

Drivers of Green Economic Growth in China: The Roles of Renewable Energy, Renewable Energy Technology Innovation, and Green Finance under Government Intervention

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ABSTRACT:

Green economic growth, which balances economic development with environmental sustainability, is fundamental to achieving sustainable development goals. This study investigates the distinct roles of renewable energy, renewable energy technology innovation (RETI), green finance, and government intervention in promoting green economic growth across 30 Chinese provinces from 2010 to 2022. To address cross-sectional dependence and enhance robustness, the analysis employs the Driscoll-Kraay estimator, Panel-Corrected Standard Errors (PCSEs), and the Method of Panel quantile regression (PQR). Results indicate that renewable energy, RETI, and green finance significantly promote green economic growth. In contrast, government intervention exhibits a U-shaped relationship with green economic growth. Furthermore, government intervention positively moderates the effects of renewable energy and RETI, but its moderating effect on green finance is weak and statistically insignificant. This study therefore recommends optimizing government functions by strengthening coordination in renewable energy development and technological innovation, while reducing excessive intervention in green finance to promote sustainable development.

Keywords: Green economic growth; Renewable energy; Renewable energy technology innovation; Green finance; Government intervention

1. Introduction

Since the launch of the reform and opening-up, China has undergone rapid economic development. However, as China's industrialization continues to advance, an expanded growth model has led to low productivity, resource depletion, and environmental degradation, which undermine public well-being and impede the country's sustainable development (Lee et al., 2024). To address the escalating challenges of resource scarcity and environmental issues, China officially introduced the concept of “green development” in 2015 and subsequently launched a range of policies and initiatives to build an economic system oriented toward sustainable growth. This aligns with the United Nations Sustainable Development Goals (SDGs), particularly SDG 8.1, which emphasize “sustained, inclusive, and sustainable economic growth.” Guided by China's “dual carbon” goals, green economic growth (GEG) acts as the primary driver of the comprehensive green transition. Therefore, analyzing key drivers and synergistic mechanisms of green growth to achieve sustainable development can provide valuable insights and serve as an effective reference for other developing countries striving for an economic green transformation.

Energy production and consumption are fundamental to economic growth, yet fossil fuels (coal, oil, and natural gas) still supply 66% of global primary energy (IEA, 2022), driving climate change and biodiversity loss. China exhibits an even higher dependence on fossil fuels, which account for 78.8% of primary energy production and 82.1% of consumption, while renewable energy (REN) represents only 21.2% and 17.9%, respectively (see Figure 1). This heavy reliance highlights the urgent need to accelerate the transition toward renewable energy. China's heavy reliance on fossil fuels underscores the imperative for an urgent transition to

renewable energy sources. REN utilization plays a dual role in curbing CO₂ emissions from energy-intensive sectors and replacing non-renewable resources. Extant literature indicates that renewable energy—particularly hydropower, wind, and solar—plays a crucial role in enhancing GEG by reducing reliance on fossil fuels and reducing carbon emissions (Lee et al., 2024; Paraschiv and Paraschiv, 2023). This supports SDG 7, which emphasizes access to sustainable and modern energy.

Nevertheless, the deployment of renewable energy is constrained by significant financial and technological barriers (Saadaoui and Chtourou, 2023), which pose substantial challenges to the development of a green economy. Against this backdrop, RETI is indispensable for expanding renewable energy utilization and achieving sustainable development, primarily through its role in reducing carbon emissions. This corresponds to SDG 9 by fostering innovation, sustainable industrial development, and resilient infrastructure, and contributes to SDG 13 through climate change mitigation. RETI serves as a catalyst for energy system decarbonization, effectively curbing the environmental externalities of fossil fuel based energy production (Zhao et al., 2022). Moreover, by reducing the cost disparity between renewable and fossil-fuel energy and improving renewable energy efficiency, RETI strengthens market demand for clean energy and delivers cleaner energy to the economy (Zheng et al., 2021). Similarly, green finance (GF) is essential for mobilizing financial resources toward sustainable projects. Traditional financing mechanisms often perceive green investments as high-risk, discouraging participation (H. Zhang et al., 2022). Traditional financing channels often perceive green enterprises as high-risk investments, which discourages investor participation. On the positive side, investing in green projects promotes employment, increases social welfare,

facilitates the transition toward green technology-oriented economic structures, and reduces mortality from air pollution. Consequently, renewable energy development

enhances overall economic conditions and supports sustainable development and green economic growth (Xu et al., 2023).

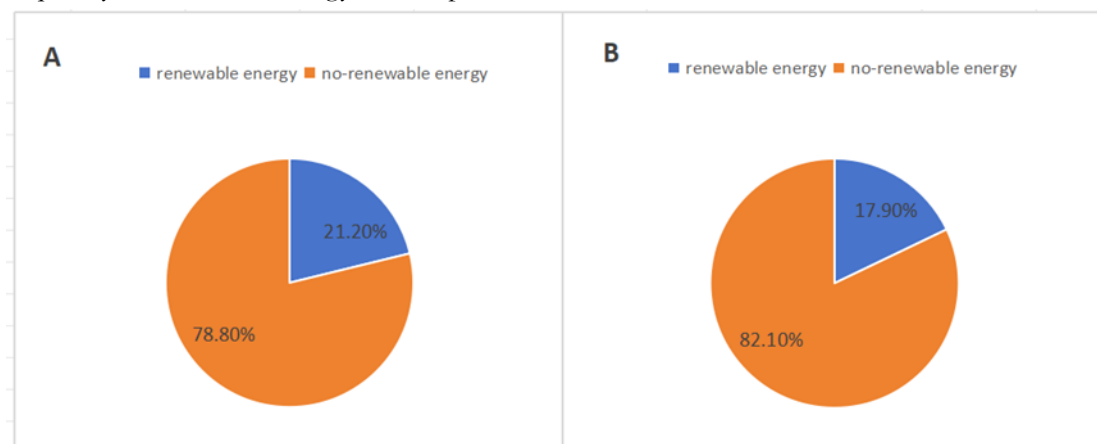


Fig. 1. Share of primary energy production (A) and consumption (B) in China.

Source: <https://www.stats.gov.cn/sj/ndsj/2024/indexch.htm>.

The government, as a key stakeholder in economic development and the primary authority responsible for policy formulation, plays a crucial role in promoting green economic growth (Guo et al., 2023). A successful transition toward a green economy requires directing both public and private financial resources toward sustainable development. Therefore, government intervention (GOV), through targeted expenditures, policy reforms, and regulatory frameworks, is essential. For instance, governments can promote green development by strengthening environmental regulations and directing investments toward renewable energy and green innovation (Akhtaruzzaman et al., 2025). Additionally, fiscal instruments such as tax incentives for clean technologies and penalties for high emissions create strong market signals for sustainable transformation (Sarpong et al., 2023). Thus, achieving sustainable economic growth is unlikely without active government support (Uzar, 2020).

