ORIGINAL ARTICLE

Energy efficiency and China's carbon emissions: evidence from non-parametric approaches

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Abstract In the recent times, the issue of excessive carbon emission is a hot topic among the scholars and governors. In this context, it is necessary to examine the factors affecting the emissions level, particularly in emerging economy like China. Using the extended period from 1990 to 2021, this study analyzes the impact of energy efficiency, economic growth, and renewable energy along with the testing of environmental Kuznets curve (EKC) paradox. The empirical results validate the cointegration between the mentioned variables. Employing the novel non-parametric approaches, this study found the existence of the EKC hypothesis in the country as the economic growth initially increases environmental challenges, while reducing it after reaching a specific income level. On the other hand, energy efficiency and renewable energy consumption are found to be significant tools for improving environmental sustainability and reducing of carbon emissions. The robustness of the results is confirmed by the non-parametric (bootstrap quantile regression) and parametric (fully modified ordinary least square) approaches. Based on the outcomes, this study also revealed policy implications for the scholars and governors.

Introduction

In the twenty first century, carbon emissions, energy efficiency, and sustainable growth have been a topic of concern for academics, scholars, and

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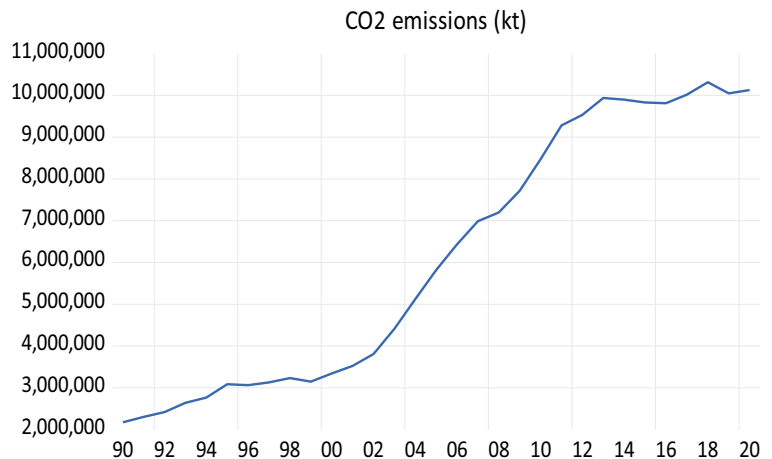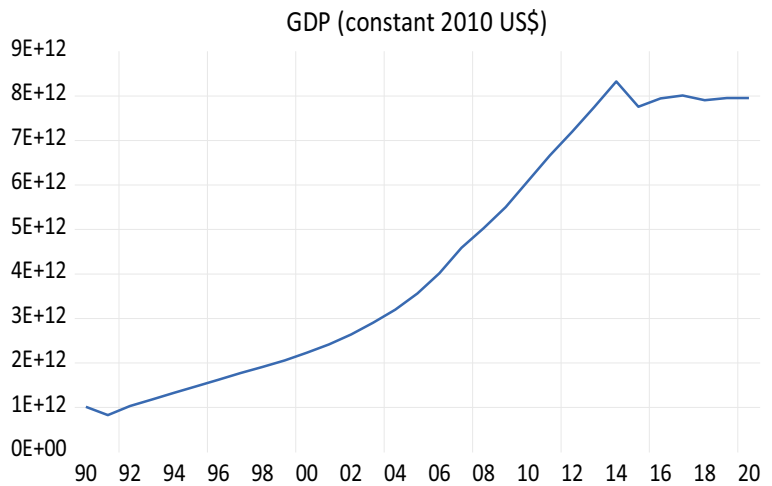**Fig. 1** Carbon emissions over the years. Source: World Bank (2022)

CO2 emissions (kt)

Fig. 2 GDP of China. Source: World Bank (2022)

GDP (constant 2010 US$)

environmentalists all over the world. With the ongoing development across the world, energy is one of the major determinants of sustainable development. Economic evolution has a momentous impact on energy consumption. Due to that reason, the energy demand has been mounting directly contributing to environmental deterioration. The escalating atmospheric concentrations of carbon and GHG emissions have increased global temperatures. Based on the World Population Review, China emits almost 30% of the World's carbon dioxide emissions in 2022. Attributable to this, climate change has projected an adverse effect on the environment (Lee et al., 2018; Raihan & Tuspekova, 2022). Therefore, limiting emissions has become the number one priority of sustainable development. Environmental sustainability requires

