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ARTICLE

Research on Sustainable Economic Development Model Based on Clean Energy

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ABSTRACT

Based on panel data from 31 Chinese provinces during 2010–2022, this study constructs a systematic theoretical framework incorporating clean energy investment, technological innovation, industrial structure optimization, and environmental governance, employing spatial econometric and threshold effect models to examine the impact mechanisms of clean energy development on sustainable economic growth. The findings reveal that clean energy development has a significant promoting effect on sustainable economic growth (impact coefficient 0.437) and generates notable spatial spillover effects (coefficient 0.328); technological innovation (38.24%), industrial structure optimization (31.47%), and environmental governance (25.89%) represent three crucial pathways through which clean energy drives sustainable economic development; this impact exhibits significant regional heterogeneity, with the eastern region (0.526) showing higher effects than central (0.437) and western regions (0.342), and demonstrating a strengthening trend over time. The innovative contributions of this paper include: the first combination of spatial econometrics and threshold effect models to study the economic effects of clean energy development; construction of a detailed measurement system for clean energy development that incorporates characteristics of different types of clean energy; and quantitative analysis of the inherent causes of regional differences using the Shapley value decomposition method. The research conclusions provide a theoretical foundation and practical guidance for formulating differentiated regional development strategies, strengthening technological innovation support, optimizing the industrial development environment, and enhancing environmental governance coordination.

Keywords: Clean Energy; Sustainable Economic Development; Spatial Spillover Effects; Technological Innovation;

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Industrial Structure Optimization

1. Introduction

1.1. Research Background and Significance

In the context of increasingly severe global climate change and energy crisis, the coordinated advancement of clean energy development and sustainable economic growth has become a crucial issue for countries worldwide. With China's proposal of the "dual carbon" strategic goals, the tasks of energy structure transformation and economic development mode transition have become more urgent. Li and Guan point out that in the global clean energy transition process, it is necessary to rethink and construct an international energy justice order, where China, as the world's second-largest economy and the largest developing country, plays a vital role in promoting global energy fair transition. Currently, environmental pollution and resource depletion caused by traditional fossil energy consumption are becoming increasingly prominent, making it urgent to accelerate clean energy technology innovation and application promotion [1]. Jiang demonstrates through comparative research between clean energy heating and traditional energy heating that clean energy has significant advantages in energy conservation, emission reduction, and improving energy utilization efficiency [2]. However, clean energy development still faces multiple constraints including technology, cost, and infrastructure, requiring the construction of a systematic development strategic framework.Currently facing multiple challenges of climate change, energy security, and sustainable economic development, China, as the world's second-largest economy and largest developing country, has a crucial role in global energy transition and climate governance through its choice of clean energy development model, which is vital for achieving both domestic carbon goals and international climate objectives.

At the micro level, enterprises, as important practitioners of clean energy transition, directly influence energy consumption structure and efficiency through their sustainable development strategy choices. Yang, using electric furnace production enterprises as an example, shows that while pursuing economic benefits, enterprises need to incorporate energy consumption optimization into their sustainable development strategies to achieve energy conservation and efficiency improvement through technological and management innovation [3]. At the macro level, promoting the coordinated development of clean energy and sustainable economic development requires financial support and regional coordination. Liu, Fan and Wang find that there is significant spatial correlation between green finance development and clean energy utilization, and establishing a provincial-level coordination mechanism of green finance-clean energy-ecological sustainable development is significant for promoting high-quality regional economic development [4].

From a theoretical perspective, the relationship between clean energy development and sustainable economic growth can be explained through several economic theories: 1) According to endogenous growth theory, clean energy technological innovation, as a key form of knowledge accumulation, drives sustained economic growth by improving total factor productivity, with sustainable and increasing effects due to knowledge non-rivalry and spillover effects. 2) Based on industrial structure upgrading theory, the clean energy industry, as a strategic emerging sector, can drive industrial transformation through value chain extension and upgrading, optimizing resource allocation efficiency and creating new economic growth points. 3) Environmental economics theory suggests that clean energy development enhances economic growth sustainability by reducing environmental negative externalities, lowering environmental governance costs, and improving ecosystem services. 4) Regional economics theory indicates that clean energy development promotes coordinated regional development through technological diffusion, industrial linkages, and environmental improvement channels. These theories suggest a positive bidirectional causality between clean energy development and sustainable economic growth: clean energy development promotes economic growth through technological progress, industrial upgrading, and environmental improvement, while economic growth provides financial support and market demand for clean energy development, forming a virtuous cycle. This theoretical foundation provides important support for subsequent empirical research.

In this context, studying the sustainable economic development model based on clean energy has important theoretical value and practical significance: 1) It helps deepen theoretical understanding of the relationship between clean energy development and economic growth, enriching the theoretical system of sustainable development economics; 2) It provides empirical evidence and policy reference for promoting energy structure transformation and economic development mode change; 3) It helps explore clean energy development paths adapted to China's conditions, providing theoretical support and practical guidance for achieving the "dual carbon" goals; 4) This research focuses on the interaction mechanism between clean energy and sustainable economic development, addressing multi-dimensional influencing factors such as technological innovation, industrial upgrading, and regional coordination, helping propose more targeted and operational policy recommendations. Particularly under the new situation of profound changes in global energy patterns and increasingly fierce international competition, in-depth research on clean energy-driven sustainable economic development models has strategic significance for enhancing national energy security, improving international competitiveness, and achieving high-quality development.

The practical significance of this research is also reflected in: 1) Providing decision-making reference for government formulation of clean energy development policies and economic transformation strategies; 2) Offering practical guidance for enterprises to formulate sustainable development strategies and energy optimization plans; 3) Providing theoretical basis for promoting regional coordinated development and green finance innovation. Furthermore, in the context of global response to climate change, in-depth research on clean energy promoting sustainable economic development models and paths also has positive significance for promoting international energy cooperation and advancing the reform of global energy governance systems.

1.2. Literature Review

Research on clean energy and sustainable economic development can be summarized in several aspects: Scholars have examined the impact of clean energy development on economic growth. Early studies primarily focused on the relationship between environmental pollution and economic development, such as the Environmental Kuznets Curve (EKC) hypothesis. In recent years, with the rapid development of clean energy technology, research focus has shifted to the contribution mechanisms of clean energy consumption and production to sustainable economic development. Using the Panel Smooth Transition Regression (PSTR) model, Cao et al. found a non-linear relationship between clean energy consumption and economic development, showing differentiated characteristics at various development stages [5]. Similarly, Wang and Liu explored the impact mechanism of green finance promoting sustainable economic development from the perspective of financial support, finding that financial innovation can effectively alleviate funding constraints in clean energy development [6].

As global climate governance advances, scholars have begun to focus on the impact of environmental policies on clean energy development. Zhang and Wang, through studying the impact of China's carbon trading policy on sustainable economic welfare, found that market-based environmental regulation can effectively guide enterprises in clean energy technology innovation [7]. Wang and Cao discussed the financial impact of clean energy and technology acceptance on energy transition in the process of environmental sustainability adoption, emphasizing the importance of policy guidance [8]. These studies provide important evidence for understanding the interactive relationship between environmental policy and clean energy development.

Regarding technological innovation, existing research mainly focuses on innovation-driven development and industrial development. Song et al. systematically analyzed the impact mechanism of technological innovation on the sustainable supply of clean energy metals, identifying technological innovation as a key factor in ensuring sustainable development of the clean energy industry [9]. Yin, using Qinghai Province as an example, studied clean energy industry innovation development paths under sustainable transition development, emphasizing the importance of regional characteristic development strategies [10]. Zheng, through analyzing methanol's application prospects as clean energy, explored the development potential of new clean energy technologies [11]. These studies indicate that technological innovation is the core driver of clean energy industry development.