Although a growing body of literature has examined the relationships among REN, RETI, GF, and economic growth, several important

gaps remain. First, existing studies largely focus on the individual effects of these variables, with limited attention to their integrated and interactive impacts on GEG. Second, few studies within the Chinese context have explored nonlinear relationships, particularly by incorporating squared terms of REN, RETI, and GOV to capture potential non-monotonic effects. Third, the moderating role of government intervention remains underexplored, especially regarding interaction effects such as $REN \times GOV$, $RETI \times GOV$, and $GF \times GOV$.

To address these gaps, this study investigates the interplay among REN, RETI, GF, GOV, and GEG across 30 Chinese provinces. Specifically, it aims to:

1. Assess the direct impact of REN, RETI, GF, and GOV on GEG.
2. Examine the nonlinear relationships between REN, RETI, GOV, and GEG.
3. Explore the moderating role of GOV in shaping these relationships.

This study makes three main contributions. First, few studies have examined the intrinsic

relationships and interactions among REN, RETI, GOV, GF, and green economic growth. This study integrates these factors into a unified analytical framework, exploring the nonlinear effects of REN, RETI, and GOV on GEG, and further investigates the moderating role of GOV in strengthening these relationships. Examining the interaction effects is essential because countries with lower levels of GOV often lack strong institutional support to implement effective policies for promoting green economic growth. In contrast, countries with higher GOV levels can better facilitate the transition toward renewable energy use by strengthening environmental regulations. Considering the moderating effects of GOV also helps capture the complexity of these interactions and provides deeper insights into how REN, RETI, and GF influence green economic growth under varying institutional conditions. Second, unlike previous studies that examined only a limited set of SDGs, this research adopts a broader perspective by integrating Goals 7, 8, 9, 12, and 13, providing a more comprehensive understanding of the interconnections within sustainable development.

Finally, to ensure reliable estimation, the analysis utilizes Driscoll–Kraay Standard Errors (DKSE) and Panel-Corrected Standard Errors (PCSE), which effectively correct for heteroskedasticity, autocorrelation, and cross-sectional dependence. Furthermore, robustness is evaluated using Panel Quantile Regression (PQR). Examining these dynamics enables policymakers to formulate more effective strategies that accelerate the transition toward sustainable economic development and provide a foundation for future research, given China's priority of achieving the Sustainable Development Goals (SDGs). The findings indicate that REN, RETI, and GF significantly promote green economic growth, whereas GOV has a direct negative effect but positively moderates the impacts of REN and RETI while weakening that of GF.

The remainder of the paper is organized as follows. Section 2 reviews literature, Section 3 presents the conceptual framework and hypotheses, Section 4 describes the data and methodology, Section 5 discusses the empirical results, and Section 6 concludes with policy implications.

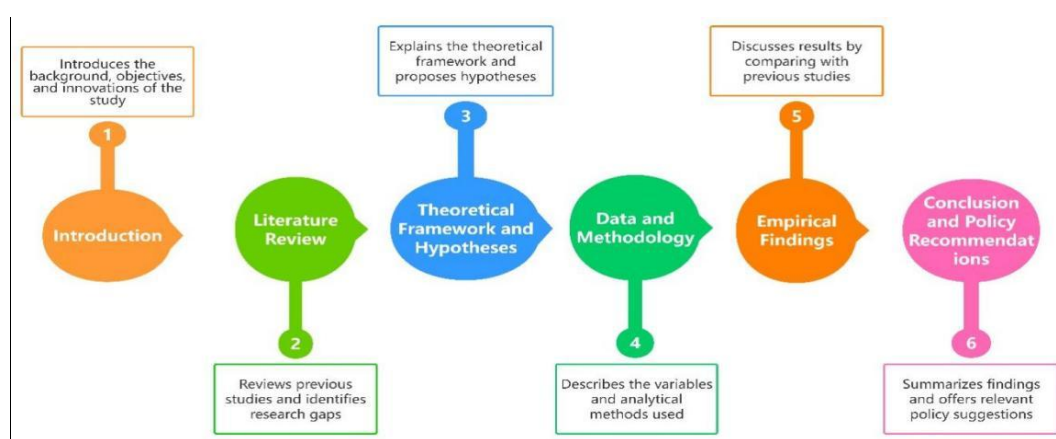


Fig. 2. Roadmap of the study.

2. Literature review

To mitigate carbon emission-related environmental damage and achieve sustainable development goals, it is essential to improve economic quality and promote GEG. Against

this background, this section reviews the existing literature by focusing on the roles of REN, RETI, GF, and GOV in driving GEG.

2.1 Renewable energy use, technology innovation and green economic growth

Renewable energy has attracted wide attention for its role in mitigating global warming and promoting sustainable economic development. Numerous studies have examined the correlation between renewable energy and green economic growth, offering practical for China's low-carbon development efforts. Using Data Envelopment Analysis (DEA), Mohsin et al. (2022) examined the impact of government R&D expenditure and renewable energy expansion on green economic growth in the ECOWAS region over the period 1990–2018. The results show that a 1% increase in renewable energy deployment improves sustainable performance by 3.2%. Similarly, Hwang and Díez (2024) examined the effect of renewable energy transition on green economic growth in fourteen Latin American countries over the period 2003–2020. Their findings indicate that the transition significantly enhances green economic growth, with the magnitude of the impact differing across countries depending on geography, fossil fuel dependence, and mineral resource reliance. The study further identifies capital investment, hydropower dependence, residential electricity consumption, human capital, and formal employment generation as the main transmission channels. However, Zhao et al. (2022), argue that uneven levels of renewable energy technological innovation across regions constrain sustained innovation, hinder renewable energy deployment and the low-carbon transition, and ultimately exert a negative impact on sustainable economic development.

Further evidence highlights the nonlinear relationship between renewable energy and economic growth. Using OECD panel data from 1997 to 2005, Wang et al. (2022) applied a panel threshold model and identified a single threshold effect between renewable energy consumption and economic growth, as well as a double-threshold effect when economic and financial risks were introduced as threshold

variables. Despite these findings, the authors emphasize that accelerating renewable energy adoption and achieving sustainable economic growth fundamentally depends on technological innovation. In this regard, Chen et al. (2023) highlight the critical role of green technology innovation in facilitating China's renewable energy transition. For example, innovations such as smart grid integration improve energy system optimization and enhance renewable energy generation efficiency (Godil et al., 2021; L. Zhang et al., 2022). Using the system generalized method of moments (SYS-GMM), J. Li et al. (2022) further demonstrate that both renewable energy development and technological innovation significantly promote green economic growth. Moreover, technological innovation strengthens the contribution of renewable energy, thereby accelerating economic expansion and advancing sustainability. At the regional level, Su and Fan (2022) using panel data from 30 Chinese provinces (2013–2019) and a spatial econometric model, find that renewable energy technological innovation significantly promotes green development. However, they also observe that when technological innovation interacts with industrial structure rationalization, the combined effect may weaken individual contributions, resulting in a “1+1<2” phenomenon. Additionally, the findings of Yan et al. (2020) reveal that renewable energy technology innovation contributes to green productivity only when a province's relative income exceeds a critical threshold; once surpassed, the positive effect not only emerges but continues to strengthen with rising income levels.

