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Research Article

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The Role of Economic Growth in the Validation of Environmental Sustainability: New Evidence from the Inverted Load Capacity Factor and Renewable Energy Indicators

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Abstract

China, which has been making economic reforms since the 1980s, has become an important actor on a global scale with high growth rates. These developments occurred with the opening up policies, industrialisation, and technological enhancement. However, China is still the most polluting country according to ecological footprint measurement. Therefore, it is essential to determine the factors causing environmental degradation in China and to take new measures. This study investigates environmental sustainability within the framework of the Inverted Load Capacity Factor Curve (ILCC) and Renewable Energy Kuznets Curve (RKC) hypotheses. Empirical analyses are conducted with the Inverted Load Capacity Factor (ILCF), economic growth, renewable and non-renewable energy, trade openness, and urbanisation for the period 1990-2022 for China. The non-linear methodology was used in this study. In this context, the co-integration method developed by Hepsağ (2021) is used to investigate the ILCC and RKC hypotheses. The FMOLS estimator is also used as a robustness test. The Fourier Toda-Yamamoto causality analysis implies short-term causal associations. Empirical findings showed that the ILCC and RKC hypotheses are valid for China. Moreover, the RKC inflection point occurred before that of the ILCC. These results provide significant evidence that income growth in China can increase environmental quality before environmental degradation.

Keywords Renewable Energy · Economic Growth · Inverted Load Capacity Factor

Jel Codes Q56, F64, K32, and O44.

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The Role of Economic Growth in the Validation of Environmental Sustainability: New Evidence from the Inverted Load Capacity Factor and Renewable Energy Indicators

Climate change imposes a heavy economic burden on a global scale. The economic cost of climate change is estimated to be 38 trillion dollars per year for the next 25 years (Hart, 2024). Therefore, policies to tackle the climate crisis are critical for ensuring environmental sustainability. To achieve this goal, greenhouse gas emissions (GHGs) need to be cut down by 50% in the next decade (UNEP, 2024). This goal places a special responsibility on countries with high global pollution. China stands out among the highest polluters. China is responsible for 31.1% of the GHGs. In the period 2000-2022, China's total CO2 emissions increased by 245% and per capita CO2 emissions by 208% (IEA, 2022). The per capita ecological footprint in China is 3.6 gha, and the per capita biocapacity is 0.8 gha. The biocapacity gap in China is measured as 2.8 gha. China has been running a biocapacity deficit in an increasing trend since 1965. Today, China's ecological footprint exceeds its biocapacity by 340% (GFN, 2022).

China has significant commitments to combat climate change. China is a regular participant in international climate negotiations under the UNFCCC and a non-Annexe I party to the relevant convention. Accordingly, China has no obligation to contribute to climate finance and emission cuts. China's prominence among high-polluting countries makes it more likely to face pressure to increase measures to address climate change (Liu et al., 2023). Currently, China's policies towards climate change are quite inadequate, and the main rationale behind this outcome is the energy resources mixture (Climate Action Tracker, 2024). With the Energy Law enacted on January 1, 2025, China is struggling to escalate the proportion of renewable energy (REN) by encouraging energy innovation (Hill, 2025). However, China still relies on coal for more than 60% of its electricity generation. The share of the energy industry in China's GHGs is 90%. Therefore, energy transition is a crucial policy instrument in ensuring environmental sustainability in China. China has made significant investments in REN recently. Hence, low-carbon energy sources are expected to exceed high-carbon energy sources by 2040 in China. China's growth policy based on REN sources is consistent with its technology and innovation-oriented growth targets (IEA, 2021). Therefore, determining the link between REN and environmental deterioration (ED) in China is crucial for policymakers.

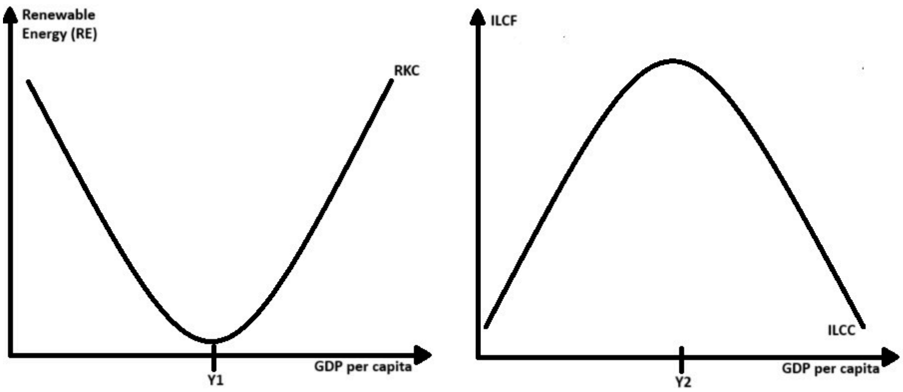
However, the association between REN, ED, and economic growth (EG) is controversial. CO2, ecological footprint, LCF, and ILCF can be used as ED indicators. Dam and Sarkodie (2023) stated that the ILCF is a more comprehensive indicator. Therefore, this research focuses on the impacts on the ILCF. Many previous studies (Dam and Sarkodi, 2023; Dam et al., 2023; Qamruzzaman, 2024) reported an EKC linkage between ILCF and EG. Accordingly, EG boosts ED at the outset, but above a certain threshold, income growth reduces environmental deterioration by escalating energy efficiency and clean energy use. Omri et al. (2015) showed that EG is a determinant of renewable energy, whereas Wang et al. (2023a) determined that the correlation between REN investments and EG is negative. However, some studies (Pao and Fu, 2013; Yildirim et al., 2012; Bhattacharya et al., 2016) reported that the consequences of EG on REN are insignificant. The contradictory results imply that the link between REN, ED, and EG can be more complex. Yao et al. (2019) first stated that the association between EG and REN can be U-shaped and proposed the RKC hypothesis. Yao et al. (2019) argued that fossil fuel consumption increases when per capita income is low, but above a certain income level, REN investments increase. Following Yao et al. (2019), Wang et al. (2023b) and Pata et al. (2025) argued that the inflection point in the RKC occurs earlier than that of the EKC.

Yao et al. (2019), Wang et al. (2023b), and Pata et al. (2025) found that a higher income first increases investment in REN and then improves environmental health, and therefore the fulfilment of the RKC hypothesis is a precondition for the validity of the EKC. Accordingly, the first step to prevent ED is for EG to increase investment in REN. Pata et al. (2025) tested the validity of the equations.

$RE = b_1 Y_1 + b_2 Y_1^2$ for RKC and $ILCF = a_1 Y_2 + a_2 Y_2^2$ for ILCC.