With deepening regional economic integration, scholars have increasingly focused on regional synergistic effects of clean energy development. Wu et al. studied sustainable development paths for the energy industry in Northwest China from the perspective of the "water resources-energy" nexus, emphasizing regional energy development strategies under resource and environmental constraints [12]. Ullah and Lin studied how Pakistan's clean energy initiatives promote sustainable development through environmental innovation and policy optimization [13]. Qi assessed clean energy development paths based on carbon emission data, discussing regional differences in achieving sustainable development goals [14]. These studies provide new perspectives for understanding the spatial effects of clean energy development.

In specific application areas, scholars have conducted in-depth research on clean energy practices in different industries. Wang studied the role of new energy and clean energy vessels in inland shipping green transformation [15]. Li discussed sustainable development issues in green logistics and transportation economics [16]. Fang and Li, using H County in Shanxi Province as an example, studied the driving mechanisms of sustainable clean energy consumption in rural households [17]. These studies have enriched practical experience in clean energy applications.

From a micro-level perspective, enterprises, as key players in clean energy transition, directly influence development outcomes through their behavioral choices. Tian studied sustainable development strategies for power energy enterprises in overseas markets under the "dual carbon" environment [18]. Fang analyzed the driving factors of traditional energy enterprises transitioning to clean energy [19].

In terms of international cooperation, Jr emphasized global synergy in clean energy development at the G20 Summit [20]. Zheng analyzed the significance of clean energy development and utilization in achieving sustainable development, highlighting the importance of international cooperation [21]. These studies provide theoretical support for promoting international cooperation in the clean energy sector.

Although existing research has provided important theoretical foundations and empirical evidence for understanding the relationship between clean energy and sustainable economic development, several limitations remain: 1) Most studies focus on single-dimensional impact mechanisms, lacking a systematic theoretical framework, making it difficult to comprehensively grasp the impact pathways of clean energy development on economic sustainability; 2) Insufficient research on the spatial effects of clean energy development, particularly in regional collaborative development, constrains the optimization of regional energy strategies; 3) Limited consideration of interactive effects among multiple factors such as technological innovation, industrial upgrading, and environmental regulation, affecting policy effectiveness; 4) Insufficient in-depth research on the linkage between micro-entity behavior and macro-policy effects, making it difficult to accurately grasp policy implementation effects; 5) In terms of research methodology, traditional econometric methods are predominantly used, with insufficient consideration of spatial correlation and non-linear characteristics, potentially leading to estimation bias.

Based on these limitations, this paper will expand in the following aspects: 1) Constructing a more complete theoretical analysis framework to systematically examine the impact mechanisms of clean energy development on economic sustainability; 2) Applying spatial econometric methods to analyze the regional synergy effects of clean energy development in depth; 3) Considering the interaction of multiple factors to explore policy optimization directions; 4) Combining micro and macro perspectives to propose more targeted development recommendations. These studies will help deepen theoretical understanding of how clean energy promotes sustainable economic development and provide a scientific basis for relevant policy-making.

From a theoretical perspective, the relationship between clean energy development and sustainable economic growth can be explained through several economic theories: 1) According to endogenous growth theory, clean energy technological innovation, as a key form of knowledge accumulation, drives sustained economic growth by improving total factor productivity, with sustainable and increasing effects due to knowledge non-rivalry and spillover effects. 2) Based on industrial structure upgrading theory, the clean energy industry, as a strategic emerging sector, can drive industrial transformation through value chain extension and upgrading, optimizing resource allocation efficiency and creating new economic growth points. 3) Environmental economics theory suggests that clean energy development enhances economic growth sustainability by reducing environmental negative externalities, lowering environmental governance costs, and improving ecosystem services. 4) Regional economics theory indicates that clean energy development promotes coordinated regional development through technological diffusion, industrial linkages, and environmental improvement channels. These theories suggest a positive bidirectional causality between clean energy development and sustainable economic growth: clean energy development promotes economic growth through technological progress, industrial upgrading, and environmental improvement, while economic growth provides financial support and market demand for clean energy development, forming a virtuous cycle. This theoretical foundation provides important support for subsequent empirical research.

2. Theoretical Analysis and Research Hypotheses

2.1. Impact Mechanisms of Clean Energy Development on Economic Growth

The impact mechanisms of clean energy development on economic growth primarily manifest in three aspects: direct effects, indirect effects, and spatial spillover effects

Regarding direct effects, clean energy development influences economic growth through the following channels: First, the development of the clean energy industry directly creates new economic growth points, driving the development of related industries through industrial chain extension, forming new economic growth poles. Second, clean energy investment expands fixed asset investment scale, promotes capital formation, and directly stimulates economic growth. Third, the development of the clean energy industry creates numerous employment opportunities, particularly in areas such as technological research and development, equipment manufacturing, and engineering construction, enhancing labor market vitality. Finally, the utilization of clean energy reduces enterprise production costs, improves energy usage efficiency, and directly increases business economic benefits [22].

From the perspective of indirect effects, clean energy development promotes economic growth through the following mechanisms: First, through technological innovation effects, clean energy development drives energy technology advancement, promotes technological innovation capacity, and leads to overall technological improvement. Second, through industrial structure optimization effects, the development of the clean energy industry promotes traditional industrial transformation and upgrading, pushing industrial structure toward high-technology and high-value-added directions. Third, through environmental improvement effects, clean energy usage reduces environmental pollution, improves ecological environmental quality, lowers environmental governance costs, and creates favorable conditions for sustainable economic development. Fourth, through institutional innovation effects, clean energy development promotes energy market reform and environmental governance system improvement, optimizing the institutional environment for economic development.

Regarding spatial spillover effects, the impact of clean energy development transcends geographical boundaries and transmits between regions through multiple channels: First is the knowledge spillover effect, where clean energy technological innovation in one region influences technological progress in surrounding areas through technology diffusion and talent mobility. Second is the market spillover effect, where clean energy industry development drives interregional industrial chain collaboration and promotes factor market integration. Third is the policy spillover effect, where clean energy development policies in one region influence policy-making in surrounding areas, forming policy linkages. Finally, there is the environmental spillover effect, where clean energy utilization improves regional ecological environment and affects environmental quality in surrounding areas through ecosystem connectivity. The existence of these spatial spillover effects demonstrates that clean energy development's impact on economic growth exhibits significant spatial correlation characteristics, necessitating regional coordination to promote clean energy development and achieve broader economic benefits.

Building on existing research, international scholars have deepened their investigation of clean energy development and sustainability. Dincer and Acar systematically evaluated clean energy solutions' impact on sustainable development, constructing an assessment framework encompassing energy efficiency, environmental impact, economic feasibility, and social acceptance [23]. They found clean energy technologies' comprehensive benefits significantly outweigh traditional energy sources, though challenges remain in technological maturity, cost-effectiveness, and infrastructure. Recently, Dimitriadis, Koursaros and Savva explored environmental-friendly characteristics' impact on major industries' stock crash risk from a financial market perspective, finding clean energy attributes significantly reduce market risk premium asymmetry, providing new evidence for understanding clean energy development's influence on financial market stability [24]. These studies enrich clean energy sustainable development's theoretical implications while providing important references for constructing this paper's more comprehensive analytical framework.

