogeneity of TMT education background and tenure has a negative impact on corporate performance, which is mediated by the greenhouse gas emission strategy (Lee et al., 2021). Ormiston et al. bridged the micro macro gap by addressing the continuous appeals from the strategic leadership, and influenced researchers to check the black box to consider the relationship between CEO characteristics and TMT emotional experience, thus affecting the company's results. We further consider the role of a key contextual factor in this relationship: TMT heterogeneity. We predict that CEO's personality, especially emotional stability, is positively related to TMT's emotional tone (Ormiston et al., 2022). Li and Jones used the concept of population fault line to study the dynamics of TMT subgroups, but the impact of TMT fault line on competitive behavior and performance results has not been well proved. In order to gain a deeper understanding, we developed a model that links TMT fault line, CEO-TMT power gap, competitive behavior and enterprise performance (Li and Jones, 2019). Su et al. examined the impact of TMT participation in decision-making and heterogeneity on management innovation. The research found that TMT participation in decision-making and heterogeneous individuals jointly promoted management innovation. In addition, the influence of TMT participation in decision-making is positively regulated by the company's age, while the influence of TMT heterogeneity is negatively regulated by the company's age. This research provides insights for the top management team on the importance of management innovation, and enriches the knowledge of the antecedents of management innovation (Su et al., 2022). Singh and Gupta studied the function and educational heterogeneity of TMT. Research the relationship between TMT quality and IPO listing date performance through the funds raised (Singh and Gupta, 2018). Yang et al. used the institutional theory for reference to explore the relationship between Chinese family participation, government relations and IPO underpricing. Compared with previous literature, we found that IPO underpricing of Chinese family firms tends to be lower than that of non-family firms. In addition, we found that the political relationship of family members enhanced the negative relationship between family participation and IPO underpricing. In contrast, state ownership alleviates these relationships (Yang et al., 2020). There are competing theoretical explanations and conflicting empirical evidence for the phenomenon of IPO underpricing of family firms. Kotlar et al. proposed a behavioral agent model with aversion to the loss realization logic to explain how the decision-making framework and preferences of household owners change during the IPO process, which depends on the initial loss of the current SEW and the new expectations of the future SEW (Kotlar et al., 2018).

The above-mentioned scholars have told a lot about vertical concurrent executives, TMT heterogeneity and IPO underpricing, but basically they only talk about one aspect. Therefore, from the perspective of China's stock market, this paper uses its related algorithms to describe the vertical concurrent positions of executives, TMT heterogeneity and IPO underpricing, and lay the foundation for the future financial stock market.

3 Methodology

At present, China's traditional financial institutions generally have the phenomenon of homogeneous competition, and the innovation ability is relatively weak. As a new business, low-carbon economy related business objectively requires financial institutions to innovate business operation mode and develop new green financial instruments under the premise of risk control. Therefore, "Low carbon economy" Development also provides opportunities for relevant financial institutions to innovate and develop. As the goal of developing a low-carbon economy matures, more and more financial institutions, enterprises and even private capital are involved in the field of carbon finance. This is an accelerator for financial institutions to improve their innovation capabilities. While financial institutions can improve their profits and competitiveness through continuous innovation, high profits will also stimulate innovation of the same kind. This will form a virtuous circle, thus To promote the continuous development of low-carbon economy, financial institutions will better meet the needs of society through financial innovation.

3.1 Analysis of the influence mechanism of senior executives' vertical concurrent jobs

The management ability of top management team is an abstract concept of supervisors. The senior management team is the strategic formulation and implementation layer of the enterprise, responsible for the organization and coordination of the whole enterprise, and has great decision-making power and control power over the enterprise management. Some variable data measuring team management ability are easy to obtain, such as relevant variable data of team composition characteristics. The management ability of the senior management team, that is, the team members rely on their own experience, knowledge, skills and resources. The ability to manage the business operation and achieve the business objectives. With Vertical concurrent appointment of executives is a vertical connection between major shareholders and the company. It can reduce the risk of a company's stock market collapse from the following two aspects: First, on an agency issue, vertical concurrent appointments of managers can make major shareholders better monitoring of management also makes it harder for management to cover up negative information, thereby reducing the risk of a company's stock price crashing in the future, a "surveillance effect." Second, on the second agency issue, the vertical concurrent management of management is a vertical connection between the major shareholder and the company, which can reduce the contradiction between the major shareholder and the minor shareholder, and also reduce the major shareholder's influence on the company. Hollowing can also reduce the cover-up of negative information about the company,

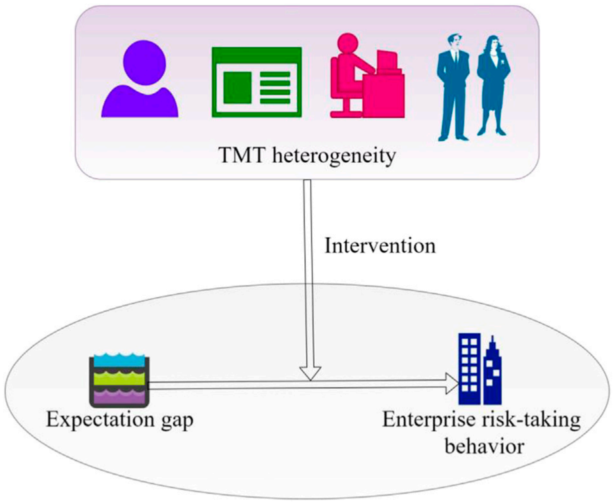


FIGURE 1
Theoretical testing model.

thereby reducing the company's future stock crash risk, reflecting the "less hollowing effect" on top managers.

3.1.1 Test the "supervision effect" hypothesis

Based on the hypothesis of "supervision effect", a hypothesis based on the first agency theory is put forward, that is, the vertical concurrent appointment of the company's top managers can enhance the company's monitoring ability, reduce the company's internal interests, reduce the bad information within the company, and then Reduce the risk of a company's stock price falling. On the basis of the hypothesis of "supervision effect," it can be concluded that when an agency problem of the company becomes more and more serious, that is, when the top management conceals self-interest such as bad information, the vertical concurrent management of the management as a means of supervision by major shareholders, its "supervision effect" will be more obvious.

3.1.2 Test the hypothesis of "less hollowing effect"

The theory of "less hollowing effect" mainly starts with the type of agency conflict. The hypothesis of "less hollowing effect" refers to a vertical relationship between the company's top managers and the company, which allows top managers to have a certain influence on the decision-making of major shareholders, and also can affect the interests of major shareholders and the company. Bundled together, so as to avoid the loss of large shareholders hollowing out the company. If executives are concurrently held vertically, the risk of stock declines can be reduced because it can reduce the cost of hollowing out large shareholders.

If the second type of agency conflict is more serious, that is, the ability to supervise large shareholders is weak, large shareholders are likely to hollow out small shareholders, causing the stock market to plummet. If the second type of proxy conflict is milder, that is, the major shareholders can get more supervision and restraint, then the major shareholders are more likely to want to empty their shares, thereby reducing the risk of the stock price falling. That is to say, if vertical concurrent executives can reduce the risk of a company's stock collapse, then the risk of stock price declines with vertical executive concurrent appointments is mainly concentrated in those second-tier companies with larger agency conflicts. In addition, executive support can improve the implementation of enterprise management practices by promoting employee authorization, establishing incentive mechanisms and enhancing communication between functional departments. A scientific and fair performance quantitative assessment system is needed to truly evaluate the work performance of each employee objectively and impartially, so that each assessment, reward and punishment can be based on, and provide a basis for further staff reduction and efficiency increase. The incentive mechanism of quantitative performance assessment can further enhance the incentive function of internal distribution, and adapt to the needs of modern enterprise downsizing and efficiency enhancement. At the same time, the results of quantitative performance appraisal are not only reflected in material distribution, but also in non-material distribution. Such as training opportunities, honors, promotion opportunities, laid-off diversion, etc. In order to give more effective play to the incentive role of quantitative performance assessment and stimulate the ability of every employee, the enterprise is full of vitality and vitality.

Low carbon procurement corresponds to the enterprise's low carbon strategy, aiming to meet the low carbon demand of products. The implementation of low-carbon procurement must fully consider the requirements of manufacturing and R&D departments. The low carbon attitude of senior executives is conducive to the communication and collaboration between multi-functional departments, and can ensure the effective implementation of low-carbon procurement. The low carbon attitude of senior executives makes the requirements for low carbon management clearer, and will strengthen the sharing of knowledge and technology related to low carbon management with suppliers.

The vertical concurrent role of senior executives will enhance the tax avoidance motivation of enterprises. According to the tunneling theory of large shareholders, the vertical concurrent role of senior executives improves the control power of large shareholders, provides convenience for large shareholders to seize or transfer enterprise resources, and causes the loss of enterprise cash resources. Tax avoidance by enterprises can directly save tax payment and increase the disposable cash flow of enterprises. The vertical concurrent role of senior executives will expand the tax avoidance space of enterprises. On the one hand, the vertical concurrent role of senior executives has aggravated the agency problem and the degree of information asymmetry, providing opportunities for tax avoidance activities of enterprises; On the other hand, the vertical concurrent tenure of senior executives has also improved the ability of management to avoid taxes, making it more difficult to supervise them.

3.2 Theoretical analysis of TMT

3.2.1 The regulatory role of TMT age heterogeneity

The experiences of peers are often the same, and this shapes their perceptions and beliefs. But young managers are more likely to make risky decisions because "trying out new, unprecedented strategies" can help them build their authority and reputation, which in turn can advance their careers. Older managers tend to avoid risky decisions for the following reasons: first, they have a strong ability to protect their financial and job security; while older managers often lack the analysis

TABLE 1 Commonly used financial data.

Method	Illustrate
Sales multiple method	Compare the total market capitalization between businesses to the sales ratio. The biggest advantage of this approach is that sales are always positive, while non-EBIT companies have negative EPS.
EBIT multiple	By comparing the ratio of total assets to EBIT among enterprises, it is found that EBIT will not have any impact on the company's profits, and can more accurately reflect the operating conditions of the company.
Customer number multiple	Compare the ratio of the total assets of the business to the number of customers. This approach is also valid for certain industries where market share is critical. In these industries, customers can bring long-term stable income to the company.

TABLE 2 IPO offering mechanism.

Mechanism	Illustrate
Cumulative bids	The issue price of new shares is determined by the underwriter, mainly based on recommendation, targeting institutional investors, collecting demand at different price levels, establishing market records, drawing demand curves, adjusting the issue price, and obtaining a reasonable issue price. During this period, the stock company has the right to freely distribute the shares.
Fixed price mechanism	Under normal circumstances, the underwriters do not have the right to allocate shares, but subscribe at a certain price. The stock price of a stock company is determined by the professional quality and professional experience of the stock company.
Auction mechanism	This is a highly market-oriented sales method, usually divided into three types: uniform price auction, differential price auction and "dirty" auction. Underwriters will sort according to the effective subscription price, and the subscription amount subscribed is equal to the issue price, which is The effective price, above which the bid is won. The so-called uniform price auction means that the effective price is the issue price of the "new stock".

TABLE 3 Comparison of general initial income of IPO pricing mechanism.

		Determination of issue price	
		Before getting information	After getting the information
Underwriter's Power	Underwriters cannot decide for themselves	Fixed price public offering (27%)	Auction method (12%)
	Underwriters can decide for themselves	Fixed price allows placement (37%)	Bookkeeping method (9%)

and processing of information to adapt to changing circumstances. Therefore, the age difference of TMT also increases when making risky decisions.

In the case of differences in expectations, although TMT has a large age heterogeneity and can help avoid extreme risk aversion and extreme risk appetite, the multiple perspectives and perspectives it provides can also help TMT better understand expectations difference. However, since TMT members vary widely in their risk tolerance, TMT can be highly divided in responding to expectations differences, making it difficult for TMT to reach consensus, leading companies to adopt risky behavioral changes in response to expectations difference. Generally speaking, the greater the environmental heterogeneity, the higher the complexity of the system. Therefore, it is a commonly adopted control method to reduce the impact of environmental heterogeneity on the system by improving the system's environmental adaptability and response speed to changes in environmental conditions. In the project, the project manager uses available resources to balance the factors that restrict each other.

3.2.2 Moderating role of TMT tenure heterogeneity

Tenure is the length of time that a specific individual works in a specific enterprise, and it represents the accumulation of individual professional and organizational-related knowledge. TMT members with shorter tenures bring different perspectives and different logics to explain events. Therefore, when tenure heterogeneity is large, TMT is more likely to see the world in different ways, which helps TMT to deeply dissect a specific problem or objective phenomenon, and ultimately have a positive impact on the enterprise.

The enterprise will change its innovation behavior under the condition of expectation gap. Specifically, enterprises will increase their R&D intensity. Considering that the change actions taken by enterprises to solve performance problems are more or less risky. The expectation gap is positively increasing the possibility of enterprise's risk taking change behavior. In the expectation gap situation, compared with TMT with less tenure heterogeneity, TMT with different perspectives and diverse viewpoints with large tenure heterogeneity have a deeper understanding of the expectation gap and may respond more quickly to the shock of the expectation gap. The greater the heterogeneity of TMT tenure, the more likely firms are to take risky change behaviors quickly in response to the shock of the expectation gap.

3.2.3 The moderating effect of TMT educational level heterogeneity

The heterogeneity of TMT education is manifested by the heterogeneity of TMT educational background and educational level. Although everyone in TMT is highly educated, this does not necessarily bring competitive advantages to the company. The reason is that the same cognitive structure and mind map make it impossible for TMT to conduct business search in an innovative way, thus causing

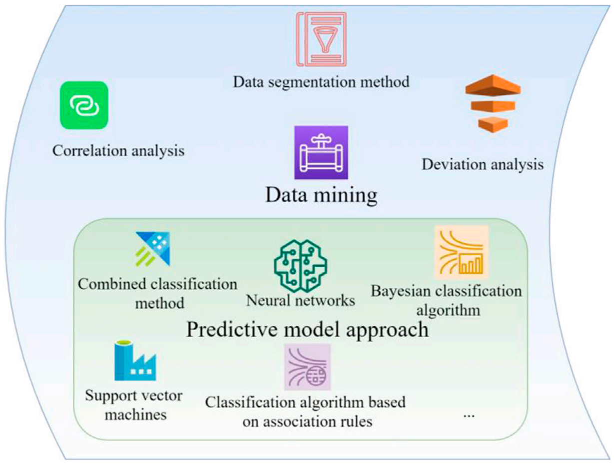


FIGURE 2
Main methods of data mining.

TMT to fall into a state of "groupthink". In sharp contrast, the diversity of TMT in terms of cognitive perspectives, information sources, and capabilities enables TMT to scan the business environment in an all-round way and formulate innovative solutions.

In the situation of expectation gap, TMT with large educational level heterogeneity can effectively avoid "groupthink," and can understand and deeply interpret the expectation gap from multiple cognitive perspectives, which helps TMT realize the reflection behind the expectation gap, which in turn increases the possibility of companies implementing change-response behaviors under the condition of expectations gap. This means that TMT with greater educational level heterogeneity will have a relatively higher propensity to engage in risk-taking activities. To sum up, it can be speculated that when faced with a gap in expectations, companies with greater heterogeneity in TMT education levels are more likely to respond by taking risky changes.

3.2.4 Moderating role of TMT functional background heterogeneity

The functional background has a great influence on the cognitive basis of managers, and its inherent meaning is: sensitivity to specific stimuli, priority awareness of opportunities, interpretation of tasks, discussion of tasks, and promotion of the company's competitiveness. preference. Heterogeneity in functional context can capture managers' skills and available network resources, while greater heterogeneity in functional context can lead to skills, abilities, open-mindedness, broader networks, and greater capacity for complex problems. Provide creative solutions.

In the expectation gap situation, although the large functional background heterogeneity promotes TMT understanding of the expectation gap, there are serious differences in the risky change behaviors that TMT members with different functional backgrounds may take in response to the expectation gap. This kind of disagreement hinders the cohesion and effective decision-making of the TMT, which makes it difficult for the TMT to reach a consensus on which risky change behaviors to take, and ultimately reduces the possibility of enterprises adopting risky changes to deal with the gap in expectations.

The theoretical test model of this paper is shown in Figure 1.

The difference in tenure and age hinders the communication between team members and the effective allocation of resources, which limits the growth of the enterprise. Therefore, it is better to choose members with small differences in age and tenure, so that everyone can have discussions at the same level. At the same time, communication between members is more smooth, reducing communication costs. Teams with highly heterogeneous professional backgrounds can obtain more external resources, diversified skills and practical theoretical knowledge. Problems can be examined and analyzed from various perspectives to effectively improve the quality of decision-making. Gender heterogeneity has a significant positive correlation with corporate performance, and coordinating gender differences in teams can not only improve team efficiency. It is also conducive to the male and female management to give full play to their talents. Team building cannot be separated from an equal and free corporate culture.

3.3 Theories related to IPO underpricing

3.3.1 Theoretical model of IPO pricing

The discounted earnings model is used to estimate the market value of a business, which is discounted based on the future cash flow of the business and the future value of the business. Due to the different assumptions about the company's future cash flow, the earnings discount model can be subdivided into a cash flow constant model, a stable growth model and a multi-stage growth model.

① Cash flow constant model: in this model, it is assumed that the cash flow of some enterprises is very stable and will not change over time. It is F assumed that the company's constant income cash flow every year after the company V_0 's issuance is the company's market value at the beginning of the stock issuance, the company's market value after V_n the n year, and r the company's cost of capital. Then the cash flow constant model can be expressed by Eq. 1:

$$V_0 = F\sum_{t=1}^{n} \frac{1}{(1+r)^t} + \frac{V_n}{(1+r)^n} \tag{1}$$

If it is assumed that the company can operate for an unlimited number of periods and generate constant income cash flow stably every year, it is shown in Eq. 2:

$$\mathrm{T}_0 = \frac{F}{r} \tag{2}$$

② Stable growth model: in the stable growth model, it is considered that the future cash flow of the enterprise is F not static, but changes at a stable and constant growth rate every year g, then the stable growth model is shown in Eq. 3:

$$H_0 = \frac{F_1}{r-g} \tag{3}$$

③ Multi-stage growth model: in many cases, the company's cash flow is not as simple as the above two models assume, neither static nor changing at a steady growth rate. A model that meets the assumption of this simple case can be expressed by Eq. 4:

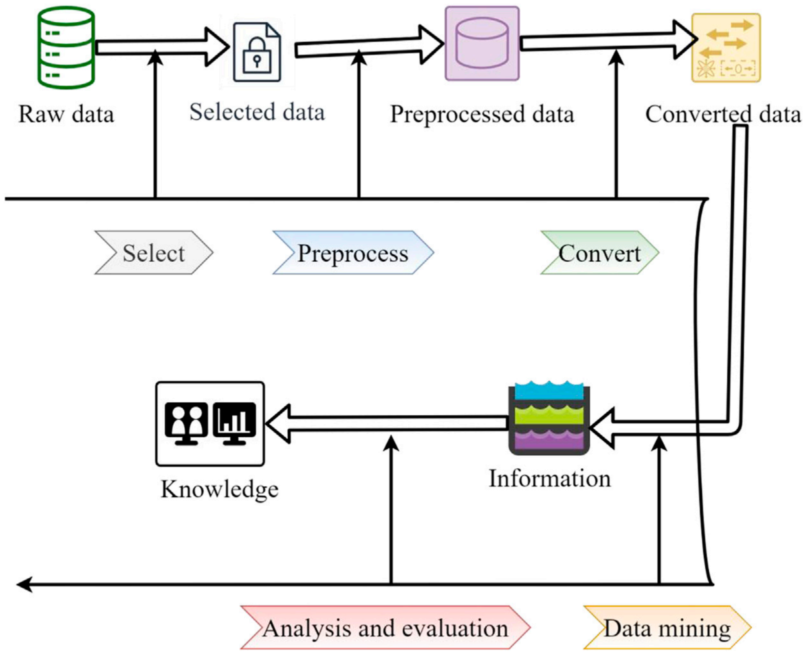


FIGURE 3
The basic process of data mining.

$$K_0 = \sum_{t=1}^{n} \frac{F_t}{(1+r)^t} + \frac{F_{n+1}}{(1+r)^n \bullet (r-g)} \quad (4)$$

Selecting low carbon suppliers is the simplest way to achieve low carbon emissions in the supplier sector. However, large-scale supplier replacement may affect the flexibility of the enterprise, and the cost, quality, innovation and other objectives of the enterprise may be adversely affected. Work with suppliers to reduce carbon emissions as a better option. Low carbon collaboration with suppliers mainly refers to the design of low carbon management behavior. Enterprises directly participate in the carbon management of suppliers. Reflect the high degree of vertical integration between enterprises and suppliers, help to improve the utilization rate of new low-carbon technologies of both sides, and enhance the confidence of enterprises in low-carbon investment. Therefore, low carbon collaboration with suppliers will help enterprises implement low carbon procurement. Discounted profit models are theoretically the most accurate for valuing a business if an accurate forecast of the company's future cash flows can be made. However, most of the companies financing in the capital market are in the early stage of development or growth stage, there are huge risks and potential growth space, so it is difficult to accurately predict the company's future cash flow.

3.3.2 Price-earnings ratio pricing model

The price-earnings ratio pricing model is actually a way of estimating the value of a company by comparing financial data. Commonly used financial indicators include price-to-book ratio, EBIT multiple, sales revenue multiple, and customer number multiple. Among the many financial sources, the most common method to use the price-earnings ratio as a way to assess the value of a new stock is a public company. When using the price-earnings ratio to evaluate the market value of a new stock, the price-earnings ratio of the listed company must be valued first, and then the market value of the listed company must be estimated by multiplying the estimated price-earnings ratio by the expected earnings of the listed company. When using the financial data comparison method to estimate the intrinsic value of new shares, the financial data often used are shown in Table 1.

3.3.3 IPO offering mechanism

To study and analyze IPO issues, it is also necessary to introduce concepts such as IPO offering mechanism and its evolution at home and abroad, especially in China. IPO offering mechanism has always been considered an important factor affecting IPO underpricing.

The IPO offering mechanism is usually a transaction mechanism for selling shares to investors, which includes the whole process of IPO pricing, issuance and sale to investors. Chemmanur et al. analyzed the relationship between venture capital (VC) support and the quality of senior management team (TMT) during the initial public offering (IPO) of the company, and the impact of VC support and TMT quality on its post IPO business performance growth and IPO company valuation, using the manually collected data from a large number of start-up company listing samples (Chemmanur et al., 2021). Ichikohji et al. investigated how the performance of start-up companies in the period before the initial public offering (IPO) was affected by the macro environment. The study found that the average time from entrepreneurship to IPO is relatively long for companies operating in a favorable economic environment. This may be because the favorable economic environment and improved business conditions have stimulated startups that have been taking a wait-and-see attitude (Ichikohji et al., 2022). Its purpose is to avoid information asymmetry in the IPO market, ensure the information disclosure of

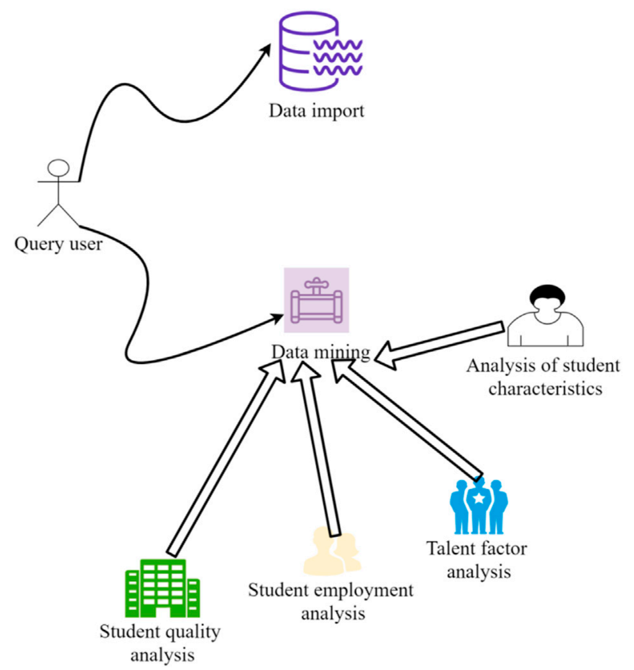


FIGURE 4
System use case diagram.

IPO issuers, and effectively reduce the underpricing rate. There are three widely used IPO offering mechanisms, as shown in Table 2.

Generally speaking, the fixed price method does not price through the market mechanism, lacks an effective price discovery process, and the subjective judgment ability is in the dominant position, but the procedure is simple and can save the cost of issuance. The general initial income levels of the above three pricing mechanisms are shown in Table 3.

3.4 Data mining

For the collection of Chinese stock market data, data mining technology needs to be used. The data mining method is shown in Figure 2.

The basic process of data mining is shown in Figure 3. The system use case diagram is shown in Figure 4. The steps in the process are described as follows.

(1) Preparatory stage: This stage includes defining problems, understanding objects, collecting data, etc., collecting internal and external data related to enterprise objects, and filtering out data suitable for data mining. It is necessary to have a clear understanding and clear purpose of the problem to be solved, which is of great help to the subsequent knowledge evaluation and analysis. And this step is also the most time-consuming, accounting for about half of the entire data mining.
(2) Preprocessing: including data cleaning, compression, transformation, etc. Investigate the quality of the data in order to prepare it for further analysis and determine the type of mining operations.
(3) Data mining: Data mining includes the design and modeling of algorithms. In data mining, how to construct an analytical model suitable for mining algorithms is crucial to the success or failure of data mining.
(4) Follow-up work: This stage includes interpreting, outputting, evaluating, analyzing and using the results, and interpreting and evaluating the results. The analysis methods it adopts are generally based on data mining operations, and often use visualization techniques. Data visualization is a scientific and technological research on the visual representation of data. The visual representation of this data is defined as information extracted in a summary form, including various attributes and variables of corresponding information units. The process of representing the data in a large dataset in the form of graphics and images, and using data analysis and development tools to discover the unknown information therein. Compared with special technical methods such as stereo modeling, data visualization covers a much wider range of technical methods. The data visualization in this paper is displayed by understanding the line graph of the trend program.

When designing normalized database logic, appropriate rules for breaking normalization should also be considered. The so-called data model optimization is to determine the dependencies between data and eliminate redundant links in the relational model. In research, it can be further studied by algorithms, as shown in Eqs 5–8.

$$H(X) = -\sum_{r=1}^{R} p(Xi)I(Xi) = -\sum_{r=1}^{r} p(X)\log p(X_i) \tag{5}$$

$$E(E) = -\frac{p}{p+N}\log\frac{p}{p+n} - \frac{N}{p+N}\log\frac{N}{p+N} \tag{6}$$

$$E(Ei) = -\frac{pi}{pi+Ni}\log\frac{pi}{pi+ni} - \frac{Ni}{\mathrm{pi}+Ni}\log\frac{Ni}{pi+Ni} \tag{7}$$

$$E(A) = \sum_{R=1}^{R}\frac{Pi+Ni}{p+N}E(Ei) \tag{8}$$

Therefore, the corresponding algorithm formulas are proposed according to the properties as shown in Eqs. 9, 10.

$$E(Ei) = -\sum_{j=1}^{c}\frac{P_{ij}}{|Ei|}\log\frac{P_{ij}}{|Ei|} \tag{9}$$

$$E(A) = \sum_{i=1}^{v}\frac{|Ei|}{|E|}E(Ei) \tag{10}$$

3.5 Model design

Using the regression equation, as shown in Eq. 11.

$$R_{j,t} = \alpha_j + \beta_1 R_{m,t-2} + \beta_2 R_{m,t-1} + \beta_3 R_{m,t} + \beta_4 R_{m,t+1} + \beta_5 R_{m,t+2} + \varepsilon_{j,t} \tag{11}$$

1) Negative return skewness coefficient NCSKEW, as shown in Eq. 12.

$$NCSKEW_{j,t} = -\frac{n(n-1)^{\frac{3}{2}}\sum W_{j,t}^3}{(n-1)(n-2)\left(\sum W_{j,t}^2\right)^{\frac{3}{2}}} \tag{12}$$

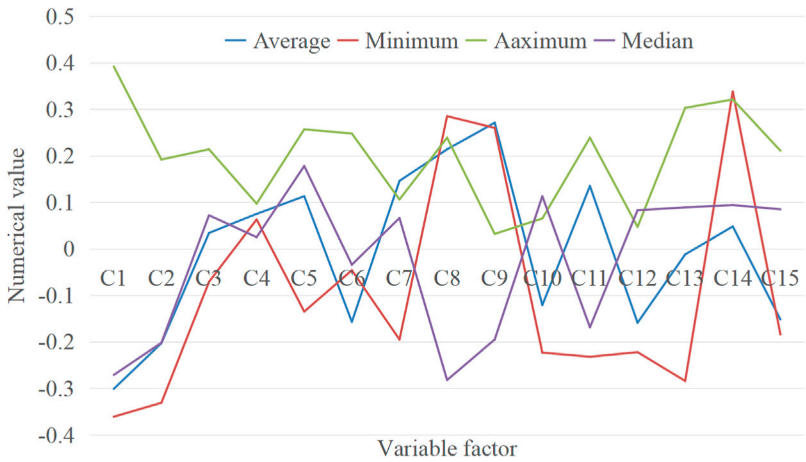


FIGURE 5
Overall distribution of variables.

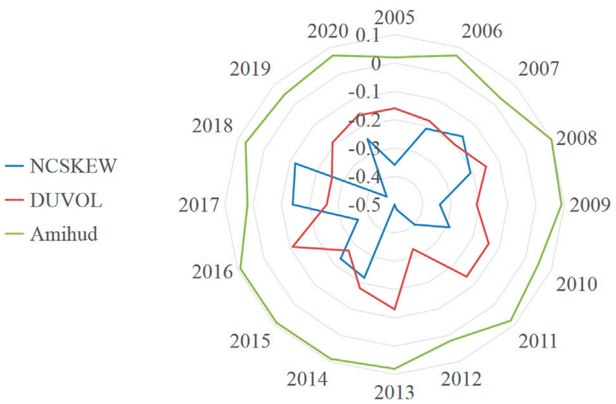


FIGURE 6
Year-by-year statistics of the mean values of key variables.

