

Assessing China's energy transition pathway: Insights from the synergistic effects of key drivers

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ABSTRACT

China's energy transition is a pivotal component of global efforts to combat climate change. This study identifies the synergistic effects of key factors driving this transition, including social-technology-economic, policy, investment, governance indicators. Asymmetric nexus impacts are explored by using quantile-on-quantile regression (QQR) method. Further, the synergistic effects of key drivers on China's energy transition are examined by model 1–4. The findings show that reconciling the tradeoffs of reducing coal emissions and promoting clean energy are crucial for China's energy transition. Urban growth, environmental taxes, financial development, and strong environmental governance and institutional quality significantly support these efforts, but show different synergistic effects scenarios. These findings also reinforce the need for a more inclusive response to China's energy sustainability challenges, in particular, coordinated policies and strategies in coal-reliant industrial sectors are critical for a successful energy transition.

1. Introduction

Sustainable Development Goal (SDG) 7 focuses on ensuring access to affordable, reliable, sustainable, and modern energy for all. This goal is pivotal in achieving net-zero emissions by 2050 and aligning with broader climate action targets [1]. Energy transition programs, such as renewable power generation and the adoption of clean energy in industrial sectors, are crucial for increasing the share of renewables in energy production. These programs are among the most effective strategies for reducing the dependence on fossil fuels and advancing the SDGs [2]. On the other hand, global investments in the clean energy market are expected to surpass \$1.7 trillion by 2023, accounting for approximately 60.7 % of global energy spending. As a pioneering country, China stands as the largest investor in clean energy worldwide, with annual investments reaching \$184 billion in 2022 [3]. The investments not only support environmental sustainability but also enhance economic resilience and energy security.

Increasing global geopolitical risks have heightened concerns over energy security, compelling governments to prioritize energy affordability and independence [4]. Governments and industries increasingly acknowledge that accelerating the energy transition should be both

affordable and just, leading to a sustainable national energy system. Therefore, while prioritizing clean energy sources, it is essential to reduce emissions from fossil fuel use, particularly from coal [1]. Emphasizing the synergies and tradeoffs between affordable energy and clean energy transition are imperative for sustained and effective transitions. This requires systematic assessment of the diverse challenges associated with the transition and its socio-economic and environmental consequences [1].

This work is intended to address certain questions of interest: (1) Asymmetric nexus dynamics: What are the dynamics of the asymmetric impacts between greenhouse gases (GHGs) and key drivers, and China's clean energy transition (CL) and its drivers? (2) Is there any evidence of a GHGs-based Environmental Kuznets Curve (EKC) in China when incorporate CL and coal emissions (CO)? (3) Do emissions from increasing coal consumption counteract the decarbonization efforts in China's CL? (4) How do the synergistic effects of key drivers influence CL when applying the expanded STIRPAT model? (5) What are the synergistic effects of financial development and institutional quality on China's CL? (6) What are the synergistic effects of environmental governance and regulatory quality on China's CL?

The following points illustrate the motivations for the proposed

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scheme to tackle these questions.

First, despite China's intensified efforts to reduce the country's dependence on fossil fuels, coal-dominated power has reached an unprecedentedly high output (Table 1), contributing to approximately 70 % of the present domestic energy consumption structure. This pattern of energy use has led to a significant increase in coal-related CO₂ emissions, reportedly accounting for up to about 70 % of the total CO₂ emissions in China (Fig. 1). Apart from that, Gielen et al. [5] concluded that renewables and improved energy efficiency, together with increasing end-use electrification, will drive 94 % of global GHGs reductions. If emissions peak in 2025, achieving carbon neutrality would require a 45–62 % electrification rate and a share of renewables in primary energy supply reaching 47–78 % [6]. Thus, the nexus of CL and CO must be addressed as a matter of a first priority to facilitate China's energy transition.

Second, the integration of clean energy into China's energy mix can offer additional benefits such as enhanced energy security since energy imports of raw materials are reduced. Clean energy projects can also create synergies with other sustainable development goals, such as promoting sustainable economic growth in China [8]. It is widely acknowledged that no specific indicator can completely capture all the complexities of the clean energy transition worldwide or at a country level [9]. Therefore, in order to assess China's energy transition pathway, a cross-sectoral and comprehensive analysis of different factors is required.

Third, another important motivation for this study is to identify and analyze the synergistic effects of factors that facilitate China's CL. Understanding the synergistic effects contribute to enhance clean energy initiatives, and emphasize the combined effects on China. To achieve this objective, a robust analytical framework, the expanded STIRPAT model is adopted to explore how these drivers can influence transitions [10].

This research contributes valuable insights to the existing literature in several ways. (i)The study contributes to display the synergistic effects of multi-dimensional factors influencing China's energy transition. Notably, China's energy transition mainly lies in the synergistic effects of accelerating the clean energy use and reducing coal emissions. (ii)The main contribution of this work is to investigate the dynamic and

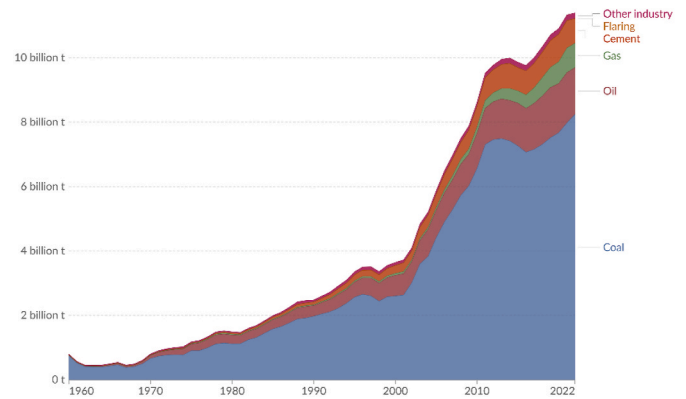


Fig. 1. Historical trend of CO₂ emissions from different sources in China (Sourced from Ref. [7]).

asymmetric nexus over different quantiles between GHGs (CL) and selected determinants. By examining these asymmetric impacts, the study aims to construct effective cointegration equations to analyze the long-run synergistic effects of key drivers on an affordable and just energy transition in China. To this end, this research uses quantile-on-quantile regression (QQR), leveraging the nonlinear property of the variables, and facilitating to display the interplay between variables across different quantiles [12,13]. (iii)This study separately uses the GHGs-based EKC model and the expanded STIRPAT models to illustrate the synergistic effects of multiple dimensions, namely, coal consumption, technology, socio-economic factors, financial elements, policy and governance. (iv) Comprehensive insights highlight that addressing the growing concerns of this transition requires cross-sectoral, collaborative efforts. This helps policymakers and academics understand the energy transition paradigm, paving the way for future policy decision-making. (v) A reliable econometric analysis framework is established in this study to eliminate biased and inconsistent estimates. Specifically, QQR is used to report the asymmetric nexus effects. Fully modified ordinary least squares (FMOLS) is employed to provide cointegration and synergistic effects analysis. Lastly, alternative regression model of robust

Table 1

An overview of China's electricity industry sector.

		2014		2018		2022	
Production (billion kwh)		% total		% total		compared to 2014	
coal power clean energy	Gross	5545.9	–	6162.6	–	10.01 %	19.22 %
		4173.1	75.20 %	4496.3	72.96 %	–2.24 %	–3.55 %
	Hydro	1066.1	19.20 %	1029.7	16.71 %	–2.49 %	–1.92 %
	Nuclear	126.2	2.28 %	263.8	4.28 %	2.01 %	0.67 %
	Wind	156.3	2.82 %	326.8	5.30 %	2.48 %	3.65 %
	solar	231	0.42 %	830.2	1.35 %	0.93 %	1.44 %
total clean			24.72 %		27.64 %		31.49 %
Investment (billion yuan)							
total	gross	776.4		226.2		552.5	
coal	thermal	95.2	12.26 %	67.2	29.71 %	73.6	13.32 %
clean energy	hydro	96	12.36 %	56.9	25.15 %	71.8	13.00 %
	nuclear	56.9	7.33 %	37.8	16.71 %	53.3	9.65 %
	wind	99.3	12.79 %	48.3	21.35 %	151.1	27.35 %
	solar	17.2	2.22 %	16	7.08 %	200	36.20 %
total clean			34.70 %		70.29 %		86.19 %
Consumption (Billion kwh)							
gross		5523.3		6219.9		7858.8	
Residents		692.8	12.54 %	895.2	14.40 %	1210.1	15.40 %
industry sector		3993	72.29 %	4198.3	67.50 %	5096	64.84 %
Technology							
standard coal consumption rate (g/kwh)		318		308		301.5	
transmission line loss rate (%)		6.34		6.21 %		4.84 %	

Note: Data sourced from China Electricity Council [11] and covers January–November for 2018 and 2022.

least squares (RLS) is employed to compare the varying effects and confirm the robustness of the results.