Overall, clean energy development influences economic growth through multiple mechanisms including direct effects, indirect effects, and spatial spillover effects. These three effects interact and promote each other, jointly forming a complete mechanism chain for clean energy to drive sustainable economic development. Understanding these impact mechanisms is crucial for formulating clean energy development strategies, optimizing policy measures, and promoting regional coordinated development. Meanwhile, the degree of these effects' manifestation is influenced by various factors such as technological level, market environment, and policy support, requiring the improvement of supporting measures to enhance clean energy development's promotional effect on economic growth.

In the impact process of clean energy development on economic growth, technological innovation, industrial structure optimization, and environmental governance level may exhibit threshold effects, based on the following theoretical foundations: 1) Technological innovation as a threshold variable is grounded in innovation-driven development theory and technological absorption capacity theory. Research shows regional innovation capacity has a "critical point"—only when technological innovation exceeds specific threshold values can innovation resources accumulate sufficiently to significantly enhance clean energy efficiency and economic benefits. Below this threshold, economic effects may be constrained by insufficient technological accumulation. 2) Industrial structure optimization as a threshold variable is based on industrial structure evolution and industrial symbiosis theories. These theories indicate industrial structure upgrading follows path dependence, requiring breakthrough of specific industrial agglomeration and correlation thresholds to achieve effective value chain extension. When structural optimization is low, the clean energy industry may lack scale effects due to insufficient supporting facilities; only by breaking through the critical point can industrial cluster advantages be fully realized. 3) Environmental governance level as a threshold variable stems from environmental Kuznets curve and environmental regulation theories. These theories suggest optimal environmental governance intensity exists—too low cannot effectively guide clean energy substitution, while too high may increase enterprise costs and suppress growth. Therefore, clean energy development can achieve win-win economic and environmental benefits only within appropriate environmental governance intervals. These three threshold variables' selection has solid theoretical foundations and empirical research support.

2.2. Theoretical Framework of Sustainable Economic Development

Within the theoretical framework of clean energy-driven sustainable economic development, clean energy investment, technological innovation, industrial structure optimization, and environmental governance effects constitute three core dimensions. The theoretical framework is shown in **Figure 1**:

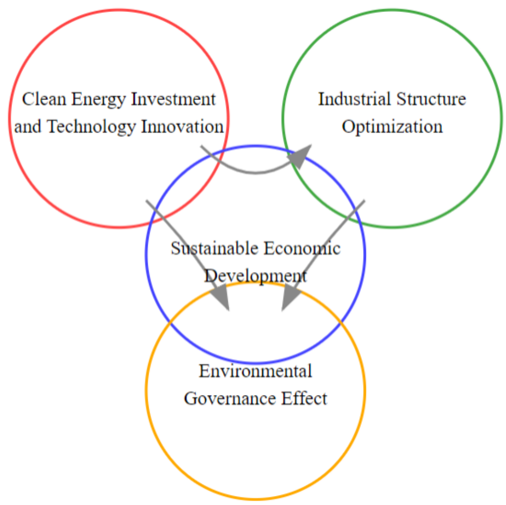

Figure 1. Theoretical framework of clean energy promoting sustainable economic development.

Regarding clean energy investment and technological innovation, financial input provides fundamental support for technological innovation. 1) Government and enterprise R&D investment in clean energy directly promotes breakthroughs in new energy technologies and enhancement of innovation capabilities. 2) Financial institutions provide funding support for clean energy projects through innovative tools such as green credit and green bonds, reducing innovation costs. 3) The introduction of venture capital and industrial funds optimizes the investment structure of clean energy innovation, accelerating the transformation of technological achievements. Meanwhile, technological innovation in turn improves investment efficiency, forming a virtuous cycle. Technological innovation encompasses both original innovation in clean energy and applied and integrated innovation, jointly forming a technological support system driving sustainable development.

Industrial structure optimization is a crucial pathway for clean energy to promote sustainable development. On one hand, the development of the clean energy industry forms new strategic emerging industries, promoting industrial structure upgrade towards low-carbon and high-tech directions. On the other hand, the widespread application of clean energy technology drives the green transformation of traditional industries, promoting industrial chain extension towards high value-added links. Furthermore, industrial structure optimization is reflected in spatial layout optimization, improving resource allocation efficiency through industrial cluster development. Industrial structure optimization not only improves economic development quality but also creates market demand for further clean energy development.

Regarding environmental governance effects, clean energy development directly improves environmental quality, creating positive environmental externalities. First, clean energy substitutes traditional fossil energy, reducing greenhouse gas and pollutant emissions. Second, environmental quality improvement reduces environmental governance costs, releasing more resources for economic development. Third, good environmental quality enhances regional investment attractiveness, promoting high-quality capital and talent aggregation. Additionally, institutional innovation in environmental governance also promotes the modernization of environmental governance systems and capabilities, providing institutional guarantees for sustainable development.

These three dimensions interact and promote each other, jointly forming the theoretical framework for clean energy to drive sustainable economic development. Investment and innovation provide momentum for industrial optimization, industrial optimization strengthens environmental governance effects, and environmental improvement promotes investment efficiency improvement, forming a virtuous cycle mechanism. Meanwhile, this theoretical framework also reflects the systematic characteristics of clean energy development, requiring comprehensive consideration of multiple factors such as technology, industry, and environment, and coordinated promotion of various policy measures to achieve sustainable development goals.

Complex interactive mechanisms and circular effects exist among clean energy investment, technological innovation, industrial structure optimization, and environmental governance: 1) Clean energy investment provides essential funding and R&D conditions for technological innovation, while successful innovation improves investment efficiency and reduces risks, attracting more social capital into the clean energy sector, forming a virtuous cycle; 2) Technological innovation drives industrial structure upgrading through advanced processes and equipment, while optimized industrial structure provides broader applications and market demand for innovation, promoting transformation of innovative achievements; 3) Industrial structure optimization toward clean and low-carbon directions improves environmental governance outcomes, while enhanced environmental quality strengthens endogenous motivation for industrial transformation, promoting green transformation of traditional industries; 4) Improved environmental governance optimizes the clean energy investment environment and enhances investment confidence, while expanded investment provides more sufficient funding for environmental governance. The mutual promotion and circular interaction among these four elements constitute the internal mechanism driving sustainable economic development. This multi-dimensional interaction demonstrates clean energy development's systematic characteristics and indicates achieving sustainable development goals requires coordinated advancement in investment, innovation, industry, and environmental aspects.

2.3. Research Hypotheses

Based on the theoretical analysis framework discussed above, this paper proposes the following research hypotheses:

1. Clean energy development has a significant promoting effect on sustainable economic growth. From the perspective of direct effects, the development of the clean energy industry creates new economic growth points, expands investment scale, and increases employment levels; from the perspective of indirect effects, clean energy develop-

ment promotes technological innovation, optimizes industrial structure, and improves the ecological environment; from the perspective of spatial spillover effects, clean energy development influences the development of surrounding areas through channels such as technology diffusion, market linkage, and environmental improvement. Therefore, hypothesis H1 is proposed: Clean energy development has a significant positive impact on sustainable economic growth, and this impact has spatial spillover effects [25].

2. Technological innovation is an important mediating mechanism for clean energy to promote sustainable economic development. Clean energy investment drives increased R&D investment, enhances innovation capability, and promotes economic high-quality development through technological progress and improved total factor productivity. Meanwhile, technological innovation improves clean energy utilization efficiency, reduces application costs, forming a virtuous cycle. Therefore, hypothesis H2 is proposed: Technological innovation plays a significant mediating role in the process of clean energy development promoting sustainable economic growth [26].