Figure 1

RKC and ILCC hypotheses



Following Yao et al. (2019), Wang et al. (2023b), and Pata et al. (2025), the current study focuses on the RKC and EKC hypotheses for China, but unlike Pata et al. (2025), it tests ILCC by considering ILCF. Unlike previous studies, this study aims to test the RKC and ILCC hypotheses for China. If the RKC is a prerequisite for the ILCC, then Y1<Y2 in Figure 1 as stated by Pata et al. (2025).

This study has several contributions to the current literature. First, unlike previous studies, this research concentrates on ILCF rather than CO2 or ecological footprint in the joint assessment of RKC and EKC. To the best of the authors' knowledge, no study has explored the link between RKC and ILCC. Second, this research conducts RKC and ILCC analyses on China, the largest global polluter, and compares the implications of these two hypotheses in terms of antecedent and consequent effects. Revealing the complex relationships between the RKC and ILCC hypotheses for China is important for combating climate change. Third, this research addresses the consequences of trade openness (TO) on ILCF by considering the studies of Qamruzzaman (2024), Yingjun et al. (2024), and Dam and Sarkodie (2023), which emphasise the TO-ILCF linkage. Moreover, this study covers the consequences of non-renewable energy on ILCF in the research model, which has been ignored in previous studies. Finally, this research considers the consequences of both TO and urbanisation, considering the work of Wang et al. (2023a), who raised awareness of the effect of TO in the RKC linkage, and Pata et al. (2025), who draw attention to the effect of urbanisation.

The following second section of this study presents the literature review and literature gap, the third section explains the data, model construction, and methodology, the fourth section depicts the empirical findings, the fifth section summarises the findings, and finally, the sixth section presents the discussion and policy implications.

Literature Review and Research Gap

In this section, research on the ILCC and RKC hypotheses in the linkage between EG and ED is presented. Furthermore, the effects of EG and REN on ED are discussed.

Literature Review

Previous studies investigating the link between environmental sustainability and economic growth have gone beyond the boundaries of the traditional EKC hypothesis and moved towards the use of more comprehensive models. The ILCF, which measures the environmental supply-demand balance and expresses environmental pressure by comparing the ecological footprint and biological capacity, is at the forefront of these models. The ILCC hypothesis, developed based on the ILCF, proposes an inverted-U-shaped linkage that does not expect a return to environmental sustainability at a certain level of economic growth and differs from the EKC in this respect. Dam and Sarkodie (2023) tested this hypothesis for Türkiye and stated that the country still falls short of the expected income level that ensures environmental balance. This result supports the ILCC hypothesis in theory, but in practice, it changes depending on the conditions. Dam et al. (2023) conducted the PMG-ARDL method in 22 OECD nations and identified that EG increases the ILCF and strengthens environmental pressure. The results showed that REN decreases the ILCF and supports sustainability. The findings of the study that the ILCC hypothesis should be assessed considering growth and energy structure. In this context, alongside findings that support the ILCC hypothesis, studies highlight that the dynamics of environmental sustainability vary across different geographies. Usman et al. (2024) explored environmental sustainability in China using the load capacity factor and tested the classical load capacity curve hypothesis. Their results revealed that the LCC relationship is not supported for China. The authors reported that EG positively affects LCF in the long run, but the square of growth reduces environmental health. Findings also indicated that clean energy increases LCF in the long run, thereby reducing environmental pressure. These findings highlighted that environmental sustainability is influenced by EG, energy source mixture, and natural resource consumption. In another study on OECD countries, Dam et al. (2024) demonstrated that green growth is instrumental in enhancing environmental health. However, institutional quality, rather than alleviating ED, is associated with increasing environmental pressure over time. The authors stated that environmental health can only be sustained when accompanied by robust institutional reforms and governance structures that are effectively aligned with long-term sustainability goals. Sun et al. (2024) investigated the EKC and LCC hypotheses in the Chinese context by incorporating three key environmental metrics: CO_2, ecological footprint, and LCF. Using a dynamic ARDL framework, the study confirmed an inverted U-shaped linkage between income and LCF, supporting the LCC hypothesis. Findings indicated that renewable electricity production enhances environmental quality and improves LCF, whereas R&D expenditures exhibit an adverse impact. The increase in LCF reflects a strengthening of China's environmental carrying capacity.

The literature emphasises that growth alone is not sufficient to achieve environmental load capacity and that a transformation based on REN is indispensable. In this context, Pata et al. (2025) made crucial contributions that expanded the debate on environmental sustainability. Pata et al. (2025) examined the EKC and RKC hypotheses using Fourier-based co-integration techniques in the United States. Findings indicated that a rise in REN preceded a decrease in CO2. Hence, the onset of the RKC curve precedes that of the EKC. This that the energy structure responds earlier to environmental changes than EG and provides a complementary theoretical framework to the ILCC hypothesis. The study emphasised that environmental transition processes should be assessed based on economic indicators and the priority of the energy transition.

The link between REN use and environmental burden is one of the cornerstones of the ILCC literature. Dam et al. (2024) determined that REN adoption reduces ILCF in BRICS countries, thus supporting environmental sustainability. Pata et al. (2023) showed that a rise in per capita income increases REN use and reduces environmental pollution in Latin American countries. These results supported the RKC hypothesis and that energy transition can be a determinant independent of growth. Furthermore, the findings showed that the CO2-reducing effect of the transition to REN emerges earlier than the EG. Yingjun et al. (2024) scrutinised the consequences of TO and EG on environmental sustainability in Türkiye and Egypt through the ILCF. The study found that TO enhances energy efficiency and improves environmental health in Türkiye and Egypt. The authors showed that EG contributes to environmental deterioration by increasing ILCF at the outset, but as income increases, environmental health can be protected by allocating more resources to cleaner technologies. The findings also highlighted that non-renewable energy use weakens environmental sustainability and poses a significant obstacle to achieving the SDGs. Yingjun et al. (2024) emphasised that the transition to REN and escalating energy efficiency are strategic necessities for developing countries such as Türkiye and Egypt. In line with these findings, Sun and Qamruzzaman (2025) further reinforced the key role of energy structure in shaping environmental sustainability. By analysing BRICS-T countries, the authors scrutinised the consequences of innovation, natural resource rents, TO, and energy types on four key indicators (CO_2 emissions, ecological footprint, LCF, and ILCF). The results showed that non-renewable energy use weakens environmental sustainability by escalating ILCF, whereas clean energy usage and technological innovation reduce ILCF and strengthen ecological balance. Within this framework, where ILCF reflects conditions where ecological demand exceeds biocapacity, the study emphasises that fossil fuels contribute to long-term ecological pressure. Riaz et al. (2025) also supported these findings. An analysis conducted in BRICS countries showed that REN consumption mitigates environmental pressure, whereas natural resource usage increases environmental pollution. These results emphasised necessity to move from fossil fuels to REN to achieve the SDGs.