continuous growth which in turn worsens the quality of the environment. In Fig. 1, carbon emissions have intensified over the years in China. Since 1990, the emissions increased gradually leading to 11,535 Mton of emissions, which the country alone emitted in the year 2022. In Fig. 2 the gross domestic product of the country has also increased which has a significant role in upsurging carbon emissions. Apart from other reasons, the increasing production activities have projected the emissions of carbon. Additionally, the smart policies and economic development in the country have raised the GDP of the country as shown in the graph. The economic growth in China upsurged and became a high-income developed economy in the world even displacing the USA as one-sixth larger than the USA (Alison, 2020).
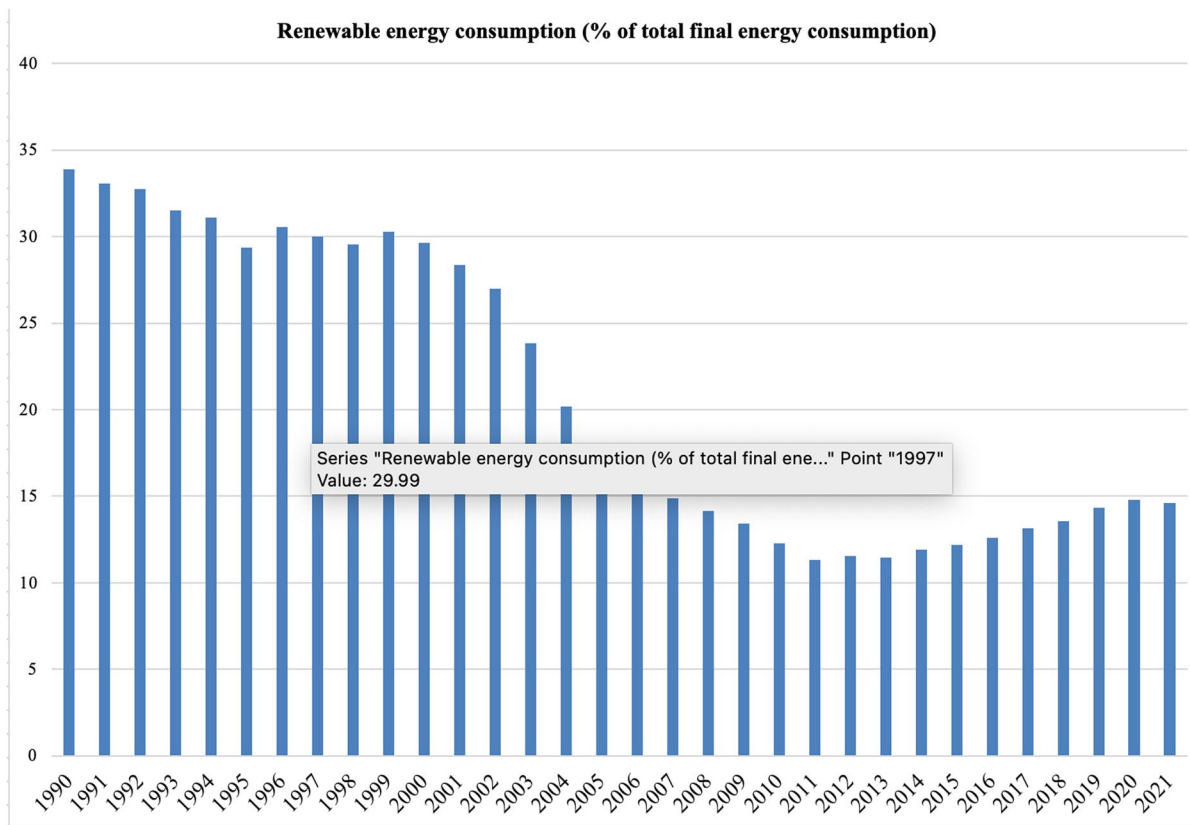
Renewable energy consumption (% of total final energy consumption)

Series "Renewable energy consumption (% of total final ene..." Point "1997"
Value: 29.99

Fig. 3 Renewable energy consumption. Source: World Bank (2022)

In retrospect, the use of renewable energy in the 1990s has fallen; after 2010, the role of renewable energy consumption in the country has improved due to increasing climatic concerns. China's renewable energy sector is growing faster than nuclear and fossil energy consumption, contributing almost 45% in the global growth (See Fig. 3). In 2021, 2.48 trillion kWh of electricity consumed is obtained from renewable energy sources (State Council, 2022). Mahmood et al. (2019) emphasized that increasing production activities emit a huge amount of emissions in the country and that economic growth has positively obstructed carbon emissions. Nonetheless, the increase in renewable energy and energy efficiency in the economy significantly reduces the emissions and pollution in the country. Because energy is the main indicator that aids in greasing the economic production activities. Therefore, efficient use of energy along with green energy and green technology can be resourceful in pollution reduction (Akram et al., 2020; He et al., 2021; Ehigiamusoe & Dogan, 2022; Mirza et al., 2022).

In the prevailing literature, the association between economic growth, renewable energy consumption, and carbon emissions is presented. Kirikkaleli et al. (2022) scrutinized the relationship between economic growth, renewable consumption, and carbon emissions. The increasing economic growth pressurized the environmental quality by increasing carbon emissions (Chen et al., 2022).

The study aims to accomplish the ensuing objectives. The primary objective is to examine the energy-environment nexus empirically in the case of China from the year 1990 to 2021. To examine this, the authors employed variables like energy efficiency and carbon dioxide emissions (CO_2) for the assessment. The second main objective of the study is to determine the impact of renewable energy on carbon emissions. Renewable energy plays a key role in limiting emissions. While thirdly, the study aims to scrutinize the

growth-environment nexus. For the investigation of the sustainable economic growth impact on environmental quality, the authors employed GDP, GDP square, and CO_2 emissions in the study; data exclusively taken from the World Bank. Correspondingly, the study employs modernized non-parametric econometric approaches to inspect these research objectives.

Energy has substantial pressure on environmental quality. Therefore, the study is significant in investigating the impact of energy efficiency and renewable energy on carbon emissions. Several studies have scrutinized the influence on different economies. However, China has a significant contribution to the consumption of non-renewable energy that deteriorates the environmental quality, affecting the world economically, environmentally, and socially. Only less than 15% comes from renewable sources which critically affects the sustainability of the economy which in turn impacts the global economy. Therefore, the study has motivated us to examine the role of assessing the nexus empirically. Secondly, several scholars have scrutinized the economic growth and environment relationshi Besides, China is among the largest carbon dioxide emitters in the world. However, it would be interesting to reexamine the linkage with the updated data period from 1990 to 2021 with the inclusion of GDP and GDP square as the explanatory variables in China. The findings demonstrate the validation of the environmental Kuznets curve hypothesis, which is a burning topic in academic research, that signifies research.

The study contributes to the literature in twofold ways. First, the present study is a revisit of energy efficiency and carbon emissions in China. However, the study employs modernized econometric analysis and an updated sample period from 1990 to 2021. Second, the study provides additional empirical evidence in energy-environment literature alongside the literature on the growth-environment nexus for assessing green energy, economic growth, and carbon emission policies and strategies. The study results have relevant and substantial policy implications for carbon neutrality.

The rest of the alignment of the study is as follows. The "Literature review" section represents the review of the empirical literature. The data, model, and methodology are explained in the "Data and methodology" section of the manuscript. The empirical results from the econometric analysis are documented in the "Results and discussions" section of the study. The concluding remarks and relevant policy implications

are presented in the "Conclusion and policy implications" section, respectively.