2) The upper and lower volatility ratio DUVOL of yield, as shown in Eq. 13.

$$DUVOL_{j,t} = \log \frac{(n_u - 1)\sum_{down} W_{j,t}^2}{(n_d - 1)\sum_{up} W_{j,t}^2} \tag{13}$$

In the part of heterogeneity analysis of institutional investors, according to their shareholding characteristics, that is, whether they can show the stability of time and industry dimension in the shareholding of relevant listed companies, dummy variables are set according to the heterogeneity, and by comparing the current year's shareholding ratio with The ratio of the standard deviation of the shareholding ratio in the previous 3 years is compared with the median of the industry in the current year. If it exceeds the median, the value is 1, representing a stable type; if it is less than the median, it is 0, representing a transaction-oriented institutional investor, as shown in the Eq. 14 shown.

$$SD_{n,t} = \frac{INVH_{nt}}{STD(INVH_{nt-3}, INVH_{nt-2}, INVH_{nt-1})} \tag{14}$$

The structure of the securities market is undergoing significant changes, that is, from the past individual investors as the main body to institutional investors as the main body. The fund has fallen into the risk of decentralized investment, and the structure has changed. Therefore, the mainstream operation behavior of institutional investors has undergone significant changes. As one of the largest institutional investors in the market, the shares held by funds have changed from relatively centralized to relatively decentralized. The reduction of shareholding concentration indicates that the funds are not more concentrated in one or several stocks than in the securities market. Instead, it adopts a decentralized strategy to invest funds evenly or relatively evenly in each fund portfolio. This can also be seen from the following analysis of shareholding quantity.

The reconstructed illiquidity index, Amihud, is used as an index to measure the stock liquidity risk in this paper, and Eq. 15 is obtained.

$$Amihud = \frac{1}{N}\sum_{t=1}^{N} \frac{|r_t|}{Q_t/10^8} \tag{15}$$

4 Result analysis and discussion

This paper collects IPO underpricing, TMT, senior executives' vertical part-time jobs and other relevant data from IPO prospectuses of listed companies in China's A-share market and other databases. The sample is composed of 550 companies listed in China's A-share market from 2011 to 2019, using a stepwise linear regression method with appropriate control variables. The business model of low-carbon industry development is relatively new and needs a large amount of funds to support it. It is necessary to vigorously explore various financing channels and ways. The government should encourage and support the listed companies on the main board, small and medium-sized board, GEM and science and technology innovation board to actively carry out low-carbon business, develop low-carbon economy and provide strong capital support. The government can also encourage companies to go public and issue bonds to carry out low-carbon business by lowering the listing standards and bond issuance

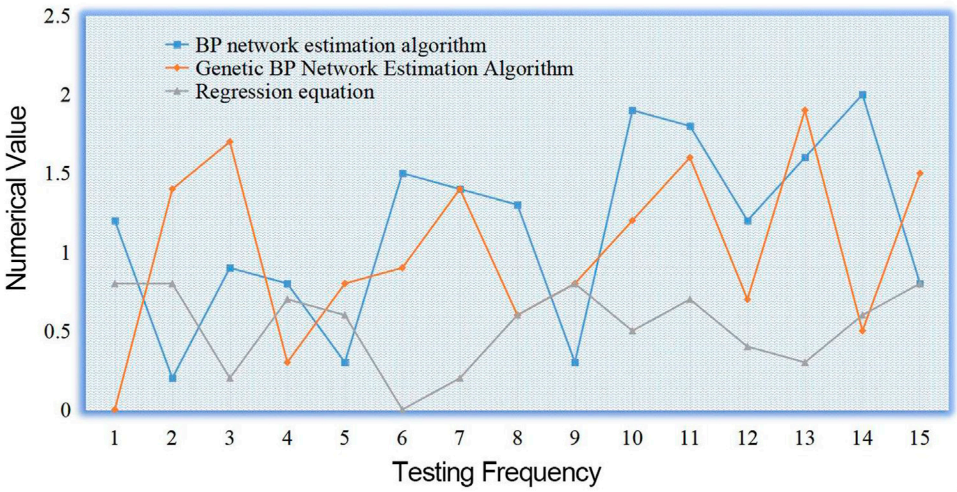


FIGURE 7
Error comparison chart of the algorithm.

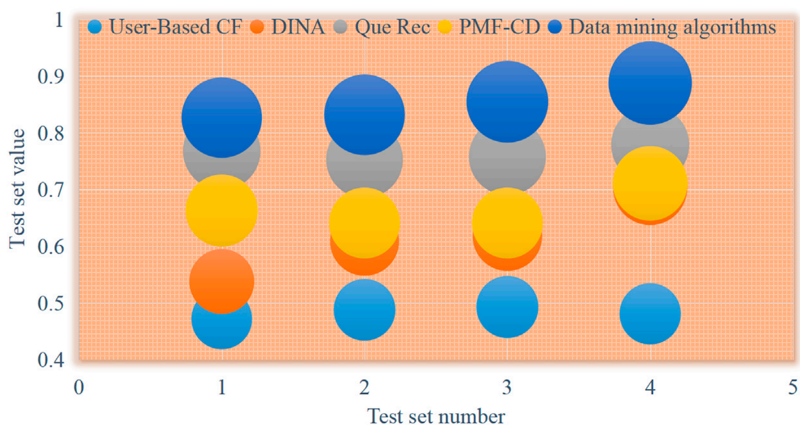


FIGURE 8
P1 value of simple stock market resource results.

standards. At the same time, energy conservation and emission reduction enterprises can issue corporate bonds, medium and long-term bills and short-term financing bonds to obtain financial support from the bond market. Strong financial support can expand the scale of the carbon financial market. Stata15.1 software was used to descriptive statistics of the samples, followed by the mean, minimum, maximum and median of the research variables and control variables in this paper, and the overall distribution of the variables was observed, as shown in Figure 5.

It can be seen from Figure 5 that the mean values of NCSKEW (C1) and DUVOL (C2) are −0.301 and −0.203, respectively, which are close to the values of the descriptive statistics studied. The dependent variable data in this paper have certain reliability. The minimum value of NCSKEW is −0.361 and the maximum value is 0.392, indicating that the degree of dispersion of the crash risk of different stocks is relatively large. Another indicator DUVOL (C3) also has the same situation, which also shows that this paper studies its influencing factors. necessity. Regarding the liquidity risk indicator Amihud (C4), the minimum value is 0.063 and the maximum value is 0.097, indicating that the scale of Chinese listed companies has a large difference.

It can be seen from Figure 6 that the average value of NCSKKEW and DUVOL has a relatively large fluctuation range, reaching the lowest point in 2015 and 2012, indicating that the probability of a relatively stable crash risk in the stock market is small. Subsequently, the risk of stock crashes in 2017 and 2018 increased sharply, and the Shenzhen and Shanghai indexes fell by more than 24% in 2018. China's stock market has been hit hard by the 18-year-old Sino-US trade war, and at the same time, a rise in the illiquidity factor value means a drop in stock liquidity. In 2019, as the impact of the trade dispute dissipated and the domestic economy recovered, the risk of a stock market price crash and the resulting volatility in liquidity.

By constructing the function of the key variable system and using the regression equation, the dynamic search of the optimal evaluation scheme is carried out under the premise of dimension direction and multi-objective constraints. It can be seen from Figure 7 that the overall fluctuation of the regression equation is relatively minimum,

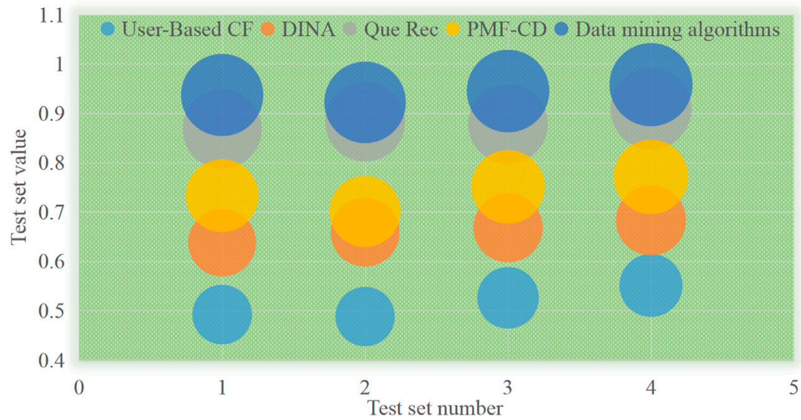


FIGURE 9
P1 value of complex stock market resource results.

and the error value is basically within 1, indicating that the numerical error effect of this method is the best. BP network estimation algorithm and genetic BP network estimation algorithm have the highest error fluctuation and data sparsity. Therefore, the two evaluation schemes are different from the regression equation.

In the experiment process, in order to observe different data sparse degrees of applying different algorithms and observe their effects, this paper selects 70%, 50%, 30%, and 10% from all data sets as test data sets, and the rest are used as training data sets. That is, when 70% of the data is randomly selected as the test data, it means that the remaining 30% is used as the training set for the test set data, and the same is true for 50%, 30%, and 10%. In addition, within the range of the difficulty value of 0.6, the stock market resources are divided into simple stock market resources and complex stock market resources, and a comparative study of the recommendation effects of different types of stock market resources is carried out, as shown in Figures 8, 9 shown.

It can be seen from Figures 8, 9 that with the continuous reduction of the test set ratio, that is, the continuous increase of the training set ratio, the recommendation accuracy of the data mining algorithm in the simple stock market resources and the complex stock market resources is generally better than other methods. Four algorithms. Specifically, when recommending simple stock market resources, the P1 value is 8.6% higher than the other four algorithms as a whole, and can reach 0.888 when the test set is 10%; when recommending complex stock market resources, the P1 value is higher than the other four algorithms. These algorithms have an average improvement of 5.6%, reaching 0.958 at 10% in the test set. The above results show that the data mining algorithm is effective in increasing the recommendation accuracy and improving the recommendation results, ensuring a higher recommendation accuracy.

5 Conclusion

This paper confirms that there is a positive relationship between the age heterogeneity of senior management team and innovation output performance. The career background heterogeneity of senior management team tenure heterogeneity has a positive relationship with innovation process performance. There is a weak positive correlation between the heterogeneity of senior management team's professional background and innovation output performance. The age heterogeneity, occupational background heterogeneity, gender heterogeneity, professional background heterogeneity and tenure heterogeneity of senior executives in high-tech enterprises have a stronger impact on enterprise innovation performance. The results verify the impact of investors in China's secondary market on IPO underpricing. In China, the enthusiasm, irrational optimism and speculation of investors directly led to the phenomenon of "underpricing" of new shares. The greater the power of senior executives, that is, their vertical part-time positions will have a greater impact on the risk of future stock collapse of the company. The management ability of the senior management team is positively related to the market valuation of the enterprise. Excellent managers enhance the value of the enterprise. The management ability of the top management team has a demonstrative effect on the enterprise value, and a good management team can act as the value signal of the enterprise. Transfer the real value of the enterprise to outsiders, and reduce the degree of information asymmetry of the enterprise in the stock market, thus affecting the valuation of investors and reducing IPO underpricing. However, in reality, there are also many different performance feedback. When faced with different performance feedback, how the heterogeneous TMT will explain, and what kind of risk changes or what kind of behavioral risk changes need to be further explored in future research.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

XZ performed methodology and validation, GF made the formal analysis and data curation, YR wrote the original draft.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Bhutta, U., Martins, J. N., Mata, M. N., Raza, A., Dantas, R. M., Correia, A. B., et al. (2021). Intellectual structure and evolution of accounting conservatism research: Past trends and future research suggestions. *Int. J. Financial Stud.* 9 (3), 35. doi:10.3390/ijfs9030035

Brunnermeier, M. K., Sockin, M., and Xiong, W. (2022). China's model of managing the financial system. *Rev. Econ. Stud.* 89 (6), 3115–3153. doi:10.1093/restud/rdab098

Chemmanur, T. J., Gupta, M., Simonyan, K., and Tehranian, H. (2021). The relationship between venture capital backing and the top management team quality of firms going public and implications for initial public offerings. *J. Bus. Ventur.* 36 (6), 106148. doi:10.1016/j.jbusvent.2021.106148

Eugene, Y., and Horowitz, J. M. (2022). The role of the PERT in the management and therapeutic decision-making in pulmonary embolism. *Eur. Heart J. Acute Cardiovasc. Care* 15 (3), 131–137.

Hasan, H. F., Khalbas, H. N., and Kadhim, S. C. (2021). Accounting conservatism and stock underpricing in high information asymmetry setting. *Industrial Eng. Manag. Syst.* 20 (4), 756–768. doi:10.7232/iems.2021.20.4.756

Heo, K., and Ryoo, S. (2021). The effect of accounting conservatism on the pricing of newly issued bonds: Evidence from korea. *Acad. Account. Financial Stud. J.* 25 (1), 1–13.

Ichikohji, T., Nakano, K., and Ogami, M. (2022). Hot market (Abenomics) impact on the time to IPO. *Ann. Bus. Adm. Sci.* 21 (2), 47–60. doi:10.7880/abas.0220125a

Kotlar, J., Signori, A., De Massis, A., and Vismara, S. (2018). Financial wealth, socioemotional wealth, and IPO underpricing in family firms: A two-stage gamble model. *Acad. Manag. J.* 61 (3), 1073–1099. doi:10.5465/amj.2016.0256

Lee, T., Liu, W. T., and Yu, J. X. (2021). Does TMT composition matter to environmental policy and firm performance? The role of organizational slack. *Corp. Soc. Responsib. Environ. Manag.* 28 (1), 196–213. doi:10.1002/csr.2042

Li, J. (2022). TMT functional complementarity and post-IPO performance: Evidence from the US biotechnology industry. *Long. Range Plan.* 55 (6), 102178. doi:10.1016/j.lrp.2021.102178

Li, M., and Jones, C. D. (2019). The effects of TMT faultlines and CEO-TMT power disparity on competitive behavior and firm performance. *Group and Organ. Manag.* 44 (5), 874–914. doi:10.1177/1059601118813790

Liu, Y., Cheng, P., OuYang, Z., and Wang, A. (2020). Information asymmetry and investor valuations of initial public offerings: Two dimensions of organizational reputation as stock market signals. *Manag. Organ. Rev.* 16 (4), 945–964. doi:10.1017/mor.2019.28

Ormiston, M. E., Wong, E. M., and Ha, J. (2022). The role of CEO emotional stability and team heterogeneity in shaping the top management team affective tone and firm performance relationship. *Leadersh. Q.* 33 (3), 101543. doi:10.1016/j.leaqua.2021.101543

Qi, S. Z., Zhou, C. B., Li, K., and Tang, S. Y. (2021). Influence of a pilot carbon trading policy on enterprises' low-carbon innovation in China. *Clim. Policy* 21 (3), 318–336. doi:10.1080/14693062.2020.1864268

Singh, B., and Gupta, K. (2018). Relationship between management quality certification and IPO underpricing: Evidence from India. *J. Entrepreneursh. Manag.* 7 (3), 1.

Sreenu, N., Pradhan, A. K., Xuan, V. V., and Naik, B. K. R. (2022). Impact of accounting conservatism on IPO under-pricing: Evidence from India. *Cogent Econ. Finance* 10 (1), 2132641. doi:10.1080/23322039.2022.2132641

Su, Z., Chen, J., Guo, H., and Wang, D. (2022). Top management team's participative decision-making, heterogeneity, and management innovation: An information processing perspective. *Asia Pac. J. Manag.* 39 (1), 149–171. doi:10.1007/s10490-021-09752-2

Tsui, C. S. K., and Li, K. C. K. (2021). IPO underpricing and prospectus readability: A machine learning approach. *J. Appl. Bus. Econ.* 23 (7), 151–159.

Wang, H., He, W., and Yang, Y. (2022). Is heterogeneity better? The impact of top management team characteristics on enterprise innovation performance. *Behav. Sci.* 12 (6), 164. doi:10.3390/bs12060164

Yang, J., Ma, J., and Doty, D. H. (2020). Family involvement, governmental connections, and IPO underpricing of SMEs in China. *Fam. Bus. Rev.* 33 (2), 175–193. doi:10.1177/0894486520905180

frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 24 March 2023
DOI 10.3389/fenrg.2023.1141793

OPEN ACCESS

EDITED BY
Wen-Tsao Pan,
Hwa Hsia University of Technology,
Taiwan

REVIEWED BY
Crenguţa-Ileana Sinisi,
University of Piteşti, Romania
Feng Hu,
Zhejiang Gongshang University, China

*CORRESPONDENCE
Min Su,
sumin@tyut.edu.cn
Yu Duan,
duanyu0997@link.tyut.edu.cn

†These authors have contributed equally to this work and share first authorship

SPECIALTY SECTION
This article was submitted to Sustainable Energy Systems,
a section of the journal
Frontiers in Energy Research

RECEIVED 10 January 2023
ACCEPTED 13 March 2023
PUBLISHED 24 March 2023

CITATION
Su M, Duan Y and Cui Y (2023), The digital economy and corporate credit risk: An empirical study based on Chinese new energy enterprises.
Front. Energy Res. 11:1141793.
doi: 10.3389/fenrg.2023.1141793

The digital economy and corporate credit risk: An empirical study based on Chinese new energy enterprises

Min Su*†, Yu Duan*† and Yifan Cui

College of Economics and Management, Taiyuan University of Technology, Taiyuan, China

The integration of digital technologies is exhibiting an upward trend in Chinese enterprises, and the degree of corporate credit risk is directly proportional to their financial sustainability. Based on panel data of new energy enterprises from 2012 to 2020, this article makes an empirical study on the direct effect, mediating effect, and moderating effect of the digital economy (DE) on the new energy enterprises' credit risk. It is found that the digital economy could significantly mitigate the credit risk of new energy enterprises by improving total factor productivity and amplifying the potential default cost. When the digital economy affects corporate credit risk, the development of the new energy industry acts as an intermediary, and knowledge spillover acts as a moderator. Furthermore, considering knowledge spillover as the threshold variable, the digital economy has a double-threshold effect. The marginal impact fluctuates from dropping to increasing as the knowledge spillover level increases. As for the region's heterogeneity, the digital economy has benefited eastern China more than central and western China, possibly due to the differences in economic structure, capital intensity, and policy institutions. In view of these findings, this study provides a reference for China to mitigate corporate credit risk in the digital economy era.

KEYWORDS

digital economy, credit risk management, knowledge spillover, new energy enterprises, KMV model

1 Introduction

As one of China's seven emerging strategic industries, the new energy industry has distinct development advantages. Characterized by low consumption, low emissions, and low energy pollution, the production model of the new energy sector satisfies the fundamental criteria for environmental protection and low-carbon development (Chen, 2011). To achieve the "double carbon" goal, the new energy industry becomes the mainstream direction of future growth for China's energy industry (Zhang and Qian, 2023). Meanwhile, it pertains to an industry that is capital- and technology-intensive. The industrial chain is extensive and comprises numerous sectors. Other businesses in the chain will then have a more significant promotional effect. Therefore, the degree of new energy industrial development has become an essential indicator of a country's or region's level of green innovation. However, China's new energy industry is still in its initial stages of transformation and is exposed to a variety of risks, including credit risk, which is progressively gaining attention.

In the era of the digital economy, new energy enterprises are presented with the historic opportunity and challenge of incorporating green transformation with economic growth. Some advanced companies have significantly increased green product innovation due to the integration of digital technologies (Cioacă, et al., 2020; Jones and Wynn, 2021). According to some earlier studies, the digital economy may impact new energy firms' performance through three paths (Zhou et al., 2022). The primary objective is to enhance the effectiveness of resource allocation (Nascimento et al., 2018). Data has evolved into a critical component of manufacturing. Its distinct value and function have increased total factor productivity. By integrating data with diverse production activities, the digital economy reshapes new energy firms' production and working modes and realizes the intelligent linkage of the supply and service chains (Li and Wang, 2022). For instance, digital trading platforms circumvent the limitations of traditional sales models, allowing new energy enterprises to optimize their production processes and design unique solutions and marketing strategies in response to market demand (Qi and Xiao, 2020). Such a business logic increases the marginal utility of customers and promotes the accurate distribution of production factors (Fu et al., 2020). The second objective is to broaden the innovation-driven impact. Digital technologies encourage resource conservation and green production and help address crucial technology constraints (Heo and Lee, 2019). In this sense, the digital economy can effectively enhance an organization's capacity for technological innovation and ground-breaking invention. The third objective is to transform new energy industries digitally. The increased usage of digital technologies constantly generates new industrial growth points, providing tremendous force for the long-term development of new energy enterprises (Jabłoński, 2018). Besides, scholars also investigate how the digital economy impacts enterprise business models (Tan et al., 2007), organizational structures (Nuryaman, 2015), governance mechanisms (Gopalakrishnan and Mohapatra, 2020), Etc.

Although the digital economy has empowered enterprises to grow sustainably, issues such as the monopoly of Internet giants, the herding effect, the siphoning impact, and information security exacerbate economic instability and negatively influence the development of enterprises. Therefore, there needs to be more concrete evidence concerning the effect of the digital economy on mitigating corporate credit risk. However, whether the digital economy contributes to reducing corporate credit risk? What is the system that allows it to function? What regional peculiarities does the impact of the digital economy have on the credit risk of new energy enterprises? The responses to these questions serve as a guide for decision-making entities. These are also essential for policy implementation and offer theoretical and empirical considerations for developing China's digital economy.

The marginal contributions of this paper are as follows: Firstly, this study aims to integrate the digital economy and corporate credit risk into a unified research framework and examine the mechanisms, thereby contributing to the relevant literature. Secondly, this paper uses the Gaussian mixture model and constructs an iterative process to determine the value of the company's assets. This enhances the accuracy and versatility of the KMV model for calculating the credit risk of new energy companies. Thirdly, this study demonstrates the geographical heterogeneity of the effect of the digital economy. Eastern China has benefited from the digital economy more than central and western China, which may be related to variations in economic structure, capital intensity, and institutional frameworks for policymaking.

The remaining sections of this work are as follows. Section 2 presents a literature review. The hypotheses are proposed in Section 3. Section 4 outlines the empirical methods and the data. Section 5 includes empirical evidence on how the digital economy affects the credit risk of new energy firms. Section 6 contains conclusions and policy implications.

2 Literature review

The digital economy has arisen as a new economic paradigm due to the rapid expansion of the information and communication technology industry. It is also a recent main economic activity after agriculture and industry (Pan et al., 2022). According to the "White Paper on the Development of China's Digital Economy (2021)," China's digital economy reached RMB 39.2 trillion in 2020, an increase of 9.7 percent annually. In comparison, GDP growth was only 2.3% in the same year. The digital economy continues to develop swiftly, even though the COVID-19 epidemic has dramatically impacted enterprises' sustainable development and interrupted the national economy's smooth operation (Ding, 2020; Ding et al., 2021). Against this background, the adoption of digital technology may assist in overcoming the limitations of crucial technologies, hence accelerating the digital transformation of the new energy business. In the field of R&D, digital carriers create favorable conditions for the rapid circulation and accurate distribution of production factors, which improve production efficiency by shortening production time and reducing the costs of operation and maintenance (do Amaral Burghi and Hirsch, 2020). In terms of transportation, AI technology can be employed to discover the optimal solution for the transit and storage of new energy based on the intelligent algorithms of machine learning (Dong et al., 2020). Machine vision technology may be used to complete dynamic evaluation and real-time monitoring and eliminate the interference caused by exceptional items during energy transportation (Zhou et al., 2016). Regarding marketing, the digital trading platform built using cloud computing and blockchain technology has effectively reduced the information imbalance between supply and demand. Therefore, new energy enterprises are empowered to base personalized solutions on the value orientation of customers (Tang et al., 2021). In terms of supervision, the digital twin technology completes mapping all elements between physical objects and virtual models, thus creating a high-fidelity digital world for the new energy industry. Then, the prediction and extrapolation of industrial activities can be carried out from various perspectives (Liu et al., 2018). The abnormal working cycles can be detected in time by comparing the digital model's virtual evaluation results with the entity industry's actual measurement results, guiding the attentive monitoring of the industrial process (Sarkis et al., 2020).

Regarding the evolutionary causes of corporate credit risk, scholars have published a great deal of literature. Enterprises' internal and external environments have been discussed in numerous ways. External factors such as changes in the macro environment, the evolution of social networks, and policy uncertainty can disrupt the production and operations of businesses and impact their credit risk levels. For instance, the onset of the financial crisis has severely hindered the normal functioning of international markets, diminished global consumer demand, and placed companies in financial distress, significantly increasing the likelihood of credit risk occurring (Lu et al., 2012). Social networks' impact on enterprises' solvency is most evident in debt financing and R&D expenditures. The greater the social network, the stronger the financing capacity of the company and the quicker the growth of R&D expenditures (Horton et al., 2012). Moreover, economic policy uncertainty can lead to increased business risks, decreased investment conversion rates, and cash shortages, all of which can hinder a company's capacity to repay its loans and increase its credit risk (Chodnicka-Jaworska, 2022). From the firm's internal environment perspective, some academics have investigated the impact of enterprise credit risk based on their own situational factors. Capital structure, equity position, and company size will influence corporate credit risk (Boubakri et al., 2013; Zhang and Zhang, 2016). In addition, promotion incentives can indirectly affect corporate credit risk by controlling the risk appetite of executives (Kini and Williams, 2012).

3 Theoretical hypothesis

3.1 Digital economy and corporate credit risk

In the existing literature, many studies explore corporate credit risk factors from the perspectives of solvency and willingness (Bharadwaj, 2000; Peng and Ye, 2011). This study also adopts these two dimensions to examine the connection between the digital economy and corporate credit risk. Regarding solvency, digital technology has gradually permeated all facets of industrial activity, presenting businesses with a new technology paradigm that has challenged their initial production methods and management structures (Jing and Sun, 2019). The digital economy can improve total factor productivity (TFP) through economies of scale and scope (Wang K K et al., 2020). On the one hand, the digital economy has clear network externalities. When a specific number of consumers is reached, enterprises can cut their average costs through bulk transactions, uniform procurement of raw materials, and dilution of R&D expenses. Subsequently, the profits generated by economies of scale can be distributed (Erdem et al., 2016). On the other hand, the diffusion of digital technology has lowered the information threshold for economic activities, broadening the sales coverage of products and promoting the low-cost development of diverse businesses (Hart and Moore, 1994). The economy of scope provides the industry with diversified products and services that satisfy long-tail demand and adds value to the core business. Besides, from the standpoint of the enterprise management, the collaboration tools provided by digital technology allow data to flow efficiently, securely and completely, thus bridging the digital divide between different departments. In this way, enterprises are activated to eliminate redundant organizational layers, for the construction of a networked and flat organizational structure (Jacobides et al., 2018). When companies are confronted with a complex and ever-changing environment, greater decision-making efficacy can significantly decrease business risks and improve their viability and competitiveness (Adner, 2017). This is conducive to preventing credit risks resulting from poor decisions.

Willingness to pay the debt is the subjective attitude of a firm toward defaulting on a debt service contract while having the financial resources to do so. It is related to the opportunistic behavior of enterprises (Abeler et al., 2014). According to the reputation mechanism theory, a company's reputation will be proportional to its future earnings. If an adverse event, such as a penalty, damages a company's reputation, it will leave an indelible imprint that will negatively impact its future profitability. The digital economy has spurred the fast growth of online social media. The information distribution is no longer restricted by time or distance. It not only makes it easier for creditors and regulators to oversee management, but its potent public opinion governance and information transmission capabilities will make it difficult for businesses to conceal bad information and raise the cost of default (Zhu et al., 2020). Consequently, rational enterprises are forced to improve information transparency and fulfill their debt repayment obligations to avoid the spread of negative public opinion. Moreover, solvency can influence an enterprise's willingness to service debt. Some research suggested that firms with superior solvency pay more attention to their corporate reputation, which means they will keep a perfect image by favorably repaying loans for long-term growth (Gino et al., 2009). Therefore, the digital economy can indirectly raise enterprises' willingness to service debt by enhancing their solvency (Tadelis, 1999). In conclusion, the following hypothesis is offered in the present study:

Hypothesis 1 (H1): The digital economy can significantly mitigate the credit risk of new energy companies.

3.2 The moderating role of knowledge spillover

As the driving force behind new energy industrial growth shifts from low-cost factors to high-value-added innovation, knowledge is acknowledged as an efficient supplement to traditional element. Some studies concluded that the Internet has contributed to enriching the dissemination of knowledge and breaking the temporal and spatial boundaries of knowledge diffusion, thus permitting the large-scale circulation of intellectual elements (Baldwin et al., 2011). Through the geographical effect of knowledge spillover, some enterprises with sophisticated digital technologies have, to a certain extent, stimulated other enterprises in the same region to improve the integration and adoption of digital technologies. Therefore, the process of digital transformation is accelerated (Zhao and Li, 2011).

There are two primary manifestations of the moderating effect of knowledge spillover in the connection between the digital economy and the credit risk of new energy firms. First, knowledge spillover has an innovation effect. Under regional innovation systems, external factors and accumulated innovation resources and conditions influence each region's innovation production (Fu, 2009). As regions are gradually absorbed into

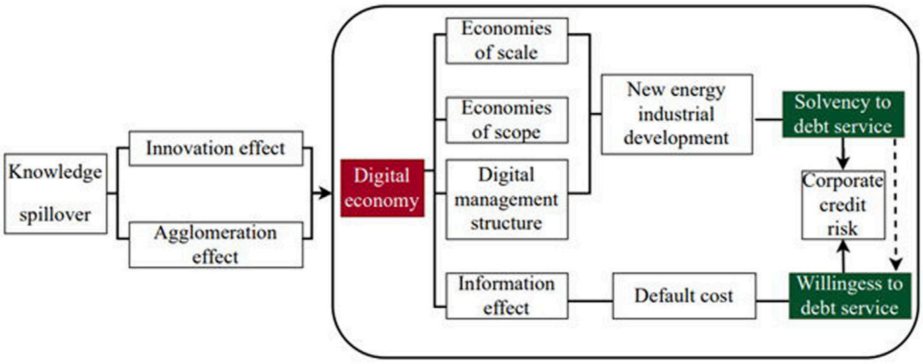


FIGURE 1
The theoretical framework of the digital economy, knowledge spillover, and corporate credit risk.

labor and capital division networks, knowledge and technology spillover channels are created to facilitate interregional collaboration and exchange. Furthermore, the closer geographic proximity between regions increases the likelihood of regional knowledge spillover (Mao, 2019). During the digitization process, a greater degree of knowledge spillovers is advantageous for decreasing R&D costs, boosting innovation output, and addressing the technical needs of new energy firms. Consequently, knowledge spillover improves organizations' solvency *via* innovation-driven benefits, thus lowering corporate credit risk. Second, knowledge spillover promotes the release of the agglomeration effect of the digital economy. As the core intellectual element that determines the competitive advantage of enterprises, tacit knowledge is highly ambient, contextual, and abstract (Hidalgo and Hausman, 2009). It can only be disseminated through face-to-face communication (Spender and Grant, 1996). Then, for the quick, precise, and cost-effective acquisition of new knowledge, enterprises will cluster around sources of knowledge spillovers voluntarily (Aydogan and Lyon, 2004). The innovation and business environment that the digital economy has created, meantime, can encourage companies to innovate more effectively and take advantage of intellectual resources, which is essential for the industrial chain to deepen and grow (Shen et al., 2022). Therefore, the higher the level of knowledge spillover, the greater the likelihood that regional new energy firms would experience the collective positive effect of knowledge spillover and the digital economy (Hong and Fu, 2011). This has played a driving role in reducing the credit risk of new energy companies. In summary, the current investigation proposes the following hypothesis:

Hypothesis 2 (H2): Knowledge spillover can positively moderate the effect of the digital economy on the credit risk of new energy firms.