The consequences of urbanisation on environmental health produced mixed results. Nuta et al. (2024) showed that urbanisation increased CO_2 emissions in Europe and Asia, but that REN consumption helped mitigate this adverse effect. Şimşek et al. (2025) found similar results for the E-7 countries. Khan et al. (2024) noted that urbanisation reduces CO_2 and positively affects EG in South Asia, but that this relationship varies depending on the context. Bashayreh et al. (2024) showed that the impact of urbanisation on environmental pressures changes direction after certain threshold values. Consistent with these findings, Koengkan et al. (2020) identified a one-way causal association running from REN to urbanisation in MERCOSUR countries and demonstrated that urbanisation does not directly shape energy transition but rather that renewable energy development has a transformative impact on the urbanisation process. These findings that urbanisation is not the sole determinant; rather, the content of urbanisation, its integration with energy infrastructure, and governance structures should be considered together.

The consequences of TO on environmental sustainability have been one of the most debated areas in the literature. Wang et al. (2023a) found in their analysis of EU countries that REN use enhances EG when TO exceeds a certain threshold level. This effect can be limited or negative when the level of openness is low. This finding showed that commercial openness is a pivotal determinant in green investments. Zeren and Akkuş (2020) reported a two-way association between foreign trade and REN in emerging economies. Ramaharo and Randriamifidy (2023) showed that TO hurts REN utilisation, using machine learning-based analysis on Madagascar and argued that import dependence on fossil fuels slows down the energy transition. Similarly, Erkılıç et al. (2025) reported that trade in BRICS countries encourages fossil fuel consumption and therefore globalisation is not always environmentally beneficial.

In sum, the literature that environmental sustainability cannot be explained solely by EG; rather, it needs to be assessed in conjunction with multilayered factors such as energy mixture, openness, and urbanisation. Holistic indicators such as the ILCF stand out as a crucial methodological tool in understanding these complex relationships, showing that environmental degradation is a multidimensional structural problem.

Research Gap

China is one of the highest polluting countries in the world. Despite many local and global measures, the consequences of environmental pollution in China are worsening rapidly. However, China is also recognised as one of the leading nations in EG. The main driver of EG is non-renewable energy consumption (Awodumi and Adewuyi, 2020; Majeed et al., 2021). Several studies (Oğul, 2022; Özbek and Özbek, 2024; Balsalobre-Lorente et al., 2025; Adebayo et al., 2025) examined the environmental impacts of energy use. However, the number of studies within the scope of ILCC is quite limited (Naimoğlu et al., 2025). The RKC hypothesis, which contradicts the inverted U-shaped relationship predicted by the ILCC hypothesis, has only recently become a subject of research (Pata et al., 2025; Özbek et al., 2025). Furthermore, there is no study on China that uses both the ILCC and RKC hypotheses together and supports them with robustness tests. Therefore, the primary motivation for this study is to determine whether environmental degradation or renewable energy growth occurred first in China alongside income growth. This motivation makes a significant contribution to the literature by prioritising the ILCC and RKC hypotheses and the environmental effects of income. Furthermore, robustness tests are conducted using advanced time series techniques, providing theoretical contributions to the literature and empirical comparisons. In this context, nonlinear techniques are used in the study and Hepsağ (2021) co-integration test is used with asymmetric nonlinear "Exponential Smooth Transition Error Correction Model (AESTAR-ECM)". Within the framework of the mentioned factors, the current study contributes to the literature and fills this gap.

Data and Methods

In this part of the study, the dataset is first outlined. Then, the basic features of the dataset are depicted. In the following section, information about the models is presented. Thereafter, the methodological design adopted in this research is presented.

Data

Two different models are established in the study. Information on the variables is provided in Table 1

Table 1

Information on the Variables Used

Acronym	Variable	Definition	Source
ILCF	ILCF	Ecological Footprint/Biocapacity	GFN (2025)
REN	Renewable Energy	Quadrillion Btu	EIA (2025)
NREN	Fossil energy consumption	Quadrillion Btu	
Y	Income	GDP per capita (constant 2015 USD)	World Bank (2025)
TO	Trade Openness	The ratio of total exports and imports to GDP	

Acronym	Variable	Definition	Source
URB	Urbanisation	Urbanisation (% of the total population)	

Table 1 shows data for China for the period 1990-2022. Descriptive statistics for the data are given in Table 2

Table 2

Overview of Data Characteristics

Stat.	ILCF	REN	GDP	NREN	TO	URB
Mean	1.125991	1.649280	8.208556	4.007631	3.706639	3.753938
Median	1.172531	1.532159	8.242958	4.146147	3.646793	3.781185
Max.	1.506585	3.240813	9.354954	4.721995	4.166343	4.151984
Min.	0.622886	0.283761	6.807971	3.209649	3.189370	3.274954
Std. Dev.	0.317190	0.957677	0.798104	0.523018	0.244529	0.274407
Skew.	−0.198671	0.167908	−0.155610	−0.147916	0.185697	−0.187892
Kurt.	1.429407	1.636315	1.719664	1.401524	2.553782	1.733884
J-B	3.608885*** (0.164566)	2.712061*** (0.257682)	2.387162*** (0.303134)	3.633634*** (0.162542)	0.463435*** (0.793170)	2.398361*** (0.301441)

Note: The values in parenthese depict the probability value. "***" represents the significance at 1%.

Data characteristics of ILCF, REN, GDP, NREN, TO, and URB are shown in Table 2. Table 2 depicts that all variables of the Chinese economy exhibit normal distribution for the period 1990-2022.

Model construction

In this study, two models are constructed to test the ILCC and RKC hypotheses: the ILCC model (1) and the RKC model (2). Natural logarithms of all variables are taken. Shahbaz et al. (2012) and Bhattacharya et al. (2016) argued that logarithmic transformations prevent problems related to dynamic properties. Therefore, the models below can provide more consistent and robust findings.