Literature review

The following literature pieces of evidence support assessing the aspects and connections between the study variables.

Economic growth and carbon emissions

Economic growth and carbon emissions nexus have significant importance in the literature. Narayan et al. (2016) examined the association between economic growth and carbon emissions in 181 economies. Out of 12%, meaning 21 countries supported the EKC hypothesis, while 27% that is 49 countries have an inverse association between growth and carbon emissions. Salman et al. (2019) analyzed the growth-emissions nexus in the East Asian economies. The empirical results indicated that efficient institutions significantly help in limiting emissions and growth simultaneously. Furthermore, the existence of a feedback causal effect is confirmed between economic growth and carbon emissions. In the latest study, Chen et al. (2022) determined the positive and significant impact of economic growth on increasing carbon emissions with bi-directional causal associations. Radmehr et al. (2021) determined a bi-directional causal association between economic growth and carbon emissions. In the case of Chile, Kirikkaleli et al. (2022) scrutinized the relationship between economic growth, renewable consumption, financial development, and carbon emissions. The growth-emissions nexus in the results indicated a positive relationshi The increase in economic growth substantially increases carbon dioxide emissions in the economy. In Malaysia, the increasing economic activities increase economic growth which in turn has a detrimental impact on the quality of the environment resulting in increased carbon emissions. In the case of Pakistan, Sufyanullah et al. (2022) scrutinized the association between economic growth and carbon emissions. The Granger causality analysis demonstrated a one-way directional causal relationship between them. Li et al. (2021) examined a panel of G20 economies. The causality analysis depicted feedback analysis between economic growth and carbon emissions. Li and Wei (2021) determined a substantial

relationship between economic growth and carbon emissions and the impacts differ significantly from region to region in China. Sadiq et al. (2022) observed the environmental Kuznets hypothesis and discovered the negative and positive impact of GDP and squared GDP on carbon emissions. Leitão et al. (2021) scrutinized the relationship between GDP and squared GDP and carbon emissions. The econometric analysis demonstrated a long-run relationship and confirmed the EKC hypothesis between the said variables. A positive linkage is observed between GDP and carbon emissions, and a negative connection is discovered between squared GDP and carbon emissions in BRICS nations. In another study, Acaravci and Ozturk (2010) examined the association between GDP, GDP square, and carbon emissions. The empirical findings depicted a positive relationship between GDP and carbon emissions, while a negative association between GDP square and carbon emissions is observed in European nations with confirmation of the EKC hypothesis. The GDP square (a threshold level of economic growth) leads to limit carbon emissions whereas GDP alone in the beginning accelerates emissions (Akram et al., 2020). In contrast, Anser et al. (2021) discovered the negative and positive impacts of GDP and GDP square on carbon emissions with uni-directional causality.

Role of energy efficiency and renewable energy consumption

Energy efficiency has a strong ability to reduce carbon emissions in the economy. Akram, et al. (2020) observed the mitigation impact of energy efficiency on carbon emissions. Likewise, renewable energy consumption significantly reduces carbon emissions in 66 developing economies. In a recent analysis, Ye et al. (2022) investigated mixed results of energy efficiency and carbon emissions that had a mitigating effect in the lower quantiles whereas an encouraging effect on carbon emissions in the upper quantiles. Wu et al. (2019) observed that in the Chinese 30 provinces, energy efficiency has played a substantial role in reducing carbon dioxide emissions. Kirikkaleli et al. (2022) discovered the negative influence of renewable energy consumption in the case of Chile. The increasing consumption of renewable energy substantially decreases the harmful carbon emissions. He et al. (2021) emphasized that energy efficiency substantially decreases carbon emissions. In a novel study, Akram et al. (2020) discovered the encouraging impact

of renewable energy and energy efficiency on environmental quality. The study applied panel econometric analysis, and the empirical findings demonstrated an inverse effect of renewable energy and energy efficiency on carbon emissions, i.e., a 1% increase in energy efficiency and renewable energy has significantly decreased 0.78% and 0.73% of carbon emissions in the BRICS. In assessing the role of energy efficiency in the N11 and BRICS nations, Yao et al. (2021) analyzed that technological advancement in an economy significantly improves energy efficiency which is necessary for environmental quality. It reduces carbon emissions and ecological footprints. Additionally, foreign direct investment has a crucial role in encouraging energy efficiency. Zhao et al. (2022) inspected that increase in FDI encourages energy efficiency that in turn improves the environmental quality. Besides, energy efficiency has a major role in limiting carbon dioxide and GHG emissions (Mirza et al., 2022). Novel research on the energy-emission nexus applied the Divisia Index method for evaluating the relationshi The empirical results showed that energy efficiency is a strong limiting and restraining factor for pollution and mitigates carbon emissions. In another panel study of ASEAN countries, Salman et al. (2019) revealed the encouraging impact of energy efficiency on environmental quality. The escalating efficient form of energy significantly reduces carbon emissions in ASEAN nations.

An upsurge in renewable energy consumption leads to substantial encouragement in the quality of the environment. In Turkey, Adebayo et al. (2022) applied a series of econometric techniques and discovered the positive impact of renewable energy consumption on environmental quality by limiting carbon emissions. Ehigiamusoe and Dogan (2022) examined low-income economies. The empirical results show positive interaction, but the effect of renewable energy on carbon emissions is restricted which means increasing renewable consumption limits emissions. Adebayo et al. (2022) inspected the asymmetric impacts of renewable energy consumption on Sweden's economy. However, the majority of quantiles presented a negative linkage between renewable energy consumption and carbon emissions. Because renewable consumption is the ultimate and most reliable solution for limiting carbon dioxide emissions (Sun et al., 2021). In studying MINT economies, Adebayo and Rjoub (2021) employed CS-ARDL and AMG techniques to determine the inverse relationship between renewable

consumption and carbon emissions. The empirical findings depicted that increasing renewable energy consumption significantly restricts carbon emissions in the long-run association. Hasanov et al. (2021) also observed a negative linkage between renewable energy consumption and carbon emissions.