3.3 The mediating role of new energy industrial development

The upstream and downstream transmission effect of the enterprise is the linchpin of their development process (Garrido and Okhrati, 2018). The digitization of supply, production, and marketing management necessitates close cooperation between upstream and downstream businesses. Otherwise, the digitization of individual companies may reduce communication and coordination efficiency rather than improve them (Aghion et al., 2015). For instance, the digital transformation of an enterprise's supply chain management system entails not only an investment in digital software and personnel but also the digital entry and administration of the enterprise's raw material procurement. If the pertinent raw materials and product information is entered solely by this enterprise, the cost will inevitably be substantially higher (Acemoglu and Restrepo, 2018). Therefore, concurrent development of the industry chain will reduce the friction between upstream and downstream enterprises in digitalization and decline the cost of supply chain management system application for enterprises, which contributes to the improvement of the solvency of new energy businesses, hence reducing corporate credit risk. The framework depicted in Figure 1 can be derived from a summary of the study's hypotheses regarding the relationship between the digital economy, knowledge spillover, and enterprise credit risk. In summary, the following hypothesis is proposed:

Hypothesis 3 (H3): New energy industrial development mediates the link between the digital economy and the credit risk of new energy businesses.

4 Methodology and data

4.1 Variables definition

4.1.1 Dependent variable

Risk management methods are commonly used to evaluate and decrease credit risk (Antràs et al., 2012). This study analyzes corporate credit risk utilizing the KMV model, which is based on the Black and Scholes (1973) and Merton (1974) option pricing models. To verify the stability of the KMV model, Kurbat and Korablev (2002) analyzed the financial data of tens of thousands of US enterprises over a decade. They discovered that the curve of expected default probabilities generated by the KMV model might closely resemble the actual default probabilities. Since enterprise stock prices were considered, Cheng and Chu (2020) demonstrated that the KMV model was more sensitive and accurate than other approaches. In accordance with the Merton model's assumptions, the equity is equivalent to a European call option with the debt value as the strike price and the asset value as the underlying, which should be assessed using the following equations:

$$E = VN(d_1) - De^{-rt}N(d_2) \tag{1}$$

$$E\sigma_E = N(d_1)V\sigma_A \tag{2}$$

$$d_1 = \frac{\ln\frac{V}{D} + \left(r + \frac{1}{2}\sigma_A^2\right)t}{\sigma_A\sqrt{t}} \tag{3}$$

$$d_2 = d_1 - \sigma_A\sqrt{t} \tag{4}$$

In these formulas, E represents the enterprise's equity's market value, V denotes the enterprise's asset's market value. D indicates the face value of debt, r reflects the risk-free rate of return, N( ) stands for the cumulative distribution function of normal distribution, σ_A measures the underlying asset's volatility,; σ_E symbolizes the equity's volatility. Using Eq. 5, the KMV model converts the values of enterprise equity and debt into an implied default point. The distance to default (DD) is then calculated using Eq. 6:

$$DP = SD + 0.5 * LD \tag{5}$$

$$DD = \frac{E(V) - DP}{E(V)\sigma_A} \tag{6}$$

Where *DP* represents the default point, *SD* denotes the face value of short-term debt, and *LD* reflects the face value of long-term debt. As *DD* increases, the enterprise's credit risk lowers. From this perspective, this study takes *DD* as the dependent variable to proxy corporate credit risk.

In the theory of option pricing, $N(d_1)$ signifies the probability that the option is real-valued, and $N(d_2)$ reflects the chance that the option's exercise may achieve the targeted return. Lu (2008) has pointed out that the variables d_1 and d_2 under the stock data of Chinese listed companies do not entirely adhere to the normal distribution assumption of the KMV model, resulting in biased asset evaluations. To improve the precision and adaptability of the original model, we re-estimate the probability distributions of variables d_1 and d_2 using the Gaussian mixture model. Eq. 7 represents the Gaussian mixture model.

$$F(X) = \sum_{i=1}^{K}\alpha_i N_i(\mu_i, \sigma_i^2),\ \sum_{i=1}^{K}\alpha_i = 1 \tag{7}$$

Where X is the variable vector, K represents the number of Gaussian distribution functions, α_i is the weight of the ith function, $N_i(\mu_i, \sigma_i^2)$ denotes the Gaussian distribution with a mean of μ_i and a variance of σ_i^2.

In addition, we construct the subsequent iterative process to determine the value of the company's assets. First, the intermediate variables d_1' and d_2', as well as the asset value V_1 and its volatility σ_{A1}, are calculated by Eqs 1–4. Second, the Gaussian mixture model is then used to derive the probability density functions $f'_{x1}$and f'_{x2}, and the probability distribution functions $F'_{x1}$and $F'_{x2}$for the variables d_1' and d_2'. This time, the fitted distribution functions are more representative to the actual distributions of variables d_1 and d_2 than the default normal distribution. Third, substitute $F'_{x1}$and $F'_{x2}$for $N(d_1)$ and $N(d_2)$ in Eqs 1, 2 to obtain the new asset value V_2 and its volatility σ_{A2}. Ultimately, V_2 and σ_{A2} are re-introduced into Eqs 3, 4 for a fresh iteration cycle. The loop is terminated when there is no substantial change in the outputs V_n and σ_{An}, and the final asset value V and volatility σ_A are calculated.

4.1.2 Independent variable

The digital economy (*DE*) is the key explanatory variable in this study. Tapscott (1996) introduced the term "digital economy" for the first time in 1996, defining it as an economic system that makes extensive use of information and communications technologies (ICT). Since then, the concept of the phrase "digital economy" has been analyzed and expanded d by multiple scholars (Chihiro et al., 2018). Based on the methods proposed by Zhang and Jiao (2017), a comprehensive assessment index system is developed to assess the digital economy along three dimensions: the digital foundation, industrial digitalization, and digital industrialization. Table 1 displays the indices used to estimate the level of the digital economy, and the entropy technique is utilized to assess the extent of the provincial level of the digital economy.

4.1.3 Mediator and moderator

New energy industrial development (*Industry*) serves as the mediator in this study. Since the low-carbon economy emerged as a new approach to attaining economically sustainable growth, new energy industrial development has become an important area of research. The ratio of each province's new energy generation to total electricity generation is chosen to represent the new energy industrial development.

Knowledge spillover (*KS*) is the moderator. Based on the measurement methods of Liu and Chai (2011), the logarithm of the number of patents granted is adopted as an indicator to reflect the knowledge spillover level. As information diffusion increases, regional innovation activities become increasingly diverse.

4.1.4 Control variable

When building a model, the enterprise credit risk is impacted by a few different variables. Therefore, we must ensure that other variables are adequately controlled to conduct an accurate quantitative analysis. Following the research of Guo and Zhu (2021), we use the four indicators as control variables: 1) Enterprise profitability (*Prof*), which is represented by ROA (Return on Assets); 2) Enterprise size (*Size*), which is calculated by the logarithm of enterprise assets; 3) Ownership concentration (*OC*), which is assessed by the percentage of the largest shareholder holding; 4) Leverage ratio (*Lev*), which is determined by the ratio of total liabilities to assets. We also add the level of government intervention (*Gov*) as the control variable since it is plausible for government spending to impact local enterprise development by influencing resource allocation. The proportion of general government expenditure to GDP is a proxy for the level of governmental intervention. Table 2 lists the variable definitions and descriptions.

4.2 Empirical methods

4.2.1 Fixed-effect model

Panel data is an excellent way to combine cross-section and time series, which not only overcomes the defects of a single method but also

TABLE 1 Comprehensive evaluation index system of digital economy degree.

Primary indicators	Secondary indicators	Measured data	Units	Weight (%)
Digital foundation	Transmission capacity	Length of optical cable line per 10,000 people	Per ten thousand people	5.31
	Mobile infrastructure	Internet penetration rate	Per one people	6.97
		Number of mobile phone base stations per 10,000 people	Per ten thousand people	7.02
Industrial digitalization	E-commerce benefit	E-commerce sales/GDP	%	6.74
	Enterprise application	E-commerce enterprises/total enterprises	%	14.81
		Websites owned per 100 people	Per hundred people	11.12
Digital industrialization	Digital benefit	Software business revenue/total business revenue	%	19.34
	Digital development	Postal income/GDP	%	14.34
		Telecommunications income/GDP	%	14.35

TABLE 2 Variable definitions and descriptions.

Variable types	Variable names	Variable symbols	Calculation
Dependent variable	Distance to default	*DD*	See Eq. 6
Independent variable	Digital economy	*DE*	Calculated by the entropy methods
Mediator	New energy industrial development	*Industry*	New energy generation/total electricity generation
Moderator	Knowledge spillover	*KS*	Number of patents granted)
Controls	Enterprise profitability	*Prof*	Mean of net profit/total assets at the beginning and end of the period
	Enterprise size	*Size*	Ln(enterprise assets)
	Ownership concentration	*OC*	Ln (1 + Shareholding ratio of the largest shareholder)
	Leverage ratio	*Lev*	Total liabilities/assets
	Government intervention	*Gov*	general government expenditure/GDP

can solve the problems of multicollinearity in time series analysis and provide more information, more changes, less collinearity, more degrees of freedom, and improved estimate efficiency. There are usually two types of models for panel data: random effects and fixed effects (Firebaugh et al., 2013). The assumption of zero correlation and the possibility of fluctuation between the observable qualities are two constraints to which the random effect model must adhere (Greene, 2001). Despite this, the fixed-effects method has many advantages. It can lessen the impact of confounding factors on estimation findings, the impact of time-invariant variables and the bias induced by omitted variables (Allison, 1996; Hsiao, 2003). To examine the direct effect of the digital economy on the credit risk of new energy enterprises, we perform the Chow test, LR test, and Hausman test on the panel data. All tests reject the null hypothesis at the 5% level of significance. Therefore, this work builds fixed-effect models for the empirical test. In addition, individual and year-fixed effects are integrated into the model to minimize the impact of differences between individuals and changes over time.

$$\boldsymbol{DD_{i,t} = \alpha_0 + \alpha_1 \ln DE_{i,t} + \alpha_2 Control_{i,t} + \mu_i + \delta_i + \varepsilon_{i,t}} \tag{8}$$

In this formula, *DD* indicates the default distance; *DE* represents the level of the digital economy in province i in period t; Control stands for the control variables; μ_i denotes the individual effect and δ_i denotes the year effect; $\varepsilon_{i,t}$ is the random disturbance term.

According to the abovementioned findings, there may be moderate mechanisms of action in addition to the direct impact of the digital economy on enterprise credit risk. Improved on Zhang's (2020) research methods, the specific test steps are as follows:

$$\begin{aligned}\boldsymbol{DD_{i,t}} &= \boldsymbol{\gamma_0 + \gamma_1 lnDE_{i,t} + \gamma_2 lnKS_{i,t} + \gamma_3 \ln DE_{i,t} * lnKS_{i,t}} \\ &\quad \boldsymbol{+\gamma_4 Control_{i,t} + \mu_i + \delta_i + \varepsilon_{i,t}}\end{aligned} \tag{9}$$

Where *KS* represents the level of knowledge spillover, and the other variables are defined in the same way as Eq. 8, whereas Eq. 9 is employed to examine the moderating effect of knowledge spillover.n

4.2.2 Panel threshold model

Considering that varying knowledge spillover levels may affect its moderating effect, the panel threshold model proposed by Hansen (1999) is selected to explore whether the threshold effect regulates the independent variables. The followings are the specifics of the single and double threshold models:

TABLE 3 Descriptive statistics.

Variable	Obs	Mean	Std	Min	Max
DD	1,008	0.626	0.206	0.001	1.000
DE	252	2.980	0.453	1.831	3.965
Industry	252	0.037	0.040	0.001	0.237
lnKS	252	2.722	1.233	1.144	4.572
Prof	1,008	0.018	0.133	−2.555	0.863
Size	1,008	22.822	1.151	19.551	26.181
OC	1,008	0.132	1.112	0.001	0.696
Lev	1,008	1.615	1.930	0.028	21.718
Gov	252	0.188	0.060	0.118	0.462

$$DD_{i,t} = \alpha_0 + \beta_1 \ln DE_{i,t} * I(lnKS_{i,t} \le \lambda) + \beta_2 lnDE_{i,t} * I(lnKS_{i,t} > \lambda) + \beta_3 Control_{i,t} + \mu_i + \varepsilon_{i,t} \quad (10)$$

$$DD_{i,t} = \alpha_0 + \beta_1 \ln DE_{i,t} \cdot I(lnKS_{i,t} \le \gamma_1) + \beta_2 \ln DE_{i,t} \cdot I(\gamma_1 < lnKS_{i,t} \le \gamma_2) + \beta_3 \ln DE_{i,t} \cdot I(lnKS_{i,t} > \gamma_2) + \beta_4 Control_{i,t} + \mu_i + \varepsilon_{i,t} \quad (11)$$

In these formulas, *lnKS* represents a threshold variable, $I(\cdot)$ is an indicative function with a value of 0 or 1, *lnKS* stands for the control variable, $\varepsilon_{i,t}$ denotes the error term, and λ and γ denote the threshold value to be estimated in the related equation.

4.3 Data sources and descriptive statistics

Due to the availability and effectiveness of data collection, this study focuses on listed new energy enterprises in China, and the period ranges from 2012 to 2020. In terms of sample selection, we use the cataloged "new energy concept sector" (BK0493) from the "East Money Information Site" to choose cooperative enterprises for research purposes. The financial data of the new energy enterprises used to calculate the distance to default (*DD*) are available in CSMAR, and the annual reports of the enterprises. Additionally, the provincial panel data used to evaluate the level of the digital economy, new energy industrial development, and knowledge spillover are collected from The China Statistical Yearbook, The China Energy Statistical Yearbook, The China Statistical Yearbook on Science and Technology, and The China Electricity Statistical Yearbook.

This paper processes the data according to the following principles: 1) Enterprises with a listing date after 2012 are eliminated; 2) ST enterprises in the sample are excluded; 3) Enterprises with incomplete data are removed. After the above steps, we obtained 1,008 samples from 112 listed companies. Meanwhile, Tibet, Qinghai, and Xinjiang are not covered since these provinces have few eligible samples. We eventually collected 252 samples in total from 28 provinces.

The descriptive statistics of each variable are shown in Table 3. Specifically, *DE* represents the development of the digital economy, and the mean value of this variable is 1.462, the maximum value is 3.546, and the minimum value is 4.198, indicating that the quality of the digital economy varies significantly between regions, which is somehow consistent with the earlier studies.

5 Empirical results analysis

5.1 Basic analysis result

This study adopts the fixed-effect models to examine whether the digital economy helps mitigate the credit risk of new energy enterprises. Table 4 reports the results. Columns 1) and 2) indicate the effects of the digital economy on the credit risk of new energy enterprises. Both the regression coefficients are statistically significant at the 1% level, indicating that new energy enterprise credit risk can be significantly decreased as the digital economy grows, supporting Hypothesis H1.

In Table 4, Columns 3) and 4) show the moderating impact of knowledge spillover. The interaction term between the digital economy and knowledge spillover has significantly positive coefficients. This suggests that knowledge spillover has innovation and agglomeration effects on businesses, moderating the relationship between the digital economy and the credit risk of new energy enterprises. As a result, Hypothesis H2 is confirmed.

The structural equation model is further performed to confirm the mediating effect of the new energy industry development. The estimation deviation is adjusted using the non-parametric bootstrapping method. As shown in Table 5, the coefficient of direct effect is 0.118, and the 95% confidence interval excludes 0 since it is [0.093,0.149]. This indicates the direct effect of the digital economy is significant. The coefficient of mediating effect is 0.023, and the 95% confidence interval excludes 0 with a range of [0.007,0.038]. This indicates that developing new energy industries is a vital mechanism for the digital economy to lower the credit risk of new energy enterprises, hence validating Hypothesis H3.

5.2 Basic analysis by region

Different regions of China have varying degrees of the digital economy. The regional fixed-effect model is adopted to investigate whether there is significant regional heterogeneity. Table 6 reveals that the influence of the eastern region's digital economy is favorable at 1% significance level. However, the significance of the central and western regions is only 10%. The reason is that the central and western regions may still be in the preliminary phase of digital economic development. In contrast, the convenient geographical conditions of the eastern region have facilitated its growth. Meanwhile, the Chow breakpoint test is employed to verify that the uneven geographical distribution of new energy enterprises does not influence the conclusions. The result demonstrates that the conclusion rejects the null hypothesis regarding the absence of regional heterogeneity at the 5% significance level. In conclusion,

TABLE 4 Basic regression results.

Variable	Direct effect		Moderating effect	
	DD (1)	DD (2)	DD (3)	DD (4)
lnDE	0.179*** (−0.014)	0.278*** (−0.020)	0.097*** (−0.030)	0.211*** (−0.032)
lnKS	—	—	0.052 (−0.038)	0.012* (−0.038)
*ln DE*lnKS*	—	—	0.026** (−0.011)	0.016*** (−0.011)
Control	NO	YES	NO	YES
Constant	0.093** (−0.041)	1.559*** (−0.265)	0.265*** (−0.083)	1.720*** (−0.283)
R^2	0.159	0.236	0.168	0.244
N	1,008	1,008	1,008	1,008

Notes: Standard errors in parentheses; ***, **, * represent statistical significance at 1%, 5%, and 10%, respectively.

TABLE 5 Mediating effect test.

	Coefficients	95% confidence interval	
		Lower limit	Upper limit
Direct effect	0.118**	0.093	0.149
Mediating effect	0.023***	0.007	0.038
Total effect	0.141***	0.100	0.187

Notes: ***, **, * indicate statistical significance at 1%, 5%, and 10%, respectively.

the impact of the digital economy on the credit risk of new energy enterprises differs between the two regional samples.

5.3 Threshold effect analysis

This study develops a panel threshold model to test whether knowledge spillover moderates the relationship between the digital economy and the credit risk of new energy enterprises beyond a predetermined threshold. Using knowledge spillover as the threshold variable, Table 7 reports that the digital economy has a double threshold effect on enterprise credit risk, with respective thresholds of 3.381 and 3.819.

Table 8 displays that the impact of the digital economy on the credit risk of new energy enterprises varies according to the level of knowledge spillover. When the knowledge spillover degree is less than 3.381, the digital economy significantly impacts the credit risk of new energy enterprises, and the regression coefficient is 0.266. Although businesses can only innovate using their intellectual capital during this stage, they eventually develop intangible assets and obtain inventive advantages through technological research. When the level of knowledge spillover is between 3.381 and 3.819, the regression coefficient is lower than in the previous period. This change may be because the increased knowledge spillover accelerates the rate of knowledge diffusion and shortens the product life cycle. To keep up with continuously evolving market needs, enterprises must raise their R&D spending and innovation efficiency. As a result, the growing uncertainty produced by the highly competitive innovation environment mitigates the influence of the digital economy on the credit risk of new energy firms. However, the digital economy's regression coefficient is significantly positive, with a value of 0.292, when the level of knowledge spillover exceeds 3.819. At a high level of knowledge spillover, learning new technologies is less expensive than developing them from scratch. Therefore, enterprises are more likely to convert external intellectual capital and innovative technologies into intrinsic growth drivers. At this phase, knowledge spillover's cost-saving and efficiency-improving effects will outweigh the uncertainty it creates. Accordingly, the digital economy's positive effect on reducing corporate credit risk will become increasingly prominent.

TABLE 6 Basic regression results by regions.

Variable	East	Central & west
	(1)	(2)
lnDE	0.325*** (−0.029)	0.213* (−0.031)
Control	YES	YES
Constant	1.794*** (−0.398)	0.902** (−0.437)
R^2	0.242	0.144
N	711	297

Notes: Standard errors in parentheses; ***, **, * represent statistical significance at 1%, 5%, and 10%, respectively.

TABLE 7 Threshold effect test.

Variable	Test	Threshold estimation	F-statistic	*p*-value	Critical value		
					10%	5%	1%
lnKS	Single threshold test	3.819** [3.757,3.856]	68.63	0.010	52.162	56.215	61.242
	Double threshold test	3.381** [3.300,4.140]	19.82	0.073	18.788	21.726	24.127
		3.819** [3.118,3.856]					
	Triple threshold test	1.493 [1.477,1.526]	11.20	0.367	47.483	53.871	63.834
		3.381 [3.300,4.140]					
		3.819 [3.118,3.856]					

Notes: ***, **, * indicate statistical significance at 1%, 5%, and 10%, respectively.

TABLE 8 Threshold model results.

Variable	Value	t-Value
lnDE ($ln\,KS \leq 3.381$)	0.266***	13.56
lnDE ($3.381 < ln\,KS \leq 3.819$)	0.234***	11.84
lnDE ($ln\,KS > 3.819$)	0.292***	15.23
Control	YES	
Constant	1.781***	6.91
R^2	0.299	
N	1,008	

Notes: ***, **, * indicate statistical significance at 1%, 5%, and 10%, respectively.

5.4 Robustness tests

5.4.1 Endogenous tests

On the hand, there may have endogenous issues that are mutually causative. Therefore, this research employs instrumental variables to address the endogeneity issue. We reference Kim et al. (2014) and use the same yearly average level of the digital economy in other provinces as an instrumental variable (*IV*) for the independent variable. On the other hand, in light of the complexity of the elements determining corporate credit risk, it is challenging to avoid missing variables in the present research design. The key explanatory variable is regarded as a one-period lag, which might mitigate endogeneity to some degree.

Table 9 reports the results of endogenous tests. Based on the findings of the first stage in column 1), the instrumental variable is significantly positively linked with the digital economy. As shown by the results of the second stage in column 2), the estimated coefficient of the digital economy (*lnDE*) is significantly positive, indicating that the findings of this research are resilient even when endogeneity is taken into account. In addition, we examine if the instrumental variable is weak and find that the F-statistic is 20.3, which is more than the threshold value of 1.242, thus excluding the notion of a weak instrument. This paper also lags the independent variables by one period to test the samples. Table 8 demonstrates that the paper's key conclusions remain unchanged with the inclusion of a one-period lagged independent variable (*L.lnDE*) to the model 8).

5.4.2 Replacement of independent variable

Considering that the results of the abovementioned empirical tests might be affected by the selection of indicators, we adopt replacing the independent variable to conduct robustness tests. Initially, government investment in science and technology is viewed as replacing the digital economy. After performing the Hausman test, the fixed-effect model is chosen for regression.

TABLE 9 Endogenous test results.

Variables	First-stage	Second-stage	Lagging independent variable
	(1)	(2)	(3)
IV	0.042*** (0.001)	—	—
ln DE	—	0.336*** (0.022)	—
L.lnDE	—	—	0.286*** (0.021)
Control	YES	YES	YES
Constant	0.750*** (0.208)	1.994*** (0.275)	1.730*** (0.315)
R^2	0.918	0.228	0.235
N	1,008	1,008	896

Notes: ***, **, * indicate statistical significance at 1%, 5%, and 10%, respectively.

TABLE 10 Robustness tests for the fixed-effect model.

Variable	DD (1)	DD (2)	DD (3)	DD (4)
lnDE	0.069*** (−0.011)	0.072*** (−0.011)	0.093*** (−0.045)	0.087*** (−0.044)
lnKS	—	—	0.131* (−0.075)	0.118 (−0.078)
*ln DE*lnKS*	—	—	0.039*** (−0.013)	0.036*** (−0.013)
Control	NO	YES	NO	YES
Constant	0.250*** (−0.060)	0.298* (−0.171)	0.822*** (−0.245)	0.859*** (−0.364)
R^2	0.066	0.082	0.130	0.145
N	1,008	1,008	1,008	1,008

Notes: Standard errors in parentheses; ***, **, * represent statistical significance at 1%, 5%, and 10%, respectively.

TABLE 11 Robustness tests for mediating effect model.

	Coefficients	95% confidence interval	
		Lower limit	Upper limit
Direct effect	0.048***	0.028	0.068
Mediating effect	0.019***	0.011	0.026
Total effect	0.067***	0.039	0.094

Notes: Standard errors in parentheses; ***, **, * represent statistical significance at 1%, 5%, and 10%, respectively.

TABLE 12 Robustness tests for the threshold regression model.

Variable	Value	t-Value
lnDE ($ln\,KS \leq 4.111$)	0.257***	12.61
lnDE ($4.111 < ln\,KS \leq 4.327$)	0.223***	10.97
lnDE ($ln\,KS > 4.327$)	0.268***	13.98
Control	YES	
Constant	1.932***	7.40
R^2	0.289	
N	1,008	

Notes: Standard errors in parentheses; ***, **, * represent statistical significance at 1%, 5%, and 10%, respectively.

According to the results of Tables 10 and 11, even though the independent variable has changed, the digital economy remains significantly advantageous for the credit risk reduction of new energy enterprises. Regarding impact mechanisms, increasing the degree of knowledge spillover and the digital economy is beneficial for mitigating corporate credit risk. And the new energy industrial development is one of its indirect mechanisms for lowering enterprise credit risk. In conclusion, the results of this study's fixed-effect model are unaffected by alternative measures of the variables.

5.4.3 Replacement of threshold variable

The logarithm of the regional book collection is then selected as the threshold variable substitutable for knowledge spillover. According to the robustness test results of Table 12, the digital economy's coefficient varies across distinct phases. As the knowledge spillover level increases, the digital economy's effect initially decreases and subsequently grows. When the degree of knowledge spillover is high, the digital economy plays the most prominent role in reducing enterprise credit risk, which is consistent with the previous empirical results. Therefore, the results of the threshold regression model are robust.

6 Conclusion and policy implications

The new energy has been a booming industry in recent years and will affect future energy usage. However, there are many uncertainties in its development. Combining the growth of the digital economy with an assessment of the credit risk of new energy enterprises is a novel and distinctive perspective of this paper. We used the KMV model, the fixed-effect model, and the PTR methods and drew the following conclusions:

1) Digital economy could mitigate the credit risk of new energy enterprises in three ways: Firstly, the digital economy increases total factor productivity (TFP) by reshaping corporate processes and bolstering financial stability. Secondly, the potential cost of default is exacerbated by the communication effect of the digital economy, which works as an intangible disciplinary control to improve firms' willingness to repay their debts. Thirdly, new energy industrial development plays an intermediary role, suggesting that the digital economy indirectly affects the credit risk of new energy enterprises through this intermediary factor.
2) In addition, when knowledge spillover is acted as the threshold variable, the digital economy exhibits a double-threshold effect on the corporate credit risk. As the level of knowledge spillover rises, the marginal impact fluctuates from decreasing to growing. Furthermore, when knowledge spillover is at high levels, especially across the threshold value of 13.029, the effect of the digital economy on reducing new energy enterprises' credit risk is particularly evident.
3) Regional heterogeneity tests reveal that the eastern region has a more favorable influence on enterprise credit risk than the central and western regions. In other words, its positive impact has been more pronounced in China's eastern provinces than in the central and western regions. The causes could be related to differences in economic location and resource abundance.

To mitigate the credit risk of new energy firms, this research provides the following policy implications:

1) Make the digital economy a "sharp weapon" to reduce corporate credit risk. To achieve this objective, government agencies need to stimulate the growth of the new energy industrial sector by promoting digital construction and integrating digital technology into the new energy industry. Meanwhile, a specialized and competitive integration mechanism based on the production processes, business patterns, and management models of new energy businesses should be developed to enable their digital transformation.
2) Given knowledge spillover's innovation and agglomeration effects, the government should focus on improving knowledge spillover and regional intellectual capital. Specifically, some innovation participants could be attracted by increasing investment in science and technology, creating an environment encouraging innovation, and establishing platforms for industry-university-research cooperation. These government practices effectively enhance the positive role of the digital economy and reduce corporate credit risk by improving regional knowledge diffusion.
3) China's regional economy needs to be more balanced since there are significant inequalities in talent, capital, and technology between the eastern and western regions. With the opportunity created by the digital economy, the central and western regions can combine their substantial energy resource advantages to develop the new energy sector. Considering the impact of the digital economy on the credit risk of new energy enterprises, the central and western regions should enhance the government's public function and guiding role, strengthen the coordinated development of new infrastructure across regions, and accelerate the commercial application of digital technologies.

Despite providing empirical evidence for developing the digital economy and new energy, this study has several limitations. The first limitation is the availability of data. In this research, the data spans only 9 years, and some of the data are only at the provincial level, which lacks representativeness at a broader scale. In future research, a more extended period and additional data levels should be used to test the validity of the results. Second, the impact mechanisms require extensive research and documentation to provide more actionable implementation advice. In particular, the future study should concentrate on refining the selection of the digital economy index to account for regional growth patterns. Thirdly, China's digital economy is undergoing dynamic and rapid development. The direction of future research should include some factors related to this dynamic digital transformation to shed light on the intricate relationship between corporate credit risk and the growth of the digital economy.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization, MS; methodology, YD; software, YD; resources, YC; writing-original draft preparation, YD; writing-review and editing, MS, YD, and YC; supervision, MS; validation, MS; project administration, MS and YC; funding support, MS. All authors have read and agreed to the published version of the manuscript.