The related literature review and gap analysis are in section 2. The hypotheses and econometrics models are established in section 3. In section 4, data and preliminary test of the study are provided. The results and a discussion are presented in section 5. Finally, conclusions with policy implications and study limitations are provided in section 6.

2. Related literature review and gaps

As the global community confronts the urgent challenges of climate changes and affordable energy, there is an increasing recognition of the need for countries like China to transition towards sustainable energy. Given the rapid expansion of the Chinese economy, population density, high fossil fuels consumption, and significant GHGs, China's resolution regarding energy transition is pivotal. It will also have profound implications for both present and future global energy sustainability, resilience, and associated conditions [14].

One strand of research asserts that China has been a key participant in world energy markets, in particular in terms of its heavy reliance on coal for primary energy production. However, such heavy reliance on coal has also had substantial costs, including environmental degradation, health problems associated with atmospheric pollution, and a large share of GHGs [15]. The IEA [3] reports that China continues to invest substantial amounts in fossil fuels, in particular coal. In spite of the rise in renewable energy capacity, coal continues to be the most dominant energy source in China's energy mix, and coal production is expected to grow to a record high in 2023. While China seeks to ensure that coal-fired power will maintain a supportive role in its energy mix, such developments reflect the country's strong emphasis on energy security, and replacing coal-fired power units with other base-load energy systems such as nuclear power plants seems attractive from an energy security point of view [16,17], though it needs to be mentioned that China is currently dependent on uranium imports [18]. Indeed, many studies have recognized that CO₂ emissions from coal-fired power generation constitute the primary driver of environmental degradation. For example, Steckel and Jakob [19] claim that coal-fired power is the most carbon-intense energy source, emitting up to twice as much CO₂ per kilowatt-hour as natural gas power, which is roughly equivalent to all GHG emissions linked to agriculture and land-based activities in 2019.

On a related note, surging electricity demand will strain global energy supplies, driving prices and emissions to unprecedented levels, which has serious implications for the public, global economies, and transitions [20]. It is notable that coal-fired power generation will reach a new historic high in 2024, as a result of robust growth in the deployment of coal-fired power in developing countries such as India and China, and in the developed economies of the European Union (EU). Also, in the United States, a pioneer in coal phase-out [19], CO₂ emissions from coal combustion accounted for about 20 % of total U.S. energy-related CO₂ emissions and nearly 60 % of total CO₂ emissions from the power sector in 2021 [21]. It is expected that global coal use will decline by 30–70 % by 2030 to comply with the goals set by the 2015 Paris Climate Agreement [19,22]. Thus, assessing the trade-offs between coal and clean energy, as well as examining the complexity of the various drivers and challenges that help shape the energy transition pathways in coal-dominated economies, has received increasing attention.

More importantly, the synergistic effects of key drivers of the energy transition have become a promising and widely addressed theme in many studies. Integrating these drivers and identifying their combined effects is vital for promoting the transition to renewable energy in specific geopolitical and economic conditions [10]. Numerous studies have presented in-depth analyses and helpful policy implications for accelerating the energy transition by including diversified indicators systems. For example, Du et al. [23] contributed greatly to the debate on the nexus between green finance and energy transition by analyzing a

mechanism of transmission effects. This empirical study used a generalized method of moments (GMM) method of based on data from Chinese provinces from 2001 to 2019. The findings illustrate that improved energy efficiency governance and upgraded environmental legislation positively moderate the impact of green finance on China's transition. Sampene, Li and Nsiah [10] carried out a detailed investigation into the factors driving renewable energy deployment in Mercosur countries, by focusing on economic growth, green finance, technology, human capital, government effectiveness, and urbanization. Results indicate that these factors are critical in encouraging renewable energy development in Mercosur, and thus contribute valuable insights for stakeholders, policymakers, and researchers that aim to address the complexities of the transition towards a more resilient and greener energy system. Omri and Ben Jabeur [24] explored the energy transition in the 10 most polluting economies from 1996 to 2019, using various indicators. The findings indicate that clean energy policies and climate change regulations are insufficient on their own to promote the transitions, and financial development and governance practices are critical as well. A combination of these factors helps accelerate the transition.

It is notable that studies consistently highlight the instrumental role of technological innovation in driving renewable energy use and reaching carbon neutrality [23,26]. Østergaard et al. [27] emphasized the importance of developing science and research efforts that address GHG mitigation, particularly through increased reliance on renewable energy sources and the pursuit of required technologies and practices. Behera et al. [25] showed that renewable energy can reduce CO₂ emissions at a steady pace, while green technology exhibits a U-shaped effect on CO₂ emissions in 18 developing countries between 1990 and 2018. Bakry et al. [28] claimed that both finance and renewable energy have a large and negative impact on CO₂ emissions, thus reaffirming the compelling importance of promoting green finance and renewable energy. Su et al. [29] concluded that the impact of renewable energy is notable in reducing environmental degradation; however, technological innovation affects emissions relatively less compared to renewable energy, thereby indicating a rather weak impact in facilitating emissions reduction. As a result, industries are encouraged to raise environmental awareness and foster renewable energy-related technological innovation to accelerate energy structure transition toward a lower carbon footprint.

In summary, the transition to sustainable energy is multidimensional, involving economic, technological, governance, etc. The synergistic effects of these components are imperative to help establish a resilient and greener energy system across the globe, particularly in coal-dominated economies such as China. The combined efforts of finance, technological innovation, and solid policy frameworks produce a robust synergistic effect that can significantly drive the energy transition. These combined solutions not only improve the effectiveness of individual solution, but also establish a comprehensive strategy to address the multiple challenges of energy transition and energy security. Therefore, identifying and leveraging the synergistic effects of these key factors is critical to advancing the energy transition and energy security.

While we have reviewed an extensive body of literature on the energy transition, several gaps in existing studies still need to be addressed. (i) A critical gap in the existing literature lies in the lack of extensive studies that perform a GHGs-based EKC analysis for China's energy transition, and most existing studies do not emphasize that the key to China's energy transition mainly lies in the synergistic effects of accelerating clean energy use and reducing coal emissions. (ii) A notable gap in the existing literature is the lack of a comprehensive analysis of the synergistic effects of multiple factors influencing China's CL. Addressing this gap is crucial for developing an understanding of the drivers and barriers to China's CL. (iii) A significant gap in the current literature lies in the lack of robust econometric studies that capture both asymmetric effects and cointegration associated with China's CL. This research intends to fill these gaps by employing robust econometric analysis, combining the QQR and FMOLS to provide the asymmetric and

cointegration effects analysis. By doing so, the study intends to propose more precise and focused policies that can be adapted to accelerating China's energy transition.

3. Theoretical analyses and methods

3.1. Theoretical analysis

The STIRPAT model proposes a more versatile and statistically precise conceptual model for assessing the socio-economic-environmental linkages. The model presented by Dietz and Rosa [30] disaggregates total environmental pressures into responses from population (P), increases in per capita income (A), and technology (T). In the original STIRPAT model, this can be expressed as equation (1):

$$I_{it} = aP_{it}^b A_{it}^c T_{it}^d e_{it} \quad (1)$$

Several studies have extended the STIRPAT model, incorporating various theoretical and empirical advancements to enhance its explanatory power. Liddle [31] notably integrated the principles of the EKC hypothesis within the STIRPAT framework, proposing an EKC-based STIRPAT model. This integration allows for a useful analysis of how economic development impacts environmental quality. Empirical studies utilizing the EKC typically take the form shown in equation (2):

$$\ln \left(\frac{I}{P} \right)_{it} = \alpha_i + \gamma_t + \beta_1 \ln(A)_{it} + \beta_2 (\ln(A))_{it}^2 + \beta_3 \ln(T)_{it} + e_{it} \quad (2)$$

Mohsin et al. [32] further expanded the EKC-STIRPAT model by incorporating environmental policies (EP), and variables of resources including non-renewables (NR), and renewables (RE), which can be denoted by equation (3)

$$GHGs = \alpha_0 \cdot EP^{\beta_1} \cdot A^{\beta_2} \cdot A^{2\beta_3} \cdot NR^{\beta_4} \cdot RE^{\beta_5} \cdot P^{\beta_6} \quad (3)$$

Sampene et al. [10] developed a mathematical system that shows the synergistic effects of different variables on renewables (REC). This enhancement allows for a more comprehensive analysis of the drivers of REC deployment. The specific equation is shown in equation (4):

$$\ln REC_{it} = K_i + a \ln EP_{it} + b \ln GN_{it} + c \ln TI_{it} + d \ln HC_{it} + a \ln GF_{it} + a \ln UB_{it} + \mu_{it} \quad (4)$$

Where EP (economic expansion), T (technology), GN (green finance), GF (government effectiveness), HC (human capital), UB (urbanization).