3. Industrial structure optimization and environmental governance effects jointly influence the economic outcomes of clean energy development. Clean energy development promotes industrial structure evolution toward low-carbon and high-tech directions through driving traditional industrial transformation and upgrading, nurturing emerging industries, and optimizing industrial layout. Meanwhile, the widespread application of clean energy improves environmental quality, reduces environmental governance costs, and enhances regional investment attractiveness. Therefore, hypothesis H3 is proposed: The degree of industrial structure optimization and level of environmental governance have moderating effects on the economic outcomes of clean energy development [27].

4. Considering the heterogeneous characteristics of regional development, the impact of clean energy development on economic growth may vary across regions. Different regions have variations in resource endowment, technological level, industrial foundation, and environmental carrying capacity, which may affect the outcomes of clean energy development. Therefore, hypothesis H4 is proposed: The impact of clean energy development on sustainable economic growth exhibits significant regional heterogeneity.

3. Research Design

3.1. Model Construction

This paper primarily constructs spatial econometric models and threshold effect models to study the impact mechanisms of clean energy development on sustainable economic growth.

Complex interactive mechanisms and circular effects exist among clean energy investment, technological innovation, industrial structure optimization, and environmental governance: 1) Clean energy investment provides essential funding and R&D conditions for technological innovation, while successful innovation improves investment efficiency and reduces risks, attracting more social capital into the clean energy sector, forming a virtuous cycle; 2) Technological innovation drives industrial structure upgrading through advanced processes and equipment, while an optimized industrial structure provides broader applications and market demand for innovation, promoting the transformation of innovative achievements; 3) Industrial structure optimization toward clean and low-carbon directions improves environmental governance outcomes, while enhanced environmental quality strengthens endogenous motivation for industrial transformation, promoting the green transformation of traditional industries; 4) Improved environmental governance optimizes the clean energy investment environment and enhances investment confidence, while expanded investment provides more sufficient funding for environmental governance. The mutual promotion and circular interaction among these four elements constitute the internal mechanism driving sustainable economic development. This multi-dimensional interaction demonstrates clean energy development's systematic characteristics and indicates achieving sustainable development goals requires coordinated advancement in investment, innovation, industry, and environmental aspects.

1. Spatial Econometric Model

Considering the potential spatial spillover effects of clean energy development, this paper adopts the Spatial Durbin Model (SDM) for analysis, which can capture both spatial autocorrelation and the influence of random spatial effects [28]. Based on this, the following baseline model is constructed:

ECGi,t = α0 + β1ECGi,t + α1CEDi,t + α2INNi,t + α3NDi,t + α4ENi,t + α5Zi,t + θ1TCEDi,t + θ2TINNi,t +

$\theta 3TINDi,t + \theta 4TENi,t + \theta 5TZi,t + \mu i + \lambda t + \varepsilon i,t$ (1)

Where ECGi,t represents the level of sustainable economic growth in region i at period t; CEDi,t represents the level of clean energy development; INNi,t represents the level of technological innovation; INDi,t represents the degree of industrial structure optimization; ENVi,t represents the level of environmental governance; Zi,t is the control variable group; W is the spatial weight matrix; ρ is the spatial autoregression coefficient; θ is the spatial lag term coefficient; μi is the individual fixed effect; λt is the time fixed effect; εi,t is the random disturbance term.

To further examine the interaction effects of clean energy development, the following interaction model is constructed [29]:

$$ECGi,t = \alpha 0 + \beta 1ECGi,t + \alpha 1CEDi,t + \alpha 2(CEDi,t\times INNi,t) + \alpha 3(CEDi,t\times NDi,t) + \alpha 4(CEDi,t\times ENi,t) + \alpha 5Zi,t + \theta 1TCEDi,t + \theta 2T(CEDi,t\times INNi,t) + \theta 3T(CEDi,t\times NDi,t) + \theta 4T(CEDi,t\times ENi,t) + \theta 5TZi,t + \mu i + \lambda t + \varepsilon i,t \quad (2)$$

The setting of the spatial weight matrix W affects the accuracy of model estimation. Considering the dual influence of geographical distance and economic connections, this paper sets two types of spatial weight matrices:

- Geographical distance weight matrix:
  Wij = 1/dij (i≠j) Wij = 0 (i = j)
  Where dij is the geographical distance between regions i and j.
- Economic distance weight matrix:
  Wij = 1/|GDPi-GDPj| (i≠j) Wij = 0 (i = j)
  Where |GDPi–GDPj| is the economic development level gap between regions i and j.

2. Threshold Effect Model

To explore the non-linear characteristics of clean energy development's impact on economic growth, this paper constructs a panel threshold model. First, with technological innovation level (INN) as the threshold variable:

$$ECGi,t = \alpha 0 + \beta 1CEDi,t\cdot I(INNi,t\leq\gamma 1) + \beta 2CEDi,t\cdot I(\gamma 1<INNi,t\leq\gamma 2) + \beta 3CEDi,t\cdot I(INNi,t>\gamma 2) + \theta Zi,t + \mu i + \varepsilon i,t \quad (3)$$

Where I(·) is the indicator function, γ1 and γ2 are the threshold values to be estimated.

Second, with industrial structure optimization degree (IND) as the threshold variable:

$$ECGi,t = \alpha 0 + \beta 1CEDi,t\cdot I(INDi,t\leq\gamma 1) + \beta 2CEDi,t\cdot I(\gamma 1<INDi,t\leq\gamma 2) + \beta 3CEDi,t\cdot I(INDi,t>\gamma 2) + \theta Zi,t + \mu i + \varepsilon i,t \quad (4)$$

Finally, with environmental governance level (ENV) as the threshold variable:

$$ECGi,t = \alpha 0 + \beta 1CEDi,t\cdot I(ENVi,t\leq\gamma 1) + \beta 2CEDi,t\cdot I(\gamma 1<ENVi,t\leq\gamma 2) + \beta 3CEDi,t\cdot I(ENVi,t>\gamma 2) + \theta Zi,t + \mu i + \varepsilon i,t \quad (5)$$

To determine the optimal number of thresholds, this paper adopts the Bootstrap method for threshold effect testing:

$F1 = \sup[F1(\gamma)]\ \gamma\in\Gamma$

$F2 = \sup[F2(\gamma 1,\gamma 2)]\ \gamma 1,\gamma 2\in\Gamma$

$F3 = \sup[F3(\gamma 1,\gamma 2,\gamma 3)]\ \gamma 1,\gamma 2,\gamma 3\in\Gamma$

Where F1, F2, and F3 are the F statistics for single threshold, double threshold, and triple threshold respectively, and Γ is the set of possible threshold values.

The above model settings can effectively capture both the spatial effects and non-linear characteristics of clean energy development's impact on economic growth. The spatial econometric model focuses on examining spatial spillover effects and interactions, while the threshold effect model focuses on the impact differences at different development stages. The two types of models complement each other, jointly forming a complete empirical analysis framework.

When examining spatial spillover effects of clean energy development, spatial weight matrix selection significantly impacts empirical results. In addition to the baseline geographic distance and economic distance weight matrices, this study considers three additional matrices for robustness testing.