Nonetheless, the higher level of emissions causes health-related issues (Wei et al., 2022). In order to reduce emissions, the existing literature reports other remedial measure for environmental recovery. Specifically, the measures include environmental stringent policies (Shahzad et al., 2021), financial Inclusion (Qin et al., 2021), environmental R&D (Jiang et al., 2022), investment in the pollution prevention industry (Luan et al., 2022), renewable energy (Cai et al., 2022), financial development (Qin et al., 2021), and high-quality institutions (Bashir et al., 2022). Improvement in these indicators could significantly reduce the level of emissions and improve environmental quality.

Research gap

After a critical analysis of the existing literature, the body of knowledge is extensive concerning renewable energy, economic growth, and energy efficiency; however, the present study scrutinizes the energy efficiency and carbon emissions from a non-parametric analysis with an updated data period using modernized explanatory factors and techniques. The study is a new input in the empirical literature on the energy-environment and growth-environment nexus.

Data and methodology

Theoretical foundation and model vevelopment

The environmental Kuznets curve (EKC) is a proposed correlation between several aspects of the environment's deterioration and the income level. During the first phases of economic expansion, pollutant emissions enhance and environmental quality deteriorates. That is, the growth in industrial production in nations with a low degree of economic prosperity causes a rise in energy-intensive manufacturing and a rise in emitting harmful gases such as CO_2, given as follows: $\delta_1 = \frac{\partial CO_{2,t}}{\partial GDP_t} > 0$, and hence this study expected the positive impact of GDP on the CO_2

emissions. However, at a certain threshold of income (which varies among measures), the tendency reverses, such that at significant levels of affluence, economic expansion results in environmental sustainability. This suggests that environmental effects or emissions are an inverted U-shaped relationship of income. Particularly, the EKC is called after Simon Kuznets, who claimed that as economic growth advances, income disparity first increases and subsequently decreases, which can be depicted as follows: $\delta_2 = \frac{\partial CO_{2,t}}{\partial GDPS_t} < 0$, due to which this study assumes the negative association between these variables. Apart from the income level, there are several environmental indicators that could help attain environmental sustainability. If the production of power causes carbon emissions, then increasing energy efficiency is among the greatest strategies to minimize air pollution. Energy efficiency enhancement involves both making systems operate more effectively so they use less energy to run and increasing the amount of energy produced per unit of environmental pollution. It cuts emissions significantly, both directly from burning fossil fuel or usage and indirectly from power production. Therefore, this study also assumes the negative influence of energy efficiency (ENEF) on CO_2 emissions, given as follows: $\delta_3 = \frac{\partial CO_{2,t}}{\partial ENEF_t} < 0$. Among the environmental and economic advantages of renewable energy is the production of electricity without emitting greenhouse gases from fossil fuels and reducing certain kinds of air pollution. It leads to expanding energy resources and decreasing reliance on foreign fuels. The sort of energy that renewables replace tends to depend on the time of the day and the generational composition of the grid at that moment. Numerous studies have shown that when solar and wind energy replace fossil fuel production, renewable energy cuts CO2 emissions (see the "Literature review" section). Hence, this study also proposes the negative influence of renewable energy consumption (REC) on CO_2 emissions, given as follows: $\delta_4 = \frac{\partial CO_{2,t}}{\partial REC_t} < 0$.

Based on the above discussion and objectives of this research, the current study constructed the following model:

$$CO_{2,t} = f\left(GDP_t, GDPS_t, ENEF_t, REC_t\right)$$

From the study model, the CO_2 represents the carbon dioxide emission in kilotons (kt), and GDP reports the gross domestic product, and is regarded as a prominent measure of the economic growth and

is measured at constant US$ 2015 prices. Besides, to test the EKC hypothesis, this study uses the squared term of GDP (GDPS), which replicates the higher or increased economic activity of the country. On the other hand, the primary focus variable of this study is energy efficiency (ENEF: GDP per unit of energy used (constant 2017 PPP $ per kg of oil equivalent)). In addition, this study also controls for the omitted variables biasedness; thus, renewable energy consumption (REC: percentage of the total energy) is added to the model. The prior study model could be transformed into the regression form below:

$$CO_{2,t} = \alpha_1 + \beta_1 GDP_t + \beta_2 GDPS_t + \beta_3 ENEF_t + \beta_4 REC_t + \varepsilon_t \tag{1}$$

From Eq. (1), the α indicates the model's intercept, while the slopes are presented by $\beta_{1, 2, 3, \text{and } 4}$, respectively. The random error of the model is captured by vector ε, whereas the time period is depicted by t in the subscript, which is from 1990 to 2021 in the case of China. Data for the stated variables is obtained from the World Bank (2022)[1].

Estimation strategy

This study assessed descriptive statistics for the researched elements in order to offer a more thorough perspective of the time series data. Descriptive analytics, for instance, include the mean, median, and range (maximum and minimum) of data values. This study also explores the standard deviation of variables, which indicates the instability of the temporal factors by illustrating the divergence of observations from the general mean. In addition, two normality measures are used to evaluate the distributional features of the data. In particular, skewness and Kurtosis have been employed to determine if the distribution of a variable fits the normality criterion. Skewness and Kurtosis can give accurate data about the variables' dispersion. Nonetheless, this study addresses the topic of normalcy with more clarity. The present study employed the Jarque and Bera (1987) normalcy estimator, which evaluates both excess Kurtosis and skewness and maintains their critical values at zero, hence verifying the assumption that the variables are normally distributed. Below is the Jarque-Bera equation for normalcy metrics:

$$JB = N \cdot \frac{1}{6} \left(S^2 + \frac{(K-3)^2}{4} \right), \tag{2}$$

Once the variables normality is analyzed, this study considers the unit root estimations. Nonetheless, the unit root in time series can cause unpredictability in the estimated results. Therefore, this study employed the Augmented Dickey-Fuller (ADF) estimator proposed by Dickey and Fuller (1979). Serial correlation is compatible with the ADF test. Therefore, this test is more comprehensive and can accommodate more complicated models than the conventional Dickey-Fuller test.