Funding

This research is a part of the research project funded by the National Social Science Foundation (Grant No. 21BJY125). This work was supported by the National Social Science Fund of China [21BJY125].

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Abeler, J., Becker, A., and Falk, A. (2014). Representative evidence on lying costs. *J. Public Econ.* 113, 96–104. doi:10.1016/j.jpubeco.2014.01.005

Acemoglu, D., and Restrepo, P. (2018). *Artificial intelligence, automation, and work*. America: NBER working paper.

Adner, R. (2017). Ecosystem as structure: An actionable construct for strategy. *J. Manag.* 43, 39–58. doi:10.1177/0149206316678451

Aghion, P., Cai, J., Dewatripont, M., Du, L., Harrison, A., and Legros, P. (2015). Industrial policy and competition. *Am. Econ. J. Macroecon.* 7, 1–32. doi:10.1257/mac.20120103

Allison, P. D. (1996). Fixed-effects partial likelihood for repeated events. *Sociol. Methods Res.* 25, 207–222. doi:10.1177/0049124196025002003

Antràs, P., Chor, D., Fally, T., and Hillberry, R. (2012). Measuring the upstreamness of production and trade flows. *Am. Econ. Rev.* 102, 412–416. doi:10.1257/aer.102.3.412

Aydogan, N., and Lyon, T. P. (2004). Spatial proximity and complementarities in the trading of tacit knowledge. *Int. J. Industrial Organ.* 22, 1115–1135. doi:10.1016/j.ijindorg.2004.09.003

Baldwin, R., Forslid, R., Martin, P., Ottaviano, G., and Robert-Nicoud, F. (2011). "Economic geography and public policy," in *Economic geography and public policy* (Beijing, China: Princeton University Press).

Bharadwaj, A. S. (2000). A resource-based perspective on information technology capability and firm performance: An empirical investigation. *MIS Q.* 24, 169–196. doi:10.2307/3250983

Black, F., and Scholes, M. (1973). The pricing of options and corporate liabilities. *J. political Econ.* 81, 637–654. doi:10.1086/260062

Boubakri, N., Cosset, J. C., and Saffar, W. (2013). The role of state and foreign owners in corporate risk-taking: Evidence from privatization. *J. financial Econ.* 108, 641–658. doi:10.1016/j.jfineco.2012.12.007

Chen, J. (2011). China's experiment on the differential electricity pricing policy and the struggle for energy conservation. *Energy Policy* 39, 5076–5085. doi:10.1016/j.enpol.2011.06.006

Cheng, X. Y., and Chu, X. F. (2020). Credit risk of GEM listed companies based on KMV model. *J. Huazhong Univ. Sci. Technol. Med. Sci.* 38, 51–57. doi:10.15926/j.cnki.hkdsk.2020.02.008

Chihiro, W., Kashif, N., Yuji, T., and Pekka, N. (2018). Measuring GDP in the digital economy: Increasing dependence on uncaptured GDP. *Technol. Forecast. Soc. change* 37, 286. doi:10.1016/j.techfore.2018.07.053

Chodnicka-Jaworska, P. (2022). Environmental, social, and governance impact on energy sector default risk—long-term issuer credit ratings perspective. *Front. Energy Res.* 457, 1. doi:10.3389/fenrg.2022.817679

Cioacă, S. I., Cristache, S. E., Vuţă, M., Marin, E., and Vuţă, M. (2020). Assessing the impact of ICT sector on sustainable development in the European Union: An empirical analysis using panel data. *Sustainability* 12, 592. doi:10.3390/su12020592

Ding, C., Liu, C., Zheng, C., and Li, F. (2021). Digital economy, technological innovation and high-quality economic development: Based on spatial effect and mediation effect. *Sustainability* 2021, 14. doi:10.3390/su14010216

Ding, Z. (2020). Research on the mechanism of digital economy driving high-quality economic development: A theoretical analysis framework. *Mod. Econ. Res.* 1, 85–92. doi:10.13891/j.cnki.mer.2020.01.011

do Amaral Burghi, A. C., and Hirsch, T. (2020). Pitz-Paal, R. Artificial learning dispatch planning for flexible renewable-energy systems. *Energies* 13, 1517. doi:10.3390/en13061517

Dong, L., Sun, D., Han, G., Li, X., Hu, Q., and Shu, L. (2020). Velocity-free localization of autonomous driverless vehicles in underground intelligent mines. *IEEE Trans. Veh. Technol.* 69, 9292–9303. doi:10.1109/tvt.2020.2970842

Erdem, T., Keller, K. L., Kuksov, D., and Pieters, R. (2016). Understanding branding in a digitally empowered world. *Int. J. Res. Mark.* 33, 3–10. doi:10.1016/j.ijresmar.2015.12.003

Firebaugh, G., Warner, C., and Massoglia, M. (2013). "Fixed effects, random effects, and hybrid models for causal analysis," in *Handbook of causal analysis for social research*. Editor S. L. Morgan (Dordrecht, The Netherlands: Springer), 113–132.

Fu, C., Zhang, S. Q., and Chao, K. H. (2020). Energy management of a power system for economic load dispatch using the artificial intelligent algorithm. *Electronics* 9, 108. doi:10.3390/electronics9010108

Fu, M. (2009). Geographical distance and technological spillover effects: A spatial econometric explanation of technological and economic agglomeration phenomena. *China Econ. Q.* 8, 1549–1566. doi:10.4236/me.2016.72015

Garrido, J, and Okhrati, R (2018). Desirable portfolios in fixed income markets: Application to credit risk premiums. *Risks* 6, 23. doi:10.3390/risks6010023

Gino, F., Ayal, S., and Ariely, D. (2009). Contagion and differentiation in unethical behavior: The effect of one bad apple on the barrel. *Psychol. Sci.* 20, 393–398. doi:10.1111/j.1467-9280.2009.02306.x

Gopalakrishnan, B., and Mohapatra, S. (2020). Insolvency regimes and firms' default risk under economic uncertainty and shocks. *Econ. Model.* 91, 180–197. doi:10.1016/j.econmod.2020.06.005

Greene, W. (2001). *Estimating econometric models with fixed effects*. Leonard N: New York University.

Guo, J. T., and Zhu, Y. X. (2021). The impact of digital economy on corporate credit risks. *J. Shenzhen Univ. Humanit. Soc. Sci.* 38, 69–80.

Hansen, B. E. (1999). Threshold effects in non-dynamic panels: Estimation, testing, and inference. *J. Econ.* 93, 345–368. doi:10.1016/s0304-4076(99)00025-1

Hart, O., and Moore, J. (1994). A theory of debt based on the inalienability of human capital. *Soc. Sci. Electron. Publ.* 109, 841–879. doi:10.2307/2118350

Heo, P. S., and Lee, D. H. (2019). Evolution of the linkage structure of ICT industry and its role in the economic system: The case of korea. *Inf. Technol. Dev.* 25, 424–454. doi:10.1080/02681102.2018.1470486

Hidalgo, C. A., and Hausmann, R. (2009). The building blocks of economic complexity. *Proc. Natl. Acad. Sci.* 106, 10570–10575. doi:10.1073/pnas.0900943106

Hong, J., and Fu, S. (2011). Information and communication technologies and the geographical concentration of manufacturing industries: Evidence from China. *Urban Stud.* 48, 2339–2354. doi:10.1177/0042098010388956

Horton, J., Millo, Y., and Serafeim, G. (2012). Resources or power? Implications of social networks on compensation and firm performance. *J. Bus. Finance Account.* 39, 399–426. doi:10.1111/j.1468-5957.2011.02276.x

Hsiao, C. (2003). *Analysis of panel data*. Cambridge, UK: Cambridge University Press, 382.

Jabłoński, M. (2018). Value migration to the sustainable business models of digital economy companies on the capital market. *Sustainability* 10, 3113. doi:10.3390/su10093113

Jacobides, M. G., Cennamo, C., and Gawer, A. (2018). Towards a theory of ecosystems. *Strategic Manag. J.* 39, 2255–2276. doi:10.1002/smj.2904

Jing, W. J., and Sun, B. W. (2019). Digital economy promotes high-quality economic development: A theoretical analysis framework. *Economist* 2, 66–73. doi:10.16158/j.cnki.51-1312/f.2019.02.008

Jones, P., and Wynn, M. (2021). The leading digital technology companies and their approach to sustainable development. *Sustainability* 13, 6612. doi:10.3390/su13126612

Kim, Y., Li, H., and Li, S. (2014). Corporate social responsibility and stock price crash risk. *J. Bank. Finance* 43, 1–13. doi:10.1016/j.jbankfin.2014.02.013

Kini, O., and Williams, R. (2012). Tournament incentives, firm risk, and corporate policies. *J. Financial Econ.* 103, 350–376. doi:10.1016/j.jfineco.2011.09.005

Kurbat, M., and Korablev, I. (2002). *Methodology for testing the level of the EDF credit measure*. Hyderabad: KMV Corporation.

Li, C., and Wang, S. (2022). Digital optimization, green R&D collaboration, and green technological innovation in manufacturing enterprises. *Sustainability* 14, 12106. doi:10.3390/su141912106

Liu, S. A., and Chai, C. L. (2011). Analysis of knowledge spillover effect from the perspective of manufacturing agglomeration and R&D investment. *Sci. Technol. Forum* 07, 32–37+57. doi:10.13580/j.cnki.fstc.2011.07.015

Liu, D. T., Guo, K., Wang, B. K., and Peng, Y. (2018). Summary and perspective survey on digital twin technology. *Chin. J. Sci. Instrum.* 39, 1–10. doi:10.19650/j.cnki.cjsi.J1804099

Lu, Y. (2008). *Default forecasting in KMV. Oriel college*. Oxford: University of Oxford.

Lu, Z., Zhu, J., and Zhang, W. (2012). Bank discrimination, holding bank ownership, and economic consequences: Evidence from China. *J. Bank. Finance* 36, 341–354. doi:10.1016/j.jbankfin.2011.07.012

Mao, Q. L. (2019). Time-space compression, spatial knowledge spillovers, and industrial upgrading. *Stud. Sci. Sci.* 37, 422–435. doi:10.16192/j.cnki.1003-2053.2019.03.006

Merton, R. C. (1974). On the pricing of corporate debt: The risk structure of interest rates. *J. finance* 29, 449–470. doi:10.2307/2978814

Nascimento, D. L. M., Alencastro, V., Quelhas, O. L. G., Caiado, R. G. G., Garza-Reyes, J. A., Rocha-Lona, L., et al. (2018). Exploring industry 4.0 technologies to enable circular economy practices in a manufacturing context: A business model proposal. *J. Manuf. Technol. Manag.* 30, 607–627. doi:10.1108/jmtm-03-2018-0071

Nuryaman, N. (2015). The influence of intellectual capital on the firm's value with the financial performance as intervening variable. *Procedia–Social Behav. Sci.* 211, 292–298. doi:10.1016/j.sbspro.2015.11.037

Pan, W., Xie, T., Wang, Z., and Ma, L. (2022). Digital economy: An innovation driver for total factor productivity. *J. Bus. Res.* 139, 303–311. doi:10.1016/j.jbusres.2021.09.061

Peng, H. F., and Ye, Y. G. (2011). Loan-pricing model based on repayment ability and repayment willingness. *Chin. J. Manag. Sci.* 19, 40–47. doi:10.16381/j.cnki.issn1003-207x.2011.06.004

Qi, Y. D., and Xiao, X. (2020). Transformation of enterprise management in the era of digital economy. *J. Manag. World* 36, 135–152. doi:10.19744/j.cnki.11-1235/f.2020.0091

Sarkis, J., Kouhizadeh, M., and Zhu, Q. S. (2020). *Digitalization and the greening of supply chains*. United Kingdom: Industrial Management & Data Systems.

Shen, M. H., Tan, W. J., and Chen, Z. Y. (2022). The impact of digital economy development on enterprise innovation: Empirical evidence from Chinese listed companies. *South China Finance* 02, 30–44.

Spender, J. C., and Grant, R. M. (1996). Knowledge and the firm: Overview. *Strategic Manag. J.* 17, 5–9. doi:10.1002/smj.4250171103

Tadelis, S. (1999). What's in a name? Reputation as a tradeable asset. *Am. Econ. Rev.* 89, 548–563. doi:10.1257/aer.89.3.548

Tan, H. P., Plowman, D., and Hancock, P. (2007). Intellectual capital and financial returns of companies. *J. Intellect. Cap.* 8, 76–95. doi:10.1108/14691930710715079

Tang, X. Y., Liang, Y., and Sun, B. (2021). Application prospect of digital twinning technology in regional multi -energy systems. *South. Power Syst. Technol.* 15, 104–114. doi:10.13648/j.cnki.issn1674-0629.2021.05.013

Tapscott, D. (1996). *The digital economy promise and peril in the age of networked intelligence*. New York: MacGraw Hill, 1987–1992.

Wang, K. K., Wu, G. B., and Zhang, G. J. (2020). Has the development of the digital economy improved production efficiency? *Economist* 10, 24–34. doi:10.16158/j.cnki.51-1312/f.2020.10.004

Zhang, C. (2020). Clans, entrepreneurship, and development of the private sector in China. *J. Comp. Econ.* 48, 100–123. doi:10.1016/j.jce.2019.08.008

Zhang, H. H., and Zhang, L. Y. (2016). Ownership, tournament incentive and risk-taking. *Econ. Manag.* 38, 110–121. doi:10.19616/j.cnki.bmj.2016.05.011

Zhang, J., and Qian, F. (2023). Digital economy enables common prosperity: Analysis of mediating and moderating effects based on green finance and environmental pollution. *Front. Energy Res.* 10, 1991. doi:10.3389/fenrg.2022.1080230

Zhang, X. L., and Jiao, Y. X. (2017). A preliminary study of China's digital economy development index and its application. *Zhejiang Soc. Sci.* 04, 32–40+157. doi:10.14167/j.zjss.2017.04.005

Zhao, H., and Li, Y. (2011). A technology innovation model of leading enterprise dominant cluster— considering the distance decay effect of technological spillover. *Sci. Res. Manag.* 32, 157–164. doi:10.19571/j.cnki.1000-2995.2011.06.020

Zhou, K. L., Yang, S. L., and Shao, Z. (2016). Energy Internet: The business perspective. *Appl. Energy* 178, 212–222. doi:10.1016/j.apenergy.2016.06.052

Zhou, Z., Liu, W., Cheng, P., and Li, Z. (2022). The impact of the digital economy on enterprise sustainable development and its spatial-temporal evolution: An empirical analysis based on urban panel data in China. *Sustainability* 14, 11948. doi:10.3390/su141911948

Zhu, M. N., Liang, Y. H., and Wu, Z. M. (2020). Information interaction network and price crash risk: Public opinion supervision or irrational contagion. *China Ind. Econ.* 10, 81–99. doi:10.19581/j.cnki.ciejournal.2020.10.003

frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 14 November 2023
DOI 10.3389/fenrg.2023.1256000

Check for updates

OPEN ACCESS

EDITED BY
Chi Lau,
Teesside University, United Kingdom

REVIEWED BY
Davide Papurello,
Polytechnic University of Turin, Italy
Houcheng Zhang,
Ningbo University, China
Wenjia Li,
Tianjin University, China

*CORRESPONDENCE
Liqiang Duan,
dlq@ncepu.edu.cn

RECEIVED 10 July 2023
ACCEPTED 19 October 2023
PUBLISHED 14 November 2023

CITATION
Bian J and Duan L (2023), Study on MCFC-integrated GSCC systems with SEGR in parallel or series and CO_2 capture.
Front. Energy Res. 11:1256000.
doi: 10.3389/fenrg.2023.1256000

Study on MCFC-integrated GSCC systems with SEGR in parallel or series and CO_2 capture

Jing Bian and Liqiang Duan*

Key Laboratory of Power Station Energy Transfer Conversion and System, School of Energy, Power and Mechanical Engineering, North China Electric Power University, Beijing, China

In this paper, two new molten carbonate fuel cell (MCFC)-integrated gas–steam combined cycle (GSCC) systems with selective exhaust gas recirculation (SEGR) and CO_2 capture are proposed and analyzed. The CO_2 concentration in the gas turbine emission is increased because CO_2 is selectively recycled with the help of SEGR. Molten carbonate fuel cells (MCFCs) are another way to increase CO_2 concentration in the gas turbine flue gas by translating only CO_2 from the cathode to the anode. In these two new gas–steam combined cycle systems, SEGR connected with MCFC, either in parallel or series, increases CO_2 concentration beyond 11%. A gas–steam combined cycle system combined with MCFC and CO_2 capture without SEGR is used as the reference system. Aspen Plus software is adopted to build the system models, and the performances of different systems are discussed and compared. The research results reveal that for the MCFC-integrated gas–steam combined cycle system with SEGR in series and CO_2 capture, the CO_2 concentration of gas turbine exhaust increases to 11.72% and the thermal efficiency is 56.29% when the overall CO_2 capture rate is 88.16%, which is 1.13% higher than that of the reference system; for the MCFC-integrated gas–steam combined cycle system with SEGR in parallel and CO_2 capture, the CO_2 concentration of gas turbine exhaust increases to 14.15% and the thermal efficiency is 56.62%, which is 1.46% higher than that of the reference system. Furthermore, the economic analysis results show that the economic performances of new systems are mainly influenced by MCFC cost and will be gradually improved with the decrease in the MCFC cost.

KEYWORDS

gas turbine, molten carbonate fuel cell, selective exhaust gas recirculation, CO_2 emissions, economic analysis

1 Introduction

The topic of CO_2 emission is attracting considerable attention with the rise in global warming, which poses a severe hazard to human health and survival. Total CO_2 discharge in China has increased from 9.122 billion tons (2011) to 9.912 billion tons (2020) (Miao et al., 2022). CO_2 emissions are mainly generated from fossil fuel-fired power systems, such as coal-fired power generation systems and gas–steam combined cycle (GSCC) systems. Although the gas–steam combined cycle has high efficiency, capturing CO_2 from the GSCC system is still a focus of attention in various countries since natural gas is usually applied as a fuel and still emits a large amount of CO_2. The F-class gas turbine (GT) is widely applied (Tsukagoshi et al., 2007), and its turbine inlet temperature can reach up to 1,400°C (ElKady et al., 2009). Choi et al. (2014) found that

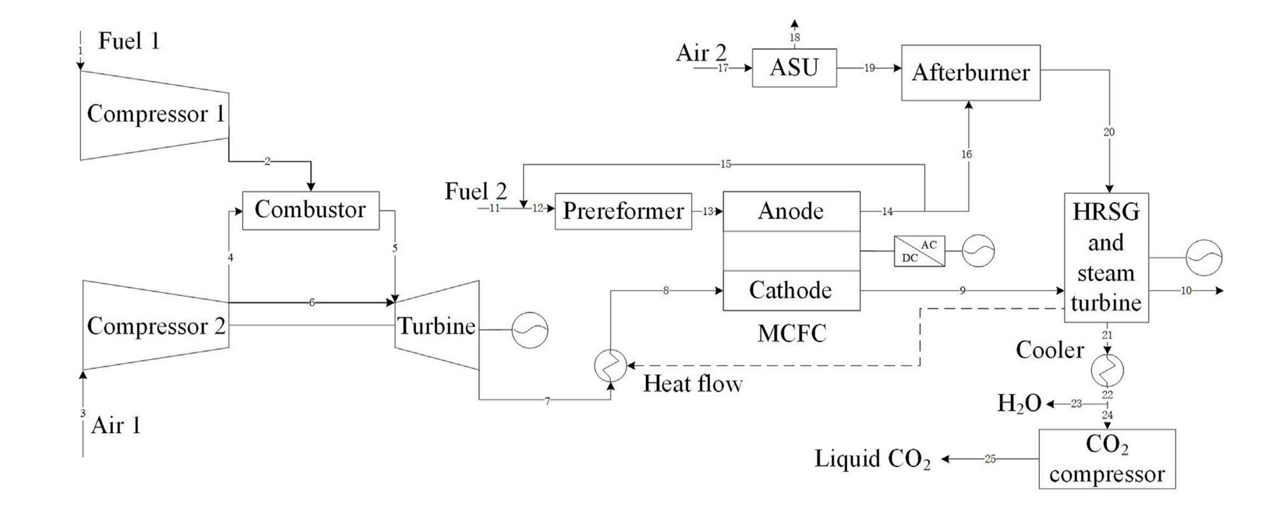


FIGURE 1
Flowchart of the GSCC system combined with MCFC and CO_2 capture without flue gas recirculation.

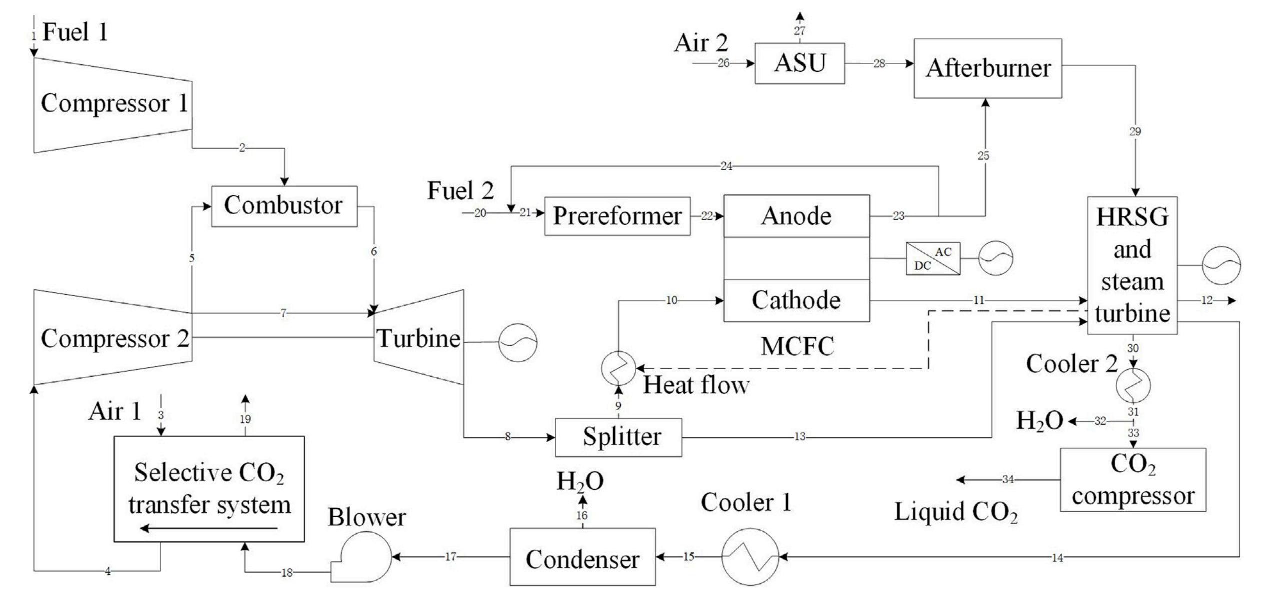


FIGURE 2
Flowchart of the MCFC-integrated GSCC system with SEGR in parallel and CO_2 capture.

using the F-class GT, for the GSCC system integrated with a solid oxide fuel cell (SOFC), without carbon capture, the efficiency reaches almost 70%.

Conventional CO_2 capture methods usually result in a significant decrease in efficiency and output power. Compared with the conventional CO_2 capture techniques, MCFC has special advantages of increasing the efficiency of the entire system. CO_2 and O_2 from the GT exhaust gas can form carbonate ions in the cathode of MCFC, which are carried to the anode by the molten electrolyte of MCFC. After the carbonate ions react with fuels such as CH_4 or H_2, H_2O and CO_2 are generated at the anode; therefore, after the combustion of anode flue gas and pure O_2 in the afterburner, only CO_2 and H_2O are left. The MCFC has higher efficiency and lower cost than the phosphoric acid fuel cell (PAFC) and a more simple structure than the SOFC (Zhao and Hou, 2022). Carapellucci et al. (2019) compared the systems of the steam power plant (SPP) combined with MCFC and the SPP combined with the monoethanolamine (MEA) method. The results showed that the system of SPP combined with MCFC had a higher overall efficiency and CO_2 removal capacity.

Selective exhaust gas recirculation (SEGR) is a type of technique to recycle CO_2 from GT flue gas with membranes

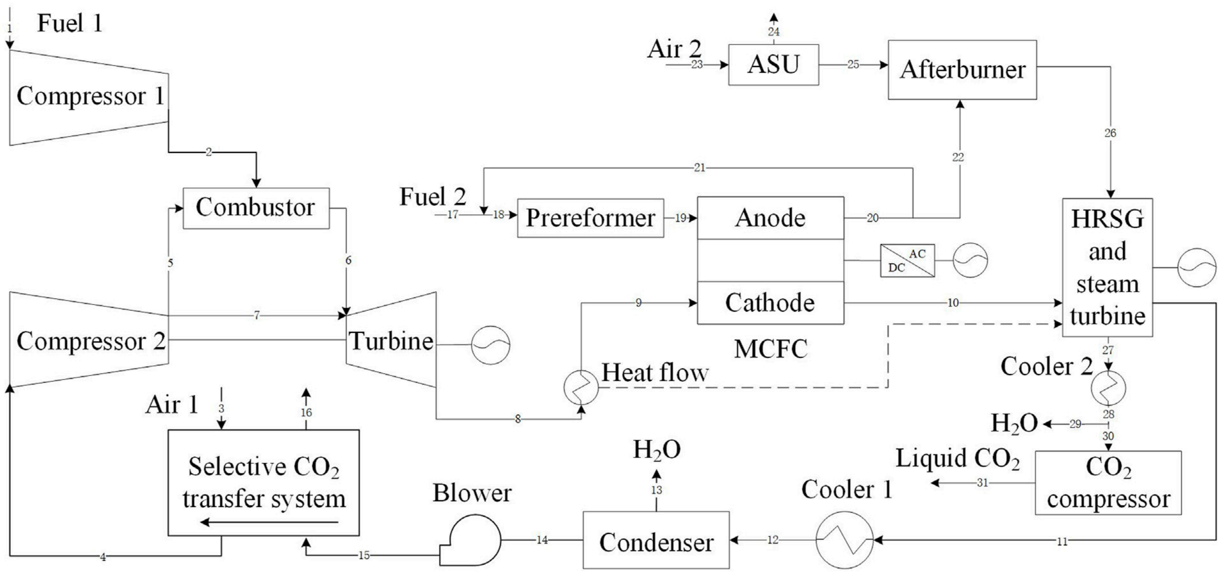


FIGURE 3
Flowchart of the MCFC-integrated GSCC system with SEGR in series and CO_2 capture.

to increase the CO_2 concentration (c_{CO_2}) in the cycle. CO_2 is selectively conveyed through membranes from the exhaust gas; therefore, higher c_{CO_2} is possible in the emission. As N_2 and H_2O in the exhaust gas are ideally not recirculated, the flow rate of emitted gas is reduced. When the air is applied as the sweep gas, SEGR can be driven by the c_{CO_2} difference between the air side and the flue gas side, which means that the CO_2 can be enriched by SEGR with nearly no energy consumption and without requiring pressurization equipment. Bellas et al. (2019) conducted experiments on a micro-GT with SEGR and revealed that c_{CO_2} in the exhaust gas was significantly improved with the help of SEGR, and the nitrogen oxide (NOx) emissions were reduced. The c_{CO_2} in the GT exhaust could be raised to 18% when SEGR and MEA were integrated into natural gas combined cycle (NGCC) plants (Herraiz et al., 2018). Diego et al. (2018) proved that SEGR effectively reduced the energy demand of the NGCC plant combined with MEA. Merkel et al. (2012) used the H_2-selective and CO_2-selective membranes to capture CO_2 formed in the integrated gasification combined cycle (IGCC) power plants. The research results revealed that there was a decrease in both capital cost and energy utilization compared with the cold absorption method of CO_2 capture.

Even though both the methods of MCFC and SEGR can enrich CO_2 with less energy consumption compared with the conventional CO_2 capture methods, there are still limitations to using either MCFC or SEGR alone. When MCFC is adopted alone, Milewski et al. (2013) verified with experiments that the performance of MCFC was deeply limited by the c_{CO_2} of the cathode. When SEGR was adopted alone, Richard et al. (2017) studied that the rise in c_{CO_2} of exhaust gas was limited, which could be 15–20 vol%. Therefore, if SEGR is integrated into MCFC, the c_{CO_2} of exhaust gas can be additionally increased, and the performance of MCFC can be significantly improved, which has not been studied yet.

To reduce CO_2 emission with less energy consumption and increase the whole system performance, two GSCC systems combined with MCFC, SEGR, and CO_2 capture are proposed in this work. The SEGR operating in parallel with the GSCC system combined with MCFC is investigated in the first system; in the second system, the SEGR operating in series with the GSCC system integrated into MCFC is investigated. The thermal and economic performances of different systems are discussed and compared. The effects of the SEGR ratio and the CO_2 capture rate on the thermal efficiency and economic performance of new systems are examined.

2 Description of different systems

2.1 GSCC system integrated into MCFC and CO_2 capture (reference system)

In this study, the GSCC system combined with MCFC and CO_2 capture without SEGR is selected as the reference system, and the system flowchart is shown in Figure 1. After passing through compressor 1, the fuel (2) is supplied to the combustor. After passing through compressor 2, the air (3) is separated into compressed air (4) and (6). Compressed air (4) is supplied into the combustor; compressed air (6) is transferred into the GT as the coolant gas. The combustion chamber emission expands in the gas turbine to produce electricity, and the gas turbine flue gas is then transferred to the MCFC cathode. A portion of the anode flue gas (15) is sent to the pre-reformer to convert the fuel into H_2 and CO in order to prevent the carbon deposition problem (Duan et al., 2014). After being transported from the cathode, the

TABLE 1 System simulation parameters.