This study is inspired by Sampene, Li and Nsiah [10] and Mohsin, Kamran, Atif Nawaz, Sajjad Hussain and Dahri [32], and proposes an extended model 1 (equation (5)) and model 2 (equation (6)) to examine the synergistic effects of various indicators across multiple dimensions for China's energy transition.

Model1. GHGs-based EKC

$$GHGs = \alpha_0 \cdot GDP^{\alpha_1} \cdot GDP^{\alpha_2} \cdot CO^{\alpha_3} \cdot CL^{\alpha_4} \quad (5)$$

Model 2. The synergistic effects of key drivers on China's CL

$$CL = \alpha_0 \cdot GDP^{\alpha_1} \cdot CO^{\alpha_2} \cdot TECH^{\alpha_3} \cdot URG^{\alpha_4} \cdot TAX^{\alpha_5} \quad (6)$$

Based on the results of Models 1 and 2, this study proposes an additional hypothesis: escalating coal emissions counteract China's CL efforts toward achieving carbon neutrality. In addition, technological progress serves as an indispensable catalyst for an effective CL in China. Consequently, Models 3 and 4 are expressed by equations (7) and (8).

Model 3. the synergistic effects on CL: the role of financial development and institutional quality

$$CL = \alpha_0 \cdot CO^{\alpha_1} \cdot TECH^{\alpha_2} \cdot FD^{\alpha_3} \cdot REGU^{\alpha_4} \cdot LAW^{\alpha_5} \quad (7)$$

Model 4. the synergistic effects on CL: the role of environmental governance and regulatory quality

$$CL = \alpha_0 \cdot CO^{\alpha_1} \cdot TECH^{\alpha_2} \cdot IGI^{\alpha_3} \cdot REGU^{\alpha_4} \quad (8)$$

3.2. Econometric methods

3.2.1. Quantile-on-quantile regression (QQR)

Following the empirical method of Quantile-Quantile Regression (QQR) established by Sim and Zhou [33], this study explores the dynamic asymmetric nexus in two main groups: (1) the nexus of GHGs and GDP, CO and CL, and (2) the nexus of CL and its drivers. Our analysis of asymmetric effects across quantiles aims to identify the mechanisms affecting China's GHGs and CL, thus obtaining important insights for establishing cointegration models.

Given that x is the independent variable and γ is the dependent variable, then the QQR model relating the quantile of γ to the quantile of x is defined by equations (9) and (10):

$$\gamma_{ghgs,t} = \beta^\theta(x_{ghgs,t}) + \epsilon_t^\theta \quad (9)$$

$$\gamma_{cl,t} = \beta^\theta(x_{cl,t}) + \epsilon_t^\theta \quad (10)$$

where γ_t denotes a given GHGs or CL in period t , x_t represents the determinants in period t , which refers to (GDP, CO, and CL), and (CO, TECH, TAX, URG, FD, LAW, REGU and IGI). β^θ captures the correlation between γ_t and x_t . ϵ_t^θ is defined as the quantile residual term and its conditional θ -quantile is presumed to be 0. Then, to display the asymmetric nexus, we computed a first order of a quantile of x^r to develop $\beta^\theta(x_t)$, which leads to:

$$\beta^\theta(x_t) \approx \beta^\theta(x^r) + \beta^\theta(x^r)(x_t - x^r) \quad (11)$$

In equation (11), where $\beta^\theta(x^r)$ is the fractional derivative of $\beta^\theta(x_t)$ relative to x_t , referred to be the marginal effect. Furthermore, the functions $\beta^\theta(x^r)$ and $\beta^\theta(x^r)$ can be stated as $\beta_0(\theta, \tau)$ and $\beta_1(\theta, \tau)$, respectively, thus the adjusted equation (12) can be given by:

$$\beta^\theta(x_t) \approx \beta_0(\theta, \tau) + \beta_1(\theta, \tau)(x_t - x^r) \quad (12)$$

Equations (13) and (14) are obtained by substituting equation (12) into equations (9) and (10):

$$\gamma_{ghgs,t} = \underbrace{\beta_0(\theta, \tau) + \beta_1(\theta, \tau)(x_t - x^r)}_{*} + \mu_t^\theta \quad (13)$$

$$\gamma_{cl,t} = \underbrace{\beta_0(\theta, \tau) + \beta_1(\theta, \tau)(x_t - x^r)}_{*} + \mu_t^\theta \quad (14)$$

Where Part (*) of equations (13) and (14) describes the total dependence pattern between γ and x via the dependence of their distributions.

3.2.2. Fully modified ordinary least squares (FMOLS)

The FMOLS estimation procedures consist of a fully asymptotic ordinary mix, which allows for standard Wald tests by utilizing the asymptotic inference of the Chi-square, taking advantage of the prior estimation of the symmetric and the residuals generated by the long-run covariance matrices. The estimator $\hat{\theta}$ is illustrated in equation (15):

$$\hat{\theta} = \begin{bmatrix} \beta \\ \gamma_1 \end{bmatrix} = \left(\sum_{t=2}^T Z_t Z_t' \right)^{-1} \left(\sum_{t=2}^T Z_t v_t^+ - T \begin{bmatrix} \mathbf{X}_{12}^+ \\ 0 \end{bmatrix} \right) \quad (15)$$

where ϑ is followed by the regressors $\mathbf{X}$, and $\hat{\Omega}$ and $\hat{\lambda}$ stand for long-run covariance matrices using the residuals that can be shown as follows:

$$\vartheta_t^+ = \vartheta_t - \hat{\omega}_{12} \hat{\Omega}_{22}^{-1} \hat{u}_2 \quad (16)$$

$$\hat{\lambda}_{12}^+ = \hat{\lambda}_{12} - \hat{\omega}_{12} \hat{\Omega}_{22}^{-1} \hat{\lambda}_{22} \quad (17)$$

$$\mathbf{Z}_t = (\mathbf{X}_t', \mathbf{D}_t') \quad (18)$$

Then, the estimator $\hat{\omega}_{1,2}$ is specified as equation (19)

$$\hat{\omega}_{1,2} = \hat{\omega}_{11} - \hat{\omega}_{12} \hat{\Omega}_{22}^{-1} \hat{\omega}_{21} \quad (19)$$

The benefits of FMOLS are explained by Nguyen et al. [34], which adjusts for possible dynamic heterogeneity associated with the different dimensions of the cross section. when the cointegration is detected, the vectors yield mean regressors. The estimated t-statistics are relatively adjusted to minimize bias.

3.2.3. Robust least squares method (RLS)

RLS methods are designed to minimize the effect of outliers in regression analysis. This study adopts M-estimation and S-estimation. M-estimation techniques, addressing outliers in the GHGs and CL, while S-estimation, which is more computationally intensive, focuses on outliers in the predictor variables with high leverage.

The conventional OLS estimator $\hat{\beta}_{LS}$ is obtained by computing coefficient values that minimize the total of the squared deviations $r_i(\beta)$ between the actual and estimated values:

$$\hat{\beta}_{LS} = \operatorname{argmin}_{\beta} \sum_{i=1}^N r_i(\beta)^2 \quad (20)$$

$$r_i(\beta) = r_i = y_i - \mathbf{X}_i' \beta \quad (21)$$

The M-estimator offers robust regression by replacing the squared residuals with a function that reduces the influence of outliers. This M-estimator calculates coefficients by minimizing the sum of a function ρ applied to the residuals.

$$\hat{\beta}_M = \operatorname{argmin}_{\beta} \sum_{i=1}^N \rho_0 \left(\frac{r_i(\beta)}{\sigma w_i} \right) \quad (22)$$

Where σ represents the scale of residuals and w_i are individual weights, typically set to 1, but can be adjusted as needed.

$$w_i = \sqrt{1 - \mathbf{X}_i' (\mathbf{X}' \mathbf{X})^{-1} \mathbf{X}_i} \quad (23)$$

The S-estimator, a high-breakdown-value estimator, measures robustness to outliers. It determines the coefficients β that minimize the scale S such that:

$$\frac{1}{N-k} \sum_{i=1}^N h_0 \left(\frac{r_i(\beta)}{S} \right) = b \quad (24)$$

The constant b determines the breakdown point. Calculating S-estimates is computationally demanding, but there are several fast algorithms that offer accurate approximations.

4. Data and unit root test

Table 2 shows the sources and measurement of the data, and multidimensional indicators to comprehensively capture the complexity of China's energy transition. First, Du et al. [23] highlighted that no single metric can perfectly capture the shift from fossil fuels to renewable energy. Therefore, following their approach, this study uses the share of clean energy (including nuclear, hydro, and renewables) in total energy consumption to represent the CL. This proxy effectively captures

Table 2

Data measurements and sources.