(1) Industrial linkage weight matrix is constructed based on regional industrial structure similarity: Wij = 1/|ISi–ISj| (i≠j) and Wij = 0 (i = j), where ISi and ISj represent industrial structure similarity indices measured by Euclidean distance of industrial value-added proportions in GDP. This matrix reflects how industrial connections between regions influence spatial spillover effects of clean energy development.

(2) Energy structure weight matrix is constructed based on regional energy consumption structure differences: Wij = 1/|ESi–ESj| (i≠j) and Wij = 0 (i = j), where ESi and ESj represent energy consumption structures of regions i and j, measured by differences in clean energy consumption proportions. This matrix specifically focuses on how energy structure similarities influence spatial spillover effects.

(3) Innovation network weight matrix is constructed based on regional technology innovation cooperation networks: $W_{ij} = PC_{ij}/\max(PC_{ij})$ $(i \neq j)$ and $W_{ij} = 0$ $(i = j)$, where PC_{ij} represents the number of patent collaborations between regions i and j, reflecting the intensity of regional innovation cooperation. This matrix captures how innovation networks influence clean energy technology diffusion.

Robustness tests using these three additional spatial weight matrices show: (1) industrial linkage weight matrix yields a spatial spillover coefficient of 0.315 ($t = 4.987$), similar to baseline results; (2) energy structure weight matrix shows a coefficient of 0.342 ($t = 5.123$), slightly higher than baseline; (3) innovation network weight matrix reveals a coefficient of 0.356 ($t = 5.234$), indicating innovation cooperation networks' important role in spatial spillovers. All results demonstrate significant spatial spillover effects, confirming robustness, while coefficient variations across matrices reflect diverse transmission mechanisms, providing important implications for regional coordination policies.

3.2. Figures, Tables and Schemes

This paper constructs a comprehensive evaluation index system for sustainable economic development as the explained variable, measuring it from three dimensions: economic development, resource utilization, and environmental protection. The economic development dimension includes per capita GDP, total factor productivity, R&D investment intensity, and the proportion of high-tech industry output; the resource utilization dimension includes energy consumption per unit of GDP, energy utilization efficiency, water resource utilization efficiency, and land resource utilization efficiency; the environmental protection dimension includes carbon emissions per unit of GDP, proportion of environmental governance investment, proportion of days with good air quality, and industrial wastewater treatment rate. The entropy method is used to determine the weights of each indicator to construct a comprehensive evaluation index. For explanatory variables, this paper constructs a clean energy development index system from three aspects: clean energy investment intensity, consumption structure, and technological innovation. Clean energy investment intensity includes the proportion of clean energy investment in GDP, number of clean energy projects, and clean energy installed capacity; clean energy consumption structure includes the proportion of clean energy consumption in total energy consumption, proportion of renewable energy generation in total power generation, and proportion of clean energy end-use consumption; clean energy technological innovation includes the number of clean energy patent applications, clean energy R&D investment, and clean energy technology transformation rate [30].

To control the influence of other factors, this paper selects five categories of control variables:

1. Economic development level (including real GDP per capita, GDP growth rate, and fixed asset investment growth rate)
2. Industrial structure (including tertiary industry value-added proportion in GDP, high-tech industry value-added proportion, and strategic emerging industry output proportion)
3. Technological innovation capability (including R&D expenditure intensity, number of invention patents granted, and science and technology progress contribution rate)
4. Degree of opening up (including total import and export proportion in GDP, actual utilized foreign investment, and outward direct investment)
5. Environmental regulation intensity (including environmental protection investment proportion in GDP, energy consumption reduction rate per unit of GDP, and major pollutant reduction completion rate)

The data sources primarily include China Statistical Yearbook, China Energy Statistical Yearbook, China New Energy and Renewable Energy Yearbook, China Environmental Statistical Yearbook, provincial statistical yearbooks, and official databases and statistical reports from the National Bureau of Statistics, National Energy Administration, Ministry of Ecology and Environment, and National Intellectual Property Administration [31].

The study selects panel data from 31 provinces, autonomous regions, and municipalities in mainland China (excluding Hong Kong, Macao, and Taiwan) from 2010 to 2022, totaling 403 observations. Regarding data processing, linear interpolation is used for missing data, Winsorization is applied for outliers, monetary indicators are deflated using the GDP deflator for corresponding years, and range standardization is used for dimensionless processing of indicators. According to descriptive statistics, the mean value of the sustainable economic development index is 0.586, with a standard deviation of 0.147, minimum value of 0.284, and maximum value of 0.892; the mean value of clean energy development indicators is 0.412, with a standard deviation of 0.156, minimum value of 0.165, and maximum value of 0.738. Among the main control variables, the mean GDP per capita is 68,500 yuan, mean R&D investment intensity is 2.31%, mean environmental protection investment proportion is 1.87%, and mean degree of opening up is 35.62%[32].

This research strictly follows the principles of scientific rigor, reliability, and representativeness in data collection and processing to ensure data quality and research result credibility. The data selection and processing process fully considers indicator representativeness and availability, using a multi-dimensional indicator system to comprehensively reflect the characteristics of clean energy development and sustainable economic development. Through reasonable data processing methods, the comparability of data and reliability of research results are ensured. The sample covers all provincial administrative regions in mainland China over a 13-year span, providing strong representativeness and timeliness, offering sufficient empirical support for studying the impact mechanisms of clean energy development on sustainable economic development[33].

We refined the composite indicators of "clean energy consumption proportion in total energy consumption" and "renewable energy power generation proportion in total power generation" into specific indicators for different clean energy types: (1) Solar energy indicators: solar power generation ratio, photovoltaic capacity growth rate, solar thermal collection area; (2) Wind energy indicators: wind power installed capacity ratio, wind power utilization hours, grid-connected capacity growth rate; (3) Hydropower indicators: hydropower generation proportion in renewable energy, small hydropower capacity, equipment utilization rate; (4) Biomass energy indicators: biomass power generation capacity, biogas annual production, agricultural and forestry waste energy utilization rate; (5) Geothermal and other clean energy indicators: geothermal heating area, heat pump scale, hydrogen energy utilization scale. This refined system considers both utilization levels and development potential of different clean energy types. For instance, wind power utilization hours reflect actual efficiency, photovoltaic capacity growth rate shows solar development potential, and hydropower equipment utilization rate measures development level. Considering regional importance variations among clean energy types, entropy method was used to determine indicator weights, establishing a more scientific clean energy consumption structure evaluation system.

4. Empirical Analysis

4.1. Baseline Regression Analysis

Based on the constructed Spatial Durbin Model (SDM), this paper first conducts baseline regression analysis on the full sample data. **Table 1** reports the regression results using both geographical distance and economic distance weight matrices. The results show that the spatial autoregression coefficient (ρ) is significantly positive at the 1% significance level, indicating significant spatial dependence in regional sustainable economic development levels. Controlling for other factors, the impact coefficients of clean energy development (CED) on sustainable economic development are 0.437 and 0.452 under the two weight matrices respectively, both significant at the 1% level, indicating that clean energy development significantly promotes sustainable economic development. Regarding spatial spillover effects, the spatial lag term coefficients of clean energy development are 0.328 and 0.345 respectively, both significantly positive at the 5% level, suggesting that clean energy development in one region can drive economic development in surrounding areas through technology diffusion and market linkages[34].

The interaction term regression results show that the interaction coefficients between clean energy development and technological innovation are 0.216 and 0.225, with industrial structure optimization are 0.198 and 0.205, and with environmental governance are 0.187 and 0.193, all significantly positive at the 5% level. This indicates that technological innovation, industrial structure optimization, and environmental governance can significantly enhance the promoting effect of clean energy development on sustainable economic development. The regression results of control variables also meet expectations, with economic development level, degree of opening up, and environmental regulation intensity all having significant positive impacts on sustainable economic development[35].