Ambient condition (Duan et al., 2014)		298.15 K, 1.01 atm
Generator efficiency (Duan et al., 2014)		99%
Compositions of air (Duan et al., 2014)		N_2 79% and O_2 21%
Gas turbine		
Mass flow of GT fuel (kg/s)		15
Content of fuel		CH_4 100%
Lower heating value of fuel (kJ/kg) (Duan et al., 2014)		50,030
Pressure ratio		16
Turbine entrance temperature (K)		1,673
Membranes		
CO_2/N_2 selectivity (−) (Ramasubramanian et al., 2012)		140
CO_2 permeance (gpu) (Ramasubramanian et al., 2012)		3,000
HRSG		
LP/MP/HP pressure (MPa) (Duan et al., 2014)		0.39/3.6/17.6
Isentropic efficiency of LP/MP/HP (Duan et al., 2014)		92%/91%/90%
Mechanical efficiency of turbine (Duan et al., 2014)		99%
Air separation unit		
Operating pressure (MPa) (Duan et al., 2015)		0.6
Isentropic efficiency (Duan et al., 2015)		80%
CO_2 compression		
Compression stage quantity (Duan et al., 2014)		3
Exit pressure (atm) (Duan et al., 2014)		80
Exit temperature (K) (Duan et al., 2014)		303.15
MCFC		
Mass flow of fuel (kg/s)		3.75
Content of fuel		CH_4 100%
Lower heating value of fuel (kJ/kg)		50,030
Area (m^2)		102,245
Ratio of steam to carbon (Duan et al., 2014)		3.5
Current density (A/m^2) (Duan et al., 2014)		1,500
Fuel utilization rate		0.85
Working temperature (K) (Duan et al., 2015)		923.15
η_{DC-AC}		95%
Active surface area (m^2/m^3) (Bian et al., 2020)	Anode	2.7E5
	Cathode	3.0E5
Thickness (mm) (Bian et al., 2020)	Anode	0.6
	Cathode	0.6
	Electrolyte	1
Electrical conductivity (S/m) (Bian et al., 2020)	Anode	100
	Cathode	100
	Electrolyte	138.6

(Continued on following page)

TABLE 1 (*Continued*) **System simulation parameters.**

Standard exchange current (A/m^2) (Bian et al., 2020)	Anode	50
	Cathode	2
Effective diffusivity (m^2/s) (Bian et al., 2020)	Anode	3.97E-6
	Cathode	1.89E-6

carbonate ions react with H_2 in the anode and produce H_2O and CO_2 (Milewski et al., 2013). The cathode flue gas (9) has low c_{CO_2} and high temperature after the electrochemical reaction, and after discharging heat in the heat recovery steam generator (HRSG), the cathode flue gas (9) is released into the atmosphere (10). In the afterburner, pure O_2 (19) generated from the air separation unit is utilized to combust the rest anode flue gas (16). Then, the afterburner flue gas (20) is supplied into the HRSG to release heat. Finally, the afterburner flue gas (21), consisting of H_2O and CO_2, is condensed and compressed to generate the liquid CO_2 (25).

2.2 MCFC-integrated GSCC system with SEGR in parallel and CO_2 capture

The simplified flowchart of the MCFC-integrated GSCC system with SEGR in parallel and CO_2 capture is shown in Figure 2. The GT exhaust gas (8) is separated into two parts: (9) and (13). After being heated by the afterburner flue gas to 923.15 K (Duan et al., 2014), the flue gas (9) is transferred to the MCFC cathode. After being cooled in the HRSG and further cooled in cooler 1 to 353.15 K, exhaust gas (13) is supplied into the condenser to remove H_2O (15). Then, the water-excluded flue gas (17) is blown into the selective CO_2 transfer system. The air mixed with CO_2 selected by the membranes is then compressed in compressor 2.

2.3 MCFC-integrated GSCC system with SEGR in series and CO_2 capture

Figure 3 shows a simplified flowchart of the MCFC-integrated GSCC system with SEGR in series and CO_2 capture. The GT flue gas (11) is cooled in HRSG and further cooled in cooler 1 to a temperature of 303.15 K. Then, the water-excluded flue gas (14) is blown into the selective CO_2 transfer system. The sweep air 1 (3) is transferred to the selective CO_2 transfer system.

3 System modeling

Aspen Plus software is adopted to establish the simulation models. In brief, the MCFC is simulated using a Fortran code, and the selective CO_2 transfer system is modeled using Aspen Custom Modeler. The new system parameters are obtained as shown in Table 1. During the establishment of the models, the suppositions to be considered are as follows (Bian et al., 2022):

1) Thermally insulated MCFC, and no entropy flow to the outside environment.
2) Constant membrane permeability, and the coupling impact is ignored.
3) Kinetic or potential energy effects are ignored.
4) Incompressible ideal gas and steady-state conditions are supposed.

The main equations of the MCFC model used in the Fortran code are listed in Table 2 (Eqs 1–25). To guarantee that the afterburner combustion gas contains only CO_2 and H_2O, the MCFC anode is supplied with pure CH_4. In Eq. 5, ΔG is the Gibbs free energy (kJ/kg) and p_i represents the partial pressure of species i (MPa). In Eqs 8–11, j is the current density (A/m^2); j_0 represents the exchange current density (A/m^2); and j_0^0 is the standard exchange current density (A/m^2). In Eq. 13, R_{ohm} stands for the Ohmic polarization cell resistance ($\Omega \cdot m^2$); τ is the thickness (mm); and σ is the electrical conductivity (S/m^{-1}). The gas transport models in porous media are used (Eqs 17–21) to calculate the gas partial pressures at the three-phase boundaries ($p_{i,TPB}$). $p_{i,TPB}$ represents the partial pressure of the species i at the three-phase boundary (MPa) and D_{eff} is the effective diffusivity (m^2/s).

The gas permeance equations are listed in Table 2 (Eq. 26). The selective CO_2 transfer system is arranged as counter-current. Q_i is the permeability of the species i (kmol/($m^2 s \cdot$ MPa)); $d\dot{n}_i$ represents the gas permeance of species i for a segment of area (kmol/s); A represents the area (m^2); $p_{i,f}$ represents the partial pressure of the species i at the feed side (MPa); and $p_{i,p}$ represents the partial pressure of species i at the permeate side (MPa).

4 Model validation with experimentation

4.1 Gas turbine system model validation with literature data

The GT system model is validated with the data from Choi et al. (2014). In the literature, an F-class GSCC system with SOFC is studied. The specifications of the two GSCC systems are shown in Table 3. The simulated data are in excellent agreement with the literature data.

4.2 MCFC model validation using experiments

The model accuracy is validated using unit MCFC cell equipment, as shown in Figure 4A. The unit fuel cell includes

TABLE 2 Main reaction equations.

MCFC	
Reforming reaction (Duan et al., 2014)	$CH_4 + H_2O \rightarrow CO + 3H_2$ (1)
	$CO + H_2O \rightarrow CO_2 + H_2$ (2)
Cathode reaction (Duan et al., 2014)	$0.5O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$ (3)
Anode reaction (Duan et al., 2014)	$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$ (4)
Ideal reversible voltage (Bian et al., 2020)	$E_{Nerst} = \frac{\Delta G}{nF} + \frac{RT}{nF}\ln\left[\frac{p_{H_2}(p_{O_2})^{0.5}P_{CO_2,ca}}{P_{H_2O}P_{CO_2,an}}\right]$ (5)
	$\Delta G = 242,000 - 45.8T$ (6)
Activation loss (Bian et al., 2020)	$\eta_{act} = \eta_{act,an} + \eta_{act.ca}$ (7)
	$\eta_{act,an} = \frac{RT}{\alpha nF}\ln\frac{jp_{H_2}}{j_{0,an}p_{H_2,TPB}}$ (8)
	$\eta_{act,ca} = \frac{RT}{\alpha nF}\ln\frac{j(p_{O_2})^{0.5}p_{CO_2,ca}}{j_{0,ca}(p_{O_2,TPB})^{0.5}p_{CO_2,ca,TPB}}$ (9)
	$j_{0,an} = j^0_{0,an}(p_{H_2})^{0.25}(p_{H_2O})^{0.25}(p_{CO_2,an})^{0.25}$ (10)
	$j_{0,ca} = j^0_{0,ca}(p_{O_2})^{0.375}(p_{CO_2,ca})^{-1.25}$ (11)
Ohmic loss (Arpornwichanop et al., 2013)	$\eta_{ohm} = jR_{ohm}$ (12)
	$R_{ohm} = \frac{\tau_{an}}{\sigma_{an}} + \frac{\tau_{elec}}{\sigma_{elec}} + \frac{\tau_{ca}}{\sigma_{ca}}$ (13)
Concentration loss (Arpornwichanop et al., 2013)	$\eta_{conc} = \eta_{conc,an} + \eta_{conc.ca}$ (14)
	$\eta_{conc,an} = \frac{RT}{2F}\ln\left(\frac{p_{H_2}p_{H_2O,TPB}p_{CO_2,an,TPB}}{p_{H_2,TPB}p_{H_2O}p_{CO_2,an}}\right)$ (15)
	$\eta_{conc.ca} = \frac{RT}{2F}\ln\left(\frac{p_{CO_2,ca}(p_{O_2})^{0.5}}{p_{CO_2,ca,TPB}(p_{O_2,TPB})^{0.5}}\right)$ (16)
	$p_{H_2,TPB} = p_{H_2} - \frac{RT\tau_{an}}{2FD_{eff,an}}j$ (17)
	$p_{H_2O,TPB} = p_{H_2O} + \frac{RT\tau_{an}}{2FD_{eff,an}}j$ (18)
	$p_{CO_2,an,TPB} = p_{CO_2,an} + \frac{RT\tau_{an}}{2FD_{eff,an}}j$ (19)
	$p_{O_2,TPB} = p_{O_2} - \frac{RT\tau_{ca}}{4FD_{eff,ca}}j$ (20)
	$p_{CO_2,ca,TPB} = p_{CO_2,ca} - \frac{RT\tau_{ca}}{2FD_{eff,ca}}j$ (21)
Actual MCFC voltage (Bian et al., 2022)	$V_{cell} = E_{Nerst} - \eta_{act} - \eta_{ohm} - \eta_{conc}$ (22)
MCFC power output (Bian et al., 2020)	$W_{MCFC} = A_c jV_{cell}$ (23)
Net power output	$W_{MCFC,net} = \eta_{DC-AC}W_{MCFC}$ (24)
MCFC thermal efficiency	$\eta_{MCFC} = \frac{W_{MCFC,net}}{m_{MCFC}LHV}$ (25)
Selective CO_2 transfer system	
Species i gas permeance (Franz et al., 2013)	$d\dot{n}_i = dA \cdot Q_i(p_{i,f} - p_{i,p})$ (26)
Performance indicators	
MCFC fuel utilization rate (Duan et al., 2015)	$U_{fuel} = 1 - \frac{m_{fuel,outlet}}{m_{fuel,inlet}}$ (27)
MCFC CO_2 utilization rate (Duan et al., 2015)	$U_{CO_2} = 1 - \frac{m_{CO_2,outlet}}{m_{CO_2,inlet}}$ (28)
Overall CO_2 capture rate (Duan et al., 2015)	$OCCR = \frac{m_{CO_2,capture}}{m_{CO_2,emissions}}$ (29)

(Continued in next column)

TABLE 2 (*Continued*) Main reaction equations.

MCFC	
Thermal efficiency of MCFC	$\eta_{MCFC} = \frac{W_{MCFC}}{m_{MCFC}LHV}$ (30)
Overall thermal efficiency	$\eta = \frac{W_{total,net}}{m_{MCFC}LHV + m_{GT}LHV}$ (31)

a porous anode of Ni/Cr alloy, a porous cathode of NiO, and an electrolyte matrix filled with the combination of 62% Li_2CO_3 and 38% K_2CO_3. The experimental device consists of a temperature control facility, a gas flow control facility, and the unit fuel cell. The operating temperature is 650°C under atmospheric conditions. The electrochemical workstation is applied to set and measure the current density and voltage. The simulation and actual voltage values at different c_{CO_2} are shown in Figure 4B. In this paper, the value of the error indicator RMSE is 0.014 V, which is calculated using Eq. 32. It is noticeable that the simulation results are in good agreement with the test values.

$$RMSE(x) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(I_i^{experimental} - I_i^{estimated}\right)^2}. \quad (32)$$

5 Results and discussion

In this section, results of the models with SEGR in parallel and series are discussed and compared with the reference system.

5.1 MCFC-integrated GSCC system with SEGR in parallel and CO_2 capture

The flowchart of an MCFC-integrated GSCC system with SEGR in parallel and CO_2 capture is shown in Figure 2. One part of the exhaust gas regenerated by the HRSG is supplied to the selective CO_2 transfer system. CO_2 is passed through membranes selectively and then supplied to the compressor with the sweep air.

Figure 5A shows the variations in the MCFC CO_2 utilization rate that is demanded to capture 88.16% of CO_2 produced by the combustion as a function of the SEGR for different selective CO_2 transfer rates (SCTRs). For a constant SCTR, the MCFC CO_2 utilization rate rises at a higher recirculation rate. This is because the CO_2 discharged by the selective CO_2 transfer system increases with the increase in the recirculation rate since the c_{CO_2} in the exhaust gas is higher. A considerable amount of CO_2 is captured in the MCFC.

When the SCTR is held constant at 0.95 and the selective exhaust gas recirculation rate is increased from 0 to 0.7, the mass flow rate of sweep air decreases. The reason is that the turbine entrance temperature should be kept invariable. Therefore, the c_{CO_2} in GT flue gas increases, and the O_2 concentration (c_{O_2}) decreases, as illustrated in Figure 5B. O_2 in the combustor exceeds the limit of 17% for F-class GT (Evulet et al., 2009), as shown in Figure 5B.

When the SCTR is held constant at 0.95 and the selective exhaust gas recirculation rate is raised from 0 to 0.7, the c_{CO_2} is

TABLE 3 GSCC specifications.

Parameter	Reference (Choi et al., 2014)	Simulation result
Turbine entrance temperature (K)	1,673	1,673
Turbine rotor entrance temperature (K)	1,600	1,600
Compressor pressure ratio	16	16
Turbine coolant rate to compressor intake (%)	16	16
Fuel mass flow of GT (kg/s)	10.16	15
Specific GT power (MJ/kg)	18.07	19.28
Specific ST power (MJ/kg)	10.09	8.96
Combined cycle power/fuel mass flow (MJ/kg)	28.16	28.23
Combined cycle efficiency (%)	57.1	56.4

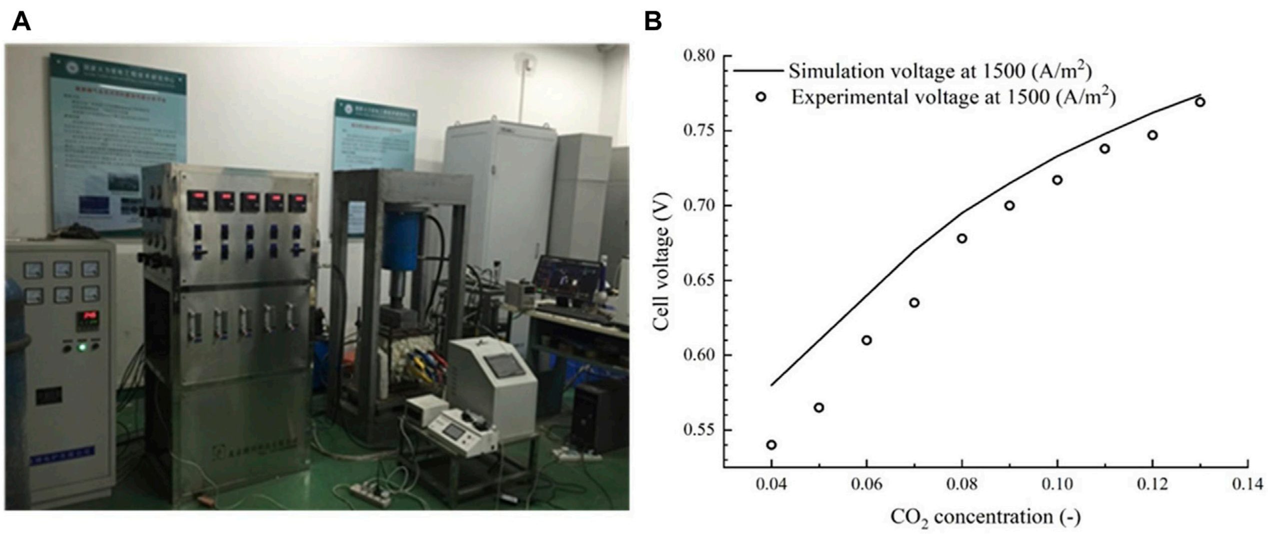


FIGURE 4
(A) Unit MCFC cell facility and **(B)** simulation and test voltages under various c_{CO_2}.

significantly influenced by the change in the SEGR. According to Eq. 5, the ideal reversible voltage mainly increases with the increase in c_{CO_2} in GT exhaust gas. According to Eq. 16, the cathode concentration loss is reduced with the increase in c_{CO_2}. Therefore, the actual cell voltage increases with the increase in SEGR as the c_{CO_2} increases, according to Eq. 22. As shown in Figure 5C, when the SEGR increases from 0.6 to 0.7, the slope of the voltage is smaller because of the significant decrease in the O_2 concentration, leading to a massive rise in the cathode concentration loss according to Eq. 16. When the SEGR is changed and the SCTR is held constant, the system thermal efficiency is principally affected by the output of MCFC. The output of MCFC is regulated by the voltage as the current density is maintained at 1500 A/m^2. As the SEGR is increased from 0 to 0.6, the system thermal efficiency increases as the voltage increases. With the increase in the SEGR, the sweep air mass flow rate decreases to maintain the invariable turbine entrance temperature, which gives rise to the reduction in the mass flow rate of the expanding gas into the gas turbine. Therefore, the output of GT is reduced with the increase in the SEGR. While the SEGR increases from 0.6 to 0.7, as the drop in the GT output is larger than the increase in the MCFC output, the system thermal efficiency decreases, as shown in Figure 5C.

5.2 MCFC-integrated GSCC system with SEGR in series and CO_2 capture

The flowchart of the MCFC-integrated GSCC system with SEGR in series and CO_2 capture is illustrated in Figure 3. After CO_2 is excluded by MCFC, the emission of GT is supplied to the selective CO_2 transfer system.

Figure 6A shows the changes in the MCFC CO_2 utilization rate required to capture 88.16% of CO_2 as a function of SCTRs. The more the CO_2 conveyed to the combustion air, the less the CO_2 utilization rate demanded by the MCFC.

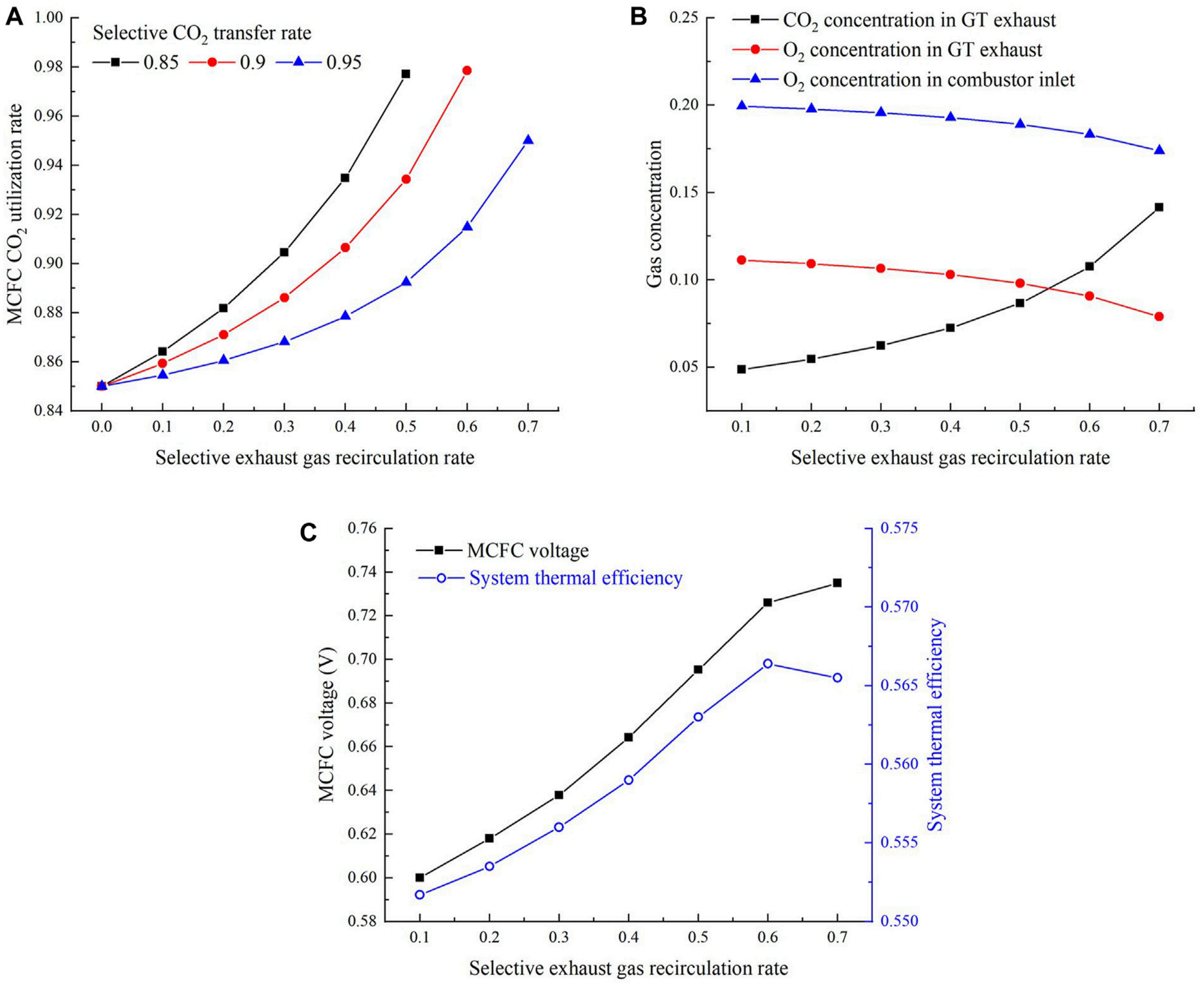


FIGURE 5
Impact of the SEGR on **(A)** U_{CO_2}, **(B)** gas concentration, and **(C)** MCFC voltage and system thermal efficiency (the OCCR is 88.16%).

When the SCTR increases from 0.65 to 0.91, the mass flow of sweep air (air 1) decreases to maintain the turbine entrance temperature constant; therefore, the c_{CO_2} in GT exhaust increases, and the c_{O_2} decreases, as illustrated in Figure 6B. As O_2 in the combustor must be maintained above 17 vol% for an F-class gas turbine, the largest c_{CO_2} in GT exhaust gas can be achieved at 11.72% when the SCTR is 0.91.

When the SCTR increases from 0.65 to 0.91, the MCFC voltage is mainly regulated by the c_{CO_2} in the GT exhaust gas as the c_{CO_2} is influenced by the change in the SCTR. The MCFC voltage increases with the increase in the SCTR as the c_{CO_2} increases, according to Eqs 5 and 16. When the SCTR increases from 0.9 to 0.91, the slope of the MCFC voltage is smaller because of the decrease in the O_2 concentration, as shown in Figure 6C. As the SCTR is varied, according to Eq. 23, the MCFC power output increases as the MCFC voltage increases and the current density is held constant. The system thermal efficiency increases as the MCFC power output increases, according to Eq. 25. However, with the increase in the SCTR, the sweep air mass flow rate decreases to maintain the invariable turbine entrance temperature, which gives rise to the reduction in the mass flow rate of the expanding gas into the gas turbine. Therefore, the output power of the GT is reduced with the increase in the SCTR. When the SCTR increases from 0.9 to 0.91, as the drop in the GT output is larger than the increase in the MCFC output, the system thermal efficiency decreases, as shown in Figure 6C.

5.3 Comparison of the results for different systems

The major operating parameters of the MCFC voltage and GSCC system for SEGR in series and parallel with MCFC are shown in Table 4. Parallel 96/90 denotes that the new system with SEGR in parallel operates with a 0.96 CO_2 utilization rate of MCFC and 0.9 SCTR of the membrane. Series 91/28, 90/36, and 85/46 denote that the new system with SEGR in series operates

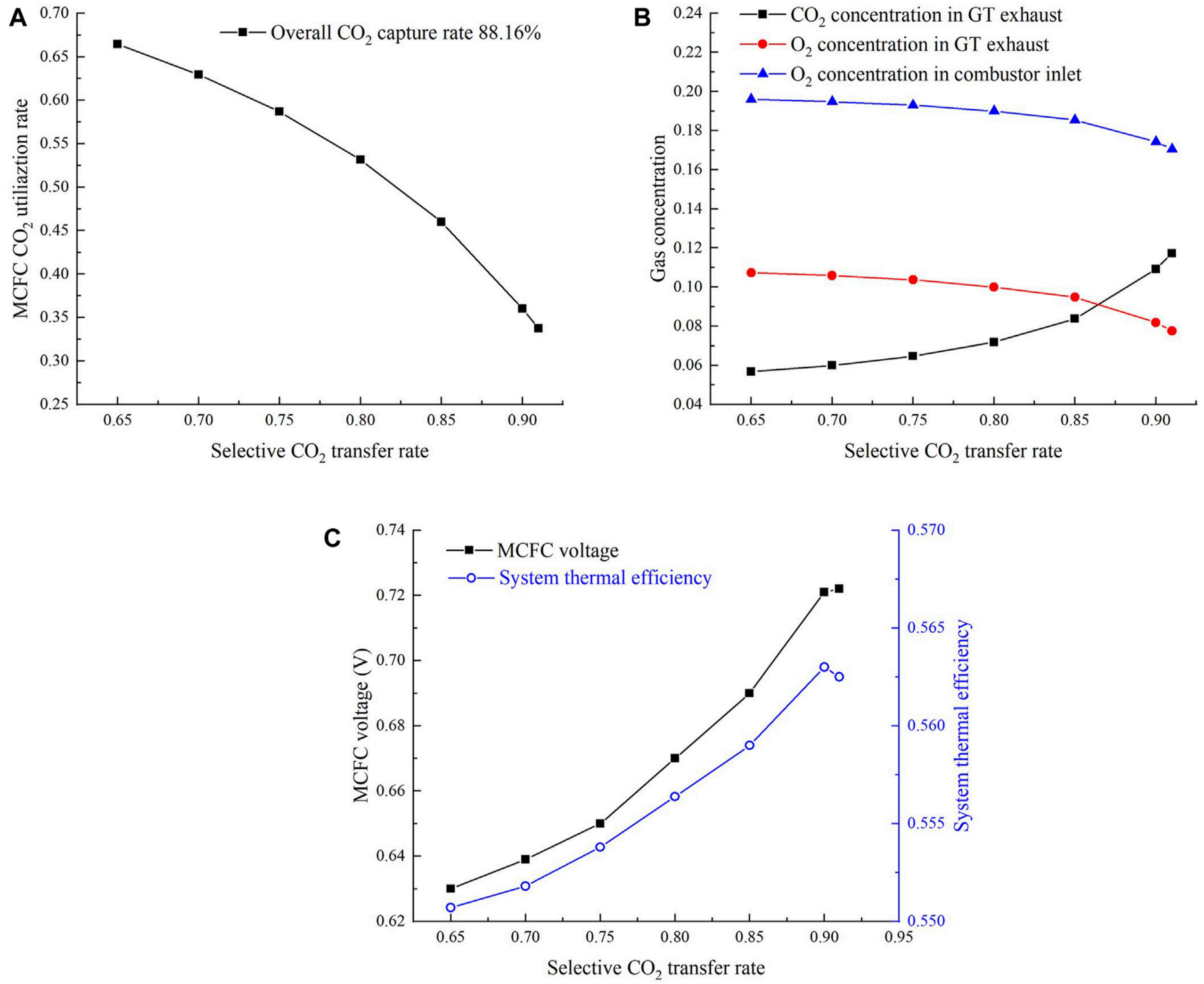


FIGURE 6
Impact of SCTR on **(A)** U_{CO_2}, **(B)** gas concentration, and **(C)** MCFC voltage and system thermal efficiency (SEGR in series when the OCCR is 88.16%).

with MCFC CO_2 utilization rates of 0.91, 0.9, and 0.85 and membrane SCTRs of 0.28, 0.36, and 0.46, respectively. An MCFC-integrated GSCC system with CO_2 capture and without SEGR is considered the reference system. The current density and the area of MCFC are held constant. The key stream data of different systems are shown in Table 4. The data on the streams from parallel 96/90 and series 90/36 are shown in detail in the Supplementary Material. The power and thermal efficiency of different systems are listed in Table 4. Compared with the reference system, there is an increase in the entire thermal efficiencies of the systems with SEGR in parallel and series. The efficiency of the parallel 96/90 system is greater than that of the series 90/36 system.

Figure 7A indicates the air mole flow rate at the compressor entrance and the GT net output. In contrast to the reference system, with the increase in the selective flue gas recirculation, to keep the GT inlet temperature constant at 1400°C, the air into the selective CO_2 transfer system decreases. Therefore, the air mole flow rate at the compressor inlet decreases, which results in the decrease in the GT output power, which is in contrast to the reference case. When the SCTR of the GSCC system with SEGR in series is reduced from 0.91 to 0.85, the air mole flow rate at the compressor entrance increases and so is the GT net power. The GT exhaust gas mole flow rate is regulated by the air mole flow rate at the compressor entrance, and the net power consumed by the blower is affected by the GT exhaust gas mole flow rate, as shown in Figure 7B.

Figure 7C shows the comparison of c_{CO_2} and c_{O_2} in the GT exhaust gas and MCFC voltage of the GSCC system with SEGR in parallel and series and the reference case. For the reference system, the c_{CO_2} in GT exhaust is 4.39%, which results in a low MCFC voltage as the fuel cell performance is significantly influenced by the c_{CO_2} of the gas mixture fed into the MCFC cathode. With SEGR in parallel or in series, the c_{CO_2} in GT exhaust gas increases, and c_{O_2} is decreases, which leads to the increase in the MCFC voltage.

TABLE 4 Parameters of the investigated configurations.

