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A Study on the Spatio-Temporal Variations in the Impact of Provincial Energy Investment on the Green Economy, Empowered by Attention Mechanisms

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Abstract. Against the backdrop of global efforts to address climate change and the advancement of China's 'dual carbon' goals, the green economy has become a core direction for high-quality development, with the structure and distribution of energy investment playing a pivotal role in the transition towards a green economy. Using panel data from 30 Chinese provinces covering 2005–2022, this study constructs a multi-dimensional 'energy investment–green economy' indicator system. It innovatively introduces an attention-mechanism-enhanced CNN-LSTM hybrid model to quantify the spatio-temporal differentiated contributions of infrastructure, R&D, and energy efficiency investment to the green economy. All three categories positively drive green economic development, with R&D investment making the highest contribution. The driving role shows distinct phase characteristics: infrastructure investment dominated during the 12th Five-Year Plan period, energy efficiency investment during the 13th Five-Year Plan period, and R&D investment after the dual carbon goals proposal. Significant spatial heterogeneity exists across eastern, central and western regions. The CNN-LSTM model with enhanced attention mechanism is superior to the traditional model in terms of fitting accuracy and interpretability. This study reveals the core mechanism and differentiated path of energy investment affecting the green economy, and provides a scientific decision-making basis for optimising the provincial energy investment structure and promoting the high-quality development of the green economy.

Keywords: energy investment, green economy, attention mechanism, spatiotemporal differentiation, provincial panel data

1. Introduction

The green economy has become a new engine driving the transformation and upgrading of the global economy, whilst the investment orientation of the energy system fundamentally determines the trajectory and quality of the green economic transition. The process by which energy investment drives green economic development is highly complex, influenced by multiple factors including macroeconomic policies, meso-level market dynamics and external shocks; traditional economic models struggle to accurately identify key driving factors.

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Scholars at home and abroad have carried out a lot of research on energy investment, the green economy and the impact mechanisms of the two, but there are still shortcomings: first, there is a lack of quantitative analysis of the differentiated contributions of infrastructure, research and development, and energy efficiency investment; second, the exploration of spatiotemporal heterogeneity is not deep; third, it is difficult for traditional econometric models to deal with nonlinear and high-dimensional problems, and the existing machine learning research is mostly "black box" models, which lack explainability; fourth, there is a lack of systematic research on the provincial scale, which is difficult to meet precise policy needs, and the lack of research on the adaptability of the green economy and energy investment at the regional level restricts the accurate implementation of policies.

2. Literature review

2.1. Current state of energy investment research

Overseas research began early and has developed a comprehensive framework. Early studies focused on the efficiency of fossil fuel investment and market mechanisms. From the 1970s to the 1990s, the focus shifted to the feasibility of alternative energy investment, forming a 'energy security–investment policy–economic impact' framework. Since the 21st century, research has deepened in multiple dimensions, confirming the emission-reduction effects of renewable energy investment, proposing a 'policy–investment–technology' transmission model, and examining regional investment equilibrium and interactions with technological innovation.

Domestic research began later but has developed rapidly. During the 1980s and 1990s, it focused on the introduction and regional distribution of traditional energy investments. From the early 21st century to 2012, research expanded to include cost forecasting, risk assessment and international investment in new energy. From 2013 to the present, research has been integrated with the "dual carbon" goals, revealing regional variations in the effectiveness of new energy investment, exploring the optimisation of investment allocation [1, 2], and confirming its global emissions reduction spillover effects; however, shortcomings remain in areas such as the micro-level effects of distributed energy investment and dynamic modelling [3].

2.2. Current status of green economy research

The concept of the green economy originated in the 1960s and 1970s. Overseas research has evolved through the stages of "theoretical construction – practical validation – global coordination". The theoretical construction phase proposed concepts such as "environmental asset preservation" and emissions trading theory. The practical validation phase focused on policy evaluation and model exploration. The global coordination phase centres on green technology spillovers, industrial value chains and "just transition".

Domestic research began in the 1990s, progressing through the stages of "theoretical introduction – practical deepening – high-quality development" [4]. Early research involved the introduction and adaptation of foreign theories. Mid-stage research shifted towards micro-level practice, such as evaluating the effectiveness of green credit. Recently, under the "dual carbon" goals, research has focused on regional coordination of new energy investment and the prospects of CCUS technology; however, empirical studies on corporate transformation drivers and regional coordination remain insufficient [5].

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2.3. Current status of research on the mechanisms through which energy investment influences the green economy

Overseas research has progressed through the stages of "theoretical construction – quantitative validation – systemic coordination". During the theoretical construction phase, an analytical framework of "policy guidance – investment transition – multi-effect output" was established. The quantitative validation phase confirmed the mediating role of technological innovation and analysed the mechanistic differences among various energy investments. Recent research has focused on synergistic effects under carbon neutrality, exploring the integration of digitalisation and intelligentisation as well as risk hedging mechanisms, whilst also paying attention to the social effects of "just transition".