Abbrev.	Measurement	Source	period
GHGs	Greenhouse Gas Emissions (tCO ₂ e per capita)	[36]	1985–2021
GDP	GDP per capita (international dollars in 2011)	[37]	1985–2022
GDP2	Square term of GDP per capita	[37]	1985–2022
CO	Coal consumption-based emissions: Per capita CO ₂ emissions from coal(tonnes/person)	[7]	1985–2022
CL	Clean energy transition: the share of total of nuclear, hydro and renewables to primary energy consumption (%)	[38]	1985–2022
TECH	Technological progress: patents grants (Unit: piece)	[39]	1995–2022
URG	Urban population growth (%)	[40]	1995–2022
TAX	Environmentally related taxes (%)	[41]	1998–2020
FD	Financial development index	[42]	1995–2021
IGI	Environmental governance: industrial pollution control completed investment (ten thousand yuan)	[39]	2000–2021
REGU	Regulatory quality	[43]	1996–2022
LAW	Rule of law	[43]	1996–2022

the broader trend towards clean energy, despite some limitations in data comprehensiveness. Second, missing data for institutional quality indicators were estimated via linear interpolation, following Rahman and Alam [35], ensuring dataset continuity and completeness. Third, technological progress was quantified by granted patents, using data from China's government sources rather than the World Bank. Finally, the IMF Financial Development Index (FD), evaluating financial institutions and markets on access, depth, and efficiency, was used to gauge financial systems' performance.

Table 3 illustrates the outcome of the unit root test, which was carried out using Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) methodologies. It has been determined that all the variables under inspection are stationary in a first-order difference. Consequently, these variables are integrated of order I (1), rendering them suitable for utilization in the subsequent analysis (see Table 4).

5. Results and discussion

5.1. QQR results

Overall, this study investigates the dynamic asymmetric nexus within two primary groups: (1) the nexus between GHGs and specified drivers, and (2) the nexus between CL and main drivers. As shown in Figs. 2 and 3 the three-dimensional graphs of the QQR provide estimates of the slope coefficient, and display how the quantiles of drivers (independent variables) relate to the quantiles of GHGs and CL.

5.1.1. Asymmetric nexus between GHGs and GDP, CO and CL

Our investigation into the GDP-GHG nexus reveals that among the 361 (19 × 19) area combinations analyzed, 95.84 % display a positive

Table 3

ADF and PP test.

variables	ADF			PP		
	Prob.	c,t	result	Prob.	c,t	result
D(CL)	0	c,t	Stationary	0.0002	c	Stationary
D(CO)	0.0793	c	Stationary	0.0707	c	Stationary
D(GDP)	0	c,t	Stationary	0	c,t	Stationary
D(GHGs)	0.0653	c	Stationary	0.0913	none	Stationary
D(IGI)	0.0013	c,t	Stationary	0.0046	c	Stationary
D(TECH)	0.0538	c	Stationary	0.0106	c	Stationary
D(REGU)	0.0083	c	Stationary	0.0001	c	Stationary
D(TAX)	0.0833	c	Stationary	0.003	c	Stationary
D(URG)	0.0036	c	Stationary	0.0009	c	Stationary
D(FD)	0.0006	c	Stationary	0	c	Stationary
D(LAW)	0.0132	c	Stationary	0	c	Stationary

Note: c, constant, t, trend.

Table 4

Cointegration test results for model 1–4.

		lag	Value	Prob.*
Mode 1	E-G tau-statistic	1	−4.9081	0.0429
	E-G z-statistic	1	−51.3523	0.0000
Model 2	E-G tau-statistic	0	−5.4485	0.0548
	E-G z-statistic	0	−25.0909	0.0620
Model 3	E-G tau-statistic	0	−5.9271	0.0104
	E-G z-statistic	0	−29.6224	0.0065
Model 4	E-G tau-statistic	0	−6.0405	0.0174
	E-G z-statistic	0	−29.6218	0.0191

Note: Cointegrating equation includes c; Null hypothesis: Series are not cointegrated.

correlation, while only 4.16 % show a negative correlation. The negative impacts are mainly observed in the lower quantiles (0.05–0.15) of both GDP and GHG emissions, with an average value of 0.972 (Fig. 2a). The asymmetric nexus between CO and GHGs, as illustrated in Fig. 2b, consistently indicates a positive correlation. The average effect of CO on GHGs across the 361 area combinations is approximately 1.25. Significantly, at the 0.95 quantile, CO demonstrates its most substantial positive impact on GHGs, with a value of 1.712 within the 0.3 to 0.55 quantile range. The findings highlight the urgent necessity to transform coal-fired power plants to low-carbon energy production. Fig. 2c depicts the influence of CL on GHGs in China. The overall effect of CL on GHG emissions is mainly negative, with substantial variation across different quantiles. The slope coefficient ranges from −1.41 to 2.11. Among the 361 area combinations, 93.91 % exhibit a negative relationship, only 6.19 % show a positive correlation. The most notable positive impact of

CL on GHGs occurs when low to middle quantiles (0.05–0.55) of CL align with higher quantiles (0.65–0.95) of GHGs. The most extreme negative effect is observed between the 0.1 to 0.95 quantiles for CL and the 0.95 quantile for GHGs, with an average value of −1.08 and a maximum negative value of −1.41. The findings indicate that the increased CL has contributed to GHGs mitigation in China, a trend evident over long, medium, and long-term periods. Given China's energy structure, which is heavily dependent on coal, it is vital to accelerate the low-carbon transition of coal-reliant industry sectors.

It can be concluded that the increase in CL has significantly contributed to mitigating GHGs in China. This trend is evident across short, medium, and long-term horizons, confirming the argument that, given that China's energy structure heavily relies on fossil fuels, especially coal, it is crucial to accelerate the low-carbon transition of the energy system swiftly. Increasing the proportion of clean energy in the future energy supply is imperative. Despite notable progress in the clean energy use, China's carbon neutrality goal still faces substantial challenges. Advanced technologies and greater investment are essential for driving this extensive and profound systemic reform in China's economy and society. These changes will simultaneously create significant economic opportunities and geopolitical advantages [44].

5.1.2. Asymmetric nexus between CL and key drivers

5.1.2.1. CO-CL. Fig. 3a illustrates the asymmetric effect of CO on CL. The slope coefficient ranges from −1.67 to 1.27, indicating that the impact of CO on CL is predominantly negative, with 70.64 % of the effects being negative and 29.36 % positive. A substantial negative

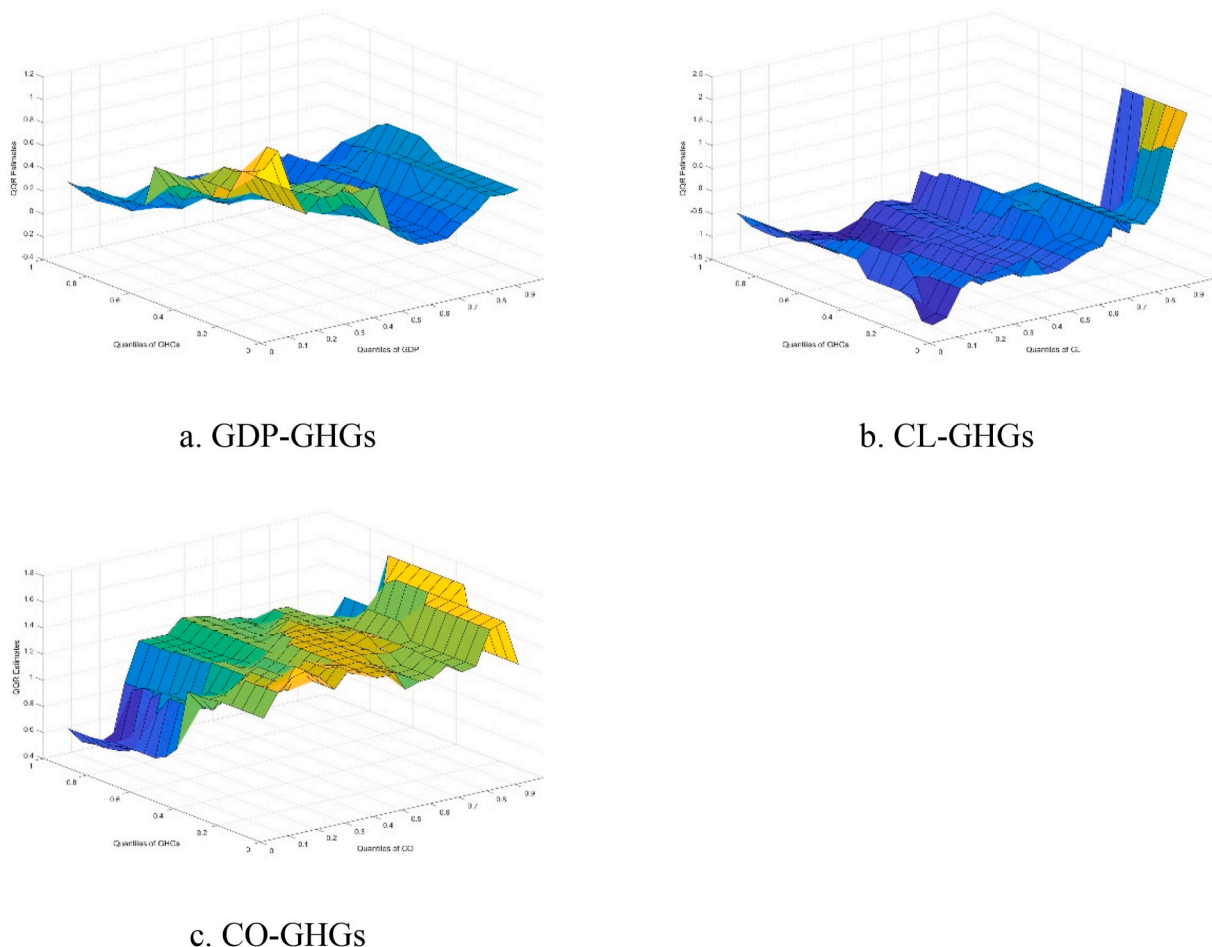
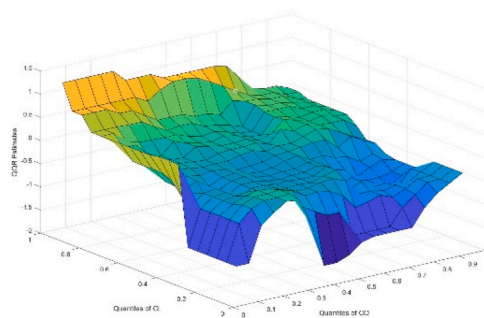
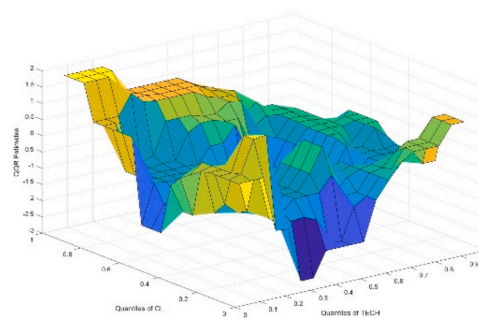


