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The role of renewable energy in mitigating carbon emissions: Insights from China's energy consumption patterns

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ABSTRACT

China's rapid economic growth has made it the world's largest carbon emitter, creating urgent environmental challenges that require immediate attention. As urbanization advances, so does the energy demand, with a large proportion of that energy being provided by fossil fuels, which has further escalated carbon emissions. The resulting increase in carbon emissions poses a serious threat to global climate stability and requires immediate action to mitigate its impact on the environment. The urge to reduce environmental effects has called for solutions, such as a shift to renewable energy. Thus, this study aims to establish the relationship between renewable energy consumption, economic growth, fossil fuel use, urbanization, industrialization, and carbon emissions in China from 1990 to 2022. We explore these variables using Autoregressive Distributed Lag (ARDL) and nonlinear symmetrical estimation methods. These findings suggest that carbon emissions are positively linked to fossil fuel use, economic growth, urbanization, and industrialization, indicating that these determinants play a significant role in environmental degradation. Conversely, renewable energy reduces carbon emissions and contributes to environmental sustainability. It confirms the need to improve renewable energy integration and increase awareness of China's severe environmental concerns, which are exacerbated by its economic and industrial development. This study offers critical insights for Chinese policymakers by analyzing data from 1990 to 2022 to quantify the extent to which the adoption of renewable energy can offset emissions resulting from economic growth, fossil fuel use, urbanization, and industrialization. Our findings provide China-specific evidence to support its emission reduction targets and contribute globally relevant methods for sustainable development planning. The quantified relationships provide a framework for evaluating the effectiveness of policies in transitioning to low-carbon growth.

1. Introduction

China has experienced unprecedented economic growth and urbanization over the past few decades, transforming from a rural and underdeveloped country into a global industrial powerhouse [1]. However, this growth has come at a considerable environmental cost, namely, increased carbon dioxide (CO_2) emissions [2]. These emissions are primarily attributed to fossil fuel consumption, economic growth, a shift towards urban living, and increased industrial activities. Fossil fuels, such as coal, oil, and gas, are energy sources formed from ancient organic matter that release CO_2 emissions when burned. Renewable energy is shifting from fossil fuels to clean energy (solar, wind, hydropower) to reduce emissions and meet climate goals. In light of these developments, renewable energy has the potential to mitigate CO_2 emissions and has emerged as an essential research area. China's economic landscape has undergone profound changes in the past two decades. The region's gross domestic product (GDP) has increased, and cities and industrial activities have expanded in recent years. As a result of these factors, there has been a significant increase in energy usage and the proportion of fossil fuels used in the country. Consequently, CO_2

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emissions have increased significantly, resulting in major environmental problems, including global warming [3]. Renewable energy sources foster a link between economic advancement and ecological conservation, stimulate financial investments in sustainable energy, decrease pollution levels, and contribute to stable economic progress [4]. CO_2 emissions from fossil fuels have contributed to global warming, and the promotion of renewable energy sources is urgently required to address this issue. Renewable energy has become a key focus of policy and academic debate, with growing urgency regarding environmental sustainability issues. Renewable energy sources, such as solar, wind, and hydropower, contribute to reducing carbon emissions and have a lower environmental impact than traditional fossil fuels [5].

Understanding the interplay between energy consumption, economic growth, and CO_2 emissions is crucial for developing effective energy policies that promote sustainable development. China faces urgent pressure to balance economic growth with its 2060 carbon neutrality pledge despite the continued dominance of fossil fuels. This study quantifies the impact of renewable energy adoption on carbon emissions in China, providing policymakers with actionable data. Recent studies [6,7] highlight China-specific gaps, including grid instability due to renewable intermittency, uneven policy implementation, and land-use conflicts, which are addressed here through a robust econometric analysis. Thus, the motivation for the current investigation is to examine these relationships in the Chinese context, as China is a significant global energy player and one of the largest energy consumers and CO_2 emitters [8]. Owing to rapid economic growth and high energy consumption, China faces the twin challenges of meeting increasing energy demand and ensuring a stable energy supply. Between 1990 and 2022, China experienced a 4.83 % annual increase in overall energy output, rising from 627.70 million tons of coal to 3.6 billion tons [7]. During the same period, energy consumption increased 7.45 times to 4.26 billion, with an annual increase of 5.58 %. In summary, China accounted for 23 % of the global energy use in 2022 and 61 % of the expansion in net global energy usage [9]. By 2025, China aims to reduce its CO_2 emissions per GDP unit by 40–45 % compared to 2015, aligning with the nation's objectives. The immense pressure to reduce CO_2 emissions poses unprecedented challenges for China [10]. CO_2 emissions account for approximately 60 % of atmospheric greenhouse gas (GHG) emissions, which are mainly related to industrial expansion [11]. The graph in Fig. 1 illustrates the change in CO_2 emissions in China between 1990 and 2022, showing a significant and continuous increase in CO_2 emissions during this period. The World Development Indicators (WDI) [12] highlight China's growing carbon emissions, reflecting its rapid industrialization and economic growth.

The share of renewable energy in China's total energy mix is significantly lower than the global average [13]. According to the Chinese government's announcement in September 2017, the share of renewable energy in China's total energy mix will increase from 8 % to 15 % by 2025. Similar to many other developing countries, China has taken significant steps towards building renewable energy sources [12]. China's renewable energy now accounts for 56 % of the total installed capacity (surpassing the 15 % target), with renewables accounting for 86 % of new capacity additions. The 19 % growth in renewable generation to 3.46 trillion kWh (35 % of the total output) demonstrates significant progress towards China's dual-carbon goals. These updates provide concrete evidence of China's progress in energy transition [14]. Financial and technological constraints limit the deployment of renewable energy in China. China faces three key renewable energy constraints: grid limitations cause ~5 % renewable curtailment due to inadequate transmission and storage [15], policy hurdles, such as subsidy cuts and local protectionism, slow investment, and resource trade-offs that emerge from land scarcity and rare earth dependencies for solar and wind expansion. During the rush to reduce the climate crisis, new energy advancements must not hinder but rather enhance other sustainable development goals [16]. In response to the growing demand for low-carbon energy, solar energy infrastructure has been rapidly deployed worldwide, including solar and solar thermal innovations [17,18]. Fossil fuel consumption is rising rapidly owing to increasing living standards, automation in developing countries, and the expansion of the global population. Owing to the excessive use of fossil fuels, the rate of depletion of fossil fuel resources has increased [19]. However, it also harms the environment, increases health issues, and threatens global climate change [20]. It is becoming increasingly accepted by society's norms in established countries worldwide to

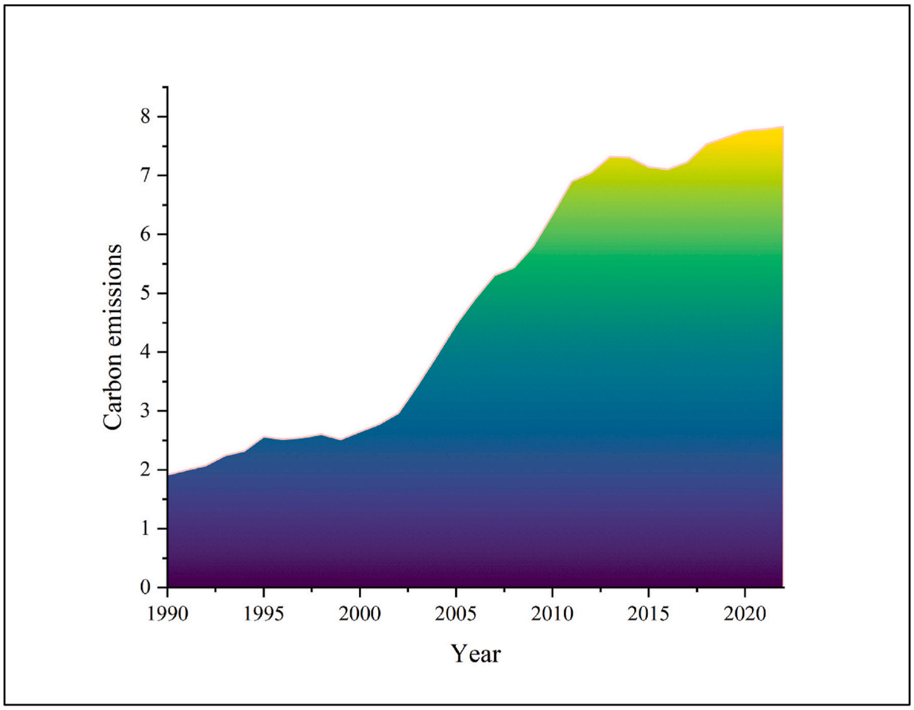

Fig. 1. CO_2 emissions in China. Source: WDI [12].

implement environmental improvements, such as sustainable production methods that reduce GHG emissions. The primary objective of this study was to investigate the impact of renewable energy, economic growth, fossil fuel consumption, urbanization, and industrialization on CO_2 emissions in China. The Autoregressive Distributed Lag (ARDL) and Nonlinear (N)ARDL estimators (both linear and symmetric) describe the dynamic relationships underlying these variables. This study determined the driving forces of carbon emissions and gauges for the use of renewable energy to decrease CO_2 emissions in the region.

According to the authors' research, there are a limited number of studies that have utilized an extensive sampling period and recent data from China, addressing urbanization and industrialization as key factors. Since 2015, the government has implemented measures to accelerate the transition to renewable energy sources. China has set goals to increase the amount of electricity produced from renewable sources. This study makes a significant contribution to the existing literature in several ways. First, this study enhances our understanding of how renewable energy has affected CO_2 emission reductions in China over the past three decades. It examines the interrelationships among fossil fuels, renewable energy, urbanization, economic growth, and CO_2 emissions in China. The model integrates the key indicators of urbanization and industrialization, as urban development is linked to electricity usage and public awareness. This connection has a positive influence on China's efforts to implement sustainable energy policies. Second, it underscores how renewable energy offsets carbon emissions and how energy from renewable sources can be made more sustainable. Third, using novel econometric methods, such as ARDL and NARDL, provides strong inferences regarding the nonlinear and dynamic relationships between all variables under consideration. Finally, this study has important policy implications for the benefit of the overall public good, urging the Chinese government to develop renewable energy sources to create a greener and more sustainable environment.