After establishing the stationarity of the time series, the long-term interaction between the variables is studied. The Bayer-Hanck combined cointegration test, which integrates the cointegration evaluation methods of Engle and Granger (1987), Johansen (1991), Banerjee et al. (1998), and Boswijk (1994), was used to evaluate the cointegration relationship between the research variables. Nevertheless, if the preceding approaches are executed independently, the predictive accuracy of the cointegration test may provide erroneous findings (Shahbaz et al., 2018). We used the combined cointegration test method outlined by Bayer and Hanck (2013) for enhanced cointegration analysis and to prevent unclear or perplexing computations. This test combines all previously published cointegration tests using the Fisher's F-statistics and provides consistent results (Shahbaz et al., 2018). Moreover, this evaluation requires a distinct integrating sequence, i.e., I (1). This test implies that the variables under investigation are not cointegrated. The assertion may be refused, however, if the predicted values exceed the threshold limits. These following equations describe the Fisher's technique for Bayer-Hanck cointegration.

$$EG - J = -2 \left[\ln \left(P_{EG} \right) + \ln \left(P_J \right) \right], \tag{3}$$

$$EG - J - Ba - Bo = -2 \left[\ln \left(P_{EG} \right) + \ln \left(P_J \right) + \ln \left(P_{Ba} \right) + \ln \left(P_{Bo} \right) \right], \tag{4}$$

where P_{EG}, P_j, P_{Ba}, and P_{Bo} indicate probabilities for the cointegration tests conducted by Engle and Granger (1987), Johansen (1991), Banerjee et al. (1998), and Boswijk (1994), respectively.

Therefore, this study takes into account the non-normal data distribution, necessitating the employment of a Method of Moment Quantile Regression (MMQR) estimation technique. Koenker and Bassett

Jr. (1978) invented the quantile regression modeling technique for assessing the conditional variance and mean dependence for the reduction of non-linearity difficulties in its beginnings. Machado and Silva (2019) have just created the novel MMQR method for examining the distribution of quantile projections based on the quantile approach (Sarkodie & Strezov, 2018). The formula for the conditional location-scale variance $Q_y(\tau|R)$ is as follows:

$$Y_{it} = \alpha_i + \beta R_{it} + \left(\gamma_i + \rho \acute{Z}_{it}\right)\mu_{it}, \tag{5}$$

In the above formulation, the probabilistic expression $p\left(\gamma_i + \rho \acute{Z}_{it} > 0\right)$ is identical to only one, while α, β, γ, and ρ reflect the projected model parameters in the ongoing study. The subscript i signifies the fixed effect defined by the coefficients α_i and γ_i which is restricted to the range $i = 1, 2, \ldots, n$. Here, the characteristic constituent of R, represented by Z, is the k-vector, whereas the variability is marked by the vector "$\imath$."

$$Z_{\mathbb{I}} = Z_{\imath}(R), \quad \imath = 1, 2, \ldots, k, \tag{6}$$

where R it is autonomously and symmetrically distributed for the fixed i and time (t), which would be orthogonal to i and t. (Machado & Silva, 2019). Therefore, both the exterior components and reserves are steady. Based on the preceding rationale, the research model (Eq. (1)) might be restated as follows:

$$Q_y\left(\tau|R_{it}\right) = \left(\alpha_i + \gamma_i q(\tau)\right) + \beta R_{it} + \rho \acute{Z}_{it} q(\tau), \tag{7}$$

In the prior model of the study, Y_{it} represents the collection of independent factors, which includes GDP, GDPS, ENEF, and REC. To describe the projected result as a %, Each of these elements is transformed into natural logarithms, leaving them unitless and allowing for the use of percentages. In addition, R_{it} illustrates the quantile dispersion of the explanatory variables, as demonstrated by Y_{it}, which in the present example represents the CO_2 and is likewise dependent on the quantile location. In addition, the equation $-\alpha_i(\tau) \equiv \alpha_i + \gamma_i q(\tau)$ represents the vector component that produces the fixed influence of τ quantiles on i. However, such quantiles really had no consequence on the interception. Given the structural autonomy of the variables, several responses are sensitive to change. Finally, $q(\tau)$ denotes the $\tau - th$ quantile sample, which

has the values $Q_{0.25}$, $Q_{0.50}$, and $Q_{0.75}$. Hence, the below is the quantile expression utilized in this investigation:

$$\min_q \sum_i \sum_t \theta_\tau \left(R_{it} - \left(\gamma_i + \rho \acute{Z}_{it}\right)q\right) \tag{8}$$

where $\quad \theta_\tau(A) = (\tau - 1) \quad AI\{A \le 0\} + TAI\{A > 0\}$ reports the formula to be evaluated.

Nevertheless, the MMQR method provides accurate projections at a certain location and scale by displaying quantile values. Yet, this research focuses on assessing the robustness of the framework. Consequently, the present research used the bootstrap quantile regression (BSQR) technique. The BSQR technique is an interstitial technique for analyzing confidence intervals and statistical significance. The benefit of these limitations is that they resample the information to get conclusive results while avoiding the asymptotically normal sampling dispersion restrictions (Efron & Tibshirani, 1994). More precisely, the BSQR employs algorithmic capabilities for estimating the sample dispersion of the assessed model. In addition, this methodology provides more effective estimating methods and experimental findings (Efron & Tibshirani, 1994). In addition to the robustness of the model, this study also uses the parametric econometric approach, i.e., the fully modified ordinary least square (FMOLS) approach proposed by Phillips and Hansen (1990), which offers efficient estimates of stationary time series and cointegration regression.

Results and discussions

Now the estimated results and their discussion are presented in this segment of the manuscript. The synchronized procedure with interpretation is as follows.