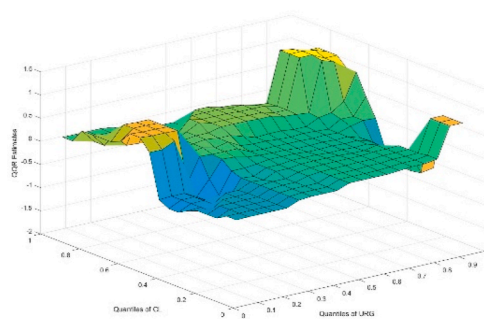
Fig. 2. (a–c). results of QQR: Responses of GHGs to GDP, CL and CO.



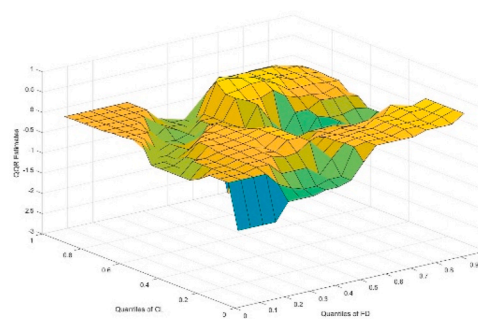
a CO-CL



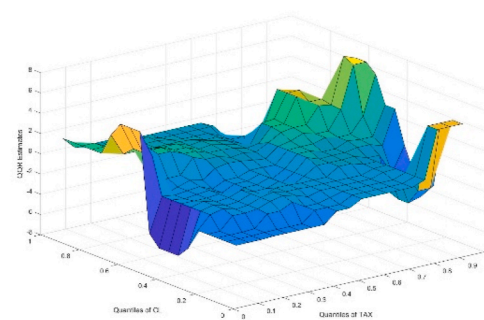
b TECH-CL



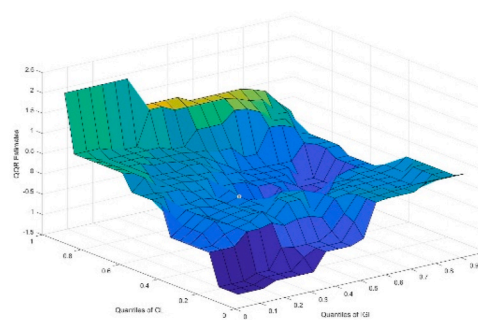
c URG-CL



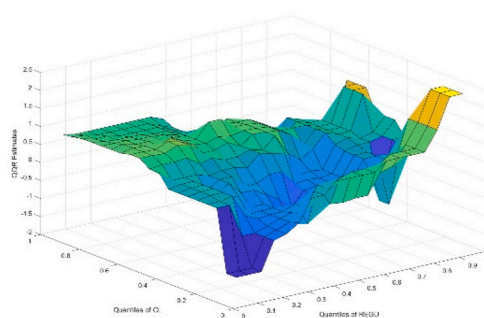
d FD-CL



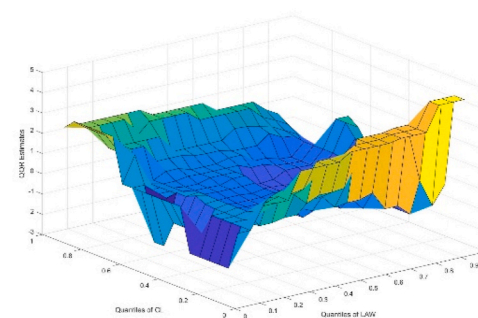
e TAX-CL



f FIGI-CL



g REGU-CL



h LAW-CL

Fig. 3. (a–h). results of QQR: Responses of CL to its drivers.

association between CO and CL is observed across the lower to upper quantiles (0.05–0.95) of CO and the upper quantile (0.95) of CL, with an average value of -0.94 . The most negative value (-1.67) appears between the 0.4–0.45 quantile of CL and the 0.05 quantile of CL. These results demonstrate that from low to upper quantiles of CO, there is a negative impact on CL across most quantiles. Positive effects of CO on CL are rare and are observed when combining the 0.05–0.9 quantiles of CO with the 0.9 quantile of CL. However, these positive effects are weak, with an average positive value of 0.72. The most significant positive effect is found when combining the 0.05–0.25 lower quantiles of CO with the 0.95 quantile of CL, yielding a value of 1.27.

Most importantly, the findings reveal that the expansion of CO appears to counteract GHGs mitigation effects of China's CL. In the long term, as the power sector transitions towards decarbonization, the role of coal in the clean energy transition may become increasingly significant. For instance, coal generates over 60 % of the electricity used for global solar PV manufacturing, which is significantly higher than its share in global power generation (36 %) [45]. Therefore, China's CL must emphasize the clean and efficient utilization of coal resources, promote the low-carbon transformation of coal-fired power, and advance the use of clean energy.

5.1.2.2. TECH-CO. Fig. 3b depicts the asymmetric impact of TECH on CL. The slope coefficient ranges from -2.83 to 1.27 , indicating that the effect of TECH on CL is predominantly negative, with negative effects observed in 72.3 % and positive effects in 27.7 %. Negative effects are particularly evident in areas where medium quantiles (0.4–0.65) of TECH correspond to all quantiles (0.05–0.95) of CL, with an average effect coefficient of -0.75 . Although these negative effects span a wide range of CL quantiles, the positive effects are more pronounced at the quantiles (0.05–0.45) of TECH. Specifically, the most substantial positive effect is observed when low to medium quantiles (0.05–0.45) of TECH are combined with upper quantiles (0.85–0.95) of CL, yielding an average impact coefficient of 1.38.

Our findings indicate that TECH cannot drive the transition independently. Rather than focusing on the TECH-CL nexus, integrating multiple variables is indispensable to produce positive synergistic effects of TECH on China's CL. In this regard, TECH is usually used as an indispensable variable in transitions analysis.

5.1.2.3. URG-CL. Fig. 3c shows that the effect of URB on CL is predominantly positive, with positive effects observed in 62.88 % of the cases and negative effects in 37.12 %. While the positive effects of URB span a wide range of CL quantiles, negative effects are evident in specific areas. Notably, negative effects are pronounced when high quantiles (0.8–0.95) of URB are combined with high quantiles (0.85–0.95) of CL, with an effect coefficient of -1.708 .

These findings help reconcile the contrasting results from various literatures, some of which report negative effects while others report positive effects. This result highlights the importance of fostering sustainable urban development amidst rapid urbanization and climate change for China. Chinese cities are actively pursuing green initiatives. Notably, the promotion of electric vehicles in recent years has shown significant progress. This alignment with urban sustainability goals leverages technology-driven approaches to stimulate China's CL.