2.2 Green finance and green economic growth

GF originates from green economy theory and aims to address climate change, strengthen environmental protection, and promote sustainable socio-economic development (X. Li et al., 2022). A growing body of literature has examined the role of financial development in

fostering both economic growth and environmental sustainability. Using panel data covering the 25 leading green bond issuers worldwide from 2014 to 2021, Shah et al. (2025) employed an instrumental variable generalized method of moments (IV-GMM) approach combined with Driscoll–Kraay standard errors. Their findings indicate that a 1% expansion in the green bond market increases clean energy capacity by 0.350% and 0.029% under the IV-GMM and Driscoll–Kraay estimations, respectively. In addition, a 1% increase in green economic growth leads to improvements in clean energy capacity of 0.398% (IV-GMM) and 0.008% (Driscoll–Kraay). Similarly, Swaty (2023) employed a bootstrap rolling-window Granger causality approach to examine the bidirectional relationship between GF and sustainable development (SD) across global contexts. His findings reveal that GF positively influences SD during several subperiods, supporting interaction theory. However, the study finds no consistent evidence regarding the reverse causality from SD to GF. Furthermore, green finance directs funds toward industries with low energy consumption, fast technical innovation, low pollution, and high resource efficiency. Optimizing capital allocation and reducing financial assistance for polluting companies fosters economic transformation and sustainable development (Meo and Abd Karim, 2022). For instance, based on a negative binomial regression model, Bai and Lin (2023) examined China's industrial sector from 2008 to 2018 and revealed that green finance significantly enhances the efficiency of renewable energy technology research and development by directing and optimizing the financing and allocation of resources for green projects and innovation, thereby accelerating the energy structure transition.

2.3 Government intervention, renewable energy, technology innovation, green finance and green economic growth

A substantial body of literature has examined the determinants of green economic growth (Fang et al., 2022; Razzaq et al., 2023; Xu et al., 2025). However, the role of GOV in shaping GEG remains relatively underexplored. As a key institutional actor, the government can guide industries toward green transformation through policy instruments such as environmental taxation, subsidies, and regulatory frameworks (Aguilar and Vlosky, 2007). In particular, due to the presence of positive externalities, GTI relies heavily on governmental guidance and financial support. Environmental regulations can trigger an “innovation compensation effect,” encouraging GTI, or a “cost compliance effect,” which may suppress it (Tian et al., 2021). Hence, government intervention can lead to diverse outcomes for GTI. Likewise, Deng et al. (2024) examined the link among green finance, clean technology innovation (CTI), environmental tax, and green economic growth (GEG) in 28 developed countries from 1995 to 2019, applying two-stage least squares (2SLS) and System GMM. Their findings reveal that green finance significantly promotes green economic growth, with CTI acting as a mediator that explains 14.06% of the total effect. In addition, environmental tax demonstrates a significant threshold effect, amplifying the influence of green finance on CTI at higher tax levels. Furthermore, Zhao et al. (2021) analyzed provincial panel data from 1990 to 2021 to assess how local government intervention moderates the effect of feed-in tariffs and knowledge stocks on renewable energy innovation. The results underscore that both renewable energy policies and investments in R&D are key factors driving technological innovation.

From the perspective of energy transition, GEG requires a shift from fossil fuels to renewable

energy sources. Based on survey data, Smirnova et al. (2021) explore the determinants of government support for renewable energy in China, India, and Russia. The results show that expanding financing channels, reducing dependence on traditional energy sources, and promoting public–private partnerships are essential for renewable energy development. These findings suggest that renewable energy expansion is highly dependent on government support, thereby highlighting the indirect role of GOV in influencing GEG. Nonetheless, Wang and Zhang (2024) found that financial development significantly promotes green economic growth in China, with technological innovation and urbanization serving as mediating factors. However, government fiscal pressure weakens this positive effect.

2.4 Research gap

The body of literature on GEG and its determinants is extensive, the conclusions remain inconsistent and limited, leaving gaps in the existing research. Existing research often examines REN, RETI, GF, and GOV in isolation, failing to capture their synergies. An integrated model is therefore essential to evaluate their collective role in driving GEG. While research has explored the impact of these factors on GEG in different contexts, there remains a need for more clarity, especially in the context of China. Moreover, previous studies have primarily focused on GTI, with less attention paid to innovations in solar, wind, and other renewable energy technologies. These advancements can reduce installation and power generation costs while improving energy efficiency, playing a critical role in driving the energy transition. However, how RETI specifically contribute to sustained economic growth remain underexplored in current research. Additionally, unlike previous studies that have focused on corruption or political risk as key institutional variables, this study examines the role of GOV in

promoting sustainable economic growth, as it reflects the capacity of policy responses to internal and external economic fluctuations. Finally, earlier studies have largely overlooked the moderating role of GOV, despite its potential indirect impact on sustainable economic growth. The importance of non-linear relationships between variables has also been underestimated, even though such relationships are crucial for effective policymaking. Identifying the specific manifestation of nonlinearity can help researchers and policymakers develop more effective strategies for green development. Therefore, this study addresses this research gap and promotes further empirical exploration toward GEG.

3. Theoretical background and hypotheses development

For the achievement of environmental and economic sustainability, it is essential to transition toward cleaner and more sustainable energy sources. The Energy–Growth Nexus Theory **recognizes** energy as a fundamental input in the production process. In this context, renewable energy plays a crucial role in promoting economic growth by providing a stable, clean, and increasingly cost-effective energy supply (Dincer and Acar, 2015). Specifically, renewable energy contributes to sustainable economic development by diversifying the energy mix, reducing dependence on volatile fossil fuels, lowering environmental pollution, and enhancing energy security (Osuma and Yusuf, 2025). Based on this theoretical foundation, renewable energy is expected to positively influence GEG. Accordingly, **Hypothesis 1 is proposed as**

follows, i.e., $\frac{\beta_{GEG_{it}}}{\beta_{REN_{it}}} > 0$.

However, the transition to renewable, cleaner, and more affordable energy alternatives demands advanced technologies and significant initial capital investments, which pose major barriers to

GEG. To address these challenges, RETI and GF play a critical role in enhancing GEG (Iqbal et al., 2025). Ecological modernization theory posits that technological innovation enhances resource efficiency and facilitates the transition toward environmentally sustainable economic development (Qing et al., 2024; Sun et al., 2021). In particular, RETI supports the development of green products and energy-saving technologies, thereby improving the efficiency of renewable energy generation and utilization and contributing to the advancement of a green economy (Su and Fan, 2022). Therefore, RETI is expected to have a positive effect on

GEG, i.e., $\frac{\beta_{GEG_{it}}}{\beta_{RETI_{it}}} > 0$, in hypothesis 2.

Likewise, studies have shown that GF acts as an effective policy tool in developing countries by mitigating the investment risks associated with green projects and improving their operational efficiency, which in turn increases their appeal to private-sector investors (Taghizadeh-Hesary and Yoshino, 2019). Green finance theory further emphasizes that GF should comply with environmental, social, and governance (ESG) criteria. Such practices not only support economic and environmental policies but also raise public awareness of the importance of adopting clean and renewable energy, thereby facilitating the transition toward a green economy (Behera et al., 2024). Accordingly, GF is expected to have a positive effect on GEG, i.e., $\frac{\beta_{GEG_{it}}}{\beta_{GF_{it}}} >$

0, in hypothesis 3.