Results

The pre-estimation diagnostics of the data variables are analyzed first. Table 1 illustrates the descriptive analysis of the statistics utilized for the study. The mean and median values are identical to each other. The average and median values present the symmetry of the information. The variation of the data is demonstrated by the values of the standard deviations. However, the outcomes from skewness, Kurtosis, and Jarque-Bera tests represent the non-normal, skewed, and non-symmetrical distribution of the data under consideration.

Table 1 Descriptive and normality statistics

	CO_2	GDP	ENEF	REC
Mean	6.736284	12.66163	0.586708	1.285295
Median	6.786992	12.67148	0.606532	1.228063
Maximum	7.029677	13.19871	0.726566	1.532546
Minimum	6.337132	12.01173	0.268686	1.054613
Std. dev.	0.246807	0.367938	0.127316	0.181509
Skewness	−0.176120	−0.153931	−0.943808	0.115882
Kurtosis	1.414862	1.748494	2.927325	1.257622
Jarque-Bera	3.515650	2.214730	4.757832	4.119460
Probability	0.172419	0.330429	0.092651	0.127488

After information diagnostics, the study employed the Augmented Dickey-Fuller unit root test for scrutiny of a unit root presence and the results are displayed in Table 2. The study variables carbon dioxide, gross domestic product, energy efficiency, and renewable energy consumption are insignificant at level I (0). The first differences in statistics of all variables under consideration are significant results and reject the null hypothesis. Moreover, the values of stationarity outcomes are highly negative depicting a stronger presence of unit root in the data at 1% and 10% level of significance. The higher the negative value the higher will be the root in the information.

The successful root analysis leads to examining the possible correlation of the variables using the Bayer-Hanck combined cointegration tests (2009). The non-cointegration test includes the combined Engle-Granger (EG), Johansen (J), Banerjee (Ba), and Boswijk (Bo) tests. The separate analysis gives ambiguous and unreliable outcomes; thus, the study employs combined cointegration analysis using the above-mentioned tests. The null hypothesis suggests a joint hypothesis of no cointegration. The outcomes demonstrated significant results as shown in Table 3 of the study. All combined tests rejected the null hypothesis and showed the presence of cointegration among the variables. There exists a correlation between carbon dioxide, economic growth, energy efficiency, and renewable energy consumption that explanatory variables and the dependent variable are correlated leading to the examination of Regression analysis for assessing the impact of exogenous variables (GDP, ENEF, REC) on the endogenous variable of CO_2 emissions.

To scrutinize the correlations among the study's non-normal variables, the quantile regression estimation analysis is applied. The results from quantile regressions (MMQR) are illustrated in Table 4 of the manuscript.

Table 2 Unit root test

Augmented Dickey-Fuller		
Variable	I (0)	I (1)
CO_2	−1.157725	−1.852657*
GDP	−1.644938	−5.154128***
ENEF	−1.996392	−3.535650*
REC	−1.288064	−5.475333***

Significance level is denoted by *** for 1%, ** for 5%, and * for 10%

Table 3 Cointegration tests

Bayer-Hanck combined cointegration (2009)			
Engle-Granger (EG)	Johansen (J)	Banerjee (Ba)	Boswijk (Bo)
−4.4761**	50.4746***	−4.1553**	22.3623**
EG-J		EG-J-Ba-Bo	
23.512543**		37.86026**	

Significance level is denoted by *** for 1%, ** for 5%, and * for 10%

The standard errors of the outcomes are presented in the brackets depicting the absolute measure of the data points from the mean. They demonstrate the precision of estimated coefficients. Above and beyond, the lower values of error depict the reliability of the data. The estimated findings from quantile regressions are significant in all four quantiles for all variables at a 10% level of significance. The Economic growth (GDP) is statistically significant in all quantiles with a reliable standard error coefficient. The economic interpretation would be that carbon emissions and economic growth are related. The increase in economic growth increases the carbon emissions in the economy. The values of the coefficient in all quantiles are positive indicating a positive association with carbon dioxide emissions. The improved economic growth to the threshold level (GDPS) is also significantly associated with carbon emissions. The quantiles of GDPS show negative signs demonstrating a negative association with carbon emissions. That increase in GDPS substantially lowers the emissions of carbon in China. Likewise, energy efficiency and renewable energy consumption are negatively associated with carbon emissions in all quantiles with a 1% significance level. The increase in energy efficiency and renewable energy consumption leads to a significant decrease in emissions of carbon. The overall findings of quantile

Table 4 Estimates of quantile regression–MMQR

Variable	Location	Scale	Quantiles		
			Q_{0.25}	Q_{0.50}	Q_{0.75}
GDP	3.079***	−0.628	3.654***	3.002***	2.516***
	(0.810)	(0.473)	(0.884)	(0.835)	(0.973)
GDPS	−0.100***	0.024	−0.122***	−0.097***	−0.078***
	(0.030)	(0.017)	(0.033)	(0.031)	(0.036)
ENEF	−0.384***	0.036	−0.418***	−0.380***	−0.351***
	(0.096)	(0.056)	(0.102)	(0.098)	(0.115)
REC	−0.520***	−0.001	−0.519***	−0.520***	−0.522***
	(0.040)	(0.023)	(0.042)	(0.040)	(0.047)
Constant	−15.288***	3.999	−18.948***	−14.799***	−11.705***
	(5.372)	(3.133)	(5.845)	(5.527)	(6.447)

The dependent variable is CO_2. Significance level is denoted by *** for 1%, ** for 5%, and * for 10%

regression depict that increasing economic activities lead to escalating emissions of carbon while increasing other factors such as energy efficiency and renewable energy in the economy will lead to a substantial reduction in carbon emissions.