2. Literature review

China's growing adoption of renewable energy sources plays a crucial role in tackling the challenge of severe carbon emissions. Shifts in energy usage patterns and an increased emphasis on sustainable energy sources demonstrate the slow and incremental transformation of energy systems, production behaviour, and consumption. The Environmental Kuznets Curve (EKC) tests whether China's economic growth has reached the inflection point where GDP gains reduce emissions, a pattern observed in developed economies but unclear for China [21]. Energy Transition Theory identifies renewable energy's "penetration threshold" (typically 15–20 % of the mix), where renewable energy consumption (REC) meaningfully displaces fossil fuels (FF), a critical benchmark for China's 2060 goals [22]. Urban-Industrial Synergy explains how clustered development multiplies energy demand through infrastructure lock-in and supply chain concentration, which is crucial for understanding regional emission disparities [23]. Chen et al. [24] identified critical bottlenecks in China's solar and wind adoption, particularly in western provinces with high curtailment rates (up to 15 %). Kataray et al. [25] revealed grid integration challenges, showing 8 % waste of renewable energy during peak generation periods. Ren et al. [26] demonstrated that renewable projects yield 23 % higher long-term return on investment (ROI) than coal plants when accounting for carbon pricing. Ouyang & Fu [27] found 40 % ROI disparities between coastal and inland provinces due to unequal policy implementation. Countries that use coal-based systems, such as China, require renewable energy to mitigate carbon emissions [28]. Ou et al. [29] point out that China's electricity generation sector heavily relies on coal, resulting in substantial consumption of primary FF and significant emissions of GHG. These problems stem from the prevalence of coal and the inefficient energy distribution systems.

The researchers highlighted that substantial reductions in electricity-related GHG emissions could be achieved by allocating resources to nuclear power, renewable energy, and low-carbon footprint technologies. Dong et al. [30] investigated the relationships among CO_2 emissions, GDP, FF consumption, nuclear energy usage, and REC in China. They employed econometric methods to examine these connections using the EKC framework. The results underscore the importance of utilizing renewable energy sources to reduce carbon emissions and enhance the environmental conditions in China. Similarly, Xiao et al. [31] studied modelling renewable electricity supply for metropolitan areas in China, stressing the importance of shifting to renewable energy sources. This study not only highlights the spatial infrastructure, resources, and end uses of regions such as the Beijing-Tianjin-Hebei region (BTH) and Inner Mongolia in a true sense, but also shows how renewable energy can be a game changer for China's energy system.

Under environmental pressure and self-imposed climate targets, China has massively deployed renewable energy in recent years, mainly through solar panels and wind turbines. However, in recent years, renewables have undergone drastic changes; in 2015, renewable energy accounted for only 2.5 % of China's total energy consumption [32]. Local power use in rural and remote areas accounted for approximately 70 %. Additionally, China's adoption of renewable energy poses a significant threat to the biological environments of developing countries. Kumar et al. [33] emphasize that the increase in peasant income, the adjustment of the country's industrial sector structure, and sustainable growth are crucial. Conversely, China's renewable energy sector relies heavily on government support for its growth and expansion. Since the late 1990s, the Chinese government has promoted REC through various policy initiatives. These initiatives recognize the potential of renewable energy to replace coal, a major source of pollution. In a 2017 survey conducted by the Horizon Research and Consultancy Group in major Chinese cities, 64 % of respondents identified pollution as their top environmental concern [34]. Chinese authorities have enforced new vehicle discharge standards, particularly in urban areas [35]. These findings suggest that urban air pollution is a significant concern for the government and public. If the increased use of renewable energy reduces air pollution, public provision of renewable energy is likely to increase. Fig. 2 illustrates the changes in China's REC from 1990 to 2022 using WDI data [12]. The figure shows a marked increase in REC, indicating China's efforts to diversify its energy sources and promote sustainable practices.

Lin and Zhu [36] identified a connection between REC, technological innovation, and CO_2 emissions, emphasizing the importance of REC in addressing climate change. Sarkodie et al. [37] highlighted the detrimental effect of FF energy use on climate change, underscoring the need to shift towards renewable energy sources. Alola et al. [38] further explored the link between energy sources and CO_2 emissions, indicating that economic growth and FF consumption contribute to increased CO_2 emissions. Adebayo et al. [39] investigated the interaction among technological innovation, REC, and carbon emissions in Brazil, Russia, India, China, South Africa (BRICS) economies, including China, demonstrating the role of renewable energy in limiting carbon emissions. Moreover, Kartal et al. [40] focused on the long-term effect of a decrease in coal usage on China's carbon emissions and economic growth, highlighting the importance of transitioning to cleaner energy sources for sustainable development. Sarpong et al. [41] considered environmental taxation and renewable energy as key factors in promoting carbon neutrality in China, India, Brazil, Russia, Indonesia, Mexico, Turkey (E7) economies. Ullah et al. [42] evaluate the role of green finance, technology innovations, and energy consumption in mitigating CO_2 emissions and sustainable practices. This study examined the significance of renewable energy in mitigating CO_2 emissions. It emphasizes the necessity of new technology, policy changes, and transitioning from unsustainable to sustainable techno-economic development strategies to mitigate climate change.

Wang [43] emphasized the need to regulate energy usage and increase the role of renewable energy in urban communities in China. The literature in China emphasizes the importance of renewable energy in

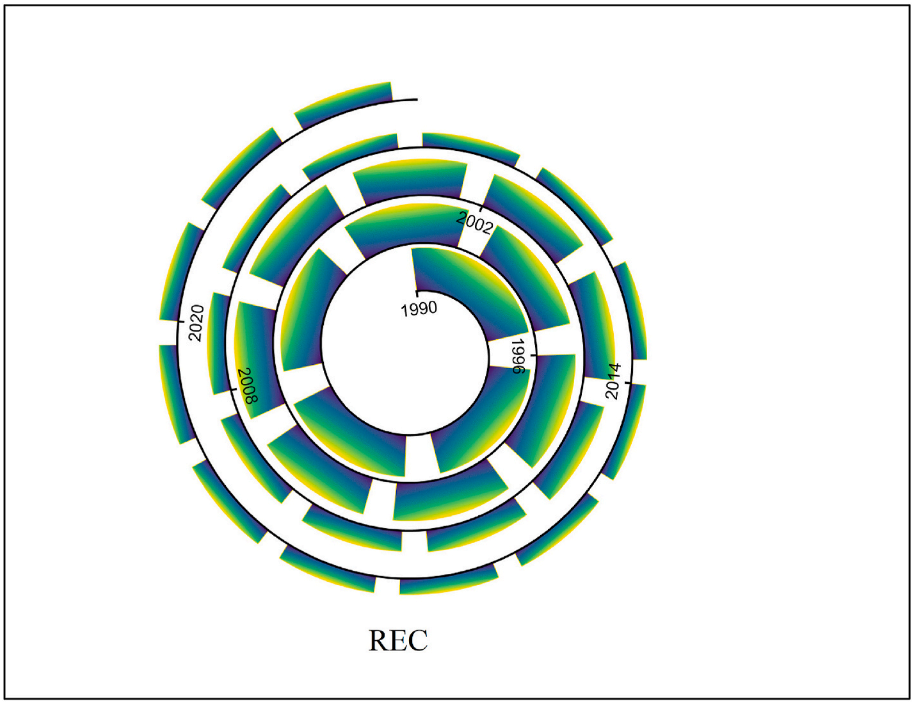

Fig. 2. Renewable Energy Consumption (REC) in China. Source: WDI [12].

reducing CO_2 emissions. Renewable resources and low-carbon technologies have also enabled China to reduce its reliance on FF. It, in turn, reduces GHG emissions. In recent years, several studies on the development of renewable energy resources have been published in academic journals. Most research published on renewable energy has concentrated on the following subfields: patterns of renewable technology, renewable structure, cost-benefit analysis, and economic returns on investment. Most of these studies have focused on renewable energy sources such as bioenergy, hydropower, and wind power. Nevertheless, research on obstacles and policy alternatives related to renewable energy in China remains limited. Driven by existing research gaps, this study explores various concerns, obstacles, and policy alternatives that could foster energy advancement in China to achieve carbon neutrality. "Carbon neutrality" refers to China's 2060 goal of balancing CO_2 emissions through renewable expansion (targeting 80 % clean energy) and industrial decarbonization. This study bridges this gap by linking key variables to renewable energy barriers (FF dependence and industrialization) and opportunities (renewable consumption growth and urbanization-driven demand). These relationships were explicitly analyzed using the ARDL model. Our study breaks new ground by revealing how China's rapid urbanization and industrial growth interact to shape the adoption of renewable energy, a critical link that prior research has overlooked. By analyzing data (1990–2022), we found that every 1 % increase in REC reduces CO_2 emissions by 0.188 %, whereas FF reductions have half the impact. These new insights, grounded in the latest energy statistics, provide actionable policy tools to accelerate China's transition, helping bridge the gap between its current FF dependence and future carbon neutrality goals.