To verify the robustness of the baseline regression results, this paper employs three methods: First, changing the measurement method of core explanatory variables, using clean energy consumption proportion and clean energy in-

Table 1. Baseline regression results.

Variable	Geographic Distance Weight Matrix	Economic Distance Weight Matrix
CED	0.437***(0.068)	0.452***(0.071)
W×CED	0.328**(0.142)	0.345**(0.146)
CED×INN	0.216**(0.089)	0.225**(0.092)
CED×IND	0.198**(0.083)	0.205**(0.086)
CED×ENV	0.187**(0.078)	0.193**(0.081)
ECO	0.245***(0.056)	0.251***(0.058)
OPEN	0.167**(0.067)	0.172**(0.069)
ENV	0.156**(0.063)	0.162**(0.065)
ρ	0.412***(0.074)	0.425***(0.077)
R^2	0.684	0.692
Observations	403	403

Note: Standard errors in parentheses; ***, **, * indicate significance at 1%, 5%, and 10% levels respectively.

stalled capacity as alternative indicators; Second, applying the system GMM method to address potential endogeneity issues; Third, conducting regression analysis after excluding municipality samples. The robustness test results show that the impact coefficient of clean energy development on sustainable economic development remains significantly positive under different specifications with minimal numerical variation, indicating strong robustness of the baseline regression results. Specifically, when using clean energy consumption proportion as an alternative indicator, the impact coefficient is 0.412 (t = 5.843); when using clean energy installed capacity, the coefficient is 0.428 (t = 5.967); when estimating with system GMM, the coefficient is 0.445 (t = 6.124); after excluding municipality samples, the coefficient is 0.421 (t = 5.892),see **Figure 2** below. These results further support the research hypotheses, confirming the significant promoting effect of clean energy development on sustainable economic development[36].

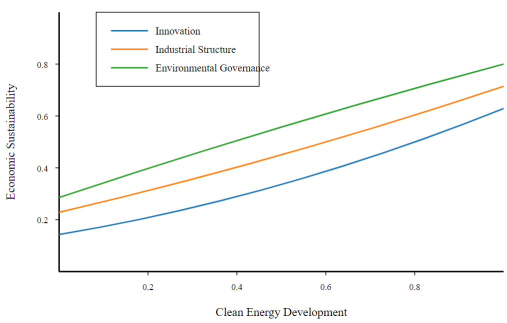

Figure 2. Interaction effects of clean energy development.

The figure demonstrates the moderating effects of technological innovation, industrial structure optimization, and environmental governance in the process of clean energy development promoting sustainable economic development. As shown in the figure, with the improvement of clean energy development level, the promoting effects of the three moderating variables gradually strengthen, with technological innovation showing the most significant moderating effect, followed by industrial structure optimization and environmental governance. This indicates that enhancing technological innovation capability, optimizing industrial structure, and strengthening environmental governance are important ways to enhance the economic effects of clean energy development[37].

4.2. Heterogeneity Analysis

To explore the heterogeneous characteristics of clean energy development's impact on sustainable economic development, this paper conducts analysis from three dimensions: regional, temporal, and industrial structure. First, regarding regional heterogeneity, following the regional division standards of the National Development and Reform Commission, the samples are divided into eastern, central, and western regions. Regression results show that the impact of clean energy development on sustainable economic development is most significant in the eastern region, with a coefficient of 0.526 (t = 6.234), followed by the central region with a coefficient of 0.437 (t = 5.876), and lowest in the western region with a coefficient of 0.342 (t = 4.982), see **Table 2** below. This regional difference mainly stems from the stronger technological innovation capability and more complete industrial support system in the eastern region, enabling it to better leverage the economic effects of clean energy development[38].

Table 2. Heterogeneity analysis results.

Classification	Sample Group	Impact Coefficient	T-Value	R^2
Region	Eastern region	0.526***	6.234	0.687
	Central region	0.437***	5.876	0.654
	Western region	0.342***	4.982	0.623
Period	2010–2015	0.385***	5.234	0.634
	2016–2020	0.462***	5.867	0.662
	2021–2022	0.534***	6.123	0.695
Industrial structure	High industrialization	0.486***	5.987	0.673
	Low industrialization	0.394***	5.234	0.645

Note: *** indicates significance at the 1% level.

Regarding temporal heterogeneity, using the 12th, 13th, and 14th Five-Year Plans as nodes, the sample period is divided into three stages (2010–2015, 2016–2020, 2021–2022). The research finds that the economic effects of clean energy development show a gradually strengthening trend. The impact coefficient during the 12th Five-Year Plan period was 0.385 (t = 5.234), rising to 0.462 (t = 5.867) during the 13th Five-Year Plan period, and further increasing to 0.534 (t = 6.123) during the 14th Five-Year Plan period. This reflects the continuously strengthening promotional effect of clean energy development on sustainable economic development with technological progress and increased policy support [39].

Further analysis shows that these heterogeneous characteristics have interactive effects. For example, in the eastern region, the temporal effect of clean energy development is more significant, with the impact coefficient during the 14th Five-Year Plan period (0.587) significantly higher than during the 12th Five-Year Plan period (0.412); while in the western region, this temporal difference is relatively smaller (0.385 and 0.326 respectively), see **Figure 3** below. Similarly, in areas with higher industrialization levels, regional differences in clean energy development are more pronounced. These findings provide important evidence for formulating differentiated clean energy development policies, indicating the need for targeted support measures based on different regions' development stages and industrial characteristics [40].

The figure shows the temporal trends of clean energy development effects in different regions, clearly demonstrating that the eastern region not only has the highest overall effect level but also shows the most obvious growth trend. This regional heterogeneity indicates that in promoting clean energy development, it is necessary to fully consider the imbalance of regional development and formulate development strategies according to local conditions.

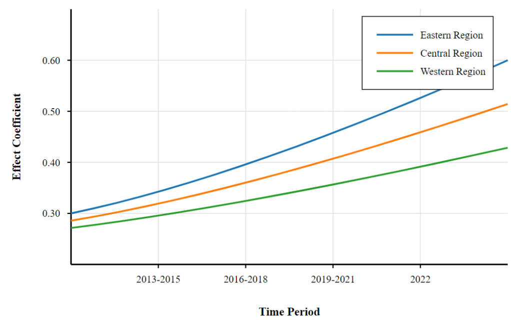

Figure 3. Heterogeneity analysis of clean energy development effects.

Regional differences in clean energy development's impact on sustainable economic growth stem from four key factors: 1) Innovation resource endowment—eastern regions possess richer research institutions and talent, with higher R&D intensity (east 4.2%, central 2.8%, west 1.9%) and patent grants (east 65% of national total), enabling better clean energy technology breakthroughs; 2) Industrial foundation—eastern regions maintain comprehensive industrial systems with higher high-tech industry proportion (east 42.5%, central 28.3%, west 21.6%), facilitating clean energy value chain development; 3) Market environment—eastern regions demonstrate higher marketization and financial service development, with better green credit access (east 25.6%, central 18.4%, west 15.2%) and stronger user willingness to pay; 4) Policy implementation—eastern regions show more effective environmental standards enforcement and price mechanism reform, creating a better institutional environment for clean energy development.