Effective governance is essential for the successful implementation of environmental and economic policies. In this context, GOV plays a critical role in facilitating the green transition in China. Through the formulation of laws and regulations, governments can define institutional responsibilities and provide strategic direction for green development. More specifically, GOV influences GEG through fiscal support and

regulatory measures. Policy instruments such as green public procurement, subsidies, and green credit programs can promote the adoption of environmentally friendly technologies. In addition, tax incentives, renewable energy subsidies, and penalties for high emissions help create a favorable institutional environment for green transformation (Sarpong et al., 2023). Accordingly, GOV is expected to have a positive effect on GEG, i.e., $\frac{\beta_{GEG_{it}}}{\beta_{GOV_{it}}} > 0$, in hypothesis

4.

The government plays a crucial role in economic development by setting strategic targets, optimizing institutional environments, and implementing policies that facilitate the efficient allocation of resources (Ren et al., 2021). More importantly, GOV can shape how key economic drivers, such as renewable energy, technological innovation, and financial development affect GEG. This study therefore examines the moderating effect of GOV on GEG by incorporating interaction terms between GOV and REN, RETI, and GF, aiming to reveal the potential dual role of government as an "accelerator" or a "brake" in the process of low-carbon transition, which are expected to be positive, i.e., $\frac{\beta_{GEG_{it}}}{\beta_{GOV \times REN_{it}}} > 0$; $\frac{\beta_{GEG_{it}}}{\beta_{GOV \times RETI_{it}}} > 0$;

$\frac{\beta_{GEG_{it}}}{\beta_{GOV \times GF_{it}}} > 0$ in hypothesis 5, hypothesis 6,

and hypothesis 7, respectively. The theoretical background and associated hypotheses are represented graphically in Figure 3.

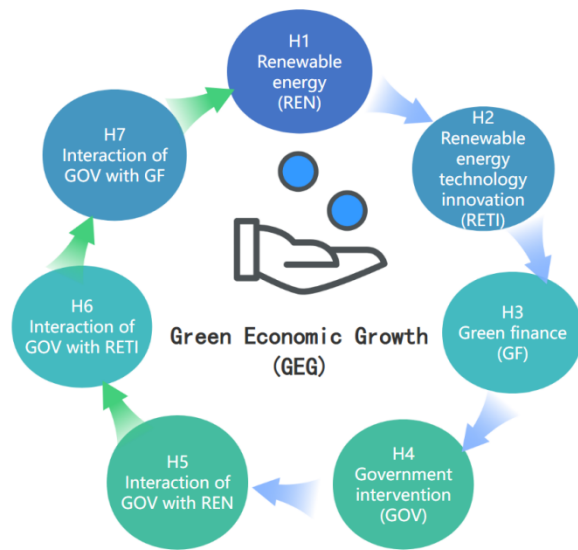


Fig. 3. The theoretical framework outlines both the direct and interaction effects of the explanatory variables across different hypotheses.

4. Data and Methodology

4.1. Data and Variables

This study uses panel data from 30 Chinese provinces (excluding Tibet due to substantial missing values) over the period 2010–2022. The concept of green growth, introduced at the Rio+20 Summit, has provided important guidance for promoting sustainable development in China. As a new development paradigm, GEG integrates environmental considerations into economic planning, promotes investment in sustainable infrastructure, supports eco-friendly industries, and enhances resource efficiency to achieve coordinated economic and ecological development.

GEG is measured by the ratio of actual regional GDP to carbon emissions, following Chen et al. (2025). The data are obtained from the *China Statistical Yearbook and Provincial Statistical Yearbooks*.

REN data are sourced from the *China Electric Power Statistical Yearbook* and include electricity generation from wind, solar, hydro, and biomass, it is measured as the renewable energy electricity

generation (Song et al., 2022; Zhu et al., 2022).

RETI, Following Zhao et al. (2024), this study adopts a perpetual inventory method to construct the stock of RETI, as specified in Equation (1):

$$RETI_{it} = REPAT_{it} + (1 - \gamma)RETI_{i,t-1} \quad (1)$$

Where, $REPAT_{it}$ denotes the number of renewable energy technology patents in province i at time t . $RETI_{it}$ represents the stock of renewable energy technological innovation in the current period, while $RETI_{i,t-1}$ refers to its lagged value. The parameter γ is the depreciation rate of knowledge stock, which is set at 10% following (Bottazzi and Peri, 2007). Patent data for RETI were sourced from the *China National Intellectual Property Administration (CNIPA)*, and relevant patents are identified based on patent classification codes.

GF, as an emerging financial instrument designed to address environmental challenges, represents an important form of financial innovation in the field of environmental protection (Umar and Safi, 2023). Following Liu et al. (2019), this study measures green finance using a multidimensional indicator system that includes four components: green credit, green investment, green securities, and green insurance. To improve the comprehensiveness of the index, an additional dimension capturing fiscal support for environmental protection is incorporated (see Table 1). A composite green finance index is then constructed using the entropy method to ensure objective weighting of the indicators.

GOV also plays a crucial role in promoting high-quality economic development. Effective government involvement can facilitate resource allocation and support sustainable growth, whereas inefficient governance may lead to resource misallocation and hinder regional green economic growth (Wang and Lee, 2022). Following Lee et al. (2024), it is measured by the

ratio of fiscal expenditure to regional gross domestic product (GDP).

With respect to control variables, this study follows existing research on energy and economic development such as Fang et al. (2022), Mohsin et al. (2022), Wani et al. (2024), Li et al. (2024), and Ashfaq et al. (2024), and selects relevant factors that may influence GEG. Urbanization (URB) is represented by the ratio of the urban population to the total population, which is closely related to energy utilization and green technological innovation. Transportation infrastructure (Tra) is proxied by the logarithmic value of highway mileage, which is the basis of economic development and is definitely linked to fossil fuels and greenhouse gases (Yu et al., 2023).

All monetary values are deflated to constant prices to eliminate inflationary distortions, and logarithmic transformations are applied to variables with skewed distributions to reduce heteroskedasticity and improve interpretability. Descriptive statistics for all variables are reported in Table 2.

Table 1			
Comprehensive evaluation system of green finance.			
Overall indicator	sub-indicator	Indicators	measurement
Green Finance Development Index	Green credit	The ratio of interest expenditure within the total industry for six high energy-consuming sectors	
	Green securities	The ratio of the market value of the six energy-intensive industries to the overall market value of A-shares	
	Green Insurance	The ratio of agricultural insurance income to the	

		gross agricultural output value	
Green investment	The investment-to-gross Domestic Product (GDP) ratio for environmental pollution prevention.		
Environmental support	The ratio of government spending on environmental protection to total government spending		

Table 2
Descriptive statistics.