5.1.2.4. FD-CL. Fig. 3d illustrates the effect of FD on the CL. The slope coefficient of the FD-CL ranges from -2.89 to 0.51 , indicating a predominantly negative effect, observed in 70.08 % of the combinations. Specifically, a significant negative effect (-2.89) is found when upper quantiles (0.7–0.95) of FD are paired with the upper quantile (0.95) of CL. Positive effects are observed in 29.91 % of the cases, with the most substantial positive effect (0.51) occurring when low quantiles (0.7–0.95) of FD are combined with the upper quantiles (0.7–0.9) and (0.05–0.25) of CL.

These findings suggest that while FD can promote the CL in China, it often fails to do so independently during the period from 1996 to 2022. This result partially aligns with the argument that higher levels of foreign direct investment (FDI) help achieve lower CO₂ per capita emissions, while financial liberalization may be detrimental without a strong institutional quality. Consequently, in subsequent cointegration studies, we aim to use institutional quality indicator to illustrate how the evolution of FD can contribute to China's CL.

Most importantly, this result reveals that financial development does not always prioritize CL. For instance, investment in coal supply is expected to rise by 10 % in 2024. Although investment in new coal-fired power plants is on a declining trend, a notable exception occurred in 2022, with 40 GW of new coal plants approved—the highest figure since 2016. Almost all these approvals were in China, reflecting the high priority to energy security following severe electricity strains in 2021 and 2022, even as China continues to deploy multiple low-carbon technologies at scale [3].

5.1.2.5. TAX and CL. Environmental taxes play a pivotal role in promoting energy transition, but they also pose certain challenges. Analyzing the positive and negative effects of environmental taxes on China's CL reveals that 55.4 % of the total area combinations exhibit positive effects, while 44.6 % exhibit negative effects. As shown in Fig. 3e, the slope coefficient for TAX-CL ranges from -5.57 to 5.2 , with negative effects observed in 54.8 % of the combinations. Specifically, significant negative effects are observed in the lower quantiles (0.05) of TAX when combined with the upper quantiles (0.55–0.65) of CL. Conversely, positive effects are observed in 44.3 % of the combinations, with the most substantial positive effect occurring when lowest quantile 0.05 of TAX are coupled with the quantiles (0.35–0.45) of CL.

This dominantly positive effects can be explained as followings: (i) Higher tax revenue from polluting activities allows countries to modernize their energy structures, shifting towards cleaner sources. (ii) Stricter environmental taxes on fossil fuels are crucial for sustainability, with revenue supporting environmental programs. (iii) Environmental taxes drive CL by increasing costs for polluters, synergizing with green financial policies, economic complexity, and globalization for a sustainable energy transition in China [46].

5.1.2.6. IGI -CL. Fig. 3f illustrates the impact of IGI on CL. The slope coefficient ranges from -1.3 to 2.017 , indicating very close positive and negative effects. Positive effects are observed in 48.75 % of the total area combinations, while negative effects are observed in 51.25 %. The most substantial positive effect is evident when low to medium quantiles (0.05–0.7) of IGI are combined with the upper quantiles (0.85–0.95) of CL. Conversely, the most negative impact occurs when low quantiles (0.05–0.15) of IGI are combined with low quantiles (0.05–0.61) of CL, with an extremely negative value of -1.3 .

This close positive and negative impacts suggests that while IGI can significantly enhance China's CL in specific contexts, this stimulation does also not work under different conditions. These findings highlight the necessity to maximize the positive impacts of environmental governance investment, and that policymakers must identify the conditions under which IGI is more effective and develop their strategies for sustainable CL.

5.1.2.7. Institutional quality and CL. Fig. 3g-h reveal significant discrepancies in the quantile effects of the quality of governance (REGU and LAW) on China's CL. The impact of LAW on CL ranges from -1.5 to 4.48 and is predominantly positive, with 51.8 % of the 361 (19×19) area combinations showing positive effects. While, the impact of REGU on CL varies from -1.514 to 2.36 , with 72.6 % of the area combinations exhibiting positive effects.

A notable positive impact of LAW on CL is observed when the upper quantiles (0.85–0.95) of LAW are combined with the lower quantiles

(0.1) of CL, yielding the most positive value of 4.48. Positive effects are also obvious when high quantiles (0.85–0.95) of LAW are combined with lower quantiles (0.1) of CL, indicating significant positive impacts of LAW correlated with lower quartiles of CL.

In comparison, the positive effects of REGU on CL are less pronounced. The highest positive impact of REGU (2.36) occurs when high quantiles (0.95) of REGU are combined with lower quantiles (0.1–0.15) of CL. Therefore, higher quantiles of both LAW and REGU governance indicators are more likely to contribute to the lower quantiles of China's CL. These findings suggest that robust governance, particularly at higher levels, play a crucial role in promoting China's CL, emphasizing the need for strong institutional frameworks and effective policy implementation to maximize the benefits of governance on clean energy initiatives.

5.2. Cointegration analysis

5.2.1. Cointegration test

Cointegration tests are useful for identifying instance where two or more time-series that are non-stationary are sufficiently integrated to avoid a deviation from a long-run equilibrium state. This study performs the Engle-Granger test to examine the cointegration linkages between GHGs (or CL) and key drivers. This test utilizes the Tau-Statistic and z-statistic to confirm the existence of cointegration. All statistical values obtained reject the null hypothesis of no cointegration, and indicate the presence of a cointegration relationship for model 1–4.

5.2.2. Results of model1 (GHGs based-EKC)

Numerous studies have explored the Environmental Kuznets Curve (EKC) hypothesis, which suggests an inverted U-shaped relationship between environmental degradation and per capita income. In this section, we investigate the interplay between income per capita and its square term, CO, CL, and GHGs in China using GHGs based-EKC model covering the period from 1985 to 2021.

As shown in Table 5 panel a, FMOLS results indicate a positive and significant long-term coefficient between economic growth and GHGs. This reveals that a 1 % increase in per capita income causes a 1.16 % rise in GHGs, while a 1 % increase in GDP2 results in a 0.44 % reduction in GHGs. Moreover, we observed that a 1 % increase in CO results in a 0.55 % rise in GHGs in the long run, while the long-term relationship between GHGs and China's CL shows a statistically significant negative response, indicating that a 1 % increase of CL leads to a 0.13 % decrease in GHGs over the long term.

This finding enriches the existing literature by affirming the validity of the GHGs-EKC model for China. It also illustrates the effects of GDP and primary energy (coal and clean energy sources) consumption on China's GHGs, and China's GHGs increase with income per capita at lower income levels but gradually decrease at higher income per capita stages during the 1985–2021. In addition, this result highlights the linkage between long-term environmental degradation and the persistent adverse effects of coal use (e.g. power generation, industrial use, heating, and coking). Thus, reducing coal-based emissions and promoting the deployment of clean energy are the key components of China's energy transition pathway.

Subsequently, we proceeded to conduct an impulse response function (IRF) analysis based on a long-run cointegration vector autoregression (VAR). A bootstrapping technique with 999 repetitions was employed to determine the 95 % confidence interval bands. Fig. 4 illustrates the dynamic relationships between GHGs and drivers, namely, GDP, GDP2, CL and CO. The response of GHGs to GDP exhibits a positive trend with an increasing pattern until the 12th year, followed by a consistent intensity up to the 9th year. The squared term of GDP2 significantly decreases, exhibiting a strong negative impact, thus validating our FMOLS results and supporting the GHG-based EKC pattern.

Moreover, the connections between CO and GHGs and CL and GHGs confirm that CO has a strong stimulation impact and that GHGs are very sensitive to fluctuations in CO (spanning 2-7th year), while a one-

Table 5

FMOLS results.

Panel a: Model1				
Variable	Coef.	Std.	t-Stat.	P-value
GDP	1.1639	0.1954	5.9570	0.0000
GDP2	-0.0444	0.0116	-3.8153	0.0006
CL	-0.1315	0.0496	-2.6499	0.0126
CO	0.5515	0.0414	13.3132	0.0000
C	-6.0135	0.8891	-6.7637	0.0000
R-squared	0.9987	Long-run variance		0.0002
Panel b: Model2				
GDP	1.1762	0.0867	13.5590	0.0000
TECH	0.1150	0.0392	2.9347	0.0097
URG	0.2123	0.0964	2.2029	0.0426
CO	-1.0271	0.0519	-19.7886	0.0000
TAX	0.0634	0.0152	4.1704	0.0007
C	-15.1816	0.5538	-27.4152	0.0000
R-squared	0.9817	Long-run variance		0.0004
Panel c: Model3				
TECH	0.3539	0.0350	10.1209	0.0000
CO	-0.8939	0.0981	-9.1093	0.0000
FD	0.8706	0.2193	3.9704	0.0008
REGU	0.4662	0.1398	3.3348	0.0035
LAW	0.2696	0.1061	2.5407	0.0199
C	-8.0590	0.8489	-9.4937	0.0000
R-squared	0.9668	Long-run variance		0.0031
Panel d: Model4				
IGI	0.9035	0.1135	7.9581	0.0000
CO	-1.5166	0.0962	-15.7575	0.0000
TECH	0.1295	0.0514	2.5178	0.0209
REGU	0.2473	0.0731	3.3815	0.0031
C	-13.7612	0.6818	-20.1825	0.0000
R-squared	0.9904	Long-run variance		0.0010

standard deviation shock in CL results in a significant and persistent negative impact on GHGs, highlighting the role of clean energy use in mitigating China's GHGs. Finally, Fig. 4 also shows the dynamics of the nexus of the CL-CO and GDP-CL. Notably, there is a significant spike in the CL-CO nexus during the 2nd to 3rd year, followed by a long-term stable positive influence on GHGs. A standard deviation impact of CO triggers a substantial increase response in CL during the initial 2–3 years, which then shifts to a significantly negative response after the 3rd year. This pattern is likely to demonstrate an asymmetric impact, further validating the appropriateness of asymmetric analysis for this study.