Domestic research began in the early 21st century, progressing through the stages of "theoretical introduction – empirical testing – systemic synergy". Early studies introduced and adapted foreign theories, but research on micro-level pathways remained weak [6]. Mechanism research in the middle phase was refined, revealing the regional heterogeneity mechanisms of new energy investment and the "investment agglomeration – industrial upgrading – green growth" chain [1, 7]. Recent research has shifted towards systemic synergy, exploring cross-regional coordination mechanisms and international spillover effects; however, empirical studies on the micro-mechanisms of distributed energy and the integration of digitalisation and intelligentisation remain underdeveloped. Although traditional 3E system models are widely applied in analysing energy-economy-environment interrelationships, their descriptions of resource production and utilisation technologies are relatively abstract, and they overlook feedback from non-technical market factors [6]. Existing machine learning models are largely 'black boxes', whereas hybrid models combining attention mechanisms with LSTMs have been shown to enhance interpretability and accuracy in time-series data processing [8, 9], further highlighting the necessity of the methodological innovation in this study [10].

3. Method

3.1. Data collection and construction of the indicator system

3.1.1. Data collection and processing

Panel data from 30 provinces in China covering 2005–2022 were selected as the sample. The data were sourced from the National Bureau of Statistics, provincial and municipal statistical yearbooks, the China Energy Statistical Yearbook, the China Environmental Statistical Yearbook, and relevant industry reports. Data pre-processing followed a standardised procedure: missing values were imputed using linear interpolation; differences in indicator units were eliminated using the Z-score method; and outliers were identified and corrected in accordance with the 3σ principle to ensure data validity

3.1.2. Construction of a multi-dimensional indicator system

The energy investment indicator system is constructed across three dimensions: infrastructure investment is represented by investment in renewable energy generation capacity; R&D investment is represented by internal expenditure on R&D in the energy sector; and energy efficiency

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investment is represented by investment in technological upgrades related to the reduction in energy consumption per unit of GDP [1, 2].

The comprehensive index of green economic development covers three dimensions: the quality of economic growth is characterised by green total factor productivity, the resource and environmental carrying capacity is characterised by per-unit GDP carbon emissions and PM2.5 concentrations [7], and the transformation results are characterised by the proportion of revenue of strategic emerging industries [4, 5], which comprehensively reflects the overall level of provincial-level green economic development [11], and aligns with the core logic of the three-dimensional coordination of the 3E system "energy-economy-environment" [6].

3.2. Selection of research methods

Adopt a comprehensive research method system that combines qualitative and quantitative analysis and confirms macro statistics and micro mechanisms:

(1) Bibliometric method: Use the CiteSpace tool to conduct keyword co-occurrence, clustering and time-series analysis of core literature, and sort out the research hotspots and evolutionary veins.

(2) Traditional econometric model: use the fixed effect model and the random effect model to carry out benchmark regression to preliminarily judge the correlation between energy investment and green economy; use the Bootstrap method to build a mediation effect model to test the mediating role of technological innovation, industrial structure upgrading and energy structure optimisation.

(3) Deep learning model: build a CNN-LSTM hybrid model with enhanced attention mechanism, CNN extracts the spatial structure characteristics of provincial energy investment, LSTM learns the long-term time-series dependence of the two, and the attention mechanism automatically identifies and quantifies the relative importance of different periods and different investment dimensions, and realises the explanatory transformation of the model [9], breaking the limitations of the traditional single modelling idea of "heavy binary, light three-dimensional" and "heavy macro, light regional" [6].

Case study method: Select the representative provinces of the Yangtze River Delta (Zhejiang), central China (Henan) and western China (Gansu), and verify the model results through secondary data analysis.

3.3. Implementation of empirical analysis

Quantification of differentiated contributions: Use the contribution decomposition method and the Shapley value decomposition method to measure the differentiated contribution of three types of energy investment to the green economy.

· Hybrid model construction and training: The model was constructed according to the architecture: "data input layer – CNN spatial feature extraction layer – LSTM temporal feature learning layer – attention mechanism weighting layer – result output layer". The attention mechanism layer was configured with dual weights for both the time and investment dimensions [9, 10]; data from 2005 to 2018 was used as the training set, and data from 2019 to 2022 as the test set; hyperparameters were tuned to optimise model convergence.

· Spatio-temporal differentiated feature analysis: The Relative Importance Index was employed to compare the intensity of influence across investment dimensions; time-period decomposition was used to analyse changes in contributions during the "Twelfth Five-Year Plan", "Thirteenth Five-Year

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Plan" and "post-proposal of the dual carbon targets" phases; regional heterogeneity analysis was conducted based on the division into eastern, central and western regions.