The findings of the quantile regressions are consistent with the following set of studies mentioned per the research variables. The association between economic growth and carbon emissions is consistent with the findings of (Chen et al., 2022; Kirikkaleli et al., 2022). The findings purposely emphasize that increasing growth and productivity increases harmful emissions levels leading to the deterioration of the environment. Next, the GDPS and carbon emissions are negatively associated with each other as detected in the novel findings and consistent with (Acaravci & Ozturk, 2010; Akram, et al., 2020). For that reason, the rise in improving economic growth to a threshold level is beneficial in limiting carbon emissions for enhancing ecological quality. Consequently, for energy efficiency and carbon emissions, the study findings are reliable to the outcomes (Mirza et al., 2022). Energy efficiency is an imperative element in reducing carbon emissions. Energy efficiency lowers emission levels by limiting the energy use for the same amount of work done which is essential for energy conservation in an economy. Therefore, efficient energy is significant in mitigating carbon emissions. Subsequently, the relationship between renewable energy and carbon emissions has been a long-debated topic, and several studies have examined the association. Therefore, the following strands of studies are consistent with the findings of the present study (Adebayo, Rjoub, et al., 2022; He

et al., 2021; Kirikkaleli et al., 2022; Sun et al., 2021). To limit emissions, renewable energy consumption and transition towards renewable energy are essential for environmental sustainability.

The graphical presentation of the quantiles of variables under study is shown in Fig. 4 beneath illustrating the subdivision of the information.

For robustness analysis, bootstrap quantile regressions are used first to eliminate the difficulties that occur due to small sample studies. BSQR is utilized and called bootstrap quantile regression. The empirical results of the variables are presented in Table 5 of the study. All variables showed significant findings except GDPS illustrated in the table beneath. The coefficient signs of the variables are consistent with the findings of quantile regressions. GDP is positively associated with CO_2 emissions, and GDPS, ENEF, and REC are negatively related to CO_2 emissions in China. Nonetheless, the coefficients of GDP, ENEF, and REC are statistically significant at 10% and 1% levels. Yet, the coefficient for GDPS is found to be insignificant, which indicates the absence of a non-linear relationship between the variables. However, it must be noted that the method (BSQR) considers the relationship only at the median (0.50) quantile, which makes the relationship possible at other quantiles such as 0.25 and 0.75, as evident in the MMQR estimates. Still, the results depict the direction of the influence, which is negative, and is consistent to the estimates of the MMQR.

Later, the parametric robustness analysis is applied in the estimation for robustness. The fully modified ordinary least squares (FMOLS) is a parametric analysis that shows the reliability of the econometric
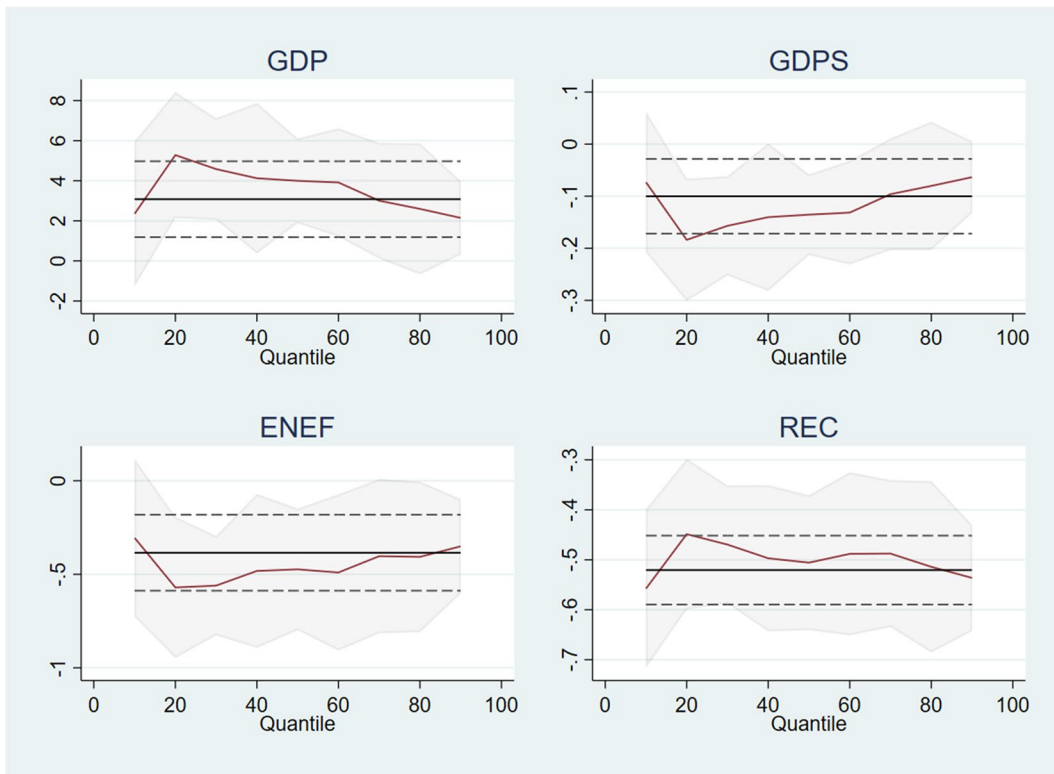
Fig. 4 Graphical depiction of the MMQR coefficients

Table 5 Robustness–BSQR (median)

Variable	Coefficient	Std. err	t-stats
GDP	3.107*	1.645	1.89
GDPS	−0.100	0.061	−1.63
ENEF	−0.399*	0.194	−2.05
REC	−0.508***	0.078	−6.51
Constant	−15.570	10.871	−1.43

The dependent variable is CO_2. Significance level is denoted by *** for 1%, ** for 5%, and * for 10%

Table 6 Parametric robustness test–FMOLS

Variable	Coefficient	Std. err	t-stats	Prob
GDP	2.903***	0.816	3.553	0.0015
GDPS	−0.093***	0.030	−3.028	0.0055
ENEF	−0.373***	0.088	−4.231	0.0003
REC	−0.539***	0.029	−18.13	0.0000
Constant	−14.075**	5.361	−2.625	0.0143

The dependent variable is CO_2. Significance level is denoted by *** for 1%, ** for 5%, and * for 10%

analysis. The statistical outcomes presented in Table 6 show substantial values. The results indicate the robustness and reliability and significance of the model. The co-coefficient signs are consistent with the above findings at a 10% level of significance.