3. Methodology and data sources

3.1. *Model specification and estimation techniques*

This study uses annual time-series data for the variables under investigation. Hadian and Madani [44] used co-integration techniques to elucidate the long-term relationships between time-series data. The multivariate co-integration examination by Pejović et al. [45] and Knopf et al. [46] employed the maximum likelihood method to investigate the long-term relationships between these series. A fundamental requirement for these co-integration techniques is that all time series must possess identical integration orders. Van de Ven and Fouquet [47] use methodologies based on residuals and modified ordinary least squares procedures, respectively. Bhattacharya et al. [48] recently developed a new co-integration method, known as the ARDLor bounds test, which addresses this limitation. The regressors in an ARDL model are either level stationary *(I(0))* or first-differenced *(I(1))*. The ARDL approach has been widely used in numerous studies due to its ease of use and reliability. We selected ARDL and NARDL because they handle mixed-order integration (I(0)/I(1)) without requiring pre-testing for unit root properties, which is critical for China's volatile energy/emissions data. NARDL specifically captures asymmetric effects (e.g., stronger emission reductions from renewable increases versus weaker impacts from decreases). This model was employed to establish a lasting connection between the series.

$$\mathrm{CO}_{2t} = \beta_0 + \beta_1 \mathrm{REC}_t + \beta_2 \mathrm{GDP}_t + \beta_3 \mathrm{FF}_t + \beta_4 \mathrm{U}_t + \beta_5 \mathrm{IND}_t + u_t \tag{1}$$

The ARDL equation is as follows: The model with an intercept and a trend in Equations (2) and (3) is as follows:

$$\begin{aligned}\Delta \mathrm{CO}_{2t} = \alpha &+ \sum_{i=1}^{m} \varphi_{1i} \Delta \mathrm{CO}_{2t-i} + \sum_{i=1}^{m} \varphi_{2i} \Delta \mathrm{REC}_{t-i} + \sum_{i=0}^{m} \varphi_{3i} \Delta \mathrm{GDP}_{t-i} \\ &+ \sum_{i=0}^{m} \varphi_{4i} \Delta FF_{t-i} + \sum_{i=0}^{m} \varphi_{5i} \Delta \mathrm{U}_{t-i} + \varphi_6 \mathrm{IND}_{2t-1} + \beta_1 \mathrm{REC}_{t-1} + \beta_2 \mathrm{GDP}_{t-1} \\ &+ \beta_3 FF_{t-1} + \beta_4 U_{t-1} + \beta_5 \mathrm{IND}_{t-1} + \gamma \mathrm{ECM}_{t-1} + \nu_t\end{aligned} \tag{2}$$

$$\begin{aligned}\Delta \mathrm{CO}_{2t} = \alpha_0 &+ \sum_{i=1}^{m} \beta_{1i} \Delta \mathrm{CO}_{2t-i} + \sum_{i=1}^{m} \beta_{2i} \Delta \mathrm{REC}_{t-i} + \sum_{i=0}^{m} \beta_{3i} \Delta \mathrm{GDP}_{t-i} \\ &+ \sum_{i=0}^{m} \beta_{4i} \Delta FF_{t-i} + \sum_{i=0}^{m} \beta_{5i} \Delta \mathrm{U}_{t-i} + \beta_6 IND_{t-1} + \gamma \mathrm{ECM}_{t-1} + \nu_t\end{aligned} \tag{3}$$

The Bounds test determines whether a long-run relationship exists between the variables. The null hypothesis, denoted as H_0: $\beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = 0$, proposes the absence of co-integration. It is in contrast to the alternative hypothesis H_1: $\beta_1 \neq \beta_2 \neq \beta_3 \neq \beta_4 \neq \beta_5 \neq 0$, which suggests that co-integration exists. The null hypothesis is rejected when the computed F statistic exceeds the threshold of Janet Ruiz-Mendoza and Sheinbaum-Pardo [49] 's maximum critical threshold *I(1)* for the number of predictor variables (k). The null hypothesis cannot be rejected when the F-statistic falls below the critical lower bound value, *I(0)*. The value of the F-statistic lies between *I(0)* and *I(1)*, indicating the possibility of co-integration. According to Pesaran & Shin [50], *I(0)* and *I(1)* are more suitable for small samples. Model selection criteria, such as the information criteria, determine the optimal lag value *m* in Equations (2) and (3) [51]. The optimal *m* was found in the model that exhibited the smallest Akaike Information Criterion (AIC) or Schwarz Information Criterion (SIC) value. In addition, the model must not have residuals that are serially correlated. It is the long-run ARDL equation if co-integration is present in the ARDL process:

$$\mathrm{CO}_{2t} = \beta_0 + \sum_{i=0}^{p} \beta_{1i}\mathrm{CO}_{2t-i} + \sum_{i=0}^{p} \beta_{2i}\mathrm{REC}_{t-i} + \sum_{i=1}^{q} \beta_{3i}\mathrm{GDP}_{t-i} + \sum_{i=0}^{r} \beta_{4i}FF_{t-i} + \sum_{i=0}^{s} \beta_{5i}\mathrm{U}_{t-i} + \sum_{i=0}^{s} \beta_{6i}\mathrm{IND}_{t-i} + \varepsilon_t \tag{4}$$

Equation (4) incorporates model selection criteria, including the Adjusted R-squared and Hannan-Quinn information criteria; AIC and SIC are used to select lag values *p*, *q*, *r*, and *s*. The optimal estimation is achieved through a model that exhibits either the smallest information criterion or the greatest coefficient of determination (R-squared). Finally, the ARDL model's short-term estimation is calculated using the following Equation, which is presented as an error-correction model:

$$\mathrm{CO}_{2t} = \delta_0 + \sum_{i=0}^{p} \delta_{1i}\Delta\mathrm{CO}_{2t-i} + \sum_{i=0}^{p} \delta_{2i}\Delta\mathrm{REC}_{t-i} + \sum_{i=1}^{q} \delta_{3i}\Delta\mathrm{GDP}_{t-i} + \sum_{i=0}^{r} \delta_{4i}\Delta\mathrm{FF}_{t-i} + \sum_{i=0}^{s} \delta_{5i}\Delta\mathrm{U}_{t-i} + \sum_{i=0}^{s} \delta_{6i}\Delta\mathrm{IND}_{t-i} + \lambda\mathrm{ECM}_{t-1} + \tau_t \tag{5}$$

The coefficient of the error-correction term ($\mathrm{ECM}_{t\text{-}1}$) in Equation (5) represents the speed of the adjustment parameter, indicating the rapidity with which the series attains long-term equilibrium. This parameter is expected to be negative and statistically significant in the model. Heteroscedasticity, normality, functional form, and serial correlation tests were used to ensure that the model fit its purpose prior to implementation. To strengthen our nonlinear analysis, we carefully determined the optimal lag structures using the AIC and SIC criteria to ensure model stability. Then explicitly compared the differential impacts of positive versus negative shocks across all variables.

3.2. Data sources

The variables and their respective data sources are listed in Table 1. CO_2 emissions encompass those resulting from the combustion of FF and the production of cement. These emissions encompass CO_2 generated from the combustion of solid, liquid, and gaseous fuels and gas flaring processes. REC is the share of renewable energy in the total final energy consumption. The total value added by all domestic producers in an economy, combined with any product taxes and excluding subsidies not factored into product values, constitutes the GDP. Coal, oil, petroleum, and natural gas are all types of FF. The term 'urban population' denotes individuals residing in urban areas. Industrialization (IND) is the percentage of a country's GDP that is derived from the industrial sector. This metric provides insights into the economic contributions of the manufacturing, mining, construction, and utility sectors. The WDI were used as the data source [12]. This study used data on the Chinese economy from 1990 to 2022. In the empirical analysis, logarithmic transformations were applied to the model variables. This process reduces the sharpness of the data and improves the distributional characteristics of variables. The application of natural logarithmic transformation effectively addressed the issues of autocorrelation and heteroscedasticity in the datasets. Log-transformation models yielded more consistent and efficient outcomes than linear transformation models. Table 2 presents the descriptive statistics and variance inflation factors (VIF) of the variables used in this study. All VIF values were below 3 (well below the conservative threshold of 5), confirming negligible multicollinearity among the predictors. These results validate the stability of our model and the independence of key variables.

Table 1
Summary of variables and data sources.

Variable name	Symbol	Definition	Measurement Unit	Data source
Carbon Dioxide Emissions	CO₂ Emissions	CO_2 Emissions is stemming from the burning of fossil fuels.	metric tons per capita	WDI
Renewable Energy Consumption	REC	Renewable energy consumption (% of total final energy usage).	%	WDI
Economic Growth	GDP	The country's gross domestic product (GDP) represents its financial health.	Constant 2015 US dollars	WDI
Fossil fuel use	FF	Fossil fuel energy consumption (% of total energy use)	%	WDI
Urbanization	U	Urban population (% of total population)	%	WDI
Industrialization	IND	% of GDP from the industrial sector.	%	WDI

WDI = World Development Indicators.

4. Results and discussion

We employed three widely recognized unit root tests [52] to determine the order of integration of the variables. Owing to its resilience against time-dependent serial correlations and heteroscedasticity, this study employs the Phillips–Perron (PP) [53] and the Augmented Dickey-Fuller (ADF) [54] tests to assess unit roots. The results of the ADF, PP, and Kwiatkowski-Phillips-Schmidt-Shin (KPSS) unit root tests are presented in Table 3 for *I(0)* and *I(1)* [55]. According to all unit root tests, CO_2 emissions , REC, GDP, FF, and U demonstrate stationarity at the first differences. Conversely, the ADF and PP tests indicate that IND remains stationary at *I(0)* and *I(1),* respectively. The KPSS unit root test reveals that CO_2 emissions, REC, GDP, FF, and IND are stationary at the level, while U achieves stationarity at *the I(1) level.* None of the variables exhibits stationarity at *I(2)*. Thus, all series progress through the bounds test procedure, following the KPSS, the PP, and the ADF tests.

Table 2
Descriptive statistics.

Descriptive Statistics	*lnCO₂ emissions*	*lnREC*	*lnGDP*	*lnIND*	*lnFF*	*lnU*
Mean	7.855	12.636	27.855	6.334	2.871	5.685
Median	7.474	15.748	27.254	6.485	2.698	5.428
Maximum	8.418	12.749	29.636	7.486	2.746	6.326
Minimum	7.186	9.637	19.477	5.247	0.549	5.175
Std. Dev.	0.367	0.747	2.516	0.854	0.362	0.397
Skewness	0.476	−0.632	0.547	−0.423	0.091	−0.683
Kurtosis	3.547	3.416	3.899	2.482	2.483	2.186
Jarque–Bera	3.146	4.787	4.796	3.681	5.636	4.629
Probability	0.498	0.288	0.368	0.339	0.483	0.277
VIF		1.217	2.147	2.423	1.835	2.685
1/VIF		0.822	0.466	0.413	0.545	0.372

Number of Observations: 33.

Table 3
Results of unit root tests for stationarity (ADF, PP, and KPSS).

Variables	Augmented Dickey-Fuller (ADF)		Phillip-Perron (PP)		Order of integration
	Level	1st difference	Level	1st difference	
CO_2 emissions	−1.059	−5.25***	−0.55	−5.24***	I(1)
REC	−0.471	−6.588***	−0.471	−6.588***	I(1)
GDP	0.327	−3.999**	0.28	−4.065**	I(1)
FF	−1.718	−7.58***	−1.647	−7.710***	I(1)
IND	−3.930**	−7.105***	−3.149**	−7.278***	I(1)
U	−1.851	−5.469***	−2.219	5.436***	I(1)
KPSS test (constant)			KPSS test (Constant & Trend)		
	Level	1st difference	Level	1st difference	
CO_2 emissions	0.901***	0.119	0.161**	0.056	I(0)
REC	0.892***	0.053	0.122***	0.054	I(0)
GDP	0.897***	0.133	0.148**	0.118	I(0)
FF	0.735***	0.109	0.083*	0.076	I(0)
IND	0.652**	0.198	0.059***	0.075	I(0)
U	−1.546	−5.759***	−2.359	5.946***	I(1)

Note: ***, **, and * refer to significance levels of 1 %, 5 %, and 10 %, respectively.