Model-1

$$ILCF_t = \beta_{10} + \beta_{11}GDP_t + \beta_{12}GDP_t^2 + \beta_{13}NREN_t + \beta_{14}TO_t + \varepsilon_{1t} \tag{1}$$

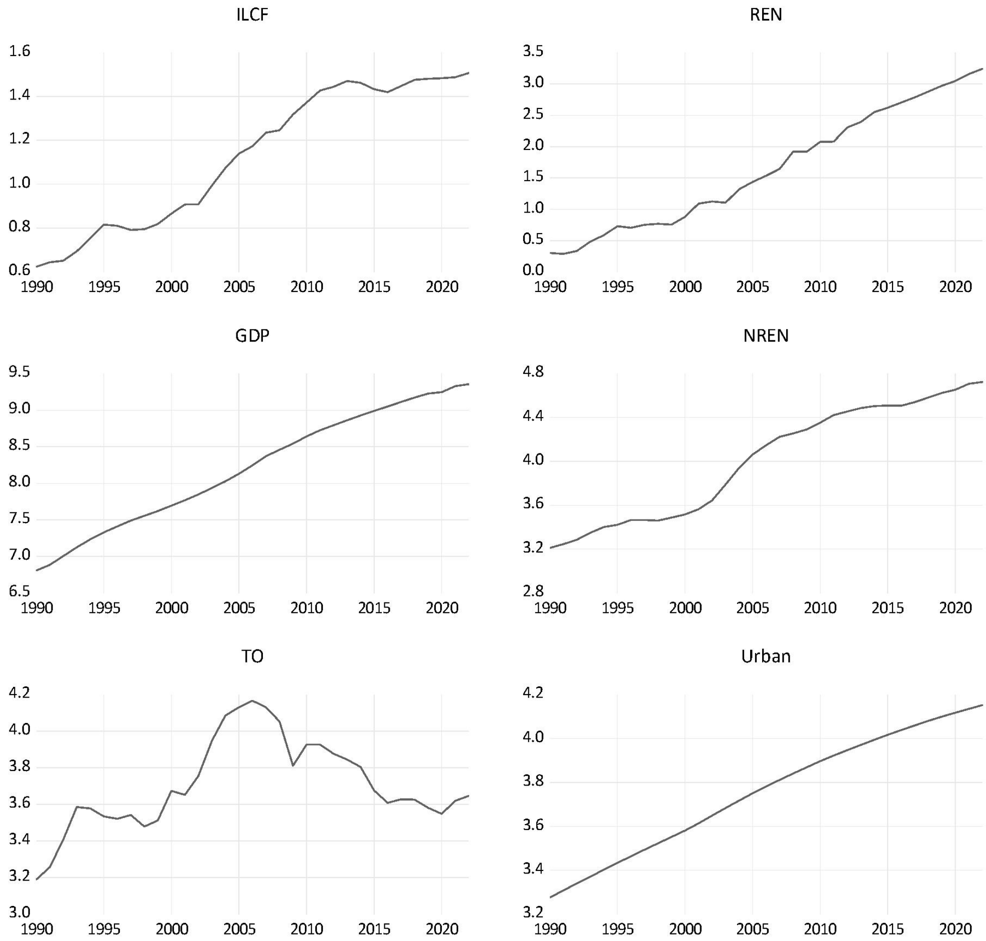
Model-2

$$REN_t = \beta_{20} + \beta_{21}GDP_t + \beta_{22}GDP_t^2 + \beta_{23}TO_t + \beta_{24}URB_t + \varepsilon_{2t} \tag{2}$$

In both models, we denote the period 1990-2022 by t and the constant terms by β_{10} and β_{20}, respectively. In Model-1, β_{11}, β_{12}, β_{13}, and β_{14} depict the estimated elasticities of GDP, GDP2, NREN, and TO, respectively. In Model-2, β_{21}, β_{22}, β_{23}, and β_{24} show the estimated elasticities of GDP, GDP2, TO, and URB, respectively. In addition, ε_{1t} and ε_{2t} represent the error terms of Models 1-2, respectively. Figure 2 depicts the graphs of the model.

Figure 2

Graphs of the Variables



An examination of the time series plots in Figure 2 an upward trend in most variables, except for TO. This observation can be interpreted as a preliminary finding that models with a trend component are preferable. However, this observation needs to be supported by empirical testing.

Methodology

In this study, traditional unit root tests and nonlinear methods are examined. Therefore, linearity tests gain importance. Harvey et al. (2008) linearity analysis is first implemented. The series must comply with I(1) properties to use the Hepsağ (2021) nonlinear co-integration test. Leybourne et al. (LNV) (1998) and Harvey and Mills (HM) (2002) nonlinear stationarity analyses are examined to investigate the stationarity process. Moreover, ADF and PP unit root tests are also examined. The long-term linkage is examined with the Hepsağ (2021) nonlinear co-integration test. Finally, short-term casual associations are explored using the Nazlioglu et al. (2016) Fourier Bootstrap Toda-Yamamoto test.

In this study, the transition function in the nonlinear unit root test, first by LNV (1998), is based on the logistic function. In LNV, the unit root process is investigated through three different models. These are stated in (3), (4), and (5).

Model A:

$$y_t = a_1 + a_2 S_t(\gamma,\ \tau) + \sigma_t \tag{3}$$

Model B:

$$y_t = a_1 + \beta_1 t + a_2 S_t(\gamma,\ \tau) + \sigma_t \tag{4}$$

Model C:

$$y_t = a_1 + \beta_1 t + a_2 S_t(\gamma,\ \tau) + \beta_2 t S_t(\gamma,\ \tau) + \sigma_t \tag{5}$$

In Models A, B, and C, σ_t represents the zero-mean $I(0)$ process. The sample size is T the parameter controlling the pace of structural change between regimes is specified by γ. The γ coefficient has the property 0< γ<1. An increase in the γ value reveals that the smooth transition is fast and sudden, whereas the opposite situation indicates that the transition is gradual. We specify the closed form of the logistic function by $S_t(\gamma,\ \tau)$ and this function takes the form shown in (6).

$$S_t(\gamma, \tau) = [1 + \exp\{-\gamma(t - \tau T)\}]^{-1} \tag{6}$$

The LNV test is confirmed under the null hypothesis of the unit root process. The models in the LNV test are summarised as Model A: 1 soft break in the constant, Model B: 1 soft break in the constant under the non-stochastic trend, and Model C: 1 soft break in both the constant and trend. Harvey and Mills (2002) that there is more than one structural change. In this context, they proposed a two-soft transition version of LNV (1998). In Harvey and Mills (2002), an additional soft transition function is added to all models in addition to LNV (1998). In other words, the model is created by adding $S_{2t}(\gamma, \tau)$ to all three models in LNV. The null hypothesis of Harvey and Mills (2002) implies the validity of the unit root process. The models in the Harvey and Mills (2002) test are summarised as Model A: 2 soft breaks in the constant, Model B: 2 soft breaks in the constant under the deterministic trend, and Model C: 2 soft breaks in both the constant and trend.

Traditional unit root tests are also performed. When the difference operation is applied to the LNV and HM tests, the nonlinearity of the deterministic terms is eliminated. In this case, traditional ADF and PP tests can determine the level of stationarity. Compared to the ADF (Said and Dickey, 1984) test, the PP unit root test (Phillips and Perron, 1988) can apply the unit root test validly in time series containing serial correlation and heterogeneity. In this respect, the PP unit root test is more powerful than the ADF unit root test.