Along with the long-run estimates, this study employs two diagnostic tests: the Breusch-Pagan-Godfrey Heteroskedasticity and Breusch-Godfrey serial correlation LM Test, which assumes homoskedasticity and no serial correlation, respectively. The results for both the tests are portrayed in Table 7. In the former test, the results asserted homoskedasticity, while the null assumption of no serial correlation could not be rejected, which validates the absence of the serial correlation in the series.

Discussion

The practical implications are discussed in this part. The study showed consistent results with few studies

Table 7 Diagnostic test

Breusch-Pagan-Godfrey heteroskedasticity test: H^0, homoskedasticity			
F-statistic	1.989712	Prob. F (3,28)	0.1384
Obs*R^2	5.623114	Prob. Chi^2 (3)	0.1315
Scaled explained SS	2.577921	Prob. Chi^2 (3)	0.4614
Breusch-Godfrey serial correlation LM test: H^0, no serial correlation			
F-statistic	1.760827	Prob. F (9,19)	0.5299
Obs* R^2	10.13374	Prob. Chi^2 (9)	0.4337

from the prevalent literature (Kirikkaleli et al., 2022; Chen et al., 2022; Acaravci & Ozturk, 2010; Akram, et al., 2020; He et al., 2021; Kirikkaleli et al., 2022; Sun et al., 2021; Adebayo, Rjoub, et al., 2022; and Mirza et al., 2022). The study validates the presence of the environmental Kuznets hypothesis. The positive and negative signs of the coefficients demonstrate the confirmation of the EKC hypothesis in China from the year 1990 to 2021. In other words, it can be stated as increasing economic development is increasing environmental deterioration. However, after a certain threshold level, the increase in economic growth will reduce the emissions level and improves environmental quality in China. To obtain this, the role of energy efficiency and renewable energy consumption is of significant importance. The results depicted that the increasing usage of renewable energy besides efficient energy is substantial for environmental sustainability and development. These will lower pollution levels and the cost of energy for future purposes which will lower substantial fuel risks and improve energy security. The importance of sustainable economic development is insufficient without renewable energy and energy efficiency that positively relates to environmental quality. Improved economic growth, renewable energy consumption, and energy efficiency are considered favorable factors in determining environmental quality that reduces carbon emissions.

Conclusion and policy implications

Conslusion

On the energy-environment and growth-environment nexus, the available literature has shown several studies. However, the present study revisits on the above-mentioned linkages with an updated data period from 1990 to 2021. In addition, the study scrutinizes both nexuses simultaneously in the study. To accomplish these, the study uses carbon dioxide emissions (CO2), economic growth (GDP), improved economic growth level (GDPS), energy efficiency (ENEF), and renewable energy (REC) and employs novel time series econometric analysis for the estimation purposes such as the augmented Dickey-Fuller test, Bayer and Hanck's (2013) combined cointegration analysis, quantile regressions (MMQR), and robustness analysis (BSQR and FMOLS). Moreover, the results from the estimation procedures provided consistent findings with the prevailing body of knowledge. That Economic growth, GDPS, energy efficiency, and renewable energy consumption are significant factors in affecting and determining carbon dioxide emissions in China.

After pre-diagnostic data analysis and unit root identification, the cointegration tests gave significant results. The tests depicted that the variables have a significant correlation among them. The findings demonstrated that the relationship between carbon dioxide, economic growth, energy efficiency, and the renewable energy consumption is present which leads to the regression analysis of research variables. The outcomes were tested for robustness analysis using the bootsrap quantile regression and a fully modified OLS which gave reliable and validated results. The study findings illustrated consistency with the results of (Acaravci & Ozturk, 2010; Akram, et al., 2020; He et al., 2021; Kirikkaleli et al., 2022; Sun et al., 2021; Adebayo, Rjoub, et al., 2022; and Mirza et al., 2022). The study validated the environmental Kuznets theory for environmental sustainability and the importance of energy efficiency and renewable energy consumption for enhancing the environment. China is an emerging superpower that has directly contributed to the upsurging of carbon emissions. The study emphasizes increasing renewable energy consumption and efficient energy for lowering emissions levels which is beneficial for the country itself but also has a noteworthy impact on other nations of the world.

Policy implications and limitations

Based on the precise findings of the study, the following policy implications are effective and recommended for the economy. Firstly, to achieve carbon

neutrality goals, China needs to promote green plus renewable energy and technologies for an efficient and sustainable environment, which requires an improved financial system. Thus, policies related to technological innovation and green energy need to be revamped. The country is adopting new and improved strategies for carbon mitigation; anyhow, more work is required to achieve neutrality targets by 2030. Secondly, renewable energy shares in electricity production are recommended to be enhanced. Furthermore, investment in the energy sector must be done in the renewable energy sector for energy consumption. For that reason, it will limit emissions and improve environmental quality. Lastly, the promotion of knowledge on energy efficiency and transition towards renewable sources must be increased. People must adopt energy-efficient practices, and the government has a significant role in maintaining, providing guidelines, and expediting the implementation processes. Well-designed energy-efficient policies are useful in reducing pollution, reducing costs, and promoting sustainable development.

The study has the following limitations. The study is limited to the analysis of relationships in China. It can be extended to other countries for comparative analysis. Furthermore, the inclusion of new and innovative variables or factors in the present scrutiny can be useful for synthesizing economic growth and sustainability.

Author contribution   The idea of the original draft belongs to Rong Zhou and Li Zheng. Liu Li designed the experiment and collected the dataset. The introduction and literature review sections are written by Najaf Iqbal. Zeeshan Fareed constructed the methodology section and empirical outcomes in the study.

Data Availability   The data that support the findings of this study are available from the International Monetary Fund (IMF), the Organization for Economic Cooperation and Development (OECD) Website, and the World Bank (WB).

Declarations

Ethical approval   We confirmed that this manuscript has not been published elsewhere and is not under consideration by another journal. Ethical approval and informed consent are not applicable for this study.

Consent to participate   Not applicable

Consent for publication   Not applicable

Competing interests   The authors declare no competing interests.

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