The initial phase of this study examined CO_2 emissions, FF, U, IND, REC, and GDP. Under the cross-sectional dependence (CD) test, the null hypothesis indicates the absence of CD. These findings suggest that a CD exists between these variables. The CD test results are statistically significant at the 1 % level, confirming the presence of CD (Table 4). The cross-sectionally augmented Dickey-Fuller (CADF) test results and cross-sectionally augmented IPS (CIPS) technique results are shown in Table 5 for the stationarity analysis. The statistical analysis results indicate that all variables exhibit non-stationarity at the level but become stationary after the first difference is applied to the data. Table 6 shows that the F-statistics exceed the upper bound value and are statistically significant at the 1 % level. It confirms that the ARDL model effectively captures long- and short-term dynamics.

The study results indicate evidence of CD. Therefore, we include our long-term heterogeneous linear panel estimation results in Table 7. When used, panel data approaches that incorporate robust CD techniques to eliminate potential biases in the results. Therefore, we used estimations such as ARDL [56], fully modified ordinary least squares (FMOLS) [57], and dynamic ordinary least squares (DOLS) [57] methods. These methods have received considerable attention in the literature because they can address the potential problems associated with data. However, before proceeding with the ARDL estimation, we initiated our analysis using the FMOLS and DOLS baseline models (Table 7). Table 7 shows that REC has coefficients of 0.243 and pen0.205, respectively, which reduce CO_2 emissions in both models. As a result of these regulations, environmental degradation has been reduced through the use of REC.

The outcomes demonstrate that the Chinese government acted responsibly by reducing CO_2 emissions from renewable energy and industrialization during the study period, as supported by the study's findings [58]. Proponents argue that increased government spending on renewable energy enhances environmental sustainability. According to several studies, higher REC and lower CO_2 emissions benefit sustainability and environmental performance. Several studies have reported similar results [59,60]. Furthermore, FF have been widely criticized for

Table 4
Test results of cross-sectional dependency.

Variables	CD Test	*P*-Value
CO_2 emissions	12.030	0.001***
REC	13.160	0.002***
GDP	12.459	0.001***
FF	13.244	0.001***
IND	17.479	0.000***
U	9.328	0.002***

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

Table 5
Results of the stationary analysis (CADF and CIPS).

CADF test					
	I(0)		I(1)		
	C	C&T	C	C&T	
CO_2 emissions	−2.132	−1.962	−1.962	−4.152***	I (1)
REC	−1.740	−1.840	−1.840	−3.245***	I (1)
GDP	−2.165	−2.239	−2.239	−3.923***	I (1)
FF	−2.564	−2.930	−2.930	−3.470***	I (1)
IND	−2.120	−2.378	−2.378	−3.810***	I (1)
U	−2.195	−2.839	−2.234	−3.912***	I (1)
CIPS test					
CO_2 emissions	−1.805	−1.753	−3.462***	−3.764**	I (1)
REC	−2.008	−2.681	−4.130***	−3.125**	I (1)
GDP	−2.134	−1.954	−4.651***	−4.203***	I (1)
FF	−2.187	−2.119	−4.742***	−4.2539**	I (1)
IND	−1.519	−2.037	−5.045***	−4.051***	I (1)
U	−2.626	−1.937	−4.025***	−4.936***	I (1)

Note: *** and ** indicate significance at the 1 % and 5 % levels, respectively. C = constant; T = Trend.

Table 6
Bounds test.

Panel A: Bounds test				
F-statistics (Bound test)	2.592***			
Critical values	1 %	2.50 %	5 %	10 %
Lower bounds I (0)	3.42	2.95	2.63	2.25
Upper bounds I (1)	4.66	4.19	3.78	3.36
R^2	0.998			
Adjusted R^2	0.993			

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

Table 7
Results of FMOLS and DOLS estimations.

Variables	FMOLS		DOLS	
	Coeff.	T-stat.	Coeff.	T-stat.
REC	−0.243***	−3.571	−0.205**	−3.620
GDP	0.259**	3.313	0.254**	3.281
FF	0.340***	4.631	0.365***	4.140
U	0.313**	3.144	0.337**	3.253
IND	0.572***	5.725	0.528***	5.035

Note: *** and ** indicate significance at the 1 % and 5 % levels, respectively. Coeff = Coefficient value; T-stat = T-statistics.

their environmental harm. According to Quan et al. [13], economic development in China is prioritized over environmental protection because of the higher levels of GHG emissions resulting from increased FF consumption. Table 7 also shows a negative and statistically significant coefficient for REC, indicating that higher REC is associated with reduced CO_2 emissions. Furthermore, according to FMOLS, a 0.243 % decrease in CO_2 emissions was achieved for every 1 % increase in REC. The DOLS results indicated that a 0.205 % increase in REC could result in a decrease in CO_2 emissions during the study period [61].

Environmental degradation, such as carbon emissions, can be reduced by the implementation of sustainable technologies. It is especially true for improving energy competence, sustainability, and quality. These findings support the claim that RECs are used as a panacea for preserving the natural environment and combating environmental degradation. Governments and industries invest massively in sustainable dimensions andresearch & development (R&D) for clean and green energy sources while integrating economic development with environmental concerns. However, Gandía et al. [62] disagreed with the current findings. FF energy sources contribute to increased economic activity and IND, leading to higher carbon emissions. The DOLS results reveal a significant coefficient for REC, supporting the notion that the increased use of renewable energy sources correlates with reduced CO_2 emissions and that lower REC is associated with higher emissions. Fig. 3 summarizes the findings of this study. The REC was negatively correlated with CO_2 emissions, indicating that an increase in the REC was associated with a decrease in carbon emissions. Conversely, GDP, FF, IND, and U were positively correlated with CO_2 emissions, indicating that these factors contributed to higher emission levels.

The FMOLS and DOLS estimates demonstrate that REC is integral to lowering CO_2 emissions in the long run. The primary sources of renewable energy are those with very low or no carbon emissions. These energy sources are considered suitable options for environmental quality. Consequently, there would be a lower environmental footprint. According to Table 7, the GDP coefficients for FMOLS and DOLS are positive and significant. Specifically, increases of 0.259 and 0.254 units in GDP lead to a rise in the value of CO_2 emissions in China. Following these findings, Wan Alwi et al. [63] found that economic growth was unsustainable. As economic growth increases, the demand for non-renewable energy sources, such as FF, also increases. Such resources degrade the environment while simultaneously boosting economic development. However, environmental degradation is also linked to economic growth. A higher rate of economic development is not a good indicator of environmental sustainability [64]. According to Sarrias-Mena et al. [65], economic growth is a negative environmental indicator, resulting in higher CO_2 emissions. Other studies have examined the relationship between environmental concerns and economic development (e.g., Refs. [66,67]).

The IND in China contributes to elevated CO_2 emissions because of the nature of its activities. China's rapid IND has led to a surge in manufacturing, construction, and other energy-intensive processes. These operations rely heavily on non-renewable energy sources, including coal, petroleum, and natural gas. As industries expand and produce more, they consume more energy, leading to increased CO_2 emissions. Industrial machinery, manufacturing plants, and related infrastructure require substantial energy to operate efficiently [68]. Urbanization plays a considerable role in increasing the CO_2 emissions. Population migration to urban centers leads to an increase in energy consumption. Cities require extensive infrastructure, including transportation systems, residential and commercial buildings, and public services, to support large populations. Urban areas often have more vehicles on the roads, increased construction of high-rise buildings, and greater electricity use for lighting, heating, and cooling. This concentration of people and activities implies higher energy consumption, which typically produces higher CO_2 emissions. Additionally, urbanization often leads to lifestyle changes that favour higher energy use, such as increased use of personal vehicles and greater consumption of goods and services [28,69]. The outcomes of the FMOLS and DOLS analyses, which are derived from Table 7, are shown in Fig. 4. Both FMOLS and DOLS yielded similar trends, reinforcing these findings. Table 8 presents the ARDL results.

4.1. Symmetrical investigation using ARDL estimation

The results of the ARDL model are presented in Table 8. The Hausman test confirmed the ARDL estimator choice, as it accepted H_0. This table illustrates the long- and short-term relationships between CO_2 emissions and various factors in China, including REC, GDP, IND, FF, and U. The optimal lag structure for the model was determined using the

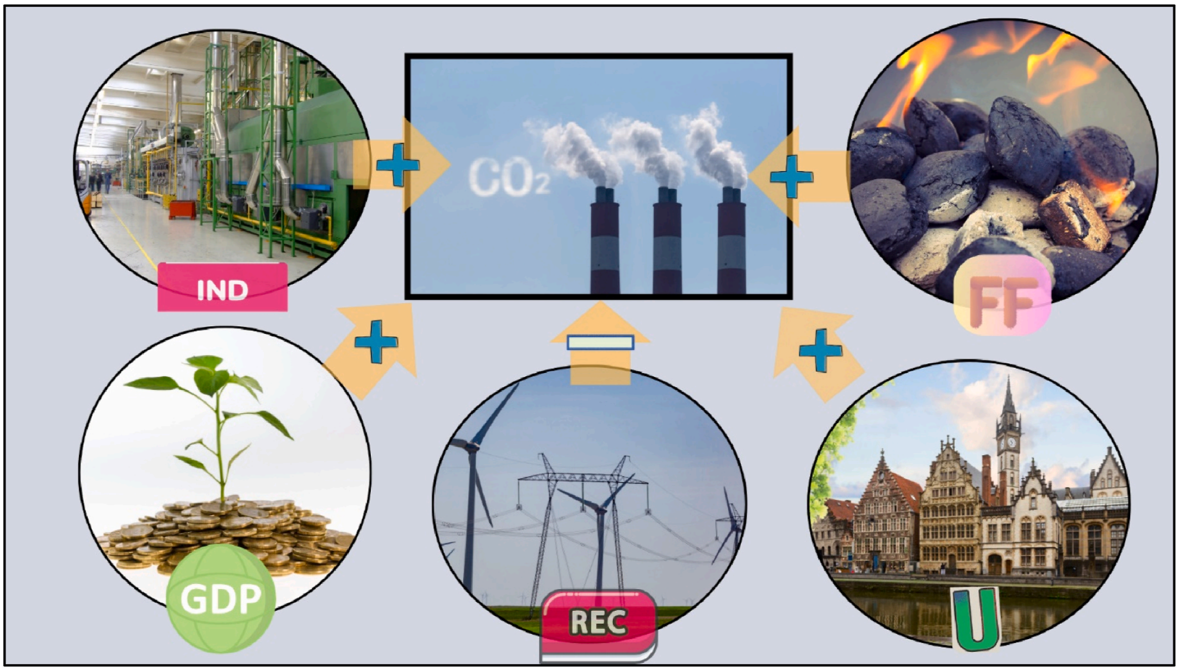

Fig. 3. Graphical results of this study. Source: Author calculation.