Variables	Symbol	Unit of Measurement	Sources
Green economic growth	GEG	Real GDP/CO ₂	CSY, PSY
Renewable energy	REN	Renewable energy electricity generation	CEPSY
Renewable energy Innovation	RETI	As calculated in the previous section	CNIPA
Green finance	GF	Comprehensive index of green finance	CISY, CESY, PSY
Government intervention	GOV	Ratio of fiscal expenditure to regional GDP	PSY
Urbanization	URB	Urban population as a share of total population	PSY
Transportation infrastructure	Tra	The logarithm of highway mileage	PSY

Notes: “CSY = China Statistical Yearbook (<https://data.stats.gov.cn/english/>); PSY=

Provincial Statistical Yearbooks (<https://data.stats.gov.cn/english/easyquery.htm?cn=E0103>); CESY= China Electric Power Statistical Yearbook (<https://www.zgtjnj.org/navibooklist-n3025030814-1.html>); CNIPA= China National Intellectual Property Administration (<https://english.cnipa.gov.cn/col/col2942/index.html>); CEPY = China Electric Power Yearbook (<https://cnki.nbsti.net/CSYDMirror/trade/Yearbook/Single/N2021050269?z=Z025>); CISY= China Industrial Statistics Yearbook (<https://cnki.nbsti.net/CSYDMirror/trade/Yearbook/Single/N2014020031?z=Z012>); CASY= China Agricultural Statistical Yearbook (<https://cnki.nbsti.net/CSYDMirror/trade/Yearbook/Single/N2023030189?z=Z009>)”

4.2. Model Specification

The baseline functional form is specified in Equation (2), which describes the relationship between green economic growth and its key explanatory variables:

$$GEG_{it} = f(REN_{it}, RETI_{it}, GF_{it}, GOV_{it}, URB_{it}, Tra_{it},) \quad (2)$$

To improve estimation efficiency and reduce potential heteroskedasticity, all continuous variables are transformed into their natural logarithmic forms. Accordingly, the baseline econometric model is specified as follows:

$$LnGEG_{it} = \alpha_0 + \alpha_1 LnREN_{it} + \alpha_2 LnRETI_{it} + \alpha_3 LnGF_{it} + \alpha_4 LnGOV_{it} + \alpha_5 Z_{it} + \mu_{it} \quad (3)$$

Where, Ln denotes logarithmically transformed variables, GEG represents green economic growth; REN denotes renewable energy consumption; $RETI$ represents renewable energy technological innovation; GF denotes green finance; GOV represents government intervention; Z_{it} is a vector of control variables, including urbanization level (URB) and

transportation infrastructure (Tra); μ_{it} is the error term.

To capture nonlinear effects, squared terms of renewable energy adoption (REN^2), renewable innovation ($RETI^2$), and government intervention (GOV^2) are introduced, leading to the extended model in Equation (4):

$$LnGEG_{it} = \alpha_0 + \alpha_1 LnREN_{it} + \alpha_2 LnRETI_{it} + \alpha_3 LnGF_{it} + \alpha_4 LnGOV_{it} + \alpha_5 (LnREN_{it})^2 + \alpha_6 (LnRETI_{it})^2 + \alpha_7 (LnGOV_{it})^2 + \alpha_8 Z_{it} + \mu_{it} \quad (4)$$

Where $(LnREN_{it})^2$, $(LnRETI_{it})^2$, and $(LnGOV_{it})^2$ represent the squared terms of renewable energy, renewable energy technological innovation, and government intervention, respectively, which are included to capture potential nonlinear relationships. All other variables are defined as in Equation (3).

Moreover, to examine how government intervention moderates the effects of REN , $RETI$, and GF on GEG , the interaction terms of $(GOV \times REN)$, $(GOV \times RETI)$, and $(GOV \times GF)$ are incorporated, as specified in Equation (5):

$$LnGEG_{it} = \alpha_0 + \alpha_1 LnREN_{it} + \alpha_2 LnRETI_{it} + \alpha_3 LnGF_{it} + \alpha_4 LnGOV_{it} + \alpha_5 (LnREN_{it} \times LnGOV_{it}) + \alpha_6 (LnRETI_{it} \times LnGOV_{it}) + \alpha_7 (LnGF_{it} \times LnGOV_{it}) + \alpha_8 Z_{it} + \mu_{it} \quad (5)$$

Where $(LnREN_{it} \times LnGOV_{it})$, $(LnRETI_{it} \times LnGOV_{it})$, and $LnGF_{it} \times LnGOV_{it}$ denote the interaction terms used to examine the moderating effect of government intervention. All other variables are defined as in Equation (3).

4.3. Estimation methods

Before conducting the empirical analysis, a series of diagnostic tests were performed to ensure the validity and robustness of the estimation strategy. First, cross-sectional dependence (CSD) was examined using the Pesaran CD test (Pesaran, 2004), the standardized LM test, and the Breusch–Pagan LM test (Breusch and Pagan,

1980), as ignoring cross-sectional interdependence may lead to biased estimates in panel data. Given the presence of cross-sectional dependence, the stationarity properties of the variables were tested using the Cross-sectionally Augmented IPS (CIPS) unit root test (Pesaran, 2007), which accounts for cross-sectional correlations by incorporating cross-sectional averages. To further investigate the long-run relationships among variables, the Westerlund (2005) panel cointegration test was employed, as it is well suited for panel data with cross-sectional dependence and allows for the identification of stable equilibrium relationships. Based on the results of these preliminary tests, this study adopts a Fixed Effects (FE) estimation framework with Driscoll–Kraay standard errors (Driscoll and Kraay, 1998) and Panel Corrected Standard Errors (PCSE) (Beck and Katz, 1995) to address potential issues of heteroskedasticity, autocorrelation, and cross-sectional dependence, thereby ensuring reliable inference. Finally, to verify the robustness of the empirical findings and capture potential heterogeneity across different levels of the dependent variable, Panel Quantile Regression (PQR) was conducted as a supplementary analysis (Pesaran, 2021). Detailed model specifications and technical formulations are provided in the Appendix.

5. Empirical results and discussion

The empirical analysis begins with descriptive statistics and the correlation matrix shown in Table 3. It reveals that *Tra* exhibits the highest mean value (11.678), followed by RETI, REN,

and GF. The Shapiro–Wilk test demonstrates asymmetric distributions across all variables. The correlation matrix in Table 3 reveals positive correlations between the dependent variable and all independent variables except for REN and *Tra*. Multicollinearity was evaluated using the variance inflation factor (VIF), as reported in Table 4.

The significant CSD results confirm the presence of interdependence among all variables. Furthermore, the unit root test indicates that the variables become stationary after first differencing, demonstrating that they are integrated of order one (I (1)).

After verifying stationarity through second-generation unit root tests, the Westerlund cointegration results presented in Table 5 reveal no long-run relationship among the variables. Additionally, Table 6 provides the results of additional diagnostic checks, including the Hausman specification, serial correlation, and test slope heterogeneity.

The slope heterogeneity test, with statistically significant coefficients, confirms that the panel exhibits heterogeneous characteristics. Furthermore, the significant results of the Wooldridge and Hausman tests indicate the presence of autocorrelation and support the use of a fixed-effects model for estimation, respectively. The results of Equations (2) – (5), estimated using D-KSE and PCSE, are reported in Table 8.

Table 3

Summary statistics and correlation analysis.