In this study, Hepsağ (2021) co-integration test, which is among the current tests among nonlinear co-integration tests, is used to determine the co-integrated relationship. This test is based on the asymmetric ESTAR process. With this assumption, the (7) model is considered.

$$\Delta y_t = G_t(\theta_1, u_{t-1})\{S_t(\theta_2, u_{t-1})\gamma_1 + (1 - S_t(\theta_2, u_{t-1}))\gamma_2\}u_{t-1} + \Psi'\Delta x_t + \sum_{i=1}^{p} \omega_i{}'\Delta z_{t-i} + \varepsilon_t \tag{7}$$

(7) model is expressed as AESTAR-Error Correction Model (AESTAR-ECM) (Hepsağ, 2022). In this model, $z_t = (y_t, x_t')'$ indicates the first-order stationary variable with n x1 dimension. The dependent variable in the model is y_ta $x_t' = (x_{1t}, \cdots, x_{1t})$ is the $k \times 1$ independent variable. We denote the error term by u_t. The error term vector is defined as $u_t = y_t - \beta_x' x_t$. The term Δx_t given in (7) is defined as $\Delta x_t = \sum_{i=1}^{p} \lceil'{}_i \Delta z_{t-i} + \eta_t$. The function G_t has the notation $G_t(\theta_1, u_{t-1}) = 1 - exp\ (-\theta_1(u_{t-1}^2)), \theta_1 \geq 0.$ S_t is specified as $S_t(\theta_2, u_{t-1} = [1 + exp(-\theta_2 u_{t-1})]^{-1}\ \ \theta_2 \geq 0.$ In the nonlinear unit root analysis proposed by Hepsağ (2021), the first-order Taylor expansion is used in model (7). The test regression obtained because of the transformation in question is specified in Equation (8).

$$\Delta y_t = \phi_1 u_{t-1}^3 + \phi_2 u_{t-1}^4 + \psi \Delta x_t + \sum_{i=1}^{p} \omega_i' \Delta z_{t-i} + \varepsilon_t \tag{8}$$

In the framework of model (8) H_0, and, the H_1 hypotheses are shown in (9) and (10), respectively.

$$H_0 : \phi_1 = \phi_2 = 0 \tag{9}$$

$$H_1 : \phi_1 = \phi_2 \neq 0 \tag{10}$$

If H_0 specified in (9) cannot be rejected, there is no co-integration. However, if (10) cannot be rejected, it indicates nonlinear symmetric or asymmetric ESTAR co-integration. FANEC and FANEG test statistics can be calculated based on the restrictions imposed on the coefficients. The test statistics are assessed against threshold values provided by Hepsağ (2021). If the calculated statistic is smaller than the threshold value, there is no co-integration linkage. In the opposite case, the symmetric or asymmetric ESTAR co-integration is reached. The important point here is to identify symmetric and asymmetric relationships under co-integration. In determining this, the hypotheses ($H_0 : \phi_2 = 0$ and $H_1 : \phi_2 \neq 0$) are tested. In the case where the F test statistic is not smaller than the critical values, asymmetric ESTAR co-integration is reached. Three different data structures emerge in the Hepsağ (2021) model. These are raw data (Raw Data-Case 1 - model without constant and trend), data demeaned from the mean (Demeaned Data-Case 2 - model with constant), and data detrended from the trend (Detrended Data-Case 3, model with constant and trend). In this study, the Phillips and Hansen (1990) FMOLS method is used as a robustness test in determining long-term relationships. This method can produce consistent estimates by eliminating bias in small sample sizes. After obtaining long-term information in the study, the Nazlioglu et al. (2016) FBTY test is used to analyse the short-term causality. FBTY analysis depends on Toda and Yamamoto (1995). Nazlioglu et al. (2016) FBTY test rely on the null hypothesis of no causal association. FBTY test can be expressed in (11).

$$\Upsilon_t = \alpha_0 + \Upsilon_1 \sin\left(\frac{2\pi kt}{T}\right) + \Upsilon 2 \cos\left(\frac{2\pi kt}{T}\right) + \beta_1 \Upsilon_{t-1} + \cdots + \beta_{p+d} + d\Upsilon_{t-(p+d)} \tag{11}$$

The constant term parameter α is defined by the VAR $(p + d)$ model, which is independent of the time dimension and considers structural breaks. Here, "p" and "d" depict the lag lengths and maximum integration level, respectively.

Empirical Findings

In this section, a linearity test is performed. Then, empirical tests appropriate to the findings are performed. Table 3 shows the linearity analysis results by Harvey et al. (2008) for all variables.

Table 3

Linearity analysis

	Variables						
	ILCF	REN	GDP	GDP2	NREN	TO	URB
F statistics	10.02***	7.11**	5.22*	6.68**	15.57***	23.46***	4.48

Note: Critical values are 4.605; 5.991 and 9.210 at 10%, 5%, and 1% significance levels, respectively. *, **, *** depict 10%, 5%, and 1% significance levels, respectively.

It is determined that the variables generally exhibit a nonlinear structure. According to the results, the F statistics of the ILCF, NREN, and TO variables revealed that the linearity assumption is rejected. This situation occurs at a significance level of 5% for the REN and GDP2 variables. This null hypothesis occurs at a significance level of 10% for the GDP variable. Harvey et al. (2008) showed that the URB exhibits a linear structure. These results showed that nonlinear empirical methods can be preferred. Compared to linear methods, nonlinear empirical methods present stronger findings. Table 4 depicts the Leybourne et al. (1998) and Harvey and Mills (2002) unit root test findings.

Table 4

Nonlinear Unit Root Test Findings

		Leybourne et al. (1998)				
Model C	T	Test Statistics	Appropriate delay length	Breaking Date	Table Value (%10; %5; %1)	Conclusion
ILCF	33	-3.02307	0	2007		Unit Root
REN	33	-4.98927	0	2006		Unit Root
GDP	33	-2.43051	0	2009		Unit Root
GDP2	33	-3.26268	1	2008	-5.555; -6.054; -7.152	Unit Root
NREN	33	-4.12739	1	2004		Unit Root
TO	33	-3.26768	0	2003		Unit Root
URB	33	-2.190024	0	2009		Unit Root
		Harvey and Mills (2002)				
Model C	T	Test Statistics	Appropriate delay length	Breaking Date	Table Value (%10; %5; %1)	Conclusion
ILCF	33	-3.35090	0	1994-2003		Unit Root
REN	33	-6.55161	0	1995-1990		Unit Root
GDP	33	-1.42543	0	1992-2005		Unit Root
GDP2	33	-1.83746	0	1992-2005	-6.74; -7.16; -8.14	Unit Root
NREN	33	-2.92170	0	1990-2003		Unit Root
TO	33	-4.42374	0	1996-2006		Unit Root
URB	33	-0.59669	0	1998-2005		Unit Root

Note: The maximum number of lags is identified using the formula $12*(\frac{n}{100})^{\frac{1}{4}}$ by Schwert (2002). The Akaiki criterion is used to determine the lag lengths.