Parameter	Reference system	Parallel 96/90	Series 91/28	Series 90/36	Series 85/46
Recirculation rate (%)	-	60	-	-	-
MCFC CO_2 utilization rate	0.85	0.9	0.28	0.36	0.46
Selective CO_2 transfer rate	-	0.96	0.91	0.9	0.85
OCCR (%)	88.16	88.16	88.16	88.16	88.16
MCFC					
Voltage (V)	0.59	0.725	0.722	0.721	0.69
Current density (A/m^2)	1,500	1,500	1,500	1,500	1,500
Area (m^2)	102,245	102,245	102,245	102,245	102,245
CO_2-enriched air at the compressor inlet					
Temperature (K)	298.15	298.15	298.15	298.15	298.15
Pressure (MPa)	0.102	0.102	0.102	0.102	0.102
Mole flow (kmol/s)	20.35	19.27	19.16	19.29	19.69
c_{CO_2} (vol%)	0.03	6.6	7.42	6.6	4.03
c_{O_2} (vol%)	20.73	19.1	17.88	18.28	19.42
Flue gas at GT exhaust					
Temperature (K)	949.03	970.49	972.48	969.97	961.91
Pressure (MPa)	0.102	0.102	0.102	0.102	0.102
Mole flow (kmol/s)	21.29	20.2	20.1	20.22	20.62
c_{CO_2} (vol%)	4.39	10.93	11.72	10.92	8.38
c_{O_2} (vol%)	11.29	8.97	7.75	8.19	9.48
H_2O concentration (vol%)	8.79	9.26	9.3	9.25	9.07
GT net power (MW)	289.25	283.08	282.42	283.17	285.52
ST net power (MW)	157.25	160.05	160.4	160.03	158.95
MCFC net power (MW)	90.96	111.24	110.71	110.65	105.91
CO_2 compressor (MW)	−17.77	−17.77	−17.77	−17.77	−17.77
ASU (MW)	−2.24	−2.24	−2.24	−2.24	−2.24
Blower (MW)	-	−3.27	−5.77	−5.81	−5.95
Net power output	517.45	531.09	527.75	528.03	524.42
Overall thermal efficiency (%)	55.16	56.62	56.26	56.29	55.91

6 Economic and environmental performance evaluation

In this section, the economic and environmental performances of new systems are compared with those of the reference system.

The principal economic criteria used to assess various CO_2 capture methods are the specific primary energy consumption for CO_2 avoided (SPECCA) and the cost of CO_2 avoided (CCA). The equations for cost estimation are listed in Table 5. For the power section, α is 0.7, β is 0.45, and γ is 0.35; for the CO_2 removal section, α is 1.1, β is 0.45, and γ is 0.7 (Gatti et al., 2020).

Table 6 shows the comparison results of the economic evaluation. Contrast to the CCA of the conventional MEA technique for CO_2 capture (Leto et al., 2011), the overall thermal efficiency of the parallel 96/90 system in this paper is higher, which results in a negative SPECCA index. Figure 8A shows the thermodynamic performance (SPECCA) of the systems investigated. The cost per kW MCFC is fixed at 555 $/kW (Gatti et al., 2020). Over the last 20 years, the MCFC cost has been reduced significantly (Campanari et al., 2014), and further decrease exists according to DOE targets (Spendelow et al., 2012). The investment lifetime is 25 years, the fuel cost is 4.5$/GJ, and the equivalent hours at full load is 7880 h per year (Gatti et al., 2020). In Figure 8B, CCA is displayed as a function of the specific TPC ($/kW). The closer the system is to the bottom left corner, the more attractive it is because it represents lower operating and specific investment costs.

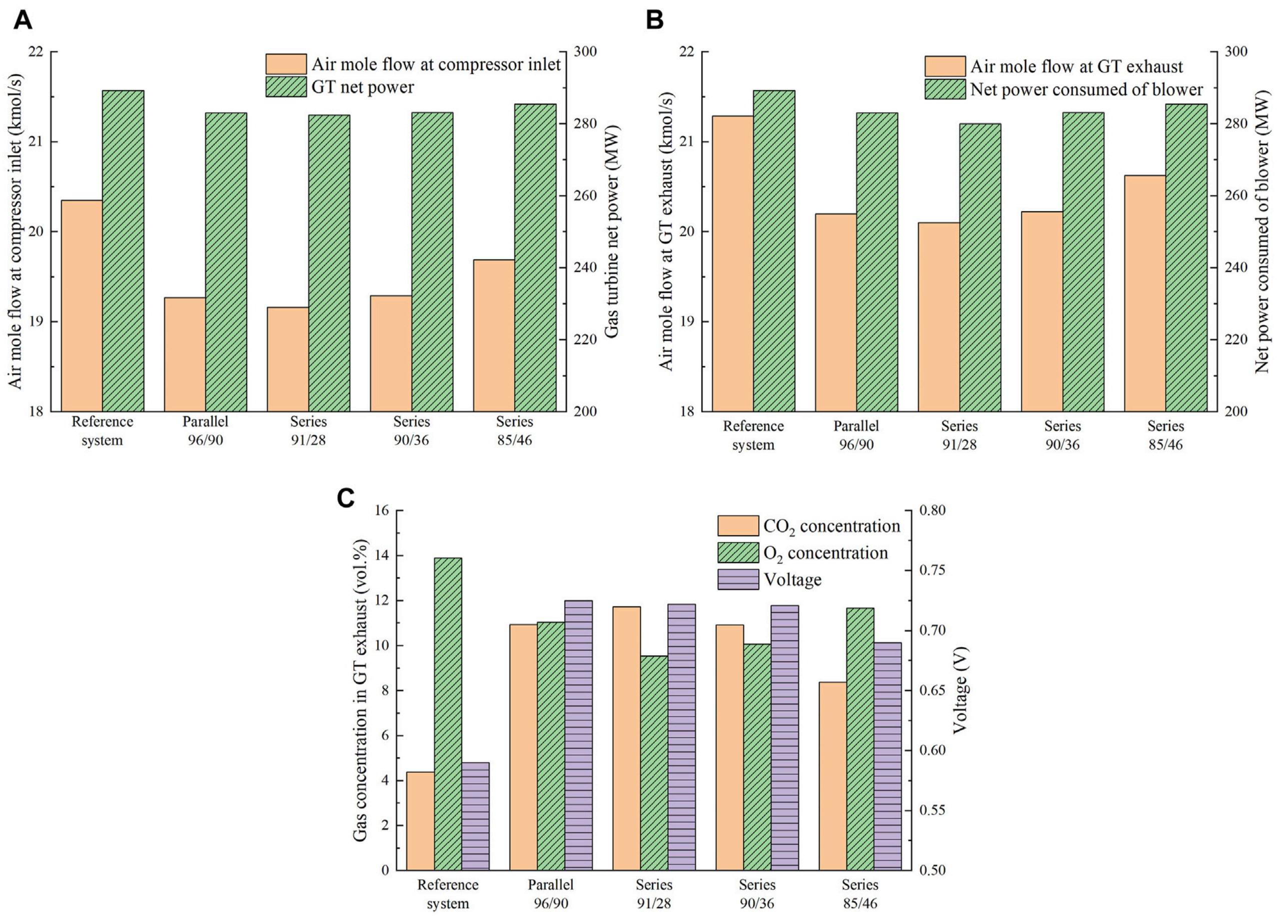


FIGURE 7
(A) Air mole flow at the compressor inlet and GT net power output. **(B)** GT exhaust gas mole flow and net power consumed by the blower. **(C)** CO_2/O_2 concentration in the GT exhaust and MCFC voltage for the GSCC system with SEGR in parallel and in series, which is in contrast to the reference system.

TABLE 5 Equations for cost estimation.

SPECCA	$SPECCA[\frac{MJ_{LHV}}{kg_{CO_{2,avoided}}}] = \frac{(\frac{1}{\eta_{CCS}} - \frac{1}{\eta_{REF}})}{E_{REF} - E_{CCS}} \cdot 3600$	(33)
TEC	$TEC[M\$] = C_0 (\frac{S}{S_0})^f$	(34)
INST	$INST = \alpha \cdot TEC$	(35)
IC	$IC = \beta \cdot (1 + \alpha) \cdot TEC$	(36)
EPC	$EPC = TEC + INST + IC = (1 + \alpha) \cdot (1 + \beta) \cdot TEC$	(37)
OCC	$OCC = \gamma \cdot EPC = \gamma \cdot (1 + \alpha) \cdot (1 + \beta) \cdot TEC$	(38)
TPC	$TPC = EPC + OCC = (1 + \alpha) \cdot (1 + \beta) \cdot (1 + \gamma) \cdot TEC$	(39)
CCA	$CCA[\frac{\$}{t_{CO_2}}] = \frac{(COE)_{CCS} - (COE)_{REF}}{(kg_{CO_2} kWh^{-1})_{REF} - (kg_{CO_2} kWh^{-1})_{CCS}}$	(40)

7 Conclusion

In this paper, the MCFC-integrated GSCC systems with CO_2 capture and SEGR in series/parallel are investigated and contrasted with the MCFC-integrated GSCC system with CO_2 capture and without SEGR (the reference case). The results show that the new systems markedly increase the c_{CO_2} in the emission of the gas turbine, maintaining oxygen concentration in the combustor at above 17 vol%. The CO_2 concentrations of the GT exhaust gas reached 14.15 vol% and 11.72 vol% for SEGR parallel (96/90) and series (91/28), respectively, when the OCCR is 88.16%. In addition, the thermal efficiencies of new systems increasingly contrasted to that of the reference system (55.16%). For SEGR in parallel (96/90) and series (90/36), the thermal efficiencies reached 56.65% and 56.29%, respectively, which are 0.19% higher and 0.14% lower than that of the GSCC system without CO_2 capture (56.43%).

1) For the systems with SEGR in parallel, the OCCR is held constant at 88.16%. As the SEGR increases and the SCTR remains unchanged, the MCFC CO_2 utilization rate increases; when SEGR is kept unchanged and SCTR increases, the MCFC CO_2 utilization rate decreases. When the SEGR increases from 0.1 to 0.7 and the SCTR is held constant at 0.95, the c_{CO_2} of the GT flue gas increases from 4.87% to 14.15% and the c_{O_2} in the combustor inlet exhaust is reduced from 20.86% to 18.27%. When the SCTR is held constant at 0.95 and the SEGR increases from 0.1 to 0.6, the

TABLE 6 Economic performance evaluation results of investigated systems.

	GSCC system without CO_2 capture (Duan et al., 2014)	Reference system	Parallel 96/90	Series 90/36
System fuel input (MW_{LHV})	750.6	938	938	938
GT net power (MW)	289.25	289.25	283.08	283.17
ST net power (MW)	134.34	157.25	160.05	160.03
MCFC net power (MW)	-	90.96	111.24	110.65
CO_2 compressor (MW)	-	−17.77	−17.77	−17.77
ASU (MW)	-	−2.24	−2.24	−2.24
Blower (MW)	-	-	−3.27	−5.81
Net power (MW)	423.59	517.45	531.09	528.03
Overall thermal efficiency (%)	56.43	55.16	56.62	56.29
Specific CO_2 emission (g/kWh)	349.22	44.34	43.2	43.45
CO_2 avoided (%)	-	87.3	87.63	87.56
SPECCA ($MJ_{LHV}/kg_{CO_{2,avoided}}$)	-	0.48	−0.072	0.052
Plant component equipment cost				
Gas turbine (M$)	62.89	62.89	62.89	62.89
Steam turbine (M$)	25.34	28.66	28.79	28.77
HRSG (M$)	28.01	46.08	41.67	41.66
Heat rejection (M$)	30.55	45.86	47.08	47.15
MCFC + BOP (M$)	-	50.48	61.74	61.41
Membrane (M$)	-	-	25.34	52.46
ASU (M$)	-	5.82	5.82	5.82
CO_2 compressor (M$)	-	16.78	16.78	16.78
Power section TEC (M$)	146.79	183.49	180.43	180.47
Power section TPC (M$)	488.48	610.61	600.43	600.56
CO_2 removal section TEC (M$)	-	73.08	109.68	136.47
CO_2 removal section TPC (M$)	-	378.3	567.76	706.44
Total TPC (M$)	488.48	988.91	1168.2	1307
Fuel cost (M$)	95.72	119.62	119.62	119.62
Fixed O and M cost (M$)	10	25.8	28	29.3
Consumables (M$)	6.4	10.22	12.73	13.3
First year capital charge (M$)	163.38	280.76	304.62	333.74
COE ($/MWh)	48.95	68.86	72.79	80.21
CO_2 specific avoidance (g/kWh)	-	304.88	306.02	305.77
CCA ($/$t_{CO_2}$)	-	65.3	77.9	102.23

system thermal efficiency increases from 55.17% to 56.64%; when the SEGR increases from 0.6 to 0.7, the system thermal efficiency decreases from 56.64% to 56.55%.

2) For the systems with SEGR in series, the OCCR is held constant at 88.16%; when the SCTR increases from 0.65 to 0.91, the MCFC CO_2 utilization rate is reduced from 0.66 to 0.34. When the SCTR increases from 0.65 to 0.91, the c_{CO_2} of the GT flue gas increases from 5.67% to 11.72% and the c_{O_2} in combustor entrance gas decreases from 20.52% to 17.88%. When the SCTR increases from 0.65 to 0.9, the system thermal efficiency increases from 55.07% to 56.29%; when the SCTR increases from 0.9 to 0.91, the system thermal efficiency is reduced from 56.29% to 56.26%.

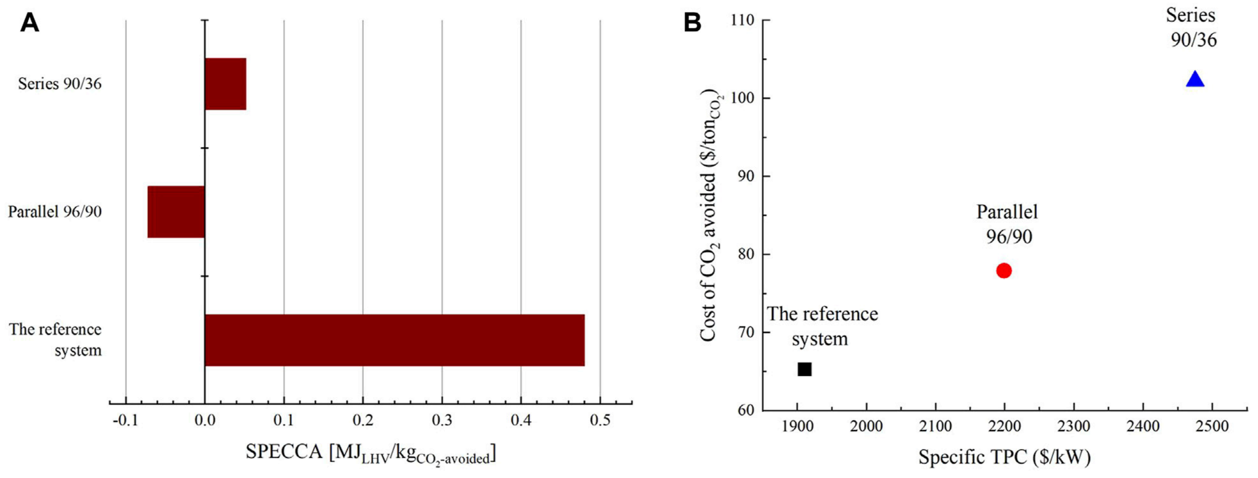


FIGURE 8
(A) SPECCA of the different systems and **(B)** CCA vs. specific TPC.

3) When the CO_2 utilization rate of the MCFC is 0.96 and the SCTR of the membrane is 0.90, the new system with SEGR in parallel exhibits a better economic and environmental performance.

Because of the high cost of the MCFC at present, the new system does not have significant advantages in terms of technical or economic performance. The advantage of the MCFC-based CO_2 capture system, as well as forthcoming technological improvements, will contribute to advancing its economic performance.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

JB: Conceptualization, Data curation, Investigation, Methodology, Software, Writing–original draft. LD: Project administration, Supervision, Writing–review and editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This work was supported by the National Nature Science Foundation Project of China (No. 52076078) and the Science Fund for Creative Research Groups of the National Natural Science Foundation of China (No. 51821004).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors, and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2023.1256000/full#supplementary-material

References

Arpornwichanop, A., Saebea, D., Patcharavorachot, Y., et al. (2013). Analysis of a pressurized solid oxide fuel cell-gas turbine hybrid power system with cathode gas recirculation. *Int. J. hydrogen energy* 38, 4748–4759. doi:10.1016/j.ijhydene.2013.01.146

Bellas, J. M., Finney, K. N., Diego, M. E., Ingham, D., and Pourkashanian, M. (2019). Experimental investigation of the impacts of selective exhaust gas recirculation on a micro gas turbine. *Int. J. Greenh. Gas Control* 90, 102809. doi:10.1016/j.ijggc.2019.102809

Bian, J., Duan, L., Lei, J., and Yang, Y. (2020). Study on the entropy generation distribution characteristics of molten carbonate fuel cell system under different CO_2 enrichment conditions. *Energies* 13, 5778. doi:10.3390/en13215778

Bian, J., Zhang, H., Duan, L., Desideri, U., and Yang, Y. (2022). Study of an integrated gas turbine -Molten carbonate fuel cell -organic Rankine cycle system with CO_2 recovery. *Appl. Energy* 323, 119620. doi:10.1016/j.apenergy.2022.119620

Campanari, S., Chiesa, P., Manzolini, G., and Bedogni, S. (2014). Economic analysis of CO_2 capture from natural gas combined cycles using molten carbonate fuel cells. *Appl. Energy* 130, 562–573. doi:10.1016/j.apenergy.2014.04.011

Carapellucci, R., Battista, D. D., and Cipollone, R. (2019). The retrofitting of a coal-fired subcritical steam power plant for carbon dioxide capture: a comparison between MCFC-based active systems and conventional MEA. *Energy Convers. Manag.* 194, 124–139. doi:10.1016/j.enconman.2019.04.077

Choi, J. H., Ahn, J. H., and Kim, T. S. (2014). Performance of a triple power generation cycle combining gas/steam turbine combined cycle and solid oxide fuel cell and the influence of carbon capture. *Appl. Therm. Eng.* 71 (1), 301–309. doi:10.1016/j.applthermaleng.2014.07.001

Diego, M. E., Bellas, J. M., Mohamed, P., et al. (2018). Techno-economic analysis of a hybrid CO2 capture system for natural gas combined cycles with selective exhaust gas recirculation. *Appl. Energy* 215, 778–791. doi:10.1016/j.apenergy.2018.02.066

Duan, L., Sun, S., Yue, L., Qu, W., and Yang, Y. (2015). Study on a new IGCC (integrated gasification combined cycle) system with CO_2 capture by integrating MCFC (molten carbonate fuel cell). *Energy* 87, 490–503. doi:10.1016/j.energy.2015.05.011

Duan, L., Zhu, J., Long, Y., and Yang, Y. (2014). Study on a gas-steam combined cycle system with CO_2 capture by integrating molten carbonate fuel cell. *Energy* 74, 417–427. doi:10.1016/j.energy.2014.07.006

ElKady, A. M., Evulet, A., Brand, A., Ursin, T. P., and Lynghjem, A. (2009). Application of exhaust gas recirculation in a DLN F-class combustion system for postcombustion carbon capture. *J.Eng. Gas. Turbines Power* 131 (5), 34505. doi:10.1115/1.2982158

Evulet, A. T., Elkady, A. M., Branda, A. R., and Chinn, D. (2009). On the performance and operability of GE's dry low NO combustors utilizing exhaust gas recirculation for PostCombustion carbon capture. *Energy Procedia* 1, 3809–3816. doi:10.1016/j.egypro.2009.02.182

Franz, J., Schiebahn, S., Zhao, L., Riensche, E., Scherer, V., and Stolten, D. (2013). Investigating the influence of sweep gas on CO_2/N_2 membranes for post-combustion capture. *Int. J. Greenh. Gas Control* 13, 180–190. doi:10.1016/j.ijggc.2012.12.008

Gatti, M., Martelli, E., Di Bona, D., Gabba, M., Scaccabarozzi, R., Spinelli, M., et al. (2020). Preliminary performance and cost evaluation of four alternative technologies for post-combustion CO2 capture in natural gas-fired power plants. *Energies* 13, 543. doi:10.3390/en13030543

Hayre, R. (2006). *Fuel cell fundamentals*. Hoboken, New Jersey, United States: Wiley.

Herraiz, L., Fernández, E. S., Palfi, E., and Lucquiaud, M. (2018). Selective exhaust gas recirculation in combined cycle gas turbine power plants with post-combustion CO_2 capture. *Int. J. Greenh. Gas Control* 71, 303–321. doi:10.1016/j.ijggc.2018.01.017

Leto, L., Dispenza, C., Moreno, A., and Calabro, A. (2011). Simulation model of a molten carbonate fuel cell–microturbine hybrid system. *Appl. Therm. Eng.* 31 (6-7), 1263–1271. doi:10.1016/j.applthermaleng.2010.12.029

Merkel, T. C., Zhou, M., and Ba Ker, R. W. (2012). Carbon dioxide capture with membranes at an IGCC power plant. *J. Membr. Sci.* 389, 441–450. doi:10.1016/j.memsci.2011.11.012

Miao, L., Tang, S., Li, X., Yu, D., Deng, Y., Hang, T., et al. (2022). Estimating the CO2 emissions of Chinese cities from 2011 to 2020 based on SPNN-GNNWR. *Environ. Res.* 218, 115060. doi:10.1016/j.envres.2022.115060

Milewski, J., Bujalski, W., Woowicz, M., Futyma, K., and Bernat, R. (2013). Experimental investigation of CO_2 separation from lignite flue gases by 100 cm^2 single molten carbonate fuel cell. *Appl. Mech. Mater.* 376 (3), 299–303. doi:10.4028/www.scientific.net/AMM.376.299

Ramasubramanian, K., Verweij, H., and Ho, W. S. W. (2012). Membrane processes for carbon capture from coal-fired power plant flue gas: a modeling and cost study. *J. Membr. Sci.* 2012, 299–310. doi:10.1016/j.memsci.2012.07.029

Richard, W., Baker, Kniep, J., Wei, X., and Merkel, T. (2017). CO_2 capture from natural gas power plants using selective exhaust gas recycle membrane designs. *Int. J. Greenh. Gas Control* 66, 35–47. doi:10.1016/j.ijggc.2017.08.016

Spendelow, J., Nguyen, T., Houchins, C., et al. (2012). Medium-scale CHP fuel cell system targets. https://www.hydrogen.energy.gov/pdfs/11014_medium_scale_chp_target.pdf (accessed on April 27, 2023).

Tsukagoshi, K., Muyama, A., Masada, J., et al. (2007). Operating status of uprating gas turbines and future trend of gas turbine development. *Tech. Rev. - Mitsubishi Heavy Ind.* 44 (4).

Zhao, H., and Hou, Q. (2022). Study on thermal performance of solar methanol reforming MCFC-GT-ST-CHP system. *Hydrogen Energy* 47, 28670–28683. doi:10.1016/j.ijhydene.2022.06.195

Nomenclature

A	area, m^2
A_c	cell active area, m^2
ASU	air separation unit
BOP	balance of the plant
c_{CO_2}	CO_2 concentration
c_{O_2}	O_2 concentration
CCA	cost of CO_2 avoided, \$/ton$_{CO_2}$
COE	cost of electricity, \$/MWh
D_{eff}	effective diffusivity, m^2/s
ECO$_2$	CO_2-specific emissions, g/kWh
E_{Nerst}	ideal reversible voltage, V
EPC	engineering, procurement, and construction costs, M\$
F	Faraday constant, 96,487 C/mol
ΔG	Gibbs free energy, kJ/kg
GSCC	gas–steam combined cycle
GT	gas turbine
HRSG	heat recovery steam generator
IC	indirect cost, M\$
IDC	interest during construction, M\$
IGCC	integrated gasification combined cycle
INST	installation cost, M\$
J	current density, A/m^2
j_0	exchange current density, A/m^2
j_0^0	standard exchange current density, A/m^2
LHV	low heat value of fuel, kJ/kg
$m_{CO_2,inlet}$	CO_2 mass flow rate in the cathode inlet, kg/s
$m_{CO_2,outlet}$	CO_2 mass flow rate in the cathode outlet, kg/s
$m_{fuel,inlet}$	fuel mass flow rate in the anode inlet, kg/s
$m_{fuel,outlet}$	fuel mass flow rate in the anode outlet, kg/s
$\dot{m}_{MCFC}$	mass flow rate of MCFC input fuel, kg/s
$\dot{m}_{GT}$	mass flow rate of gas turbine input fuel, kg/s
MCFC	molten carbonate fuel cell
N	number of single cells
NGCC	natural gas combined cycle
n	number of electrons released in the dissociation of H_2 molecule
OCC	owner's cost and contingencies
SPECCA	specific primary energy consumption per unit of CO_2 avoided
SPP	steam power plant
TEC	total equipment cost
TPC	total plant cost
η_{DC-AC}	conversion efficiency of DC (direct current) into AC (alternative current)
η_{ohm}	Ohmic voltage loss, V
η_{conc}	concentration voltage loss, V
τ	thickness, mm
σ	electrical conductivity, S/m^{-1}

Subscripts

act	activation
an	anode
ca	cathode
conc	concentration
elec	electrolyte
f	feed side
i	species i
ohm	Ohmic
p	permeate side
TPB	three-phase boundary

frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 29 December 2023
DOI 10.3389/fenrg.2023.1249144

OPEN ACCESS

EDITED BY
Wen-Tsao Pan,
Hwa Hsia University of Technology,
Taiwan

REVIEWED BY
Onder Ozgur,
Ankara Yıldırım Beyazıt University, Türkiye
Tang Xinfa,
Jiangxi Science and Technology Normal
University, China

*CORRESPONDENCE
Yukun Song,
songyk@nefu.edu.cn

RECEIVED 28 June 2023
ACCEPTED 24 November 2023
PUBLISHED 29 December 2023

CITATION
Song Y (2023), An empirical study on the relationship between economic growth and forest carbon sink value based on PVAR model.
Front. Energy Res. 11:1249144.
doi: 10.3389/fenrg.2023.1249144

An empirical study on the relationship between economic growth and forest carbon sink value based on PVAR model

Yukun Song*

School of Economics and Management, Northeast Forestry University, Harbin, China

The dynamic relationship between the value of forest carbon exchange and economic growth has a significant impact on the sustainable development of China's economy and society. Hence, the consequences cannot be ignored even when China enjoys a win-win situation concerning environment and development. This study examines the economic growth and forestry data from 1995 to 2020 (2021 data from the Statistical Yearbook of China Forestry and Grassland in February 2023 has not been released) to calculate the forest carbon sink (using the forest stock method), estimate the forest carbon sink price, and establish a panel vector autoregression model. Pulse response analysis and variance decomposition are also used to test the dynamic relationship between economic growth and forest carbon sink value. The study finding reveal that during the research period, economic growth promoted the development of forest carbon sinks; forest carbon sinks "suppressed" economic growth in the short term; and the inhibitory effect of forest carbon sinks is no longer significant. The possible innovations and contributions of this study are: 1) Expanding relevant research on the calculation of the value of forest carbon exchange, using the forest accumulation method to calculate the province's forest carbon exchange, and using the production function of the number to estimate the price of forest carbon exchange. 2) Based on the requirements of the high-quality development stage of the economy, it can serve as a reference to formulate and improve policies for relevant departments (according to the empirical results), thereby helping the country achieve the "dual carbon" goal as soon as possible.

KEYWORDS

forest carbon sink value, economic growth, PVAR model, high-quality development, carbon sink development policy

1 Introduction

As socialism reflecting Chinese features has entered a new era, the country's economy has shifted to a high-quality development stage. Ecological civilization has emerged as a common demand worldwide. The "Outline of the 13th Five-Year Planning of the National Economic and Social Development" clearly mentions that it is essential to tackle the issue of climate change actively and promptly. Since the 18th National Congress of the Communist Party of China (CPC), China has accumulated 960 million acres and 1.24 billion acres of forests, thereby increasing the forest coverage rate to 24.02%. Contributing approximately a quarter of the new green area to the world, China is being recognized today as the fastest-growing forest resource in the world. The area of preserved plantation forests has reached

1.314 billion mu in China, ranking first in the world. At the 75th Session of the United Nations General Assembly, the "double carbon" goal also put forward higher requirements for China's economic development. In the process of achieving a win-win dynamic balance between the environment and development, the role of forest carbon sinks cannot be neglected.

Hence, the 2035 vision of a "stable decline in carbon emissions after peaking, fundamental improvement of ecological environment, building a beautiful China" in accordance with the standards for a progressive economic development phase, is in perfect alignment with the principal social and economic development objectives highlighted in the 14th Five-Year Plan period, aiming for "new progress in ecological civilization construction." Therefore, from the perspective of forest carbon sequestration, this study organically integrates the value of forest carbon sequestration with the pace of economic growth, exploring the dynamic relationship between the two factors. In addition, this study proposes several policy recommendations based on the empirical results, provides references for the relevant departments to formulate and improve policies, and promotes the development of forest carbon sink project effectively. To sum up, it realizes the ecological, social, and economic benefits of the win-win scenario for China to help the achieve the "double carbon" goal in the nearest future.

2 Literature review

As highlighted by Lin Ling, considering the volume and calculation of forest carbon exchange, diverse tree species in a respective locality display fluctuations in carbon exchange volume. Also, differences in geographical locations and climate conditions across diverse areas call for the consideration of additional factors (Wang, 2022). Liu et al. (2023) evaluated the carbon sink capacity of Canadian boreal forests; approximately 43% of the forest experienced a significant increase in tree mortality, thus resulting in a significant loss of biomass carbon. With an increase in drought conditions, the capacity of the Canadian boreal forest as a carbon sink is expected to reduce further. Girardin et al. (2022) evaluated the effects of different winter conditions on tree growth and forest carbon sequestration potential. Anderegg et al. (2022) provided risk maps of key climate-sensitive disturbances in the United States to improve forest carbon cycle modeling. Using six dynamic global vegetation models, Yu et al. (2022) estimated spatially explicit patterns of biomass losses from large unmanaged forest plots to constrain predictions of net primary productivity, heterotrophic respiration, and net carbon sinks. As defined by Shi et al. (2014), forest carbon sink measurement methods are principally dependent on sample surveys and micrometeorology techniques, including biomass, forest stock, sample land inventory, micrometeorology, box, and remote sensing estimation. Wang (2022) underlines the geographical distinctions in adopting various measurement models for forest carbon sink, thereby ensuing significant variations in parameter. Therefore, the establishment of a comprehensive forest carbon sink measurement and detection system is recommended. Zhang and Lin (2021) highlighted that the forest carbon sink calculated (based on data provided by the national forest resources inventory) is simple and practical, offering the advantage of directly and macroeconomically estimating the forest carbon sink in each province.