5.2.3. Synergistic effects on CL: the expanded STIRPAT model2

As shown in Table 5 panel b, the FMOLS estimation of Model 2 reveals that GDP positively correlates with China's CL with the highest elasticity, and a 1 % rise in income per capita contributes China's CL by 1.176 %. While a large negative elasticity of CO and China's CL are −1.027, implying that a 1 % increase in coal consumption-based emissions is associated with an 1.027 % decrease in China's CL. The results imply that the growth of income per capita is the key driver of the deployment of China's clean energy. This finding is broadly consistent and confirms hypothesis 2 of a negative correlation between CO and China's CL, and that efforts to reduce coal emissions and accelerate China's CL are mutually reinforcing. Reducing coal emissions is a key component of achieving China's CL. Moreover, the disparity of the magnitude of coefficients mainly originated from the aggregate effects from variables inclusion in model 2–4, implying developing comprehensive tactics to address CO-CL nexus to ensure the successful achievement of a sustainable energy future.

A moderate elasticity of 0.115 for the nexus of TECH-CL, demonstrating the critical role of technological progress as a key driver in this synergistic framework. Investment in research and development of clean energy technologies is crucial for maintaining long-term growth and ensuring an affordable and just energy transition in China. Despite the

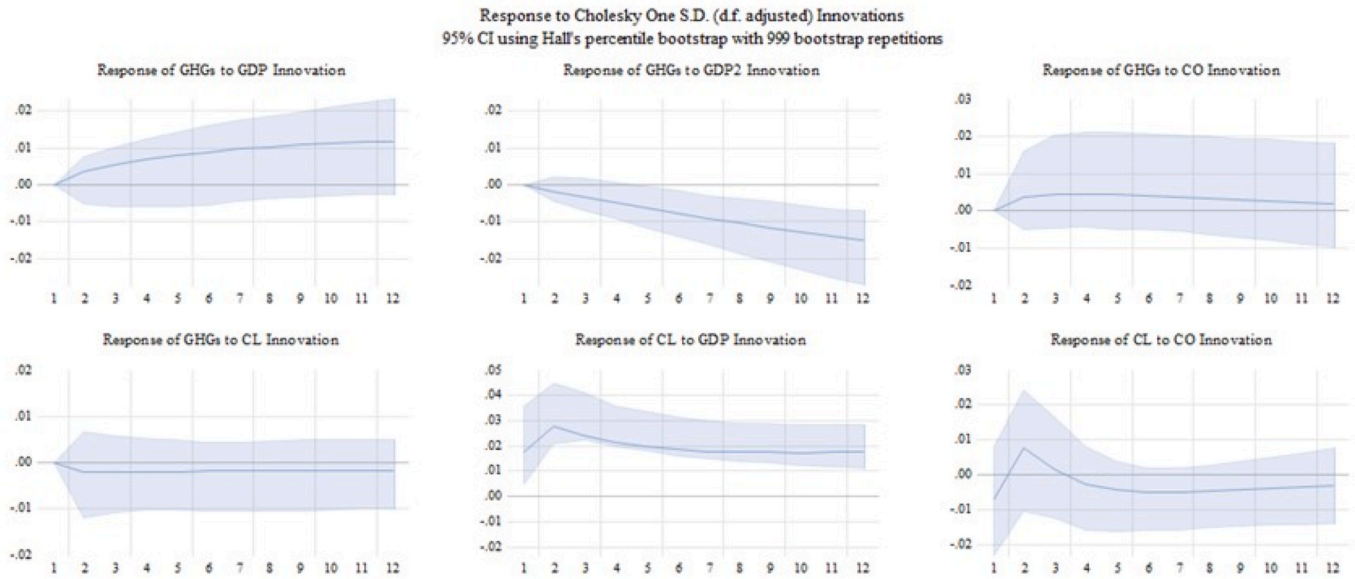


Fig. 4. Impulse response function (IRF) analysis for the GHGs based-EKC model.

relatively low elasticity coefficient of TAX-CL nexus (0.063), the results indicate that a 1 % increase in TAX corresponds to an approximately 0.063 % increase in the transition towards clean energy sources, highlighting the increased sensitivity of CL to fiscal policy incentives. These findings emphasize the importance of sustained and stringent environmental tax policies to foster environmental sustainability and accelerate the adoption of renewable energy technologies in China's energy transition.

Finally, as shown in Table 5 panel b, the estimation results yield a long-run elasticity of 0.212 for the relationship between URG and CL in model 2. This elasticity indicates that a 1 % increase in urban population growth is associated with a 0.212 % increase in clean energy adoption over the long term. This result indicates that urban development facilitates access to clean energy infrastructure and technologies, further supporting China's CL. Indeed, China has implemented several comprehensive policies to facilitate the CL in cities, and these initiatives are part of China's broader strategy to achieve carbon neutrality by 2060 and position China's cities as centers of sustainable urban development. For example: smart grids and energy management systems; electric public transport, etc.

5.2.4. The synergistic effects on CL: the role of financial development and institutional quality

In the model 3 synergistic effects framework, FD plays a pivotal role in advancing China's CL, with a high positive elasticity value of 0.871 (Table 5 panel c). This indicates that a 1 % increase in FD leads to a substantial impact of 0.871 % increase in facilitating China's CL. A solid financial sector helps ensure access to essential funding and capital for clean energy technology and infrastructure expansion. For a rapidly industrializing and expanding economy like China, the necessity of comprehensive financial development becomes even more crucial.

As shown in Table 5 panel c, regulatory quality, with an elasticity of 0.466, plays a crucial role in fostering a conducive environment for clean energy initiatives through effective policies and frameworks. Similarly, the rule of law, with an elasticity of 0.27, contributes to the clean energy transition by ensuring robust legal frameworks and enforcement mechanisms essential for protecting investments and building trust in the clean energy market. These findings underscore the importance of good governance in advancing China's clean energy transition. Strengthening governance structures can significantly contribute to sustainable development.

The distinct elasticity values of REGU and LAW highlight their unique roles in promoting China's CL. High-quality regulations significantly boost clean energy use by reducing market barriers, providing clear guidelines, and facilitating the adoption of clean technologies. A robust legal system, while fostering confidence and enforcement, has a relatively lesser impact on CL compared to regulatory frameworks. These findings also suggest a complementary interaction between REGU and LAW in this system. Effective government policies and regulations support private sector growth and encourage clean energy investments, resulting in a higher long-run elasticity value. Meanwhile, rule of law provides predictability and enforcement, creating a sound legal environment. However, the regulatory framework directly affects the viability and efficiency of clean energy investments, making it a more significant factor in promoting China's CL.

In the synergistic effects framework of Model 3, the critical variables of CO and TECH also demonstrate significant relationships with CL. The high negative correlated between CO and CL, with an elasticity of -0.894 , is slightly less intense than in model 2. Whereas, TECH appears to exert a stronger influence on CL than in model 1, where the coefficient of elasticity is 0.354.

These insights highlight the importance of a comprehensive and integrated policy approach to effectively drive China's CL. Strategies to reduce coal emissions, promote technological advancements, enhance financial development, improve regulatory quality, and strengthen the rule of law are recognized as having synergistic effects in achieving a sustainable and clean energy future for China.

5.2.5. The synergistic effects on CL: the role of environmental governance and regulatory quality

In the synergistic effects framework of Model 4, Environmental governance, especially when combined with regulatory quality, clearly contributes to China's CL as shown in Table 5 panel d. Environmental governance, with a high positive elasticity of 0.904 %, is revealed as a key driver in facilitating China's CL. On the other hand, REGU, with an elasticity coefficient of 0.247 %, is identified as a key factor in advancing China's CL by establishing a stable regulatory environment for clean energy initiatives. Moreover, the highest negative correlated between CO and CL, with an elasticity of -1.566 , is the strongest negative impact on CL among all models 2-4, while TECH appears to exert a stronger influence on CL than in model 1, but less than in model 2, where the coefficient of elasticity is 0.13 %.