Findings indicate that variables in both models are non-stationary at their levels. The results in Table 4 to Model C of the LNV and HM unit root tests. The intuitive findings that there is a general trend structure as a result of the graphical examination of the variables led us to focus on the findings of Model C, which includes the findings of the models with constant and trend. In the following methods, we test statistical significance by considering trended model structures. After the information that the nonlinear unit root test findings contain a unit root process at their levels, the traditional ADF and PP results are examined to determine the stationarity level. Since the nonlinearity of the deterministic terms disappears when the difference process is applied in LNV and HM tests, the classical ADF and PP tests are used to explore stationarity. Table 5 depicts the traditional unit root test results.

Table 5

Traditional Unit Root Test Findings

Tests	ADF		PP	
	Level	First Diff.	Level	First Diff.
ILCF	−1.312785 (0.8658)	−3.447307* (0.0634)	−0.860923 (0.9484)	−3.385733* (0.0718)
REN	−2.626793 (0.2718)	−6.967355*** (0.0000)	−2.576546 (0.2926)	−7.224870*** (0.0000)
GDP	−0.865776 (0.9471)	−3.819276*** (0.0094)	0.079726 (0.9956)	−3.695804** (0.0377)
GDP2	−1.880729 (0.6394)	−4.816890*** (0.0071)	−0.799660 (0.9552)	−3.665373** (0.0403)
NREN	−2.414336 (0.3655)	−4.902762*** (0.0009)	−1.497213 (0.8096)	−6.573581*** (0.0000)
TO	−1.592952 (0.7734)	−4.105395** (0.0152)	−1.677900 (0.7377)	−4.105395** (0.0152)
URB	0.634170 (0.9992)	−3.932845*** (0.0061)	2.269378 (1.0000)	−3.801603*** (0.0078)

Note: The Schwarz information criterion is used in the ADF unit root test. Values in parentheses display probability values. 10%, 5%, and 1% significance levels are highlighted with *, **, and ***, respectively.

Traditional test findings in Table 5 indicate that the ILCF is stationary at its first difference. However, other series show stationary properties at their first difference. Hence, all variables in these two models are I(1). This result showed that the co-integration test put forward by Hepsağ (2021) could be applied. Table 6 depicts the Hepsağ (2021) co-integration test findings.

Table 6

Hepsağ (2021) Co-integration Test Findings

Data Type	Model-1			Model-2		
	$F_{ANEC,t}$	Appropriate delay length	$F_{AS,t}$	$F_{ANEC,t}$	Appropriate delay length	$F_{AS,t}$
Detrended Data	8.98962	1	0.000654 (0.99386727)	9.12058	1	0.006928 (0.95180252)

Note: The critical values at 1%, 5%, and 10% significance levels for the trend-free data of the F_{ANEC} test statistics for Model-1 and Model-2 are 12.083; 9.312; and 8.012, respectively. The Akaike information criterion is used to assess the lag length. The expressions in parentheses indicate the probability values of the $F_{AS,t}$-test.

Table 6 shows the long-term findings for Model 1-2. The trend-free data results of the F_{ANEC} test statistic proposed by Hepsağ (2021) are reported in Table 6. In other words, the methodology followed throughout the study considers the fixed and trended model results. The null hypothesis of no co-integration in Model-1 and Model-2 is rejected. This result indicates the co-integrating relationships. However, the F_{AS} results should be interpreted to evaluate the result regarding whether the co-integrated relationship is symmetric or asymmetric. The F_{AS} results indicate that the null hypothesis indicated a symmetric co-integrated linkage. As a result, a symmetric co-integrated relationship is reached in both models. To use this relationship, the coefficient of the $\hat{u}^3_{t-1}$ term in Table 7 should be examined. Table 7 presents the findings regarding the long- and short-term results of AESTAR-ECM. Table 7 also includes diagnostic test findings for the periods.

Table 7
AESTAR-ECM Long- and Short-Term Findings

	Model-1	
	F_{ANEC} (Detrended Data)	
	Long-Term Results	
Dependent variable: ILCF		
Independent Variable	**Coefficient**	**Probability Value**
GDP	1.476445	0.0002
GDP2	−0.096279	0.0003
NREN	0.783326	0.0000
TO	−0.190650	0.0030
Diagnostic Tests		
Breusch-Godfrey autocorrelation	0.355868	0.82358421
Jargue-Bera normality	1.134770	0.567006
Ramsey functional form	0.7666395	0.3812587
ARCH heteroscedasticity	10.24644	0.24815
	Short-Term Results	
Independent Variable	**Coefficient**	**Probability Value**
$\hat{u}^3_{t-1}$	−0.036027	0.745462
$\hat{u}^4_{t-1}$	0.0292440	0.840857
∆GDP	0.720482	0.0905
∆GDP2	−0.040284	0.0739
∆NREN	0.638002	0.0000
∆TO	−0.090688	0.1020
Diagnostic Tests		
Breusch-Godfrey	0.065230	0.23624111
Jargue-Bera	0.324068	0.850412
Ramsey	0.0653414	0.7982445
ARCH	27.58004	0.27815
	Model-2	
	F_{ANEC} (Detrended Data)	
	Long-Term Results	
Dependent variable: REN		
Independent Variable	**Coefficient**	**Probability Value**
GDP	-2.786285	0.0007
GDP2	0.256814	0.0000
TO	0.083444	0.3753
URB	-1.146044	0.4630
Diagnostic Tests		
Breusch-Godfrey	0.1057794	0.47284480
Jargue-Bera	0.258308	0.5685883

Independent Variable	Coefficient	Probability Value
Ramsey	0.1431349	0.7051841
ARCH	7.25136	0.50977
	Short-Term Results	
Independent Variable	**Coefficient**	**Probability Value**
$\hat{u}^3_{t-1}$	−0.06450024	0.0308922
$\hat{u}^4_{t-1}$	0.028046296	0.4388109
∆GDP	−1.98796	0.0010
∆GDP2	0.45791	0.0004
∆ TO	0.06687	0.4396
∆URB	−0.94628	0.5892
Diagnostic Tests		
Breusch-Godfrey	0.0422013	0.58301406
Jargue-Bera	1.509013	0.470243
Ramsey	0.0774287	0.7808126
ARCH	27.35778	0.28805