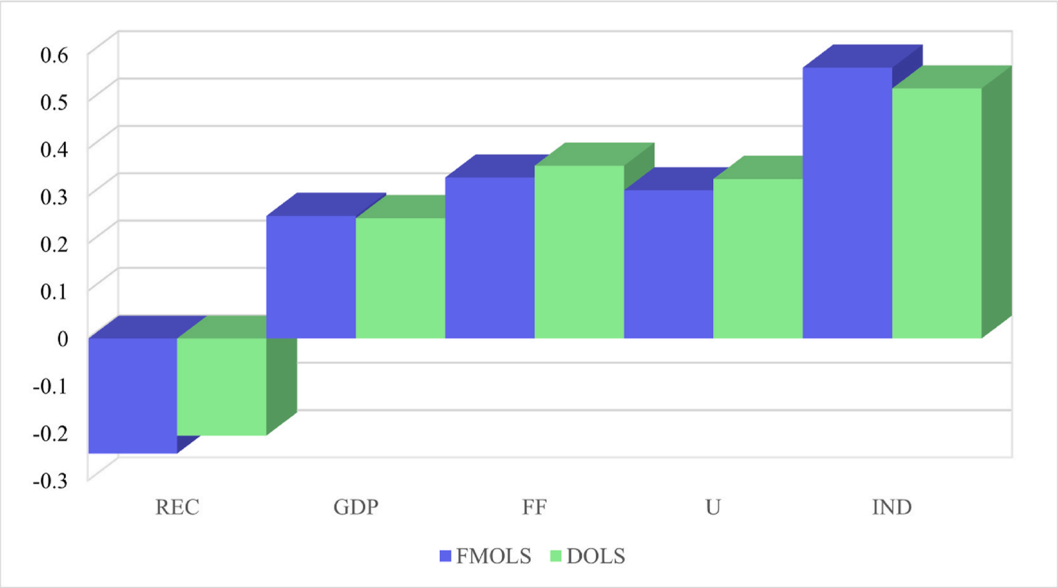

Fig. 4. FMOLS and DOLS results. Source: Author calculation.

Table 8
ARDL estimate results.

$lnCO_2$	Coefficient	Std. Error	Prob.*
Panel A: Long Run Equation			
REC	−0.188***	0.014	0.000
GDP	0.027***	0.032	0.000
IND	0.252	0.390	0.148
FF	0.341***	0.013	0.001
U	0.064***	0.075	0.000
Panel B: Short Run Equation			
REC	−0.149***	0.025	0.000
GDP	0.106***	0.038	0.000
FF	0.235**	0.095	0.018
IND	0.606***	0.028	0.000
U	0.232*	0.342	0.092
C	0.108***	0.016	0.000
Mean dependent var	0	S.D. dep. var	0.02
SE of regression	0	AIC	−7.81
Sum of squared residual	0.01	SC	−7.19
Log-likelihood	3226.8	HQC	−7.57
Hausman Test	χ^2 Statistic	p-value	
	2.890	0.580	

According to the authors' calculations, sources*,**, and *** indicate statistical significance at the 10 %, 5 %, and 1 % levels, respectively.

AIC.

The model outcomes showed that RECs were negatively correlated with the CO_2 emissions. REC has a (0.188) coefficient of elasticity, which implies that a 1 % rise in REC is projected to reduce CO_2 emissions by (1.88 %). These outcomes align with those of [58], who found a negative impact of REC on CO_2 emissions. REC has a negative impact on CO_2 emissions, as supported by current studies [70]. More REC in China does not cause CO_2 emissions, but specifies a more precise analysis for sustainable growth and an eco-friendly environment. CO_2 emissions are directly linked to the consumption of FF. In other words, a 1 % increase in FF is predicted to result in 0.341 % more CO_2 emissions. FF and CO_2 emissions have been consistently linked in previous studies [71]. CO_2 emissions are released when FF are burned to generate energy. Based on the available data, coal remains a crucial energy resource for most of China and other countries [72]. According to the data, China's rising energy use derived from non-renewable sources contributes to the country's CO_2 emissions. Policymakers must devise policies that support sustainable economic growth.

For example, it is proposed to implement a levy on non-sustainable energy sources while offering financial incentives for renewable alternatives on a large scale. Installing solar panels at home and work, and using electric vehicles for transportation, may be promising strategies for reducing the consumption of non-renewable energy. The relationship between CO_2 emissions and IND was negligible. Nguyen et al. [73] also support this insignificant impact of IND on CO_2 emissions in the long run. The estimation in this study revealed a strong correlation between IND and CO_2 emissions in the short term. Urbanization has a significant impact on CO_2 emissions in the short and long term. The migration of individuals to urban areas increases the demand for energy-consuming services, such as transportation, space heating, and air conditioning. Urban areas require substantial infrastructure development, including roads, buildings, and public services, which contribute to higher energy consumption levels. Consequently, the concentration of economic activities and lifestyles that favour increased energy use results in higher CO_2 emissions. This pattern was consistently observed, indicating that urbanization has immediate effects and contributes to increased emissions as cities grow and develop [28,74]. Fig. 5 illustrates the short- and long-run impacts of the study variables on CO_2 emissions, as shown in Table 8.

4.2. NARDL estimation results

Table 9 presents a summary of the NARDL model findings. According to the model, the decomposed explanatory variables had significant impacts on CO_2 emissions. According to these findings, a 1 % increase or decrease in GDP is predicted to reduce CO_2 emissions by 0.183 % (0.08 %). Multiple studies have demonstrated a positive relationship between GDP and CO_2 emissions [75]. Increases (decreases) in REC are likely to reduce (decrease) CO_2 emissions by (0.205 %). The findings of Chien et al. [76] were similar to those of the present study. As discussed in the linear estimation, although REC in China does not generate CO_2 emissions, these factors provide a more detailed examination of achieving a more environmentally sustainable future. The coefficient value that defines the level of carbon emissions caused by a constructive change in GDP is (0.183), and a negative change is (0.08) when considering decomposed GDP with positive (negative) shocks. These findings suggest that environmental policies in China are strictly enforced. As both negative and positive shocks to FF energy have a positive impact on CO_2 emissions, it is essential to develop regulations for FF-derived energy.

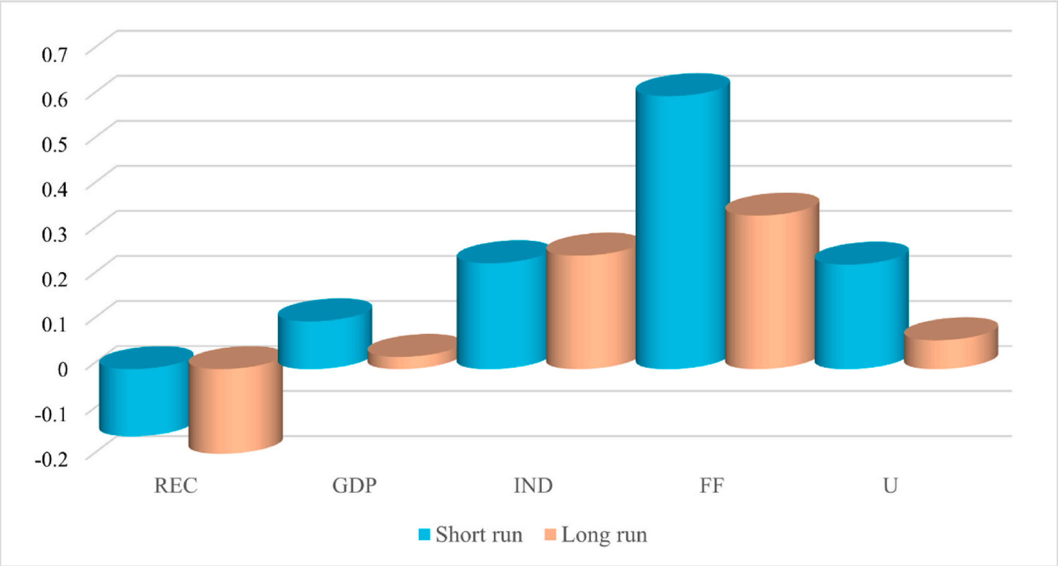

Fig. 5. ARDL results. Source: Author calculation.

Table 9
Results of the panel nonlinear ARDL estimation.