The determination of forest carbon sink price is a prerequisite for value measurement. Even though there is a fundamental difference between the two points, they affect each other considerably. The measurement of the value of forest carbon sink refers to the monetary measurement of the carbon dioxide that can be absorbed and stored by the forest. The determination of the unit price of a forest carbon sink and accurate measurement of forest carbon storage are the core processes to obtain the value of a forest carbon sink. The common forest carbon sink pricing methods in academia include the afforestation cost method, artificial fixed carbon dioxide method, carbon tax law, market price method, and mean value method. Zhang and Yi (2022) calculated the forest carbon storage of Chengde City using the accumulation expansion method. They also calculated the optimal price of forest carbon sinks using the optimal price model. Zhang and Chen (2021) calculated forest carbon storage in Fujian Province using the stock expansion method. In addition, they estimated the forest carbon sink value using the market value method. Cao et al. (2021) combined the self-value and option value of carbon sinks and built a carbon sink value evaluation model. They also engaged in the evaluation, analysis, and testing of the carbon sink value of the carbon sink afforestation project of the Fengning Qiansongba Forest Farm. According to Zhang et al. (2019), the evolutionary game has the evolutionary stable strategy (under the dynamic carbon trading price). Dynamic carbon trading pricing policy is effective in accelerating carbon reduction.

The development of forest carbon sinks contributes to both ecosystem betterment and economic development. Using the global forest product model, Ke et al. (2023), simulated the dynamic changes in China's forest resources from 2018 to 2060 under different carbon sequestration price scenarios. Thereafter, it was suggested that China's forest carbon sink would facilitate carbon peaking and carbon neutrality. Raihan and Tuspekova (2022) investigated the potential of economic growth, renewable energy utilization, and forest carbon sink capacity to achieve environmental sustainability in Malaysia. Yao et al. (2022) established a panel vector autoregression (PVAR) model based on the data from Chinese forestry from 1998 to 2018. Their findings demonstrated that economic growth could promote the development of forest carbon sinks; however, forest carbon sinks would negatively "inhibit" economic growth in the short term. Qin and Qu (2021) analyzed the advantages, disadvantages, opportunities, and challenges of county economic development to achieve carbon neutrality in Yiyang City using SWOT analysis. Du et al. (2021) discussed the transnational spillover effects of forest carbon sinks and expounded the direct effects of various economic development factors on forest carbon sinks. Xu et al. (2021) asserted that the forestry foreign exchange increase inflicts numerous positive effects on economic and social development with the tendency to promote the realization of the "carbon neutrality" goal. Based on the perspective of the social economy, Zhang and Lin (2021) claimed that the current improvement of the social and economic development may negatively enhance per capital GDP on forest carbon sinks. Miao et al. (2020) found that an increase in forest carbon storage promotes the growth of the total forestry output value in the province.

Despite the existence of different studies on forest carbon sinks, no conclusive study related to the long-term interaction between economic growth and the value of forest carbon sinks is available. Quantitative research is relatively scarce, the online carbon market time is short, and the operation situation is comparatively immature. Therefore, there is a need to further enrich the data and quantitative models. It is particularly important to select appropriate indicators to measure the price of forest carbon sinks (Wang and Zhi, 2018). In this study, 32 provinces (municipalities and autonomous regions) were selected as research samples from 1995 to 2020. The forest stock accumulation method was utilized to calculate the forest carbon sink in each province, whereas the translog production function was used to estimate the price of the forest carbon sink. Based on the available data and resources, a PVAR model was established using panel data. The dynamic relationship and mechanism between economic growth and forest carbon sink value were explored from the perspective of economic value, revealing that economic growth can positively promote the development of forest carbon sinks. Additionally, the realization of forest carbon sink value has a "negative" effect on economic growth in the short term. Hence, this study proposes the formulation of long-term forest carbon sink development policies, improvement in forest carbon sink trading platform, improvement in forest carbon sink pricing mechanism, solidification of forest protection, strengthening forest carbon sink poverty reduction function, and implementation of forest ecological compensation mechanism (Liu, 2021).

Based on the previous research experience, it can be concluded that there are mutually restricting factors in the synchronous development of economy and ecology. When it comes to the interaction between the development of forest carbon sinks and economic development, "whether constraints have always existed," "whether constraints have always existed" and "how to overcome them" are the major issues to study, address, and resolve. The possible innovations and contributions of this study are reflected in two aspects:

1) enrichment of the research theory on the relationship between forest carbon sink and economic growth. By using the transcendental logarithmic production function to estimate the price of forest carbon sink, and then calculating the value of forest carbon sink, the study could be considered persuasive and pertinent.
2) In this paper, the interaction between forest carbon sink and economic growth is explored. Additionally, the assumptions are made from the perspective of forest carbon sink and economic growth. Factors that may affect each other are analyzed in detail. Likewise, the stages of mutual promotion and constraint are deeply studied, thereby helping in the expansion of research content in related fields.

3 Theoretical analysis and hypothesis

In 1993, Panayotou propounded the Environmental Kuznets Curve (EKC) hypothesis while studying the relationship between the environment and economic growth. The EKC hypothesis describes the relationship between environmental quality and per capital income with an inverted U-shaped curve. Chinese scholars have studied the relationship between environmental quality and economic growth in the country employing both theoretical and empirical perspectives. The conclusions drawn resembled Panayotou's. The EKC pattern has a certain reference value for analyzing China's economic development practice. The above studies provide references for the analysis of the interaction between economic growth and forest carbon sink value (Figure 1).

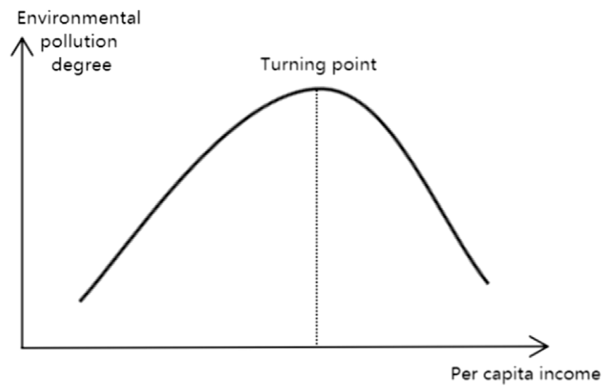


FIGURE 1
Environmental Kuznets curve.

Considering this specific study area, it is expected that economic development will experience a steady increase in environmental pollution, especially if Kuznets Curve Theory principles are employed. After reaching a critical threshold, pollution levels are expected to decline, adding to a general improvement in environmental conditions. This relationship between economic growth and environmental impact is truly dynamic. An underdeveloped economy is affected by uncontrolled population growth and the subsequent food demand. As the agricultural production level is low, more land will be reclaimed for planting food crops, crowding out forestry land. Additionally, extensive use of resources and increasing demand for wood and other forest products lead to the degradation of forest resources and low forestry economic returns. In this case, forests serve as carbon sources. However, with economic development and advancement of planting technology, food production is no longer dependent on farmland planting areas. In contrast, many farmlands with low economic yield have been returned to the forest. Scientific and technological progress has brought improvements in people's living standards; society has started to pay more attention to environmental protection; laws and regulations related to environmental protection have been improved; the structure of the forestry industry has become more reasonable; forest resources have gradually recovered; the forest carbon sink function has emerged.

Hence, this study analyzes the following two aspects:

3.1 Economic growth helps increase the value of forest carbon sinks

Despite China's switch to high-quality development, there is still a long way to go when it comes to ecological environmental protection with more emphasis on the green and low-carbon economic development model. Since the 18th National Congress of the CPC, China's key forestry ecological projects have been successful in achieving remarkable results. Forest carbon sequestration is not only an important way to offset industrial carbon emissions, but also an economic option to develop a green and low-carbon economy. Ding Shiyong, a member of the National Committee of the Chinese People's Political Consultative Conference and Vice Chairman of Chongqing, stressed in an interview that to help the green transformation of traditional industries, the development of a financial hierarchical incentive method with a combination of points and points is crucial. According to Jiang et al. (2022), when the profits of the manufacturing industry exceed the investment, enterprises can form a stable situation of adopting corporate green and low-carbon innovation technologies. Forest carbon sinks have both natural and socio-economic attributes. Therefore, the study of forest carbon sink value should be concerned with nature and social economy aspects. As identified in this study, the impact of economic growth on the value of forest carbon sinks has three aspects. First, economic growth promotes technological progress and produces a substitution effect, making forestry industry structure more reasonable. The more developed the forest economy is, the higher the output value of the tertiary industry will be. Weakening the dependence of forest farmers on the primary and secondary forestry industries helps change the extensive economic model. The impact of social economic activities on the ecosystem also increases the input to the forest ecosystem. Increasing investment in the tertiary industry, making use of the former state-owned forest farm department and other existing buildings and existing construction land, constructing the infrastructure for the integrated development of the three industries in the forest area, and constructing the infrastructure for tourism in the forest area, are conducive to the healthy development of forestry, the improvement of forest carbon reserves, and the increase of forest carbon sink value. Second, with the sustainable and healthy economic development, the government increases the investment in the forest ecosystem, continuously improves the policies supporting forest operation, expands the supply of forestry investment, promotes the increase of forest resources, and increases the value of forest carbon sink. At the same time, increasing government financial appropriation has a positive effect on improving enterprises' enthusiasm to participate in carbon sink trading activities, ultimately promoting the development of forest carbon sinks, and improving the forest carbon sink value. Third, China's traditional growth mode of "high energy consumption and high emission" did achieve high growth to some extent in the early stage of economic development. However, in recent years, as economic development gradually enters a high-quality development mode, the government gives more importance to the environment with strong efforts to reduce emissions. Consequently, it results in the reduction of carbon emissions, and forest carbon sinks become a scarce commodity. It is, therefore, essential to promote the increase of forest carbon sink scale and the value of forest carbon sink. Hypothesis H1 is proposed in this study.

H1: Economic growth promotes the development of forest carbon sinks and increases the value of forest carbon sinks.

3.2 The realization of forest carbon sink value can promote economic growth

Since the 18th National Congress of the CPC, the government has attached great importance to environmental protection. Local governments have intensified their efforts to protect forest resources. While realizing the value of forest carbon sinks, certain measures have been taken to promote economic growth, including increase in the income level of forest farmers, augmentation of training and employment opportunities, and improvement in the regional forestry industry structure. According to this study, the impact of forest carbon sink value on economic growth can be explained considering the following three aspects:

1) The route to carbon finance; through the direct implementation of carbon sink projects, expansion of financing channels, realization of diversified social capital financing, and stimulation of the vitality of carbon financial capital can be achieved. In turn, it may help in the transformation of "ecological value" to "economic value."
2) The government ecological compensation route; with forest natural capital investment as the intermediary, the diversified economic benefits of forest resources can be realized, and government financial revenue can be increased using carbon trading and carbon credit. The government will then implement long-term investment projects and forest carbon sink equity financing and issue forest carbon sink bonds. The government will also implement forestry ecological engineering projects and forest ecological benefit compensation projects. If the income is distributed to rural households, forest land investment, property rights transfer, participation in reforestation projects, forest tourism development projects, and other economic activities could help them increase their income using diverse channels. Thus, the forest carbon sink can play a critical role in poverty reduction, effective expansion of the total social supply, development of opportunities for the poor, and promotion of sustainable and healthy economic development.
3) The industrialization route of forest carbon sink; the ecological basis of forest resources provides the premise for establishing industries with forest carbon sinks as the core and promotes the optimization of the forestry industry structure. Reliance on forest carbon sinks' development and industrialization, their economic value, high-value-added agricultural and forestry products, and ecological tourism and similar economic values can be shown. The economic income can be reinvested in the forest carbon sink and other projects to ensure running a positive cycle. For example, in provinces with developed forest resources, ecological tourism can be developed utilizing the resources to achieve coordinated development of forest carbon sinks and economic growth. Therefore, hypothesis H2 is proposed in this study.

H2: The realization of forest carbon sink value can promote economic growth.

4 Research design

4.1 Research sample and data source

In this study, data from 32 provinces (municipalities and autonomous regions) from 1995 to 2020 was used for analysis.

Missing data from the Hong Kong Special Administrative Region, Macao Special Administrative Region, Taiwan Province, and Chongqing Municipality was excluded. Due to the lack of data on the number of employees and the amount of investment in fixed forestry assets at the end of 2001 in the Tibet Autonomous Region, the arithmetic average of the end of 2000 and the end of 2002 were calculated to replace it. To eliminate data heteroscedasticity and reduce data fluctuation, log processing was performed on the original data. The logarithmic gross regional product per capital (lnGDP) and the value of the forest carbon sink after logarithmic growth (lnV) were calculated. After the screening process, the study samples comprised 792 observations from 30 provinces (municipalities and autonomous regions).

Data was obtained from several authentic sources, including the National Bureau of Statistics, the State Forestry and Tobacco Administration, the China Statistical Yearbook, the China Forestry and Grassland Statistical Yearbook, the China Forestry Statistical Yearbook, National Forestry Statistical Data, and the National Tai' and Financial Research Database (CSMAR). Since the latest edition of the China Forestry and Grassland Statistical Yearbook has not yet been published, latest data from 2020 was used for empirical research and analysis.

4.2 Primary variable definition

The per-capital gross regional product of each province was selected as an indicator of economic growth, and the product of the calculated forest carbon sink and forest carbon sink prices was used to measure the value of the forest carbon sink. The variables used in this study are as follows:

4.2.1 Economic growth

Economic growth refers to the increase in the production capacity of goods and services in a country or region within a certain period. The indicators used to measure economic growth include GDP, per capital GDP, and GDP growth rate. This study used the per capital GDP of each province (city or autonomous region) to measure economic growth.

4.2.2 Forest carbon sink−related variables

4.2.2.1 Forest carbon sink (C)

Forest carbon sink can be regarded as the carbon sequestration capacity of the forest ecosystem, that encompasses tree species, understory vegetation, and woodlands. Hence, these features must be considered when analyzing and calculating forest carbon sinks. Considering data availability and calculation simplification, the forest stock method was adopted to calculate the forest carbon sink in each province. The principle of the forest stock method is to multiply the measured unit stock biomass of dominant forest tree species by the total stock to obtain the total biomass. The carbon content coefficient is also multiplied to obtain the desired forest carbon sink. Forest carbon sinks consist of three parts: biological carbon sequestration of trees, carbon sequestration of understory plants, and carbon sequestration of woodlands. The calculation method was as follows:

$$\begin{aligned} C &= C1 + C2 + C3 \\ &= \nu \times \delta \times \rho \times \gamma + \alpha(\nu \times \delta \times \rho \times \gamma) + \beta(\nu \times \delta \times \rho \times \gamma) \end{aligned} \quad (1)$$

where C represents the total forest carbon sink obtained by the study; C1, C2, and C3, respectively represent forest carbon sink, understory plant carbon sink, and forest carbon sink; v stands for forest stock; δ, ρ, and γ denote the accumulation expansion coefficient, volume density, and carbon content, respectively; α and β represent the carbon conversion coefficients of understory plants and woodland, respectively. α and β use the default values of 0.195 and 1.244, respectively, by the Intergovernmental Panel on Climate Change. Thus, (1) can be simplified as:

$$C = 2.439(\nu \times \delta \times \rho \times \gamma) \quad (2)$$

This study used the simplified method for calculating forest carbon sink, where δ, ρ, and γ were 1.9, 0.5, and 0.5, respectively. Since the update cycle of China's forest resources inventory data is 5 years, the calculated forest carbon sink of each province remains unchanged during each inventory period.

4.2.2.2 Forest carbon sink price (P)

The unit price of carbon sink is an important parameter to measure the economic value of forest carbon sinks. Currently, there is no uniform method to calculate the pricing of carbon sinks. Therefore, previous studies have employed different calculation methods, including the Cobb-Douglas Production Function Method and the Translog Production Function Method. In the Cobb-Douglas Production Function Method, the factors of each year are constant, a characteristic not aligned with reality. Hence, several studies have demonstrated the advantage of using the Translog Production Function Method to obtain more accurate results as it complements the available data. In addition, this study examined the interactive relationship between economic growth and forest carbon sink value. The Translog Production Function Method was used for forecasting considering its better reflection of the interaction between variables. The general form of the Trans-logarithmic Production Function is as follows:

$$lnY = \alpha + \sum_{i=1}^{n} \alpha_i lnX_i + \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n} \beta_{ij} lnX_i lnX_j \quad (3)$$

Considering different factors of the national economy, this study used the inclusive Translog Production Function to effectively study the interaction of input factors in the production function and the difference in the technological progress of each input. Based on the theory of marginal productivity, panel data covering the total output value of forestry, forestry capital stock, forest carbon sink, and forestry labor force and referring to the research method of Chen et al. (2022), a translogarithmic production function was used to estimate the price of forest carbon sink in each province.

$$\begin{aligned} lnY_{i,t} = {} & \alpha_1 \ln L_{i,t} + \alpha_2 \ln K_{i,t} + \alpha_3 \ln C_{i,t} + \alpha_{lc} \ln L_{i,t} \ln C_{i,t} \\ & + \alpha_{kc} \ln K_{i,t} \ln C_{i,t} + \alpha_{lk} \ln L_{i,t} \ln K_{i,t} + \alpha_{cc} (\ln C_{i,t})^2 \\ & + \alpha_{ll} (\ln L_{i,t})^2 + \alpha_{kk} (\ln K_{i,t})^2 \end{aligned} \quad (4)$$

TABLE 1 Descriptive analysis results.

VarName	Obs	Mean	Sd.	P5	Median	P95
lnGDP	792	0.6671	1.0145	−0.9576	0.7703	2.1747
lnC	792	9.6293	1.9410	5.4399	9.9339	12.1577
P	792	70.4701	248.7848	0.7649	19.5805	208.1844
lnV	792	12.4492	1.5016	9.2431	12.6959	14.5583
lnY	792	12.9111	1.4482	9.8994	13.1662	14.9606
lnL	792	0.8980	1.2974	−1.9540	1.0402	2.8956
lnK	792	11.8448	2.0324	8.3891	12.0907	14.6862

TABLE 2 Results (LLC unit root test).

Whether the time trend item is included	Variable	LLC inspection	
		Statistical value	*p*-value
No	lnV	−1.3036	0.0962
	lnGDP	−6.7276	0.0000***
Yes	lnV	−1.8472	0.0324*
	lnGDP	−1.1483	0.1254

Description: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

where Y, L, K, and C represent the total output value of forestry, forestry capital stock, forestry labor force, and the forest carbon sink, respectively; *i* and *t* represent time and study area, respectively. α_1, α_2, and α_3 respectively represent the output elasticity of forestry labor force, forestry capital stock, and forest carbon sink. A_{lc}, α_{kc}, α_{lk}, α_{cc}, α_{ll}, and α_{kk}, respectively represent the elasticity coefficients of the cross term and square term of each element of the forestry labor force, forestry capital stock, and forest carbon sink. After deriving and further simplifying Eq. 4, we can obtain:

$$P = \frac{Y}{C}\left(\alpha_c + \alpha_{kc} lnK_{i,t} + \alpha_{cc} lnC_{i,t} + \alpha_{lc} lnL_{i,t}\right) \quad (5)$$

The forestry data from provinces (municipalities and autonomous regions) during 1995–2020 were substituted into Eq. 4. Thereafter, linear regression analysis was performed using stata16.0. The elastic coefficients obtained from the regression were substituted into Eq. 5 to calculate the forest carbon sink prices for each province during 1995–2020.

4.2.2.3 Forest carbon sink value (V)

To calculate the value of the forest carbon sink, the amount of carbon dioxide absorbed by the forest was expressed in monetary form (Liu et al., 2020). To better understand the economic benefits of forest carbon sink, the product of forest carbon sink and its unit price is generally used. In this study, the product of forest carbon sink and its price was used to measure the value of forest carbon sink.

$$V = C \times P \quad (6)$$

4.2.2.4 Forestry output (Y)

Considering the availability of data, this study selected the total value of forestry output, expressed in monetary form as the total amount of tangible and intangible labor achievements in the cultivation, protection, management, and utilization of forestry resources over a certain period, as the index to measure forestry output.

4.2.2.5 Forestry labor force (L)

The forestry labor force consists of all personnel engaged, directly or indirectly, in production, technology, and economic activities in the forestry sector (Li and Zhang, 2021). However, due to the complexity of forestry production, it is relatively difficult to accurately count the number of employees outside the forestry system. Therefore, this study selected the number of employees in the local forestry system at the end of the year to reflect the forestry labor force.

4.2.2.6 Forestry capital stock (K)

The investment of forestry fixed assets in the completion of forestry fixed asset investment in each province during 1995–2020 was selected to replace capital stock.

Table 1 presents the statistical information on the numerical characteristics of the variables involved in this study.

4.3 Model construction

Newey extended the time-series analysis method to panel data analysis and proposed a Panel Vector Autoregressive (PVAR)

TABLE 3 Results (Fisher-ADF unit root test).

Whether the time trend item is included	Variable	Fisher's test—ADF	
		Statistical value	*p*-value
No	lnV	168.0946	0.0000***
	lnGDP	136.7831	0.0000***
Yes	lnV	81.7400	0.0325*
	lnGDP	279.9960	0.0000***

Description: $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

TABLE 4 AR model (lag order selection test).

Lag	CD	J	J *p*-value	MBIC	MAIC	MQIC
1	0.9997023	19.59049	0.07542	−57.75815	−4.409513	−25.1315
2	0.9999072	17.7785	0.0229498	−33.78726	1.778497	−12.03616
3	0.9999023	5.082401	0.2789466	−20.70048	−2.917599	−9.824929

TABLE 5 Estimated results [panel vector autoregressive (PVAR) model].

Variable name	lnGDP		lnV	
	Estimated value	Z value	Estimated value	Z value
L.lnGDP	1.322***	17.28	0.371***	3.60
L.lnV	−0.404***	−4.50	0.546***	4.52

Description: $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

model. The PVAR method amalgamates the advantages of both the classical VAR method and panel data to process and analyze statistical data offering better identification of the influence of individual feature differences on regression fitting. All variables in the PVAR model are analyzed as endogenous variables. The response of one variable to the impact of another variable can be obtained through the orthogonalization of the error term, thus reflecting the dynamic interaction between different variables in the model. The PVAR model can be expressed as:

$$\boldsymbol{Y}_{i,t} = \boldsymbol{\alpha}_i + \boldsymbol{\beta}_t + \boldsymbol{\varphi}_1 \boldsymbol{Y}_{i,t-1} + \boldsymbol{\varphi}_2 \boldsymbol{Y}_{i,t-2} + \cdots + \boldsymbol{\varphi}_p \boldsymbol{Y}_{i,t-p} + \boldsymbol{\varepsilon}_{i,t} \quad (7)$$

where $Y_{i,t}$ is the variable $q \times 1$-dimensional vector of the section individual i at the time point t. $\varphi_{1,} \ldots, \varphi_p$ are the coefficients of a matrix of $q \times q$ to be estimated (q is the number of variables). α_i and β_t are individual effect vectors and time effect vectors of $q \times 1$, respectively. $Y_{i,t\text{-}p}$ is the p-order lag term of $y_{i,t}$. The perturbation $\varepsilon_{i,t}$ satisfies the expectation of zero. The covariance matrix of Γ identically distributed independent variables, namely, $\varepsilon_{i,t}$~i.id(0, Γ), simultaneously meeting the conditions of E $(\varepsilon_{i,t}{}^{q}\alpha_{i,t}{}^{q},\beta_{i,t}{}^{q},y_{i,t-2}{}^{q}, \ldots) = 0$.

The endogenous problem of mutual causality is inevitable among macro variables (Fan and Peng, 2021). Therefore, this study used the PVAR model (without considering the endogenous problem) to investigate the interactive relationship between forest carbon sink value and economic growth. The selection of a PVAR model can not only retain the excellent characteristics of the vector autoregressive model, but also extends the simple time series model to the spatial direction, reduces the requirements on data length in modeling, and fully considers the heterogeneity of cross-section individuals. The PVAR model established in this study is as follows:

$$\boldsymbol{Y}_{i,t} = \boldsymbol{\omega}_0 + \sum\nolimits_{j=1}^{m} \boldsymbol{\beta}_j \boldsymbol{Y}_{i,t-j} + \boldsymbol{\varepsilon}_{i,t} \quad (8)$$

where $Y_{i,t}$ = (GDP, V) is the column vector of variables; economic growth and forest carbon sink value; ω_0 is the intercept term; i and t represent city and time, respectively; m represents the order of lag; β_j represents the coefficient of each lag term and the degree of interpretation of $Y_{i,t}$; and $\varepsilon_{i,t}$ is the random disturbance term.

5 Empirical test based on the PVAR model

5.1 Data stationarity test

Before conducting PVAR analysis, it is important to assess data stability and whether it is used without a unit root. Considering the significance of this condition, the LLC test method was adopted to conduct a unit root test on lnV and lnGDP. The LLC test results are presented in Table 2.

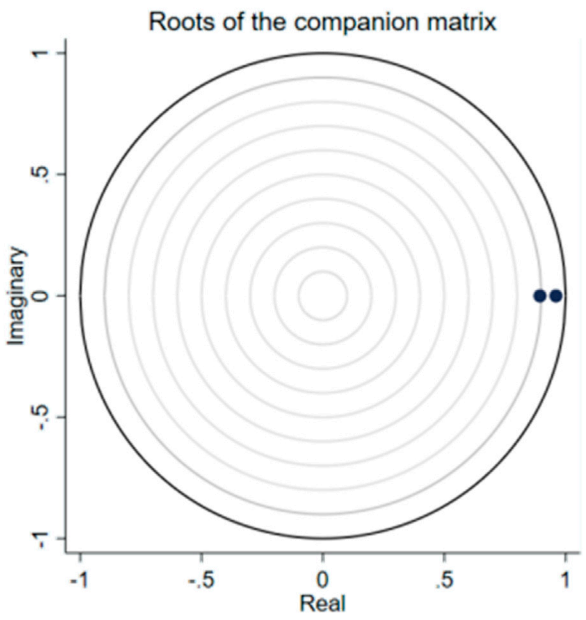


FIGURE 2
Stability test (panel vector autoregressive model).

To ensure the robustness of the unit root test results, the Fisher-ADf Test was used to conduct the second Unit Root Test for lnV and lnGDP. The results are listed in Table 3.

Based on the graph judgment, the lnV and lnGDP data passed the stationarity test, concluding that the estimation results of the model construction are significant for this study.

5.2 PVAR estimation

5.2.1 Optimal lag order selection

The PVAR model is highly sensitive to Lag Order. If the selected lag order is too large, the estimated parameters of the model will be amplified, and the degree of freedom will be reduced. If the selected lag order is too small, the reliability of the estimated results will be reduced (Ma and Zhao, 2021). Therefore, it is imperative to first determine the optimal lag order. In this study, the optimal lag order selection was conducted based on the principles of MBIC, MAIC, and MQIC (and the test results are listed in Table 4). The optimal lag order of the model was determined to be 1.

5.2.2 PVAR estimate

After the data passed the stationarity test and the optimal lag order of the model was determined, "L." was used to represent one period of lag. L.lnGDP and L. lnV are the lagged data of the primary variables, lnGDP and lnV, respectively. The PVAR model was constructed using processed data. The estimated results are shown in Table 5.

5.2.3 Model stability test

After constructing the PVAR model, it is essential to test the stability of the model. An AR root graph was used to test the stability of the PVAR model (results shown in Figure 2). The PVAR model has two real characteristic roots that fall within the unit circle. The PVAR model established in this study passed the stability test.

5.3 Granger causality test

The Granger Causality Test means that if the past information of variables X and Y are included, the prediction effect of variable Y is better than that of Y alone; that is, variable X helps to explain the future changes that may occur in variable Y; thus, variable X is considered to be the Granger cause of variable Y. Based on the PVAR model, this study further tested the Granger causality between the economic growth and forest carbon sink value of the provinces during the study period (Table 6).

At 0.01 significance level, the original hypothesis—*"economic growth is not the Granger cause of the value of forest carbon sinks"* is rejected. Instead, we suggest that economic growth is the Granger cause of the value of forest carbon sinks, indicating that the previous changes in the economic growth situation in the provinces can effectively explain the changes in the values of forest carbon sinks. Likewise, forest carbon sink value is the Granger cause of economic growth, and the early changes in forest carbon sink values in each province can also effectively explain the changes in economic growth. To sum up, a Granger causality exists between economic growth and forest carbon sink value.

5.4 Impulse response function analysis

The Impulse Response Function Model can reflect the economic significance contained in the PVAR model more intuitively and in detail. The Stata16.0 Software was used to conduct 300 Monte Carlo Simulation Impulse Response Analyses for economic growth (lnGDP) and forest carbon sink value (lnV) (results shown in Figure 3). The x-coordinate represents the number of response periods of the impact response, the y-coordinate represents the utility value of the impact, the dashed line represents the impulse response function, and the shaded part represents the standard deviation band of the 95% confidence interval. Figures 3A, B demonstrate the response of forest carbon sink value and *per capita* GDP, respectively, under the impact of forest carbon sink value. Figures 3C, D reflect the response of the forest carbon sink

TABLE 6 Results (The Granger causality test).