Table 7 shows the long- and short-term F_{ANEC} (Detrended Data) coefficients of Model-1 and Model-2. Hepsağ (2021) co-integration test reveals that the F_{ANEC} is stronger than the F_{ANEG}. Therefore, the constant and trend model results of the F_{ANEC} test are reported in this study. Short- and long-term diagnostic tests are given in Table 7. It is determined that the condition of the $\hat{u}^3_{t-1}$ term being negative is met in both Model-1 and Model-2. This situation guarantees that the co-integrated relationship is in a symmetric form (Akkaya and Hepsağ, 2021). The long-term results in Table 7 are critical for the main purpose of the study. The AESTAR-ECM long-term results of Model-1 allow for testing the ILCC hypothesis. The GDP and GDP2 long-term coefficients are 1.476445 and −0.096279, respectively. Hence, these findings imply the validity of the inverted U-shaped relationship in Model-1. The estimated values for NREN and TO are 0.783326 and −0.190650, respectively. These findings reveal that non-renewable energy sources increase the ILCF, whereas trade openness decreases it. The diagnostic test findings of the long-term results in Model-1 also indicate that the long-term coefficients can be used. In other words, the error terms are independent of each other and no modelling error problems. Furthermore, normality and constant variance assumptions are satisfied. The short-term coefficients of Model-1 closely resemble the long-term estimates. Moreover, short-term diagnostic findings are similar to long-term ones. The AESTAR-ECM long-term findings for Model-2 allow us to examine the RKC hypothesis. The GDP and GDP2 long-term coefficients are determined to be -2.786285 and 0.256814, respectively, at a significance level of 1%. These findings indicate a U-shaped relationship in Model-2. The other variables, TO and URB, are not significant. The AESTAR-ECM long-term forecast results indicate that the ILCC and RKC hypotheses are valid. The validity of these hypotheses is shown in Figure 3.

Figure 3

ILCC and RKC hypotheses and inflection points (AESTAR-ECM)

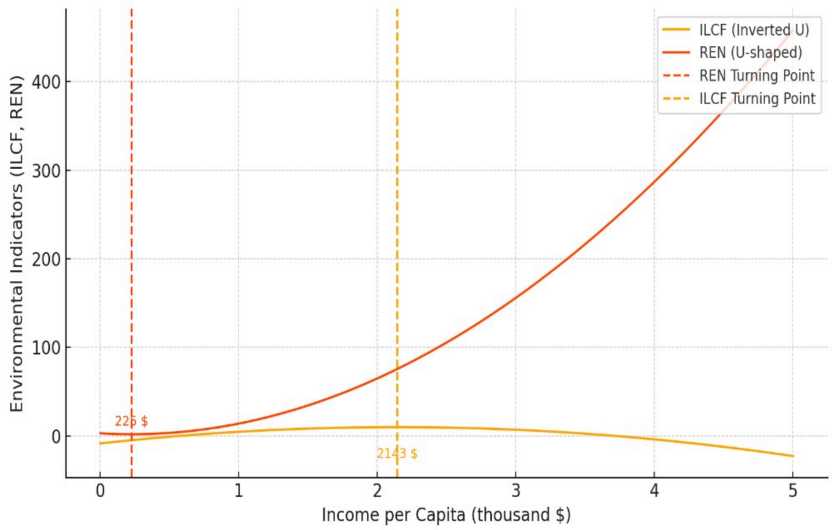


Figure 3 shows the validity and monetary value of the ILCC and RKC hypotheses. AESTAR-ECM long-term forecasts that the inflection point in the Chinese economy, starting from the inflection point of the ILCC hypothesis, is $2143. The monetary value of the inflection point of the RKC hypothesis is $225. These results reveal that the inflection point of the RKC precedes that of the ILCC. This finding implies that the income increase first enhanced environmental health by increasing renewable energy use. The inflection point of the ILCC curve occurs at a higher income category than the RKC. In addition to the AESTAR-ECM long-term estimation results, the FMOLS estimator is used as a robustness test. Table 8 depicts the FMOLS findings for Model-1 and Model-2.

Table 8

FMOLS (Robustness) Test Results

Variables	Model 1: Dependent variable: ILCF			
	Coeff.	**Std. Err.**	**t-Statistic**	**P-value**
GDP	1.873246***	0.445170	4.207930	0.0003
GDP2	−0.124385***	0.030096	−4.132970	0.0003
NREN	0.887520***	0.120902	7.340848	0.0000
TO	−0.252058***	0.076178	−3.308817	0.0027
C	−8.416011***	1.686389	−4.990552	0.0000
T	−0.034666***	0.011536	−3.004942	0.0058
Variables	**Model 2-Dependent variable: REN**			
	Coeff.	**Std. Err.**	**t-Statistic**	**P-value**
GDP	−2.717520 **	0.629990	−4.313595	0.0002
GDP2	0.251523 **	0.032305	7.785833	0.0000
TO	0.095819 ***	0.069946	1.369896	0.1824
URB	−1.347762 **	1.246738	−1.081030	0.2896
C	11.21067 ***	2.214152	5.063189	0.0000
T	−0.150341 ***	0.023813	−6.313422	0.0000

Notes: C and T depict the constant and trend terms, respectively. 10%, 5%, and 1% significance levels are highlighted with *, **, and ***, respectively.

Table 8 depicts the FMOLS estimator findings of Model-1 and Model-2. As throughout the study, the fixed&trend model findings are reported in the FMOLS estimation. The FMOLS long-term results of Model-1 allow for examining the ILCC hypothesis. The GDP and GDP2 long-term coefficients were determined to be 1.873246 and −0.124385, respectively. These results depict the validity of the inverted U-shaped relationship in Model-1. The other variables, NREN, and TO, are obtained as 0.887520 and −0.252058, respectively. These findings show that non-renewable energy sources increase the ILCF, whereas trade openness decreases it. The FMOLS long-term results of Model-2 allow for determining whether the RKC hypothesis is valid or not. The long-term coefficients of GDP and GDP2 are −2.786285 and 0.256814, respectively. These findings imply a U-shaped relationship in Model-2. The other variables, TO and URB, are statistically insignificant.