Variables	GEG	REN	RETI	GF	GOV	URB	Tra
Mean	0.367	4.361	6.077	0.746	0.246	0.589	11.678
Std. Dev.	0.211	2.187	1.465	0.076	0.102	0.125	0.851
Min	0.167	0	0	0.601	0.105	0.105	9.390
Max	1.084	8.222	9.211	0.899	0.643	0.643	12.896
S–W test	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Prob.							
Observation	360	360	360	360	360	360	360
GEG	1.000						
REN	-0.389***	1.000					
RETI	0.154***	-0.115***	1				
GF	0.234***	0.074	0.399***	1			
GOV	0.111***	0.227***	-0.665***	0.099*	1		
URB	0.575***	-0.584***	0.585***	0.343***	-0.324***	1	
Tra	-0.633***	0.659***	0.101*	0.089*	-0.138***	-0.597***	1

This table reports the descriptive statistics and pairwise correlation coefficients of the main variables. Mean, standard deviation, minimum, and maximum values are presented. The S–W test Prob. indicates the p-values of the Shapiro–

Wilk normality test. Correlation coefficients are reported in the lower triangular matrix. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. All variables are defined in Table 1.

Table 4
Variance Inflation Factor (VIF) Test Results.

Variables	VIF	1/VIF
REN	2.30	0.435
RETI	4.22	0.237
GF	1.91	0.523
GOV	2.82	0.355
URB	5.46	0.183
Tra	3.97	0.251
Mean VIF	3.45	

Note: VIF denotes the variance inflation factor. A VIF value greater than 10 is commonly considered indicative of severe multicollinearity, while values below this threshold suggest that multicollinearity is not a serious concern. The results indicate that multicollinearity is unlikely to affect the estimation in this study.

Table 5
Cross-Sectional Dependence and Unit Root Test Results.

Variable	CSD test	CIPS unit root test		CADF unit root test	
		I (0)	I (1)	I (0)	I (1)
GEG	0.367***	-2.326**	-2.544***	2.724	2.896***
REN	4.361***	-2.252**	-3.292***	1.116	7.937***
RETI	6.077***	-3.362***	-4.262***	4.859***	16.460***
GF	0.746***	-2.487***	-3.300***	2.957***	6.588***
GOV	0.246***	-1.777	-2.269**	2.088**	7.587***
URB	0.589***	-3.098***	-2.494***	12.632***	3.435***
Tra	11.678***	-1.864	-2.569***	7.911***	6.621***

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

Table 6
Westerlund Panel Cointegration Test Results.

Estimator	Value	Z-value	p-value
Gt	-2.701	-1.122	0.131
Ga	-5.458	6.107	1.000
Pt	-12.151	0.419	0.662
Pa	-6.426	3.291	1.000

Note: Gt and Ga denote the group-mean test statistics, while Pt and Pa represent the panel test statistics in the Westerlund cointegration test. The null hypothesis is that there is no cointegration relationship among the variables. The p-values indicate that the null hypothesis cannot be rejected at conventional significance levels.

Table 7
Diagnostic Test Results.

Diagnostic test	GEG
Hausman test	11.98*
Wooldridge autocorrelation test	6.255**
Slope heterogeneity test (Delta)	1.238
Adjusted Delta	2.144**

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

In Model 1 of Table 8, the results indicate that REN, RETI, and GF exert a significant positive effect on GEG. Specifically, a 1% increase in REN, RETI, and GF raises GEG by 0.042%, 0.025%, and 0.751% on average, respectively. These findings provide empirical support for Hypotheses 1, 2, and 3. In contrast, GOV has a significantly negative coefficient, which may suggest that it lies on the left side of a U-shaped relationship. This implies that excessive or inefficient administrative intervention may suppress market vitality and innovation efficiency. Therefore, Hypothesis 4 is not supported.

Among the control variables, URB shows an

insignificant effect on GEG, whereas Tra exhibits a significant negative impact across Chinese provinces. Moreover, the results from Model 2 (Table 8) demonstrate that the squared terms of RETI and GOV are statistically significant, confirming the presence of nonlinear and non-monotonic relationships with GEG. Furthermore, Model 3 (Table 8) indicates that GOV significantly strengthens the influence of REN and RETI on GEG. These results support Hypotheses 5 and 6. Conversely, the moderating effect of GOV on the relationship between GF and GEG is positive but statistically insignificant. Thus, Hypothesis 7 is not supported.

Table 8
Regression Results Using Driscoll–Kraay and PCSE Estimators.

Variables	Driscoll-Kraay Standard Error			Panel Corrected Standard Error		
	Model-I (Linear)	Model-II (Non-linear)	Model-III (Interaction)	Model-I (Linear)	Model-II (Non-linear)	Model-III (Interaction)
REN	0.042***	0.030***	0.046***	0.006*	0.002	0.008*

	(0.011)	(0.007)	(0.010)	(0.003)	(0.004)	(0.005)
RETI	0.025*	-0.062**	0.015	0.027***	-0.159***	0.025***
	(0.013)	(0.023)	(0.029)	(0.010)	(0.037)	(0.009)
GF	0.751***	0.205**	0.674***	0.353**	0.753***	0.706***
	(0.123)	(0.07)	(0.118)	(0.176)	(0.149)	(0.160)
GOV	-0.683***	-1.305***	-0.581***	-0.382**	-1.702***	-0.482***
	(0.182)	(0.320)	(0.190)	(0.195)	(0.329)	(0.152)
URB	0.0105	0.055	0.108	0.300*	-0.172	-0.052
	(0.188)	(0.109)	(0.172)	(0.166)	(0.130)	(0.144)
Tra	-0.287***	-0.165**	-0.219***	-0.142***	-0.177***	-0.177***
	(0.074)	(0.062)	(0.068)	(0.022)	(0.018)	(0.019)
REN ²		0.973**			0.432***	
		(0.345)			(0.133)	
RETI ²		0.009**			2.796***	
		(0.002)			(0.508)	
GOV ²		1.235*			0.017***	
		(0.417)			(0.003)	
REN×GOV			0.085*			0.092
			(0.044)			(0.060)
RETI×GOV			1.944*			2.057*
			(0.918)			(1.230)
GF×GOV			0.042			-0.441***
			(0.060)			(0.056)
Constant	2.981***	2.130***	2.204**	1.304***	2.530***	1.820***
	(0.811)	(0.650)	(0.717)	(0.277)	(0.243)	(0.238)

Note: This table reports regression results using Driscoll–Kraay standard errors (DKSE) and panel-corrected standard errors (PCSE). Standard errors are reported in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. Model I presents the baseline linear specification, Model II incorporates nonlinear (squared) terms, and Model III includes interaction terms to examine moderating effects. All variables are defined in Table 1.

5.1. Robustness test

To validate the robustness of the findings, Equations (2)– (5) were re-estimated using panel quantile regression, and the results are provided in Table 9. In model-I, although REN posits a positive impact GEG, the effect of REN has shown a pattern of increasing initially before decreasing across the quantiles. GF exhibits a significant positive effect only at the lower quantile (q0.25), while remaining insignificant at the median and upper quantiles. RETI is found to have a significant positive effect on GEG across all quantiles. Moreover, GOV is found to

have a detrimental effect on GEG at upper quantiles. Transportation is found to significantly hinder green economic growth at all levels. Urbanization has a negative effect on the lower quantile but turns positive on the higher side. In addition, Model 2 indicates that the squared term of REN exerts a negative influence on GEG at lower quantile levels, while this effect shifts to a positive and significant one at higher quantiles. On the other hand, the non-linear effects of RETI and GOV are observed to enhance GEG over the quantiles. Finally, Model 3 shows that the moderating interaction between GOV and

REN consistently exerts a positive effect on GEG across all quantiles. In contrast, the interaction terms of GOV with RETI and GF

have positive and significant effects on GEG only at the median quantile levels.