In brief, the findings indicate that effective CL strategies involve focusing on reducing coal emissions, encouraging technological innovations, enhancing environmental governance, and improving regulatory quality. The synergistic effects between environmental governance and regulatory quality enhances the impact of both factors, developing an integrated policy-design mechanism combining strong environmental governance with high regulatory quality that is crucial for achieving a sustainable and clean energy future for China. More importantly, the synergistic effect of these drivers on CL underlines the need for developing an integrated strategies towards environmental governance initiatives coupled with robust regulatory quality to accelerate transition for China towards a sustainable and clean energy future.

5.3. Robustness analysis

Robust least squares(RLS) are commonly used due to their robustness against outliers and model misspecification, making RLS suitable for analyzing complex aggregate systems. RLS can handle outliers efficiently and provide better predictive performance, even when traditional regression assumptions are violated.

As shown in Table 6, by comparing the estimates of coefficients, standard errors, and overall model fitness across different model specifications (model 1–4), all of the elasticity values are in line with the same sign of the coefficients but display a different magnitude of the effects in regards to FMOLS results.

Moreover, as shown in Table 6, the R-squared statistics indicate that all model 1–4 explain a substantial portion of the variance in the dependent variable. For example, Model 1 with a scaling factor of 0.0162 has an R^2 of 0.8900, while Model 4 with a scaling factor of 0.0424 has an R^2 of 0.9093. This suggests that each model 1–4 supports a good fitness, explaining around 89 % to nearly 91 % of the changes in the GHGs and CL. Moreover, when comparing the R^2 values between different models, we can observe that Model 2, with a scaling factor of 0.0309, appears to have the highest explanatory power, followed by Model 1 and Model 4. Model 3, with a scaling factor of 0.0595, has the lowest R-squared value among the four models. This suggests that increasing the scaling factor beyond 0.0309 may not necessarily improve model performance and may even lead to overfitting or increased sensitivity to outliers.

Overall, the results suggest that all four models provide a good fit to the data, with Model 2 exhibiting the best performance in terms of explanatory power. While increasing the scaling factor can improve model performance to some extent, it should be done carefully to avoid overfitting and increase sensitivity to outliers. The choice of the scaling factor depends on the specific context and the research question at hand, and it is recommended to experiment with different values to find the optimal balance between bias-variance tradeoffs and robustness.

Furthermore, in another robust analysis of the FMOLS results, the stationarity ADF test for the obtained residuals series are provided in Table 7. This test results reject the null hypothesis and conclude that the residual series are all stationary. The robust properties demonstrate that the residuals are stationary and can provide evidence that the model is well-specified, and that there are no significant unobserved variables affecting the dependent variable. This result supports the validity and robustness of the FMOLS estimates, indicating that they can be relied upon for further analysis and inference.

6. Conclusion and policy implications

The study presents a systematic assessment of China's energy transition pathway, focusing on the synergistic effects of key drivers and contributing important insights for guiding future policies and strategies. The main conclusions, which are obtained by means of a robust econometric framework, are outlined below.

(i)QQR results identified the diverse impacts of various drivers on China's GHGs and CL across different quantiles. Analyzing these

Table 6
RLS results.

Model 1:				
Variable	Coef.	Std.	z-Stat.	P-value
GDP	0.9935	0.1856	5.3517	0.0000
GDP2	−0.0383	0.0113	−3.3967	0.0007
CL	−0.0852	0.0490	−1.7385	0.0821
CO	0.5930	0.0405	14.6474	0.0000
C	−4.9167	0.8285	−5.9347	0.0000
Robust Statistics				
R-squared	0.8900	Adjusted R-squared		0.8763
Rw-squared	0.9992	Adjust Rw-squared		0.9992
Akaike info criterion	34.7136	Schwarz criterion		47.0227
Deviance	0.0076	Scale		0.0162
Rn-squared statistic	30813.9643	Prob.		0.0000
Model2				
GDP	0.8993	0.0928	9.6874	0.0000
TECH	0.3175	0.0417	7.6110	0.0000
URG	0.4544	0.1041	4.3631	0.0000
CO	−1.1855	0.0533	−22.2548	0.0000
TAX	0.0364	0.0150	2.4213	0.0155
C	−14.7019	0.5870	−25.0474	0.0000
Robust Statistics				
R-squared	0.9264	Adjusted R-squared		0.9047
Scale	0.0309	Deviance		0.0010
Rn-squared statistic	6381.7985	Prob.		0.0000
Model3				
FD	0.8227	0.1347	6.1091	0.0000
TECH	0.3633	0.0196	18.5824	0.0000
CO	−1.0096	0.0595	−16.969	0.0000
REGU	0.6839	0.0816	8.3825	0.0000
LAW	0.4833	0.0566	8.5432	0.0000
C	−9.6862	0.5110	−18.9569	0.0000
Robust Statistics				
R-squared	0.8555	Adjusted R-squared		0.8194
Scale	0.0595	Deviance		0.0035
Rn-squared statistic	2943.5180	Prob.		0.0000
Model4				
IGI	0.9625	0.1190	8.0914	0.0000
TECH	0.1196	0.0538	2.2243	0.0261
CO	−1.6131	0.1008	−16.0014	0.0000
REGU	0.2141	0.0765	2.7980	0.0051
C	−14.0633	0.7395	−19.0170	0.0000
Robust Statistics				
R-squared	0.9093	Adjusted R-squared		0.8912
Scale	0.0424	Deviance		0.0018
Rn-squared statistic	3194.2878	Prob.		0.0000

asymmetric impacts reveals the evolving bidirectional effects, thereby unveiling the dynamic causal linkages influencing China's GHGs and CL. The results also provide a solid foundation for constructing cointegration equations to investigate the dynamic synergistic effects of these variables on China's energy transition.(ii)This study validates the GHGs-EKC and reinforces the long-term environmental degradation associated with persistent coal emissions. Reducing coal emissions and supporting clean energy deployment are both critical to advancing China's energy transition pathway.(iii)Escalating coal emissions hinder China's CL efforts aiming to achieve carbon neutrality. Advances in technology also serve as an indispensable catalyst for China's effective CL.(iv)The favorable effects of URG and TAX on China's CL are manifested in the enhanced STIRPAT model.(v)The robust beneficial effect of FD on CL is confirmed in the synergistic effects framework (model 3), where a 1 %

Table 7
ADF test for the residuals from model1-4.

		t-Statistic	P-value
Model 1: ADF stat.		-4.1561	0.0026
Test critical values:	1 % level	-3.6329	
	5 % level	-2.9484	
	10 % level	-2.6129	
Model 2: ADF stat.		-4.6644	0.0015
Test critical values:	1 % level	-3.7880	
	5 % level	-3.0124	
	10 % level	-2.6461	
Model 3: ADF stat.		-6.3482	0.0000
Test critical values:	1 % level	-3.7379	
	5 % level	-2.9919	
	10 % level	-2.6355	
Model 4: ADF stat.		-5.9920	0.0001
Test critical values:	1 % level	-3.7529	
	5 % level	-2.9981	
	10 % level	-2.6388	

growth in FD leads to a 0.871 % improvement in China’s CL.(vi)Both environmental governance and regulatory quality synergize to affect China’s CL.

Taken together, these findings strengthen the argument that coordinating the synergistic effects of these key drivers and enhancing measures can help promote China’s energy transition and its pursuit of sustainable development goals.

China’s energy transition towards both energy security and carbon neutrality requires a diversified and integrated energy policy solution. Reducing long-lasting environmental degradation calls for strong regulations and supporting cleaner coal technologies to drastically reduce coal emissions. Strengthening the deployment of clean energy sources such as solar, wind and hydro projects by increasing both investment and financial incentives helps to accelerate this transition. Prioritizing technological innovation by fostering research and development in energy-saving technologies and progressive industrial practices is fundamental. The synergies of strong environmental governance and good regulatory quality will foster an inclusive policy environment for the deployment of clean energy, placing an emphasis on stringent enforcement and regulatory transparency. Facilitating financial development to invest in renewables using instruments such as green bonds and low-interest loans is essential. Embedding sustainable energy solutions in urban development and fiscal policies, particularly in urban planning and green building initiatives, will further promote the deployment of clean energy. Lastly, adopting a more integrated policy that considers the synergistic effects of socio-economic, technological, policy, and governance drivers will ensure that these strategies are mutually reinforcing. Synergistic effects drive clean energy collaboration across the public, private, and academic spheres in China, facilitating joint development and implementation of solutions to accelerate China’s energy transition.

CRedit authorship contribution statement

Binlin Li: Conceptualization, Methodology, Investigation, Validation, Data collection, Formal analysis, Visualization, Funding acquisition, Writing – original draft. **Mohammad Mafizur Rahman:** Conceptualization, Methodology, Investigation, Validation, Data collection, Formal analysis, Writing – review & editing. **Nils Haneklaus:** Investigation, Formal analysis, Funding acquisition, Writing – review & editing.

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.

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