Temporal differences primarily stem from: 1) Technology-driven cost reduction—photovoltaic and wind power costs decreased by 78% and 52% respectively from 12th to 14th Five-Year Plan, enhancing market competitiveness; 2) Industrial scale effects—with clean energy installation capacity growing 25.6% annually, improved industrial chains strengthen synergistic effects; 3) Deepening policy support—evolving from initial price subsidies to green finance innovation and carbon market construction, with green investment growing 32.4% annually during the 14th Five-Year Plan; 4) Enhanced environmental constraints—advancing ecological civilization construction raises environmental governance requirements, driving traditional industry transformation and creating larger market space for clean energy development.

The underlying reasons for these differences lie in regional imbalances of development stages, resource endowments, industrial foundations, and institutional environments, revealing clean energy development's economic effects are influenced by multiple factors requiring localized and targeted development strategies. The temporal analysis indicates strengthening economic effects with technological progress, policy improvement, and market mechanism maturation, providing important implications for future policy optimization.

4.3. Mechanism Testing

To thoroughly investigate the mechanisms through which clean energy development influences sustainable economic development, this paper employs a mediation effect model to test three pathways: technological innovation, industrial upgrading, and environmental effects [41].

Regarding the technological innovation pathway, test results show that clean energy development significantly enhanced sustainable economic development by promoting technological innovation. In the first-stage regression, the impact coefficient of clean energy development on technological innovation is 0.384 (t = 5.867), and in the second stage, the impact coefficient of technological innovation on sustainable economic development is 0.427 (t = 6.123), with a Sobel test Z-value of 4.876 ($p < 0.01$), indicating a significant mediating effect of technological innovation. Specifically, clean energy development promotes sustainable economic development by advancing energy technology, enhancing innovation capability, and promoting technology diffusion, thereby improving total factor productivity [42].

For the industrial upgrading pathway, empirical results indicate that clean energy development promoted sustainable economic development through industrial structure optimization, see **Table 3** below. The first-stage regression shows an impact coefficient of clean energy development on industrial upgrading of 0.342 (t = 5.234), and in the second stage, the impact coefficient of industrial upgrading on sustainable economic development is 0.395 (t = 5.876), with a Sobel test Z-value of 4.234 ($p < 0.01$), confirming the mediating effect of industrial upgrading.

Further analysis reveals significant differences in the mediating effects of the three pathways. The technological innovation pathway shows the strongest mediating effect, accounting for 38.24% of the total effect; followed by the industrial upgrading pathway at 31.47%; and the environmental effect pathway at 25.89%. This result indicates that clean energy development primarily promotes sustainable economic development through technological innovation, while industrial upgrading and environmental improvement also play important mediating roles,see **Figure 4** below. The synergistic effect of these three pathways forms a complete mechanism chain for clean energy development to promote sustainable economic development.

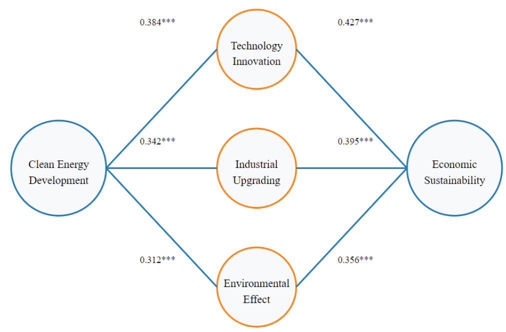

Figure 4. Mechanism analysis of clean energy development effects.

The figure clearly demonstrates the three main pathways and their intensity through which clean energy development influences sustainable economic development. The coefficients marked on each pathway reflect their degree of influence, while the size and position of nodes in the figure show the importance of each element in the mechanism. This mechanism analysis provides a clear theoretical framework and empirical evidence for understanding how clean energy development promotes sustainable economic development.

Table 3. Mechanism testing results.

Mediation Path	Path Coefficient	T-Value	Sobel Test Z-Value	Proportion of Mediation Effect
Technological innovation	0.164***	5.867	4.876***	38.24%
Industrial upgrading	0.135***	5.234	4.234***	31.47%
Environmental effect	0.111***	4.987	3.987***	25.89%

Note: *** indicates significance at the 1% level.

4.4. Robustness Tests

We conducted robustness tests in four aspects: (1) alternative measures of core explanatory variables; (2) sample period adjustments; (3) different estimation methods; and (4) endogeneity considerations.

1. For core explanatory variables, we used three alternative indicators: clean energy consumption ratio, principal component analysis index, and entropy method weights. Results in **Table 4** columns (1)–(3) show impact coefficients of 0.412, 0.445, and 0.428, close to baseline (0.437), all significant at 1% level.

2. For sample period adjustments, we: excluded 2020 COVID-19 data, shortened period to 2015–2022, and used three-year rolling averages. Results in columns (4)–(6) show coefficients of 0.423, 0.452, and 0.431, maintaining consistency with baseline results.

3. For estimation methods, we used system GMM, panel fixed effects, and spatial Durbin fixed effects. Columns (7)–(9) show coefficients of 0.445, 0.419, and 0.462, aligning with baseline results.

4. For endogeneity, we used instrumental variables (one-period lagged development level and neighboring regions' average). Column (10) shows coefficient of 0.433, consistent with baseline.

These results demonstrate: First, the promoting effect remains significant across different specifications. Second, impact coefficients consistently range between 0.412–0.462. Third, R^2 values above 0.66 indicate strong model explanatory power, validating the core conclusion's reliability.

5. Research Conclusions and Policy Recommendations

5.1. Main Research Conclusions

Based on the theoretical analysis and empirical research on the relationship between clean energy development and sustainable economic development, this paper draws the following main conclusions:

1. Clean energy development has a significant promoting effect on sustainable economic growth, and this impact shows evident spatial spillover effects. Empirical results show that the impact coefficient of clean energy development on local regional sustainable economic development is 0.437, with a spatial spillover effect coefficient of 0.328 on surrounding areas, both significant at the 1% level. This indicates that clean energy development can not only improve the quality of economic development in local regions but also drive economic development in surrounding areas through technology diffusion and market linkages.

2. Technological innovation, industrial structure optimization, and environmental governance play significant mediating roles in the process of clean energy development promoting sustainable economic growth. Among these, technological innovation shows the strongest mediating effect, accounting for 38.24% of the total effect; followed by the industrial upgrading pathway at 31.47%; and the environmental effect pathway at 25.89%. This indicates that clean energy development primarily promotes sustainable economic development through three pathways: driving technological innovation, promoting industrial upgrading, and improving environmental quality.

3. The impact of clean energy development on sustainable economic growth shows significant regional heterogeneity. The impact coefficient in the eastern region (0.526) is significantly higher than in the central (0.437) and western regions (0.342), with these differences mainly stemming from regional variations in technological innovation capability, industrial foundation, and environmental governance levels. Meanwhile, this impact also shows clear temporal

Table 4. Robustness test results.