Table 9

Panel Quantile Regression Results.

Variables	Mode-I			Mode-II			Mode-III		
	q0.25	Q0.50	Q0.75	q0.25	Q0.50	Q0.75	q0.25	Q0.50	Q0.75
REN	0.005 (0.003)	0.006*** (0.002)	0.002** (0.001)	0.003 (0.002)	0.003 (0.005)	0.013** (0.006)	0.003 (0.003)	0.012* (0.006)	0.022*** (0.007)
GF	0.237*** (0.086)	0.035 (0.133)	0.124 (0.234)	0.185** (0.073)	0.152 (0.138)	0.558*** (0.165)	0.153* (0.089)	0.168 (0.152)	0.355** (0.166)
RETI	0.0208*** (0.007)	0.046*** (0.010)	0.045** (0.018)	-0.128*** (0.016)	-0.182*** (0.030)	-0.193*** (0.036)	0.0215*** (0.006)	0.032*** (0.011)	0.021 (0.012)
GOV	0.046 (0.078)	0.297** (0.121)	-0.683*** (0.112)	-0.990*** (0.193)	-0.630* (0.360)	-1.570*** (0.430)	-0.031 (0.101)	-0.188 (0.170)	-0.624*** (0.185)
URB	-0.041 (0.089)	0.176 (0.138)	0.401* (0.242)	0.002 (0.076)	0.007 (0.143)	-0.015 (0.171)	0.0483 (0.092)	0.249 (0.156)	0.165 (0.171)
Tra	-0.095*** (0.011)	-0.144*** (0.017)	-0.155*** (0.030)	-0.087*** (0.009)	-0.119*** (0.018)	-0.213*** (0.021)	-0.073*** (0.011)	-0.146*** (0.019)	-0.228*** (0.021)
REN ²				-0.321*** (0.071)	0.286** (0.146)	0.090* (0.055)			
RETI ²				0.015*** (0.001)	0.020*** (0.002)	0.019*** (0.003)			
GOV ²				2.071*** (0.270)	1.521*** (0.504)	2.406*** (0.603)			
REN×GOV							0.003 (0.035)	0.114* (0.059)	0.069 (0.065)
RETI×GOV							-0.288 (0.748)	1.315** (0.671)	0.121 (1.378)
GF×GOV							-0.320*** (0.033)	0.280** (0.143)	0.452 (0.285)

Note: This table reports the results of panel quantile regression at the 25th (q0.25), 50th (q0.50), and 75th (q0.75) quantiles. Standard errors are reported in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. Model I presents the baseline linear specification, Model II incorporates nonlinear (squared) terms, and Model III includes interaction terms to examine moderating effects. All variables are defined in Table 1.

5.2. Discussion

The empirical findings are strongly consistent with China's green development trajectory, where the shift to a green, low-carbon economy is integral to national sustainability initiatives and climate change mitigation policies, especially in

the context of the “dual carbon” goals. China has taken a leading role in promoting green development since formally introducing the concept in 2015, launching a series of policy initiatives aimed at building an economy aligned with sustainability goals. The empirical results of

Model I indicate that REN has a positive and significant effect on GEG. This outcome corroborates the findings of Mohsin et al. (2022) for ECOWAS. Nevertheless, it is inconsistent with Zhe et al. (2021), who documented that renewable energy utilization and financial development exert no significant effect on economic growth in Turkey. It is also posited that fostering REN can enable China to reduce its dependence on fossil fuels, enhancing energy efficiency, and facilitating GEG (Sharma et al., 2021). In contrast, the substantial costs of expanding renewable energy may impose an economic burden, thereby dampening economic activity, as noted by (Marques and Fuinhas, 2012). Furthermore, RETI play a critical role in mitigating greenhouse gas emissions and fostering sustainable green economic growth, a result consistent with Marques and Fuinhas (2012) for China and Chen and Tang (2024) for the G7 countries. Renewable energy technologies provide clean power and efficiency foundations for green economic growth by replacing fossil fuels and optimizing energy allocation efficiency. Additionally, China has exhibited a firm commitment to boosting the proportion of renewable energy in its energy mix through substantial investments in renewable energy technology research and development.

Moreover, the findings from Model I (Table 8) suggest that excessive GOV reduces GEG. The result corroborates the evidence presented by Ahmed et al. (2022), who argue that excessive intervention impairs market mechanisms, decreases institutional efficiency, and leads to distorted incentive structures. According to Table 9, government intervention positively influences green economic growth at the median quantile but becomes significantly detrimental at the upper quantile. This implies that government intervention is most effective within a certain range, providing empirical justification for implementing differentiated intervention

strategies across development stages. In the context of China, studies have emphasized that sound and effective policy regulation is essential for removing barriers to green transition, stabilizing market expectations, and providing institutional support for the diffusion of clean technologies and the upgrading of low-carbon industries, thereby accelerating green economic growth (Zhang and Zhang, 2024). In addition, evidence from Model I in Tables 8 and 9 indicates that GF significantly enhances GEG in China. This finding aligns with the conclusions of Zhou et al. (2024) and Liu et al. (2023). This is primarily because GF alleviates financing constraints and steers capital toward renewable energy and green innovation projects, resulting in continuous improvements in green economic outcomes. As noted by Paramati et al. (2022), GF prioritizes credit and investment for firms that comply with environmental and social criteria, enabling traditional industries to adopt energy-efficient technologies and facilitating the growth of green industries.

Furthermore, the nonlinear estimation results presented in Model II (Table 8) reveal that improvements in RETI and GOV are associated with a U-shaped relationship with GEG, indicating that their influence transitions from initially suppressing growth to subsequently promoting it once a certain threshold is surpassed. The finding is primarily driven by high initial renewable energy costs, slow technology penetration, and the time required to refine policy frameworks, in line with Iqbal et al. (2025) and Abbas et al. (2022), who observed similar challenges in several European economies, including the Netherlands, the UK, Norway, and Portugal. Addressing these early-stage obstacles through continuous government support, economies of scale, and flexible subsidy schemes has played a crucial role in advancing the transition toward a green and low-carbon economy (Geels et al., 2021; Khattak et al., 2022).

Regarding GOV, excessive involvement may hinder growth in the early stage by distorting price signals and increasing institutional burdens. However, once the economy advances beyond key developmental thresholds and institutional systems become stable, intervention can facilitate coordination and reinforce positive externalities, generating beneficial growth effects. Additionally, in the context of China, under GDP-driven performance incentives, local governments often prioritize economic expansion during periods of weak regulatory enforcement, relaxing environmental oversight and channeling resources toward sectors capable of generating rapid economic returns. Such intervention patterns initially undermine green development, corresponding to the downward segment of the U-shaped relationship.