$\ln CO_2$ emissions	Coefficient	Std. Error	Prob.*
Results of short-run estimation			
ln (REC)+	−0.034***	0.010	0.000
ln (REC)-	−0.216***	0.020	0.000
ln (FF)+	0.305***	0.000	0.000
ln (FF)-	0.605***	0.000	0.000
ln (GDP)+	0.095***	0.010	0.000
ln (GDP)-	1.104***	0.030	0.000
ln (IND)+	0.406***	0.010	0.000
ln (IND)-	0.704**	0.020	0.010
ln (U)+	0.305***	0.000	0.000
ln (U)-	0.065***	0.010	0.000
Results of long-run estimation			
ln (REC)+	−0.303**	0.010	0.030
ln (REC)-	−0.205**	0.040	0.050
ln (FF)+	0.162	0.020	0.320
ln (FF)-	0.205***	0.010	0.000
ln (GDP)+	0.183***	0.050	0.000
ln (GDP)-	0.080	0.110	0.440
ln (IND)+	0.050**	0.010	0.050
ln (IND)-	0.030**	0.030	0.040
ln (U)+	0.105***	0.010	0.000
ln (U)-	0.143***	0.040	0.000
C	0.360***	0.110	0.000
Mean dep. var	0.000	SD dep. var	0.020
SE of reg.	0.000	AIC	−7.57
SSR	0.000	SC	−4.08
Log-likelihood	3547.300	HQC	−6.23

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

According to the positive and negative elasticities of FF energy, a 1 % increase (or reduction) in FF resulted in a 0.162 % increase (or 0.205 % decrease) in CO_2 emissions, respectively. This empirical finding is supported by many prior studies [77]. The IND process and its impact on an economy's CO_2 emissions encompass favourable and unfavourable shifts. The positive change has an elasticity of 0.05 %, whereas the negative change has an elasticity of 0.30 % at the 5 % significance level, respectively. Funding for energy-intensive industries can be obtained through renewable energy sources, storage technologies, and carbon capture. However, GDP has a substantial positive effect on CO_2 emissions in the short run. The REC had a negative impact on CO_2 emissions, whereas FF had a positive impact. Fig. 6 illustrates the short- and long-term effects of the study variables on CO_2 emissions, as determined using the NARDL method (Table 9). In the short term, positive and negative changes in REC and FF significantly affected CO_2 emissions, with negative changes having a more pronounced impact. The long-term results showed both positive and negative changes in REC and FF influenced CO_2 emissions, with negative REC and positive FF having significant effects on CO_2 emissions.

The AIC was used to determine the optimal number of lags. The optimal lag periods for the ARDL and NARDL models were (1, 1, 1, 1, 1). We conclude that GDP and IND growth in China have a negative effect on environmental sustainability. CO_2 emissions are expected to decrease by 0.036 % with a 1 % increase in REC and increase by 0.341 % with the FF use. It is based on our evaluation of the application of ARDL modelling. According to the NARDL estimates, a 1 % increase in the NARDL-decomposed REC with positive shocks is projected to reduce CO_2 emissions by 0.303 %. In comparison, a similar increase in adverse shocks was estimated to decrease emissions by 0.205 %. As shown in Table 10, the findings from various diagnostic assessments indicate that, except for the Jarque-Bera test, the probability value fell below 0.05 %. Therefore, the probability values for all other comparable tests exceeded 0.05 %, confirming that our estimated model had no bias and was adequately described by the data used.

5. Conclusion and policy implications

Achieving environmental sustainability has become increasingly important because of environmental quality issues, including unsanitary and polluted conditions. Various sustainability determinants have been identified in the literature. The primary objective of this study was to investigate the impact of REC, GDP, FF, IND, and U on enhancing sustainability and environmental quality in China. This study employed advanced data estimations to examine the short- and long-term associations between variables related to issues such as CD (unit root test) and the bound co-integration test [78]. The findings revealed a correlation between REC, GDP, and factors associated with long-term sustainability. The symmetric ARDL and asymmetric NARDL estimation results show that REC has long- and short-run negative impacts on environmental sustainability. These determinants have been empirically proven to improve the environmental quality. GDP growth has a positive relationship with environmental sustainability and has been proposed as the primary cause of the declining environmental quality. Therefore, the use of symmetric ARDL and asymmetric NARDL estimation models in this study extends the empirical literature.

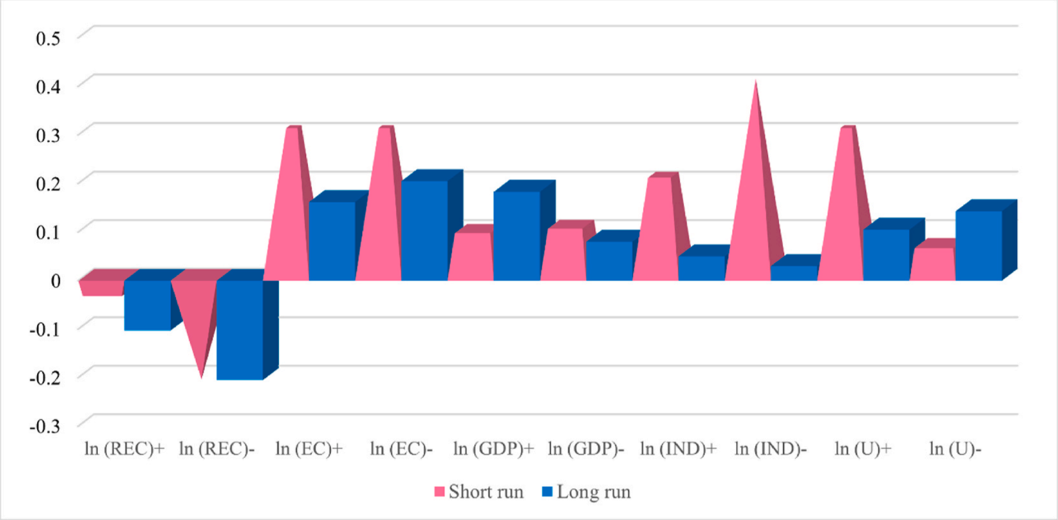

Fig. 6. NARDL results. Source: Author calculation.

Table 10
Diagnostic tests.

	F- statistics	Probability
Heteroskedasticity test: Breusch-Pagan-Godfrey	1.301	(0.160)
Breusch-Godfrey Serial Correlation LM	0.148	(0.657)
Heteroskedasticity test: White	3.671	(0.100)
Heteroskedasticity test: ARCH	0.196	(0.648)
Jarque-Bera normality	11.542	(0.003)
Ramsey RESET	0.871	(0.391)

Our analysis quantifies key energy transition trade-offs: each 1 % increase in REC reduces CO_2 emissions by 0.188 %, whereas equivalent FF increases emissions by 0.341 %. U expansion contributes an additional 0.064 % CO_2 emissions per 1 % growth rate, highlighting the need for balanced development strategies. Our findings provide three key insights into China's energy transition. First, REC adoption must prioritize equitable access between urban and rural areas to ensure social equity. Second, the environmental benefits are clear: each 1 % increase in the REC reduces CO_2 emissions by 0.188 %, providing measurable climate gains. Third, while the transition requires an upfront investment, the economic returns, including long-term GDP growth and job creation, outweigh these initial costs. According to these findings, the Chinese government should promote RECs, as clean energy is the best method for improving environmental quality by reducing carbon emissions. Governments and higher authorities must enact stringent environmental regulations to achieve these goals. They can levy a carbon tax to encourage manufacturers to use clean energy sources. Furthermore, the provision of commercial facilities stimulates an eco-friendly environment. Moreover, China, the world's largest energy consumer, must reconsider its infrastructure requirements. Raising the price of FF is a smart move to curb consumption in China. Additional ideas exist for improving environmental quality and contributing to long-term sustainability [79].

Environmental quality monitoring and management systems must be improved to achieve this goal. These strategies are based on results that can be generalized for all locations and types of deterioration, rather than being established from the ground up in any specific area. Several aspects must be considered in the government's efforts to reduce carbon emissions. Governments must re-examine industry permits and establish carbon emission limits. Therefore, new technologies must be adopted to facilitate the transition to clean energy sources. Through public-private partnerships, funds can also be raised for environmentally conscious centers to help slow the rate of environmental degradation. Technological advancements have enabled China to utilize the fastest digital solutions to reduce CO_2 emissions resulting from IND and U. Urban expansion drives greater industrial energy needs, but strategic city planning can channel this growth towards renewable solutions. We propose the mandatory adoption of RECs in urban industrial areas to align development with sustainability goals. The current study focuses on the significance of REC for China's long-term viability. Although each province has different CO_2 emissions per capita, country-specific studies on high CO_2 emissions provide valuable insights into developing effective countermeasures and strategies [80–82]. A limitation of this study is that national-level data cannot capture provincial differences, and future technological changes may impact the results. To better understand climate awareness, this study improves in the following ways: China's REC industry and future needs are better understood by examining the economic and financial obstacles and investment incentives tailored explicitly to meet China's demands.

CRediT authorship contribution statement

Muhammad Sohaib: Conceptualization, Methodology, Writing – original draft. **Abdul Majeed:** Resources, Supervision, Writing – review & editing. **Jingru Liu:** Software, Formal analysis, Visualization. **Judit Oláh:** Writing – review & editing, Funding acquisition.

Ethics statement

This is not applicable.

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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.

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Data availability

Data will be made available on request.

References

[1] J. Ding, The diffusion deficit in scientific and technological power: re-assessing China's rise, Rev. Int. Polit. Econ. 31 (2024) 173–198, https://doi.org/10.1080/09692290.2023.2173633.

[2] K. Dong, S. Wang, H. Hu, N. Guan, X. Shi, Y. Song, Financial development, carbon dioxide emissions, and sustainable development, Sustain. Dev. 32 (2024) 348–366, https://doi.org/10.1002/sd.2649.

[3] S. Boubaker, Z. Liu, Y. Mu, Y. Zhan, Carbon dioxide emissions and environmental risks: long term and short term, Risk Anal. (2024), https://doi.org/10.1111/risa.14281.

[4] J. Shekhar, D. Suri, P. Somani, S.J. Lee, M. Arora, Reduced renewable energy stability in India following COVID-19: insights and key policy recommendations, Renew. Sustain. Energy Rev. 144 (2021) 111015, https://doi.org/10.1016/j.rser.2021.111015.

[5] J. Wang, W. Azam, Natural resource scarcity, fossil fuel energy consumption, and total greenhouse gas emissions in top emitting countries, Geosci. Front. 15 (2024) 101757, https://doi.org/10.1016/j.gsf.2023.101757.

[6] T.Z. Ang, M. Salem, M. Kamarol, H.S. Das, M.A. Nazari, N. Prabaharan, A comprehensive study of renewable energy sources: classifications, challenges and suggestions, Energy Strategy Rev. 43 (2022) 100939, https://doi.org/10.1016/j.esr.2022.100939.

[7] H. Ai, X. Tan, S.K. Mangla, A. Emrouznejad, F. Liu, M. Song, Renewable energy transition and sustainable development: evidence from China, Energy Econ. 143 (2025) 108232, https://doi.org/10.1016/J.ENECO.2025.108232.