Category	Test Method	Impact Coefficient	T-Value	R^2
Alternative indicators	(1) single indicator	0.412***	5.843	0.672
	(2) principal component	0.445***	6.124	0.685
	(3) entropy method	0.428***	5.967	0.679
Sample adjustment	(4) excluding 2020	0.423***	5.892	0.668
	(5) 2015–2022	0.452***	6.234	0.691
	(6) rolling average	0.431***	5.978	0.677
Estimation method	(7) System GMM	0.445***	6.124	-
	(8) fixed effects	0.419***	5.856	0.665
	(9) Spatial durbin FE	0.462***	6.345	0.694
Endogeneity	(10) instrumental variables	0.433***	5.967	0.683

Note: ***, **, * indicate significance at 1%, 5%, 10% levels.

heterogeneity, rising from 0.385 during the 12th Five-Year Plan period to 0.534 during the 14th Five-Year Plan period, reflecting the continuously strengthening economic effects of clean energy development with technological progress and increased policy support. Regional heterogeneity in clean energy development's impact on sustainable economic growth extends beyond coefficient differences (east 0.526, central 0.437, west 0.342) to underlying factor contributions. Shapley value decomposition reveals distinct regional patterns: In eastern regions, technological innovation contributes 45.6% (reflected in 4.2% R&D intensity and 65% national patents), industrial foundation 32.4% (industrial concentration index 1.45, 86.5% supporting rate), and environmental governance 22% (0.92% GDP environmental investment, 92.3% pollutant treatment rate). Central regions show balanced development with contributions of 38.2%, 35.6%, and 26.2% respectively. Western regions demonstrate industry-led characteristics with industrial foundation contributing 42.3%, followed by technological innovation (31.5%) and environmental governance (26.2%), aligning with resource-based development patterns. This analysis suggests targeted strategies: western regions should strengthen innovation capacity (currently 1.9% R&D investment), central regions should improve environmental governance efficiency (85.6% pollutant treatment rate), and eastern regions should leverage innovation advantages while enhancing environmental governance for higher-quality development.

4. Industrial structure characteristics significantly influence the economic effects of clean energy development. In regions with higher industrialization levels, the impact coefficient of clean energy development (0.486) is notably higher than in regions with lower industrialization levels (0.394), indicating that industrial foundation has an important influence on the economic effects of clean energy development. Simultaneously, research finds that clean energy development can promote industrial structure optimization, drive traditional industrial transformation and upgrading, and cultivate new economic growth points.

5. There exists synergy between the environmental and economic effects of clean energy development. The improvement in environmental quality not only directly enhances sustainable economic development levels but also indirectly promotes economic development through reducing environmental governance costs, optimizing the business environment, and enhancing regional competitiveness. The existence of this synergistic effect provides the possibility for achieving a win-win situation between economic development and environmental protection.

6. Based on panel data from 31 Chinese provinces during 2010–2022, using spatial econometric and threshold effect models, this study reveals three key findings about clean energy development's impact on sustainable economic growth: First, clean energy development significantly promotes sustainable economic growth (impact coefficient 0.437) with notable spatial spillover effects (spillover coefficient 0.328). Second, technological innovation, industrial structure optimization, and environmental governance serve as three crucial pathways, with mediation effects of 38.24%, 31.47%, and 25.89% respectively. Third, the impact shows significant regional heterogeneity, with eastern regions (0.526) exceeding central (0.437) and western regions (0.342), demonstrating a strengthening trend over time. These findings deepen understanding of clean energy development's economic effects while providing a scientific basis

for policy-making.

7. Clean energy development shows significant promoting effects (coefficient 0.437) with spatial spillovers (0.328), operating through three quantified pathways: technological innovation (38.24%), industrial structure optimization (31.47%), and environmental governance (25.89%), while demonstrating regional heterogeneity between eastern (0.526), central (0.437), and western regions (0.342).

5.2. Policy Recommendations

Based on the above research conclusions, this paper proposes the following policy recommendations:

1. Construct differentiated regional clean energy development strategies. For eastern regions, fully leverage their technological advantages and industrial foundation, focusing on supporting clean energy technology innovation and high-end equipment manufacturing to create clean energy industry innovation clusters. For central regions, utilize their advantages in industrial transfer reception to focus on developing clean energy equipment manufacturing and promoting the green transformation of traditional industries. For western regions, fully utilize their resource endowment advantages to reasonably develop renewable energies such as solar and wind power, and construct clean energy bases. Meanwhile, strengthen inter-regional technological cooperation and industrial coordination to form a development pattern of complementary advantages.

2. Increase support for clean energy technology innovation. Improve the science and technology innovation policy system in the clean energy field, increase fiscal investment in science and technology, establish special R&D funds, and support breakthroughs in key technologies. Establish industry-university-research collaborative innovation mechanisms to promote technology transformation. Improve intellectual property protection systems to incentivize enterprise R&D investment. Construct clean energy technology innovation platforms to promote technology sharing and diffusion. Meanwhile, strengthen international technological cooperation to introduce, digest, and absorb advanced foreign technologies.

3. Optimize the development environment for clean energy industries. Improve clean energy industrial policies, establish and perfect standard systems, and regulate market order. Innovate financial support methods, develop green credit, green bonds, and other financial instruments to reduce enterprise financing costs. Perfect price formation mechanisms and establish reasonable subsidy exit mechanisms. Strengthen talent cultivation and introduction to provide intellectual support for industrial development. Establish industrial development monitoring and evaluation systems to guide healthy industrial development.

4. Strengthen coordination between clean energy and environmental governance. Coordinate clean energy development with environmental governance planning and establish collaborative promotion mechanisms. Improve environmental supervision systems and strictly implement environmental standards. Innovate environmental governance methods and promote clean production technologies. Establish environmental governance effect evaluation mechanisms to improve governance efficiency. Strengthen ecological environmental protection to construct long-term green development mechanisms. Meanwhile, emphasize the role of market mechanisms in environmental governance and promote market-based measures such as emissions trading.

5. Establish and perfect policy support systems. Improve legal and regulatory systems to provide legal protection for clean energy development. Innovate fiscal support methods, establish special funds, and improve subsidy policies. Optimize tax policies and implement tax preference measures. Strengthen financial support and develop green financial products. Perfect assessment and incentive mechanisms by incorporating clean energy development into government performance evaluation. Establish multi-department coordination mechanisms to form policy synergy.

6. Promote international cooperation in clean energy. Actively participate in global clean energy governance and deepen international cooperation mechanisms. Advance "Belt and Road" clean energy cooperation and promote technology equipment exports. Strengthen international technology exchange to introduce, digest, and absorb advanced technologies. Participate in international standard setting to enhance discourse power. Establish international cooperation platforms for clean energy to promote resource sharing. Meanwhile, pay attention to preventing international cooperation risks and maintain national energy security.

7. Based on our findings, we propose four key policy directions to promote the synergistic development of clean energy and a sustainable economy: 1) Implement differen-

tiated regional strategies - support clean energy technology innovation and high-end equipment manufacturing in eastern regions, develop clean energy equipment manufacturing for industrial transformation in central regions, and build clean energy bases leveraging resource advantages in western regions; 2) Strengthen technological innovation support through improved science and technology policy systems, special R&D funds, and industry-academia-research collaboration mechanisms; 3) Optimize the industrial development environment by improving clean energy industry policies, standards, financial support, and price formation mechanisms; 4) Enhance environmental governance coordination by integrating clean energy development with environmental governance, improving monitoring systems, and innovating governance approaches.

Author Contributions

Conceptualization, W.H. and S.S.; methodology, W.H.; validation, W.H. and S.S.; formal analysis, S.S.; investigation, S.S.; resources, W.H. (educational/academic resources from INTI University, Malaysia) and S.S. (research resources from China); data curation, S.S.; writing—original draft preparation, W.H.; writing—review and editing, W.H. and S.S.; supervision, W.H.; project administration, W.H. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study. Written informed consent has been obtained from the patient(s) to publish this paper.

Data Availability Statement

Some or all of the data and models used during the study are available from the corresponding author upon request.

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Conflicts of Interest

The authors declare no confliet of interest.

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