Moreover, Model III in Table 8 shows that the interactions of GOV with REN and RETI significantly enhance GEG in China, whereas the moderating interaction between GOV and GF exhibits a weak and insignificant effect. In addition, robustness analysis (Table 9) indicates that the moderating impact of GOV on REN, RETI, and GF is negative at the lower quantiles, significantly positive at the median quantile, and becomes insignificant at higher quantiles. This reflects the evolving effectiveness of intervention across development stages. In the early phase, excessive intervention increases institutional transaction costs and disrupts resource allocation, suppressing green economic growth. At the intermediate phase, industrial guidance, subsidies, and regulatory support effectively resolve market failures and stimulate renewable energy and green technology development, generating the strongest positive outcomes. Once the economy becomes highly developed, market mechanisms can independently drive green innovation, reducing the marginal benefit of administrative intervention (Du et al., 2021). This nonlinear pattern reflects the U-shaped effect of

government intervention.

6. Conclusion and policy implications

The question of whether renewable energy adoption, technological innovation, green finance, and government intervention promote green economic growth remains inconclusive in prior research. Accordingly, this study examines the effects of REN, RETI, GF, and GOV on GEG using provincial panel data from 30 Chinese provinces over the period 2010–2022. To ensure robustness, the analysis employs Driscoll–Kraay standard errors, panel-corrected standard errors (PCSE), and panel quantile regression.

The empirical results indicate that REN significantly promotes GEG. Similarly, RETI and GF exert positive and statistically significant effects on GEG. In contrast, the effect of GOV exhibits a significant U-shaped relationship with GEG, indicating that moderate regulatory intensity promotes GEG, while both under- and over-intervention generate adverse effects. Furthermore, GOV enhances the positive effects of REN and RETI on GEG. However, its moderating effect on the relationship between GF and GEG is positive but not statistically significant. These findings imply that green economic growth is not only driven by individual factors but also depends on the interaction between policy, technology, and market mechanisms. In particular, the nonlinear effect of government intervention underscores the importance of achieving an optimal level of regulation, while the significant roles of RETI and GF highlight the importance of innovation and financial support in enhancing the effectiveness of renewable energy development.

Against the backdrop of China's dual carbon objectives and the national green development agenda, policymakers should adopt a more coordinated and balanced approach to stimulate GEG. First, given the significant contribution of REN to GEG, authorities should prioritize the

expansion of renewable energy through supportive policies and regulatory frameworks. This includes promoting investment in renewable energy infrastructure, such as solar and wind power, and providing financial incentives, including subsidies and tax reductions, to encourage private sector participation. Second, considering the positive effects of RETI and GF, policymakers should strengthen support for research and development through targeted subsidies and increased public investment, while expanding the scope and accessibility of green financial instruments. Enhancing the integration between green finance and renewable energy industries can further facilitate technological upgrading and improve resource allocation efficiency. Third, considering the U-shaped relationship between GOV and GEG, policymakers should carefully calibrate the intensity of regulation to achieve an optimal balance. While moderate GOV can effectively promote GEG, both insufficient and excessive intervention may lead to suboptimal outcomes. Therefore, the government should focus on improving institutional quality, strengthening market-oriented regulations, and avoiding excessive administrative intervention that may distort market mechanisms. In addition, enhancing policy coordination and increasing targeted fiscal and technological support can help improve governance effectiveness and ensure that GOV plays a facilitating rather than inhibiting role in the green transition. Furthermore, the quantile regression results suggest that the effectiveness of GOV varies across different stages of green economic development, reinforcing the need for differentiated and adaptive policy design.

While acknowledging the study's limitations, future research may investigate how artificial intelligence, digitalization, and fiscal decentralization contribute to China's pursuit of sustainable development goals. AI and digital

transformation are accelerating green transition through intelligent infrastructure, low-carbon innovation, and improved governance efficiency, whereas fiscal decentralization shapes regional discretion in sustainability policy implementation. Investigating these macro-level determinants could generate new contributions to energy economics literature.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

Appendix A. Technical Formulations

A1. Cross-sectional Dependence Tests. To examine cross-sectional dependence, the following statistics are employed.

(1) Pesaran CD Test

$$CD = \sqrt{\frac{2}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^N \hat{\rho}_{ij} \sim N(0,1)$$

(2) Standardized LM Test

$$LM = \sqrt{\frac{1}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^N (T \hat{\rho}_{ij}^2 - 1) \sim N(0,1)$$

(3) Breusch–Pagan LM Test

$$LM = \sum_{i=1}^{N-1} \sum_{j=i+1}^N T \hat{\rho}_{ij}^2 \sim \chi^2 \left(\frac{N(N-1)}{2} \right)$$

(4) Correlation Coefficient

$$\hat{\rho}_{ij} = \frac{\sum_{t=1}^T \varepsilon_{it} \varepsilon_{jt}}{\sqrt{\sum_{t=1}^T \varepsilon_{it}^2} \sqrt{\sum_{t=1}^T \varepsilon_{jt}^2}}$$

A2. Panel Unit Root Test (CIPS). The Cross-sectionally Augmented IPS (CIPS) test is based on:

$$\Delta y_{it} = \alpha_i + \beta_i y_{i,t-1} + \gamma_i \bar{y}_{t-1} + \sum_{j=0}^p d_{ij} \Delta \bar{y}_{t-j} + \sum_{j=1}^p \phi_{ij} \Delta y_{i,t-j} + \varepsilon_{it}$$

CIPS Statistic

$$CIPS = \frac{1}{N} \sum_{i=1}^N CAD F_i$$

A3. Panel Cointegration Test (Westerlund, 2005)

$$\Delta z_{it} = \alpha'_i d_i + \theta_i (z_{i,t-1} | \beta'_i y_{i,t-1}) + \sum_{j=1}^m \phi_{ij} \Delta z_{i,t-j} + \sum_{j=0}^m \psi_{ij} \Delta y_{i,t-j} + \varepsilon_{it}$$

Test Statistics

Group Mean Tests:

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$$G_\tau = \frac{1}{N} \sum_{i=1}^N \frac{\hat{\theta}_i}{SE(\hat{\theta}_i)}$$

$$G_\alpha = \frac{1}{N} \sum_{i=1}^N T \hat{\theta}_i$$

Panel Tests:

$$P_\tau = \frac{\hat{\theta}}{SE(\hat{\theta})}$$

$$P_\alpha = T \hat{\theta}$$

A4. Fixed Effects Transformation

$$\tilde{z}_{it} = z_{it} - \bar{z}_i + \bar{z}$$

OLS Estimator

$$\hat{\beta} = (X'X)^{-1}X'Y$$

A5. Driscoll–Kraay Standard Errors

$$Var(\hat{\beta}) = (X'X)^{-1} \hat{S}_T (X'X)^{-1}$$

where $\hat{S}_T$ is the Newey–West estimator.

A6. Panel Quantile Regression (PQR)

$$Q_\tau(Y_{it}) = \beta_0(\tau) + \beta_1(\tau)X_{1,it} + \dots + \beta_k(\tau)X_{k,it} + \varepsilon_{it}(\tau)$$

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