[8] J. Xu, Y. Guan, J. Oldfield, D. Guan, Y. Shan, China carbon emission accounts 2020-2021, Appl. Energy 360 (2024) 122837, https://doi.org/10.1016/j.apenergy.2024.122837.

[9] N. Wiseman, S. Moebs, M. Mwale, J. Zuwarimwe, The role of support organisations in promoting organic farming innovations and sustainability, Malaysian J. Sustain. Agric. 6 (2022) 44–50.

[10] J. Urpelainen, Energy poverty and perceptions of solar power in marginalized communities: survey evidence from Uttar Pradesh, India, Renew. Energy 85 (2016) 534–539, https://doi.org/10.1016/j.renene.2015.07.001.

[11] F. Halicioglu, An econometric study of CO2 emissions, energy consumption, income and foreign trade in Turkey, Energy Policy 37 (2009) 1156–1164, https://doi.org/10.1016/j.enpol.2008.11.012.

[12] WDI, World development indicators | DataBank, DataBank. https://databank.worldbank.org/reports.aspx?source=world-development-indicators, 2024.

[13] Q. Quan, W. Liang, D. Yan, J. Lei, Influences of joint action of natural and social factors on atmospheric process of hydrological cycle in Inner Mongolia, China, Urban Clim. 41 (2022) 101043, https://doi.org/10.1016/j.uclim.2021.101043.

[14] Xinhua, The state council of the P.R.C. https://english.www.gov.cn/archive/statistics/202501/28/content_WS6798de96c6d0868f4e8ef410.html, 2025. (Accessed 1 June 2025).

[15] R. Mccullum, Nuclear Energy Institute Letters, 2025, pp. 1–2. https://www.nei.org/home. (Accessed 1 June 2025).

[16] R. Miao, Y. Liu, L. Wu, D. Wang, Y. Liu, Y. Miao, Z. Yang, M. Guo, J. Ma, Effects of long-term grazing exclusion on plant and soil properties vary with position in dune systems in the Horqin Sandy Land, Catena 209 (2022) 105860, https://doi.org/10.1016/j.catena.2021.105860.

[17] Q. Quan, S. Gao, Y. Shang, B. Wang, Assessment of the sustainability of Gymnocypris eckloni habitat under river damming in the source region of the Yellow River, Sci. Total Environ. 778 (2021), https://doi.org/10.1016/j.scitotenv.2021.146312.

[18] N. Bhattarai, R. Kumar Jha, Rooftop farming: an alternative to conventional farming for urban sustainability, Malaysian J. Sustain. Agric. 3 (2019) 39–43, https://doi.org/10.26480/mjsa.01.2019.39.43.

[19] C. Chen, B. Matzdorf, L. Zhen, B. Schröter, Social-Network Analysis of local governance models for China's eco-compensation program, Ecosyst. Serv. 45 (2020) 101191, https://doi.org/10.1016/j.ecoser.2020.101191.

[20] C.K. Pek, F. Ee, F. o, Agricultural multifunctionality for sustainable development in Malaysia: a contingent valuation method approach, Malaysian J. Sustain. Agric. 6 (2022), https://doi.org/10.26480/mjsa.01.2022.01.06, 01–06.

[21] G.M. Grossman, A.B. Krueger, Economic growth and the environment, Q. J. Econ. 110 (1995) 353–377, https://doi.org/10.2307/2118443.

[22] Y. Yang, S. Xia, P. Huang, J. Qian, Energy transition: Connotations, mechanisms and effects, Energy Strategy Rev. 52 (2024) 101320, https://doi.org/10.1016/j.esr.2024.101320.

[23] S. Li, N. Xiang, C. Shu, F. Xu, Unveiling the industrial synergy optimization pathways in Beijing-Tianjin-Hebei urban agglomeration based on water-energy-carbon nexus, J. Environ. Manag. 376 (2025) 124528, https://doi.org/10.1016/j.jenvman.2025.124528.

[24] H. Chen, J. Chen, G. Han, Q. Cui, Winding down the wind power curtailment in China: what made the difference? Renew. Sustain. Energy Rev. 167 (2022) 112725 https://doi.org/10.1016/j.rser.2022.112725.

[25] T. Kataray, B. Nitesh, B. Yarram, S. Sinha, E. Cuce, S. Shaik, P. Vigneshwaran, A. Roy, Integration of smart grid with renewable energy sources: opportunities and challenges – a comprehensive review, Sustain. Energy Technol. Assessments 58 (2023) 103363, https://doi.org/10.1016/j.seta.2023.103363.

[26] L. Ren, S. Zhou, T. Peng, X. Ou, A review of CO2 emissions reduction technologies and low-carbon development in the iron and steel industry focusing on China, Renew. Sustain. Energy Rev. 143 (2021) 110846, https://doi.org/10.1016/j.rser.2021.110846.

[27] P. Ouyang, S. Fu, Economic growth, local industrial development and inter-regional spillovers from foreign direct investment: evidence from China, China Econ, Rev. 23 (2012) 445–460, https://doi.org/10.1016/j.chieco.2012.03.005.

[28] A. Majeed, J. Wang, Y. Zhou, Muniba, the symmetric effect of financial development, human capital and urbanization on ecological footprint: insights from BRICST economies, Sustainability 16 (2024) 5051, https://doi.org/10.3390/su16125051.

[29] X. Ou, Y. Xiaoyu, X. Zhang, Life-cycle energy consumption and greenhouse gas emissions for electricity generation and supply in China, Appl. Energy 88 (2011) 289–297, https://doi.org/10.1016/j.apenergy.2010.05.010.

[30] K. Dong, R. Sun, H. Jiang, X. Zeng, CO2 emissions, economic growth, and the environmental Kuznets curve in China: what roles can nuclear energy and renewable energy play? J. Clean. Prod. 196 (2018) 51–63, https://doi.org/10.1016/j.jclepro.2018.05.271.

[31] M. Xiao, M. Wetzel, T. Pregger, S. Simon, Y. Scholz, Modelling the supply of renewable electricity to metropolitan regions in China, Energies 13 (2020) 3042, https://doi.org/10.3390/en13123042.

[32] A. Gani, Fossil fuel energy and environmental performance in an extended STIRPAT model, J. Clean. Prod. 297 (2021) 126526, https://doi.org/10.1016/j.jclepro.2021.126526.

[33] R. Kumar, J. Sharan, S. Sambhaji, S. Mondal, R. Swaroop, R. Lal, B. Krishna, S. Kumar, A. Kumar, H. Hans, P. Kumar, A. Kumar, Comprehensive environmental impact assessment for designing carbon-cum-energy efficient , cleaner and eco-friendly production system for rice-fallow agro-ecosystems of South Asia, J. Clean. Prod. 331 (2022) 129973, https://doi.org/10.1016/j.jclepro.2021.129973.

[34] S.H. Kang, F. Islam, A. Kumar Tiwari, The dynamic relationships among CO2 emissions, renewable and non-renewable energy sources, and economic growth in India: evidence from time-varying Bayesian VAR model, Struct. Change Econ. Dynam. 50 (2019) 90–101, https://doi.org/10.1016/j.strueco.2019.05.006.

[35] F.Y. Fu, M. Alharthi, Z. Bhatti, L. Sun, F. Rasul, I. Hanif, W. Iqbal, The dynamic role of energy security, energy equity and environmental sustainability in the dilemma of emission reduction and economic growth, J. Environ. Manag. 280 (2021), https://doi.org/10.1016/j.jenvman.2020.111828.

[36] B. Lin, J. Zhu, The role of renewable energy technological innovation on climate change: empirical evidence from China, Sci. Total Environ. 659 (2019) 1505–1512, https://doi.org/10.1016/j.scitotenv.2018.12.449.

[37] S.A. Sarkodie, S. Adams, P.A. Owusu, T. Leirvik, I. Ozturk, Mitigating degradation and emissions in China: the role of environmental sustainability, human capital and renewable energy, Sci. Total Environ. 719 (2020) 137530, https://doi.org/10.1016/j.scitotenv.2020.137530.

[38] A.A. Alola, F.V. Bekun, T.S. Adebayo, G. Uzuner, The nexus of disaggregated energy sources and cement production carbon emission in China, Energy Environ. 34 (2023) 1937–1956, https://doi.org/10.1177/0958305X221102047.

[39] T.S. Adebayo, S. Ullah, M.T. Kartal, K. Ali, U.K. Pata, M. Ağa, Endorsing sustainable development in BRICS: the role of technological innovation, renewable energy consumption, and natural resources in limiting carbon emission, Sci. Total Environ. 859 (2023) 160181, https://doi.org/10.1016/j.scitotenv.2022.160181.

[40] M.T. Kartal, S. Kılıç Depren, U. Ali, Z. Nurgazina, Long-run impact of coal usage decline on CO2 emissions and economic growth: evidence from disaggregated energy consumption perspective for China and India by dynamic ARDL simulations, Energy Environ. (2023), https://doi.org/10.1177/0958305X231152482.

[41] K.A. Sarpong, W. Xu, B.A. Gyamfi, E.K. Ofori, A step towards carbon neutrality in E7: the role of environmental taxes, structural change, and green energy, J. Environ. Manag. 337 (2023) 117556, https://doi.org/10.1016/j.jenvman.2023.117556.

[42] S. Ullah, R. Luo, T. Sunday Adebayo, D. Balsalobre-Lorente, Green perspectives of finance, technology innovations, and energy consumption in restraining carbon emissions in China: Fresh insights from Wavelet approach, Energy Sources, Part B Econ. Plan, Policy 18 (2023), https://doi.org/10.1080/15567249.2023.2255584.

[43] L. Wang, Assessment of land use change and carbon emission: a Log Mean Divisa (LMDI) approach, Heliyon 10 (2024) e25669, https://doi.org/10.1016/j.heliyon.2024.e25669.

[44] S. Hadian, K. Madani, A system of systems approach to energy sustainability assessment: are all renewables really green? Ecol. Indic. 52 (2015) 194–206, https://doi.org/10.1016/j.ecolind.2014.11.029.

[45] B. Pejović, V. Karadžić, Z. Dragašević, T. Backović, Economic growth, energy consumption and CO2 emissions in the countries of the European Union and the Western Balkans, Energy Rep. 7 (2021) 2775–2783, https://doi.org/10.1016/j.egyr.2021.05.011.