Null hypothesis	Chi2 statistics	Degree of freedom	*p*-value	Conclusion
lnV does not Granger-cause lnGDP	20.224	1	0.000	Refuse
lnGDP does not Granger-cause lnV	12.947	1	0.000	Refuse

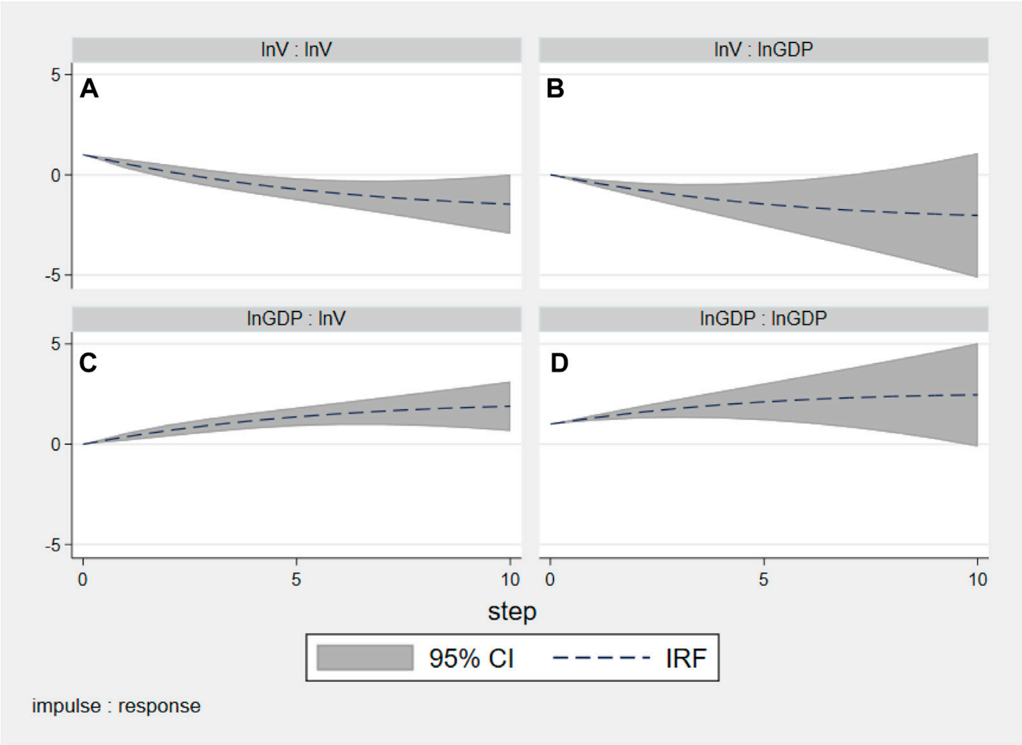


FIGURE 3
Impulse response analysis.

value and *per capita* GDP, respectively, under the impact of *per capita* GDP.

As shown in Figure 3A, the forest carbon sink value had a positive impact on itself in the first phase. However, the impact effect declined later. In the second phase, the standard deviation band of the 95% confidence interval exceeded the zero-value boundary and became a negative effect, thereby hindering the increase in the forest carbon sink value. The negative effect finally stabilized. Figure 3B shows that from the first to the fifth phase, faced with the impact of the forest carbon sink value, *per capita* GDP presented a negative inhibitory effect. In the sixth phase, the standard deviation of the 95% confidence interval covered the horizontal line y = 0. Yet, the hindrance to the increase in *per capita* GDP cannot reject the original hypothesis at the 5% significance level. As seen in Figure 3C, the shadow part gradually deviated from the horizontal line y = 0 from the first phase due to the impact of *per capita* GDP, thus indicating that the impact effect of *per capita* GDP on the value of forest carbon sink was gradually enhanced. As shown in Figure 3D, *per capita* GDP had a positive impact on itself in the first period, while the impact effect gradually became stronger and more stable.

5.5 Variance decomposition

The variance decomposition results of the endogenous variables, lnGDP and lnV, in the PVAR model obtained using the Stata16.0 Software are shown in Table 7.

According to the contribution rates of lnGDP and lnV to lnGDP, the economic growth in the first period was completely dependent on the economic growth in the previous period. To be precise, it had nothing to do with the value of forest carbon sink. In the following nine periods, the contribution rate of forest carbon sink value to economic growth showed a steady growth trend, with an average contribution degree of 43.22%. According to the contribution rates of lnGDP and lnV to lnV, the contribution of economic growth to the forest carbon sink value in the first phase was 17.8%. The remaining 82.20% was the contribution of the forest carbon sink value to itself. Progressing from the second to the fifth phase, the contribution rate of economic growth to the value of forest carbon sink gradually increased, reaching a peak of 52.61% in the fifth phase. However, there is a gradual decrease from the sixth to the tenth phase, with an average contribution of 41.04% (consistent with the conclusion of the impulse response analysis).

6 Analysis of empirical results

6.1 Economic growth has a positive effect on forest carbon sink development

In this study, the forest carbon sink value was considered the explained variable. According to the estimation results of the PVAR model, the impact of the first-order lagged economic growth on the forest carbon sink value was significantly positive, with a *p*-value <0.001, thereby indicating that economic growth had a significant positive effect on the improvement of the forest carbon sink value (supporting Hypothesis 1). The impulse response shows

TABLE7 Results (variance decomposition of forest carbon sink value and economic growth).

Period	Contribution rate to lnGDP		Contribution rate to lnV	
	lnGDP	lnV	lnGDP	lnV
0	0	0	0	0
1	1	0	0.1780283	0.8219718
2	0.8918289	0.1081711	0.2809851	0.7190149
3	0.7475816	0.2524184	0.3961055	0.6038946
4	0.624397	0.3756029	0.4868334	0.5131666
5	0.5305028	0.4694973	0.5261054	0.4738946
6	0.4604968	0.5395032	0.5188595	0.4811406
7	0.4078834	0.5921167	0.4866295	0.5133706
8	0.3676499	0.6323501	0.4469432	0.5530568
9	0.3362869	0.6637131	0.4086529	0.5913471
10	0.3113853	0.6886147	0.3749224	0.6250776
Average value	0.56780126	0.43219875	0.41040652	0.58959352

that the forward shock increased continuously from the first till the tenth period.

Economic growth has led to increased investments in forestry. Forestry, forest management, and infrastructure construction cannot be excluded or separated from capital investment. Coupled with the externality and weak condition of forestry, state financial investment is extremely important for the development of forestry. In China, with the sustained and healthy development of the economy, the central and local governments have gradually increased their investments in the forestry system, thereby vigorously implementing afforestation and forest tending projects, improving the ecological conditions of the forest, promoting the upgrading of the forestry industry, and promoting the development of the ecological economy as ongoing measures. Additionally, healthy economic growth makes forestry more attractive for social funding. Increased social investment is conducive to the construction of forest ecosystems, increasing forest stocks and promoting the development of forest carbon sinks consequently.

Economic growth has also contributed to the optimization of the structure of the forestry industry. According to the environmental Kuznets Curve, when economic development passes a critical value, the negative impact of human activities on the ecological environment weakens gradually, thus promoting an improvement in environmental quality. Presently, China's forestry industry structure is sequenced as "*two*, *one*, *three*." As China's economy enters a stage of high-quality development, the country attaches more importance to ecological environmental issues. The primary and secondary forestry industries, which were mainly based on timber harvesting, transportation, processing, and manufacturing, gradually transition to the tertiary forestry industry. It is important to note that these industries are reliant on forest landscape resources, changing the focus of the forestry economic development mode. Thus, it is significant to promote the optimization of the forestry industry structure, reduce forest resource consumption, and promote the development of forest carbon sinks through the employment of high-quality economic development, as it changes people's cognition, affects consumption preferences and consumption structures, and modifies the demand structure of forest products. This leads to the transformation of the original resource-based consumption into ecological consumption, promotion of the innovation and technological progress of forest-related science and technology, upgradation efforts to develop the forestry industry, and reduction of the irrational consumption of forest resources. Increasing the forest area and forest stock, promotion of the development of forest carbon sinks, and improvement of the value of forest carbon sinks are significantly imperative as well.

Economic growth has also optimized the allocation of forestry elements. According to the theory of economic growth, factor input serves as the principal driving force and source of economic growth. The total input of forestry capital, labor, and land, and the proportion of the input among these factors, are the key elements that affect the development of regional forestry. In the context of high-quality economic development, reliance on large-scale production factor inputs and forest resource consumption to achieve forestry production benefits and outputs is not appropriate for the current strategic position of forestry. Instead, it is suggested to utilize and depend on scientific and technological progress and employee quality as new ways of promoting the development of the forestry industry. Optimizing the input of forestry factors is an important measure to encourage high-quality development of forestry. From 1995 to 2020, the forest stock volume increased year by year, and the number of employees in the forestry system demonstrated a significant declining trend at the end of the year. In addition, forestry investment fluctuated, and the proportion of capital in the input factors increased annually. Capital investment is the key to promoting the development of high-quality forestry. It is important to mention that the forestry factor allocation is in line with the requirement of high-quality development with the propensity of effectively promoting the development of the forestry industry. In addition, it helps improve forest carbon sink capacity.

6.2 The development of forest carbon sinks "inhibits" economic growth

In this study, economic growth was taken as the explained variable, and the estimated results of the PVAR model showed that the impact of the first-order lagged forest carbon sink value (L. lnV) on economic growth (lnGDP) was −0.395, which was significant at the 1% significance level and inconsistent with hypothesis 2. It continues to reveal that forest carbon sink has a statistically significant negative "inhibition" effect on economic growth, primarily manifested in the middle and early stages. Since the sixth stage, the negative "inhibition" effect is not noteworthy at the 95% significance level.

Forest carbon sinks have a lagging effect on the economy. The development of forest carbon sinks requires the input of production factors, such as capital, land, and labor resources. Additionally, it requires a development process from factor inputs to outputs of ecological and social benefits. Moreover, it is not sustainable to promote economic growth by relying on factor driving. The reason is simple. Improvement of the total factor productivity of forestry and promotion of efficiency reform in the forestry industry would take time. The development of forest carbon sinks has a lag effect on the economy (Gupta, 2015).

The structure transformation pressure of the forestry industry is significant. With only 30 years between China's commitment to "carbon peaking" and "carbon neutrality," it is encountering several challenges, such as industrial transformation. The pressure of environmental protection is great, and forest ecosystems need to be repaired urgently. However, the economic benefits generated by the activities of increasing forest carbon sink, such as returning farmland to forest, are difficult to highlight in the early stages of forest formation. Hence, the foundation of realizing the comprehensive transformation of the forestry industry structure consequently weakens. As mentioned, the structure of China's forestry industry is presented in the form of "*two*, *one*, *three*". Under the "double carbon" goal, the primary and secondary industries of forestry can directly bring economic benefits, may be seriously impacted, and may also "restrain" the economic growth in the short term.

The forest carbon sink trading market is still in its immature phase. The national forest carbon sink trading market has recently been established, whereby several functions are imperfect, thus failing to maximize the ecological value of forest carbon sinks into economic value. Currently, the immature forest carbon sink trading market reflects the lack of laws and regulations that specifically stipulate forest carbon sink trading. A few existing departmental rules are used to guide and regulate national forest carbon sink trading, which is unauthoritative or inoperable. Further, the measurement, accounting, and pricing mechanisms of forest carbon sinks need major improvements. Forest resource endowment and forest carbon sink capacity differ in diverse parts of China. However, only the net carbon sink amount generated by approved forest carbon sink projects can participate in forest carbon sink market trading. Forest carbon sink pricing methods can be divided into direct and indirect methods. With gradual improvement in the forest carbon sink trading market, the ecological value of forest carbon sinks can be transformed into economic value. According to the pulse response chart, the negative "inhibition" effect of forest carbon sink value on economic growth will weaken gradually.

7 Research conclusion and theoretical enlightenment

7.1 Research conclusion

In this study, GDP *per capita* from 1995 to 2020 was selected as an indicator of economic growth. The product of the forest carbon sink and forest carbon sink price was utilized as an indicator of the value of forest carbon sink. Based on the PVAR model, impulse response and variance analyses were used to explore the interaction between economic growth and forest carbon sink value. Hence, it is concluded that economic growth can positively promote the development of forest carbon sinks, whereby the positive promoting effect is continuously enhanced during Period 1 to 10. These empirical results are supported by Hypothesis 1. The realization of forest carbon sink value has a "negative" effect on economic growth in the short term. It is pertinent to note that the negative effect cannot be significant at the 95% significance level since the sixth period—a finding inconsistent with Hypothesis 2. Therefore, from the perspective of development, capturing the dynamic relationship between the trend of forest carbon sink value and economic growth, and realizing the long-term development of both, are the challenging pain points. From the perspective of cost, the implementation of relevant subsidy policies and compensation measures will also play a crucial role in the realization of forest carbon sink value and economic development. Above conclusions imply that the synchronous development of economy and ecology does have mutually limiting factors. Hence, it is indeed a challenge to find out the limiting factors, find the balance point between economy and ecology, and pursue coordinated development. Due to the limitations of the current disclosed/unavailable data and reference cases related to forest carbon sink, future studies need to demonstrate the relationship between economic growth and forest carbon sink value from a multi-dimensional perspective.

7.2 Theoretical inspiration and policy suggestions

Considering China's economic and social development and the actual forest carbon sink potential, combined with the above research results, this study suggests:

7.2.1 Formulation of long-term policies for forest carbon sink development

According to the impulse response function between forest carbon sink value and economic growth obtained in this study, it is apparent that even though each curve can stabilize in the late response period, the amplitude and period of fluctuation are different. Considering the different influences exerted by forest carbon sinks and economic growth at different times in a large country with significant regional differences, it is essential to improve the long-term development policy for forest carbon sinks, design a differentiated policy combination according to the actual situation in each region, and establish and perfect the technology system of energy-saving and emission reduction. High-quality projects, enterprises, and areas with favorable conditions for the development of forest carbon sinks are required to promote the flow and agglomeration of energy factors to green, low-carbon, and circular development. For example, after the "double carbon" goal was proposed, Shanxi, Inner Mongolia, Hebei, and other heavy industry-developed regions were put under great pressure to reduce carbon and reach the peak. As there is a large space for energy conservation and emission reduction, they were compelled to employ measures to achieve industrial emission reduction. Further, these regions have low rainfall, and the cost of developing forest carbon sinks is higher than that in other regions. However, the southeastern coastal areas of China, with sufficient rain and a suitable climate, have cost advantages for the development of forest carbon sinks. Moreover, these areas are more suitable for the development of forest carbon sinks and emission reduction due to several factors—developed economy, a high proportion of tertiary industries, and small space for industrial energy conservation. Differentiated policy combinations must be implemented in different regions to reduce the cost of emission reduction for the entire society and maximize social welfare.

To increase the support for energy conservation and emission reduction according to local conditions, it is essential to take various effective measures, such as implementing tax policies conducive to the development of forest carbon sinks, strengthening the supervision of the green finance industry, provision of targeted subsidies to enterprises that exceed the level of carbon reduction target responsibility assessment, supporting enterprises to develop green energy technology, and addressing the failure of carbon market using mandatory government regulation. To legislate and supervise the development of forest carbon sink projects, it is equally important to reduce the spillover effect of the forestry economy, strengthen the macro-guiding role of the government, increase the construction and services of green infrastructure, refine the system and standards for environmental impact assessment of enterprises, mobilize enterprises to reduce carbon emissions, strengthen the supervision capacity of regulators, address both short-term benefits and long-term vision, and safeguard and regulate the legitimate rights and interests of participants. All such measures could prove critically helpful in achieving efficiency and effectiveness.

7.2.2 Improvement of trading platforms for forest carbon sinks

Carbon emission trading is a market-based environmental regulation tool that internalizes the negative external pollution of enterprises guided by the government and promoted by the market. It can encourage enterprises to adopt a low-carbon generation approach and carbon-neutral behavior. The Chinese carbon market is in the early stages of development. Therefore, it is imperative to further build and improve the carbon market trading mechanism, gradually tighten the issuing standard of the carbon quota, make carbon emission rights a scarce resource, and improve the enthusiasm of reduction enterprises to participate in carbon trading. Through the forest carbon sink market trading platform, forest carbon sinks can realize the transformation from ecological value to economic value. A sound forest carbon sink trading platform can not only guarantee the green development of the economy, but also promote the active participation of all sectors in society. Under a carbon currency market with a diversified compensation mechanism, the principle of "who invests, who gains" is followed to protect the income distribution rights of all participants. It also increases social enterprises' willingness to participate. This marketization process is beneficial for realizing carbon sink trading procedures and compliance. In the long term, such endeavors may help China realize industrial transformation and upgrading through the marketization of forest carbon sinks.

Currently, China is in the rudimentary stage of carbon sink marketization. There is, however, room for progress. In future, it is indispensable to learn from the mature carbon sink market trading modes of other countries. In this context, it is the responsibility of the government and respective authorities to take the lead and establish climate exchange as an intermediary, review forest carbon sink projects, evaluate the carbon sink credit of enterprises, promote carbon sink trading, increase publicity, and allow more enterprises to participate in carbon sink trading. This top–down participation mechanism may also contribute to the reasonable formulation of compensation standards. In the context of China's "double carbon" goal, improving the forest carbon sink trading platform would prove beneficial to adjust the interesting relationship and realize the diversification of forest carbon sink values.

7.2.3 Improvement of the pricing mechanism of forest carbon sinks

The government uses carbon pricing to regulate carbon emission reduction. It measures the impact of carbon dioxide, generated by socioeconomic activities of enterprises, on the environment in the form of money. This data allows the authorities to express the negative externalities of carbon dioxide emission of enterprises in the form of carbon emission price. The carbon emission behavior of commercial enterprises can improve their willingness to reduce emissions effectively. Simultaneously, it may also increase their enthusiasm to participate in carbon trading. Additionally, it may facilitate an increase in the government's fiscal revenue. The major types of carbon pricing include carbon emission trading system pricing, carbon taxes, and carbon pricing offset mechanisms. Carbon pricing can be interpreted as an extension of the Paris Agreement. The OECD published an environmental paper, highlighting that a joint, worldwide implementation of carbon pricing and the expansion of the carbon pricing sector can produce more economic and environmental benefits. If carbon pricing is implemented to cover non-carbon emission sectors, compared to the implementation of carbon pricing only in carbon emission sectors, the cost of emission reduction could be reduced by approximately 50%.

Owing to large differences in the measurement models and parameters of forest carbon sinks in different regions, research on the pricing of forest carbon sinks is limited to the theoretical level. Moreover, the distribution of forest resources is unbalanced. Forestry resources in the southwest and northeast areas are relatively rich, and those in the developed coastal areas are relatively short. The carbon sink price cannot accurately reflect the scarcity of resources. Regrettably, the market incentive ability is not fully utilized, and the role of resource allocation cannot be fully realized. The pricing of forest carbon sinks needs to be based on the deployment of scarce resources by the "invisible hand," with the participation of the government. Consequently, it not only supports the development of the carbon sink industry and prevents operators from altering their business strategies (due to low revenue and loss of market confidence caused by the low price of the forest carbon sink), but also prevents unreasonably high prices caused by an increased demand, which will affect the development of the forest carbon sink market.

7.2.4 Intensification of the efforts to protect forests

The development of forest carbon sinks cannot be separated from the growth of forest natural resources. Forest protection strengthening process can be initiated from the two aspects of afforestation and deforestation control, and the active prevention and control of diseases, insects, rats, and forest fires. Considering the present scenario, it is high time for all regions to increase afforestation efforts, actively implement the policies of returning farmland to forests, plan afforestation phase-wise, optimize tree species, and enrich forest vegetation diversity according to local conditions. The following processes must be considered: strictly controlling the intensity of deforestation, reasonable planning, strict examination and approval, safeguard supervision and regular inspection, and active use of biological control technology to prevent diseases, insects, and rodents. It has also provided quality training for forest management and personnel protection, strengthened forest fire prevention work, established forest fire prevention workstations, increased the number of forest patrols in dry seasons, and implemented real-time dynamic monitoring of forest land (using remote sensing and other technologies). At the same time, local governments should crack down on criminal activities related to deforestation, make authentic efforts to curb illegal occupation of forest land and other unlawful activities, and uphold the ecological red line to ensure the healthy and stable development of forestland ecosystems.

7.2.5 Giving full play to the role of forest carbon sinks in poverty reduction

Owing to the typical spatial and geographical characteristics of China's population, a large proportion is distributed in remote rural and mountainous areas, rich in forest resources. The rapid development of China's carbon market has laid a good foundation for small farmers to engage in direct participation. The government and relevant departments are constantly exploring apt models for farmer participation. As forest carbon sinks help in poverty reduction, the implementation of forest carbon sink projects in mountainous areas can help transform the external value of forest carbon sink products into financial incentives for ecological protection, thereby ensuring a win-win situation between sustainable forest development and poverty alleviation in mountainous areas. Hence, some suggestions are as follows: carbon sink projects between developed and poor areas should be coordinated, forest carbon sinks should be purchased in developed areas; from the perspective of policies, farmers' rights and interests in forestry carbon sink projects must be protected; reasonable subsidy standards for carbon sink afforestation and forest operation should be formulated; and compensation objects and ways for carbon sink afforestation must be clarified. Farmers living in mountainous areas can increase their income through participation in economic activities, such as reforestation and forest tourism projects. It vigorously conducts skill training for farmers, implements special entrepreneurship training programs for farmers, and provides training on opportunities to identify forest carbon sink participation, project selection, plan formulation, and risk avoidance. Consequently, such opportunities allow farmers to improve their understanding of current technologies, products, and models and learn about the local ecological environment. Moreover, it improves their income. In conclusion, forest carbon sequestration needs to be incorporated to combat against poverty—a measure that is conducive to the integrated development of rural primary, secondary, and tertiary industries, breaking the pattern of rural populations' dependence on agriculture.

7.2.6 Implementation of a compensation mechanism for forest ecology

Introducing and implementing a compensation mechanism for forest ecology can facilitate economic development. Currently, there are several market-based compensation methods for forest carbon sinks in developed countries, whereby the integration of ecological compensation mechanisms with the carbon sink market is relatively mature. For instance, South Korea has subsidized the declaration fees for forest carbon sink projects. Similarly, the Australian government has established a special fund for energy conservation and emission reduction to compensate for the sunk costs that forest operators give up. However, it is still dependent on the promotion and practice of the carbon emission trading market and forestry authorities. Local forest land management departments should fully understand the current situation of forest resources, forest carbon sink capacity, and related information. This information must be combined with the economic development situation for several reasons; to expand the scope and level of forest ecological compensation, to navigate through forest economic development process suitable for local conditions, to implement reasonable planning of resources, to set up special fund support and compensation, to attract high-end talent, and to intensify efforts for exploring the economic benefits of forest ecological resources. Building a forest ecological industry system and promoting low-carbon economic development would help China realize the "double carbon" goal in the nearest future.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YS: Conceptualization, methodology, software, investigation, formal analysis, and writing–original draft.

Funding

This work was sponsored in part by National Social Science Fund Project (21BJY189).

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Anderegg, W. R. L., Chegwidden, O. S., Badgley, G., Trugman, A., Cullenward, D., Abatzoglou, J. T., et al. (2022). Future climate risks from stress, insects and fire across US forests. *Ecol. Lett.* 25 (6), 1510–1520. doi:10.1111/ele.14018

Cao, X. L., Jia, X. R., and Shan, Y. J. (2021). Carbon sink value evaluation model and application of carbon sink afforestation project based on real option. *J. Central South Univ. For. Technol.* 41, 3. doi:10.14067/j.cnki.1673-923x.2021.03.020

Chen, Z. G., Long, F., and Qi, H. B. (2022). Research on forest carbon sink pricing in China. *Price Mon.* 3, 1. doi:10.14076/j.issn.1006-2025.2022.03.02

Du, Z. L., Su, T., and Ge, J. M. (2021). Forest carbon sink and spillover effect under the background of carbon neutrality. *Econ. Res.* 56, 12.

Fan, S., and Peng, H. J. (2021). Experience and enlightenment of marketization of forest ecological benefit compensation in Australia. *World For. Res.* 34 (03), 112–116. doi:10.13348/j.cnki.sjlyyj.2021.0029.y

Girardin, M. P., Guo, X. J., Gervais, D., Metsaranta, J., Campbell, E. M., Arsenault, A., et al. (2022). Cold-season freeze frequency is a pervasive driver of subcontinental forest growth. *Proc. Natl. Acad. Sci. U. S. A.* 119 (18), e2117464119. doi:10.1073/pnas.2117464119

Gupta, S. (2015). Decoupling: a step toward sustainable development with reference to OECD countries. *Int. J. Sustain. Dev. World Ecol.* 22 (6), 510–519. doi:10.1080/13504509.2015.1088485

Jiang, N., Feng, Y., and Wang, X. (2022). Fractional-order evolutionary game of green and low-carbon innovation in manufacturing enterprises. *Alexandria Eng. J.* 61 (2), 12673–12687. doi:10.1016/j.aej.2022.06.040

Ke, S. F., Zhang, Z., and Wang, Y. M. (2023). China's forest carbon sinks and mitigation potential from carbon sequestration trading perspective. *Ecol. Indic.* 148, 1. doi:10.1016/J.ECOLIND.2023.110054

Li, Y., and Zhang, D. H. (2021). Influence of social capital on forester farmers' access to forestry carbon sink projects. *Rural. Econ.* 7, 68–78.

Liu, C. X. (2021). Review of panel data vector autoregressive model. *Statistics Decis.* 37, 2. doi:10.13546/j.cnki.tjyjc.2021.02.005

Liu, P., Gao, D. D., and Li, S. L. (2020). Effect of forestry investment on economic growth. *J. Northeast For. Univ.* 48, 12. doi:10.13759/j.cnki.dlxb.2020.12.012

Liu, Q. Y., Peng, C. H., Schneider, R., Cyr, D., McDowell, N. G., and Kneeshaw, D. (2023). Drought-induced increase in tree mortality and corresponding decrease in the carbon sink capacity of Canada's boreal forests from 1970 to 2020. *Glob. Change Biol.* 29, 2274–2285. doi:10.1111/gcb.16599

Ma, H. R., and Zhao, T. Z. (2021). Research progress and prospect of forest ecological benefit compensation. *J. Beijing For. Univ. Soc. Sci. Ed.* 20, 4. doi:10.13931/j.cnki.bjfuss.2021068

Miao, P. X., Xiao, Y., and Ding, S. (2020). Analysis on the effect of forestry carbon sequestration on the structure of forestry industry in Jiangsu Province. *China For. Econ.* 2020, 5. doi:10.13691/j.cnki.cn23-1539/f.2020.05.022

Qin, Q., and Qu, L. T. (2021). Study on the economic development of Yiyang county in Hunan Province under the carbon neutral goal. *China Natl. Situat. Natl. Power* 11, 1. doi:10.13561/j.cnki.zggqgl.2021.11.007

Raihan, A., and Tuspekova, A. (2022). Toward a sustainable environment: nexus between economic growth, renewable energy use, forested area, and carbon emissions in Malaysia. *Resour. Conservation Recycl. Adv.* 15, 200096. doi:10.1016/j.rcradv.2022.200096

Shi, X. L., Zhang, Y., and Han, Z. W. (2014). Review of forest carbon sink measurement methods: based on the selection of Beijing. *For. Econ.* 36, 11. doi:10.13843/j.cnki.lyjj.2014.11.009

Wang, J. X., and Zhi, X. J. (2018). Rural revitalization and regional spatial reconstruction in China: the case, experience and future of rural revitalization with characteristic towns and beautiful villages. *J. Nanjing Agric. Univ. Soc. Sci. Ed.* 18, 2.

Wang, Z. P. (2022). Thinking on the construction of forest carbon sink measurement and monitoring system in state-owned forest area: a case study of direct state-owned forest area in Shanxi Province. *Shanxi For.* 3, 1.

Xu, Q. Q., Sun, T., and Cao, X. L. (2021). Analysis on the action path of forestry carbon sequestration to achieve the goal of carbon neutrality. *Econ. Res. Reference* 2021, 20. doi:10.16110/j.cnki.issn2095-3151.2021.20.005

Yao, R. F., Hu, Z. Z., and Guan, J. (2022). The interaction between forest carbon sequestration and economic growth. *Issues For. Econ.* 42, 1. doi:10.16832/j.cnki.1005-9709.20210244

Yu, K. L., Ciais, P., Seneviratne, S. I., Liu, Z., Chen, H. Y. H., Barichivich, J., et al. (2022). Field-based tree mortality constraint reduces estimates of model-projected forest carbon sinks. *Nat. Commun.* 13 (1), 2094. doi:10.1038/s41467-022-29619-4

Zhang, J., and Chen, Q. (2021). Economic value assessment of forest carbon sinks: a case study of fujian province. *J. Southwest Univ. Sci. Technol. Ed.* 43, 5. doi:10.13718/j.cnki.xdzk.2021.05.016

Zhang, J., and Lin, X. W. (2021). Study on influencing factors of forest carbon storage in China: based on socio-economic perspective. *J. Changchun Inst. Technol. Soc. Sci. Ed.* 4, 2.

Zhang, S., Wang, C. X., and Yu, C. (2019). The evolutionary game analysis and simulation with system dynamics of manufacturer's emissions abatement behavior under cap-and-trade regulation. *Appl. Math. Comput.* 355, 343–355. doi:10.1016/j.amc.2019.02.080

Zhang, Y., and Yi, A. J. (2022). Forest carbon sink value calculation and related issues in Chengde city. *Innovation Sci. Technol.* 22, 5. doi:10.19345/j.cxkj.1671-0037.2022.5.008

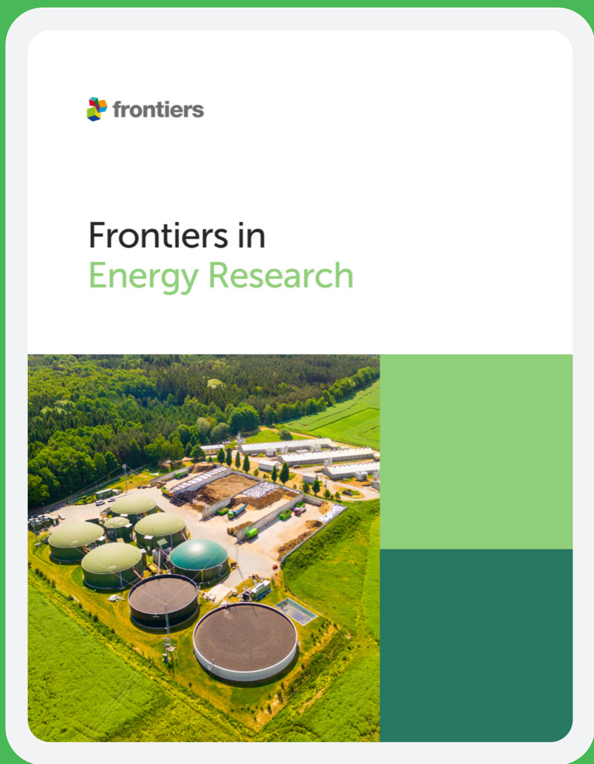
Frontiers in Energy Research

Advances and innovation in sustainable, reliable and affordable energy

Explores sustainable and environmental developments in energy. It focuses on technological advances supporting Sustainable Development Goal 7: access to affordable, reliable, sustainable and modern energy for all.

Discover the latest Research Topics

See more →



Frontiers

Avenue du Tribunal-Fédéral 34
1005 Lausanne, Switzerland
frontiersin.org

Contact us

+41 (0)21 510 17 00
frontiersin.org/about/contact