3.4. Model validation and policy scenario simulation

· Multi-model comparative validation: Selecting RMSE, MAE and R^2 as core evaluation metrics, the hybrid model is compared with traditional panel models, standard LSTM models and CNN-LSTM models without an attention mechanism [8] to test the model's superiority; extract the output weights of the attention layer to observe the ranking of investment types and time periods in terms of importance.

· Policy scenario simulation: By adjusting model input parameters to construct different policy scenarios—such as increased R&D investment or optimised infrastructure investment structures—the study calculates the potential changes in the comprehensive green economic development index and quantify the expected outcomes of various investment structure optimisation strategies.

3.5. Methodological approach

Adhering to the technical approach of "theoretical construction – empirical testing – simulation forecasting – policy refinement": systematically reviewing the theory and constructing a research framework; collecting and pre-processing data to establish an indicator system, and conducting baseline regression and mediation effect analyses; training a hybrid model to quantify differential contributions and extract spatio-temporal features; validating through multi-model comparisons and conducting policy simulations; and, by combining quantitative results with case studies, summarising conclusions and formulating policy recommendations.

4. Conclusion

4.1. Key findings

All three categories of energy investment exert a positive driving force on the green economy, though their contributions vary significantly. All three types of energy investment have a positive driving effect on the green economy, but the contribution varies significantly. R&D investment has the highest comprehensive contribution, empowering energy utilisation efficiency improvement and green industry upgrading through technological innovation [11]; energy efficiency investment is next, directly improving resource and environmental carrying capacity [1, 4]; infrastructure investment shows long-term cumulative effects at the basic security level.

The driving effect of energy investment shows obvious phased characteristics. Infrastructure investment during the 12th Five-Year Plan period was the core driver, and the contribution of energy efficiency investment during the 13th Five-Year Plan period increased rapidly. After the dual-carbon goals were put forward, R&D investment jumped to first place, which is highly consistent with the national energy strategy.

The characteristics of spatial heterogeneity are prominent. The contribution of R&D investment in the eastern region is much higher than that of the central and western regions, relying on technological and industrial advantages to achieve high conversion efficiency; the central region ranks first in the contribution of energy efficiency investment, and energy efficiency improvement technology transformation has become the core entry point; the western region is relatively

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prominent in infrastructure investment, with renewable energy development and capacity construction as the main way.

The CNN-LSTM model with enhanced attention mechanism performs better. It is superior to the traditional model in terms of indicators such as RMSE, MAE and R^2, and quantifies the relative importance of different periods and investment types, making up for the "black box" defect.

The mediating effect has differentiated characteristics. The mediating effect of technological innovation is the most significant in the driving path of R&D investment, the upgrading of industrial structure plays a prominent role in the eastern region, and the optimisation of energy structure occupies a central position in the western region.

4.2. Key implications

(1) The type of energy investment is the core factor affecting the development of the green economy. R&D, energy efficiency and infrastructure investment constitute innovation-driven, efficiency-driven and infrastructure-driven paths respectively.

(2) The driving role of energy investment is strategically oriented and stage-oriented, and needs to be matched with the needs of different stages of development.

(3) The difference between regional resource endowment and development foundation is the core cause of spatial heterogeneity, and it is necessary to achieve an accurate match between investment types and regional characteristics.

(4) The attention mechanism and the CNN-LSTM fusion model effectively solve the problem of the "black box" limitations and insufficient regional adaptability of the traditional 3E model [6], and are consistent with the application logic of similar hybrid models in time-series data processing [8-10], providing a new method for provincial-scale research on the energy-economy-environment system.

· Energy investment is transmitted through multi-path transmission, so supporting policies are needed to strengthen the mediating effect and improve conversion efficiency. This is consistent with the core characteristics of the 3E system of "three-terminal system mutual penetration and restraint" [6].

4.3. Significance of the study

4.3.1. Theoretical significance

It enriches the dimensions of research on energy investment and green economy and deepens the understanding of diversified driving paths. The spatiotemporal analysis framework has been improved to provide a new perspective for provincial-scale research. The research method system has been innovated and the superiority of the hybrid model has been verified [6]. The mechanism research has been strengthened and transmission characteristics have been clarified.

4.3.2. Practical significance

It provides a basis for the country to optimise the top-level design of energy investment and match the "dual carbon" goals [1]. It provides guidance for provinces to formulate differentiated investment strategies (strengthening R&D in the east, increasing energy efficiency in the central region, and improving infrastructure in the west) [6, 11]. It provides ideas for improving investment conversion efficiency by strengthening technology research and development and promoting

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structural optimisation. It provides reference for the layout of financial markets and social capital. It provides practical support for building a modern energy economic system and promoting high-quality development.

Declarations

Authorship

Xiaoyu Zhang: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing

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