[46] B. Knopf, Y.H.H. Chen, E. De Cian, H. Förster, A. Kanudia, I. Karkatsouli, I. Keppo, T. Koljonen, K. Schumacher, D.P. Van Vuuren, BEYOND 2020-STRATEGIES and COSTS for TRANSFORMING the EUROPEAN ENERGY SYSTEM, Clim. Chang. Econ. (2013), https://doi.org/10.1142/S2010007813400010.

[47] D.J. van de Ven, R. Fouquet, Historical energy price shocks and their changing effects on the economy, Energy Econ. 62 (2017) 204–216, https://doi.org/10.1016/j.eneco.2016.12.009.

[48] M. Bhattacharya, S. Awaworyi Churchill, S.R. Paramati, The dynamic impact of renewable energy and institutions on economic output and CO2 emissions across regions, Renew. Energy 111 (2017) 157–167, https://doi.org/10.1016/j.renene.2017.03.102.

[49] B. Janet Ruiz-Mendoza, C. Sheinbaum-Pardo, Electricity sector reforms in four Latin-American countries and their impact on carbon dioxide emissions and renewable energy, Energy Policy (2010), https://doi.org/10.1016/j.enpol.2010.06.046.

[50] M.H. Pesaran, Y. Shin, An autoregressive distributed-lag modelling approach to Co-integration analysis, in: Econom. Econ. Theory 20th Century, Cambridge University Press, 2012, pp. 371–413, https://doi.org/10.1017/ccol521633230.011.

[51] Mahidin Erdiwansyah, H. Husin, M. Nasaruddin, Zaki, Muhibbuddin, A critical review of the integration of renewable energy sources with various technologies, Prot. Control Mod. Power Syst. 6 (2021) 1–18, https://doi.org/10.1186/s41601-021-00181-3.

[52] H.M.S. Al-Maamary, H.A. Kazem, M.T. Chaichan, The impact of oil price fluctuations on common renewable energies in GCC countries, Renew. Sustain. Energy Rev. 75 (2017) 989–1007, https://doi.org/10.1016/j.rser.2016.11.079.

[53] P.C.B. Phillips, P. Perron, Testing for a unit root in time series regression, Biometrika 75 (1988) 335, https://doi.org/10.2307/2336182.

[54] D.A. Dickey, W.A. Fuller, Distribution of the estimators for autoregressive time series with a unit root, J. Am. Stat. Assoc. 74 (1979) 427–431, https://doi.org/10.1080/01621459.1979.10482531.

[55] Y. Shin, P. Schmidt, The KPSS stationarity test as a unit root test, Econ. Lett. 38 (1992) 387–392, https://doi.org/10.1016/0165-1765(92)90023-R.

[56] E. Nkoro, A.K. Uko, Autoregressive Distributed Lag (ARDL) co-integration technique: application and interpretation, J. Stat. Econom. Methods 5 (2016) 63–91. https://ideas.repec.org/a/spt/stecon/v5y2016i4f5_4_3.html.

[57] I. Yahyaoui, N. Bouchoucha, The long-run relationship between ODA, growth and governance: an application of FMOLS and DOLS approaches, Afr. Dev. Rev. 33 (2021) 38–54, https://doi.org/10.1111/1467-8268.12489.

[58] S.R. Paramati, D. Mo, R. Gupta, The effects of stock market growth and renewable energy use on CO2 emissions: evidence from G20 countries, Energy Econ. 66 (2017) 360–371, https://doi.org/10.1016/j.eneco.2017.06.025.

[59] G. Human, G. van Schoor, K.R. Uren, Genetic fuzzy rule extraction for optimised sizing and control of hybrid renewable energy hydrogen systems, Int. J. Hydrogen Energy 46 (2021) 3576–3594, https://doi.org/10.1016/j.ijhydene.2020.10.238.

[60] A. Majeed, L. Wang, X. Zhang, Muniba, D. Kirikkaleli, Modelling the dynamic links among natural resources, economic globalization, disaggregated energy consumption, and environmental quality: Fresh evidence from GCC economies, Resour. Policy 73 (2021) 102204, https://doi.org/10.1016/j.resourpol.2021.102204.

[61] D.I. Urzedo, J. Neilson, R. Fisher, R.G.P. Junqueira, A global production network for ecosystem services: the emergent governance of landscape restoration in the Brazilian Amazon, Glob. Environ. Change 61 (2020) 102059, https://doi.org/10.1016/j.gloenvcha.2020.102059.

[62] Luis M. Gandía, Raquel Oroz, Alfredo Ursúa, Pablo Sanchis, P.M. Diéguez, Renewable hydrogen production: performance of an Alkaline water electrolyzer working under emulated wind conditions. https://doi.org/10.1021/EF060491U, 2007.

[63] S.R. Wan Alwi, J.J. Klemeš, P.S. Varbanov, Cleaner energy planning, management and technologies: perspectives of supply-demand side and end-of-pipe management, J. Clean. Prod. 136 (2016) 1–13, https://doi.org/10.1016/j.jclepro.2016.07.181.

[64] F. Polzin, M. Sanders, How to finance the transition to low-carbon energy in Europe? Energy Policy (2020) https://doi.org/10.1016/j.enpol.2020.111863.

[65] R. Sarrias-Mena, L.M. Fernández-Ramírez, C.A. García-Vázquez, F. Jurado, Electrolyzer models for hydrogen production from wind energy systems, Int. J. Hydrogen Energy 40 (2015) 2927–2938, https://doi.org/10.1016/J.IJHYDENE.2014.12.125.

[66] A. Klitkou, S. Bolwig, T. Hansen, N. Wessberg, The role of lock-in mechanisms in transition processes: the case of energy for road transport, in: Environ. Innov. Soc. Transitions, Elsevier B.V., 2015, pp. 22–37, https://doi.org/10.1016/j.eist.2015.07.005.

[67] T. Hassan, H. Song, Y. Khan, D. Kirikkaleli, Energy efficiency a source of low carbon energy sources? Evidence from 16 high-income OECD economies, Energy 243 (2022) 123063, https://doi.org/10.1016/j.energy.2021.123063.

[68] K. Li, B. Lin, Impacts of urbanization and industrialization on energy consumption/CO2 emissions: does the level of development matter? Renew. Sustain. Energy Rev. 52 (2015) 1107–1122, https://doi.org/10.1016/j.rser.2015.07.185.

[69] U.K. Pata, Renewable energy consumption, urbanization, financial development, income and CO2 emissions in Turkey: testing EKC hypothesis with structural breaks, J. Clean. Prod. 187 (2018) 770–779, https://doi.org/10.1016/j.jclepro.2018.03.236.

[70] M. Radovanović, S. Filipović, D. Pavlović, Energy security measurement – a sustainable approach, Renew. Sustain. Energy Rev. 68 (2017) 1020–1032, https://doi.org/10.1016/J.RSER.2016.02.010.

[71] P.N.S. Bhasker Nair, R.R. Tan, D.C.Y. Foo, A generic algebraic targeting approach for integration of renewable energy sources, CO2 capture and storage and negative emission technologies in carbon-constrained energy planning, Energy (2021) 121280, https://doi.org/10.1016/j.energy.2021.121280.

[72] F. Vasquez-Lavín, R.D. Ponce Oliva, J.I. Hernández, S. Gelcich, M. Carrasco, M. Quiroga, Exploring dual discount rates for ecosystem services: evidence from a marine protected area network, Resour. Energy Econ. 55 (2019) 63–80, https://doi.org/10.1016/j.reseneeco.2018.11.004.

[73] X.P. Nguyen, N.D. Le, V.V. Pham, T.T. Huynh, V.H. Dong, A.T. Hoang, Mission, challenges, and prospects of renewable energy development in Vietnam, Energy Sources, Part A Recover, Util. Environ. Eff. (2021), https://doi.org/10.1080/15567036.2021.1965264.

[74] Q. Wang, S. Wu, Y. Zeng, B. Wu, Exploring the relationship between urbanization, energy consumption, and CO2 emissions in different provinces of China, Renew. Sustain. Energy Rev. 54 (2016) 1563–1579, https://doi.org/10.1016/j.rser.2015.10.090.

[75] S.R. Sinsel, R.L. Riemke, V.H. Hoffmann, Challenges and solution technologies for the integration of variable renewable energy sources—a review, Renew. Energy 145 (2020) 2271–2285, https://doi.org/10.1016/j.renene.2019.06.147.

[76] F.S. Chien, H.W. Kamran, G. Albashar, W. Iqbal, Dynamic planning, conversion, and management strategy of different renewable energy sources: a Sustainable Solution for Severe Energy Crises in Emerging Economies, Int. J. Hydrogen Energy 46 (2021) 7745–7758, https://doi.org/10.1016/j.ijhydene.2020.12.004.

[77] I. Berk, A. Kasman, D. Kılınç, Towards a common renewable future: the System-GMM approach to assess the convergence in renewable energy consumption of EU countries, Energy Econ. 87 (2020), https://doi.org/10.1016/j.eneco.2018.02.013.

[78] Y. Pan, J. Wu, Y. Zhang, X. Zhang, C. Yu, Simultaneous enhancement of ecosystem services and poverty reduction through adjustments to subsidy policies relating to grassland use in Tibet, China, Ecosyst. Serv. 48 (2021), https://doi.org/10.1016/j.ecoser.2021.101254.

[79] L. Zhu, F. Li, Agricultural data sharing and sustainable development of ecosystem based on block chain, J. Clean. Prod. 315 (2021) 127869, https://doi.org/10.1016/j.jclepro.2021.127869.

[80] R. Portela, F. Villa, L. Onofri, P.A.L.D. Nunes, A. Shepard, A Demonstration Case Study for the Wealth Accounting and the Valuation of Ecosystem Services (Waves) Global Partnership, 2012.

[81] A. Majeed, Y. Xie, C. Gao, A.M. Du, Muniba, Examining the role of artificial intelligence, financial innovation, and green energy transition in enhancing environmental quality, Int. Rev. Econ. Financ. 100 (2025) 104092. https://doi.org/10.1016/J.IREF.2025.104092.

[82] J. Yu, A. Majeed, Y. Liu, Rethinking Foreign Direct Investment's Role in Sustainable Development: Insights from the E-7 Economies Using Advanced Panel Data Methodologies, Sustainability 17 (2025) 3757. https://doi.org/10.3390/SU17083757.