FMOLS long-term estimations indicate that the ILCC and RKC hypotheses are valid. The validity of these hypotheses is shown in Figure 4

Figure 4

ILCC and RKC hypotheses and inflection points (FMOLS)

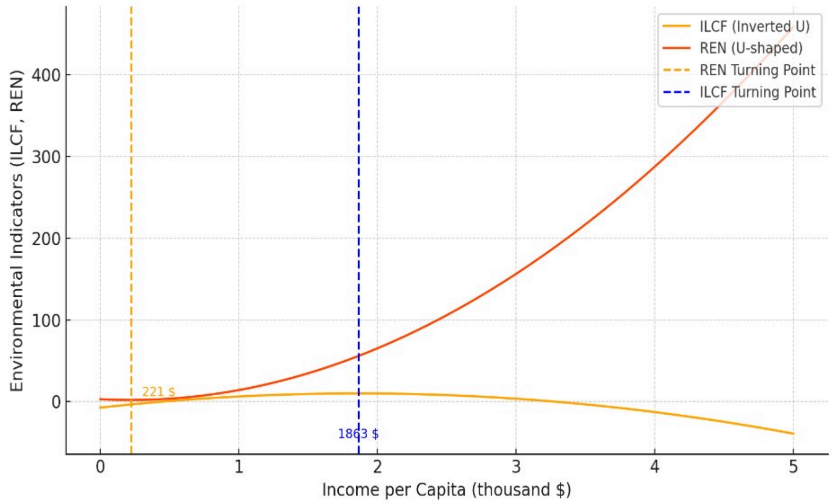


Figure 4 shows the validity and monetary value of the ILCC and RKC hypotheses. The FMOLS long-run results imply that the inflection point in the Chinese economy is $1863, starting from the inflection point of the ILCC hypothesis. The monetary value of the inflection point of the RKC hypothesis is $221. These results concluded that the inflection point of the RKC hypothesis occurs before the inflection point of the ILCC hypothesis. This finding reveals that a rise in income first increases environmental quality by causing an upsurge in the REN. The inflection point of the ILCC curve occurs at a higher income level than the RKC. Moreover, the current study concentrates on short-term associations. In this context, Nazlioglu et al. (2016) used the FBTY causality test. The findings are depicted in Table 9.

Table 9

Fourier Toda-Yamamoto Causality Findings

Causality	Wald Stat.	k+dmax	Crit. Val. (1%; 5%; 10%)
GDP→ ILCF	233.59672 *** (2)	2	66.616824; 51.255707; 44.117329
GDP2→ ILCF	218.80505 *** (1)	2	56.091859; 42.534492; 36.589103
NREN→ ILCF	229.82389 *** (1)	3	147.395298; 112.239808; 97.317023
TO→ ILCF	93.97088 *** (1)	2	13.516526; 8.326058; 6.463424
GDP → REN	237.02285 *** (3)	3	98.922069; 76.028393; 65.435519
GDP2 → REN	190.18672 *** (1)	2	56.234270; 39.785686; 33.199954
TO → REN	132.89722*** (2)	3	42.309346; 29.062663; 23.557156
URB→ REN	233.58091 *** (2)	4	185.602943; 134.340634; 116.031011

Note: Values in parentheses indicate the optimal frequency at which the sum of squares is minimised, k represents the preferred lag length according to the Akaike information criterion, and dmax represents the maximum degree of integration. Critical values are generated after 10,000 bootstrap cycles. Finally, *, **, and *** represent significance levels of 10%, 5%, and 1%, respectively.

FBTY results in Table 9 indicate causality from GDP, GDP2, NREN, TO, and URB to ILCF and REN. FBTY short-term causality confirms long-term associations.

Concluding Remarks

Environmental sustainability is among the most important issues globally. Many measures are being taken both nationally and globally to solve this global problem. Sustainable development goals at the international level are among the most crucial steps. The ILCC and RKC hypotheses are investigated by considering different dimensions of environmental sustainability in the Chinese economy. The study investigates the sample period of 1990-2022, which covers the globalisation process. The ILCF and renewable energy utilisation are used as dependent variables, and two different models are established. In this context, the link between ILCF and economic growth, non-renewable energy, and trade openness is discussed. The second model investigated the relationship between renewable energy, economic growth, trade openness, and urbanisation. Current empirical methods are used in the study. Hepsağ (2021) co-integration approach is used to investigate the long-term association in Model-1 and Model-2. Within the scope of Model-1, it is observed that the ILCC is valid. Moreover, non-renewable energy usage escalates the ILCF. However, trade openness contributes to environmental protection by reducing ILCF. Within the scope of Model-2, the validity of the RKC hypothesis is obtained because of the AESTAR-ECM long-term estimation. Trade openness and urbanisation in Model-2 are statistically insignificant. As a result, according to the AESTAR-ECM long-term estimation, the ILCC and RKC hypotheses are valid. In this study, the monetary values of the inflection points of ILCC and RKC are calculated based on the inflection point. The inflection points are calculated as $ 2143 and $ 225. These results were also tested with the FMOLS robustness test. FMOLS results support the validity of the ILCC and RKC hypotheses. The inflection points are calculated as $ 1863 and $ 221, respectively.

These results prove that the income inflection point is lower in the RKC model than in the ILCC model. This result shows that as income increases in China, renewable energy use increases, and when income reaches a higher threshold, environmental degradation is reduced as renewable energy usage increases. The FBTY causality test is utilised to analyse the short-term associations. According to the findings, it is concluded that GDP, GDP2, NREN, and TO cause ILCF. This result obtained in the short-term causality analysis supports the findings of Model-1, which has a long-term relationship. Similarly, it is determined that GDP, GDP2, TO, and URB cause REN. This result supports the long-term results of Model-2.

6. Discussion and policy recommendations

The results reveal crucial policy implications. First, policymakers need to focus on the RKC relationship in the renewable energy-environmental degradation relationship. The widespread use of renewable energy should be considered as a prerequisite for combating environmental degradation. Without renewable energy investments, it is impossible to reduce polluting production and consumption.

Second, the fact that the validity of the RKC hypothesis is a prerequisite for the ILCC hypothesis has important implications for policymakers. Accordingly, renewable energy can be in demand even at low-income levels. Therefore, policymakers must increase renewable energy investments, especially in the first phase of industrialisation and growth, when mass production increases and energy-intensive energy use continues. In this way, it is possible to protect the environment even at lower income levels. Accordingly, renewable energy sources play a primary role in raising environmental awareness in society and spreading clean production technologies. For this reason, it is important to provide tax exemptions for renewable energy investments, especially at the initial stage of industrialisation and growth, and to provide incentives for the development or transfer of technology required for renewable energy investments. Policymakers' subsidies or feed-in tariffs on the price of energy from renewable sources can accelerate renewable energy investments. Accordingly, through renewable energy investments, sustainable growth that does not lead to rationing can be achieved sooner than expected.

Third, policymakers should consider the results that trade openness mitigates environmental degradation. The fact that trade openness improves environmental quality indicates that China has shifted from pollution-intensive production to environmentally friendly production through technology transfer. Moreover, it can be argued that the rise in income resulting from increased trade increases environmental sensitivity. Therefore, policymakers taking steps towards trade liberalisation can improve environmental quality. Therefore, reducing quotas in international trade, developing bilateral cooperation, becoming a member of economic unions, and concluding free trade agreements can improve environmental quality.

The lower income inflection point in the RKC model compared to the ILCC model highlights the accelerating effect of renewable energy use on environmental quality. This contributes to the literature on China's environment-growth relationship. Unlike the ILCC model, which argues that environmental pollution reduction occurs only at a higher stage of industrial use, the RKC results emphasise that renewable energy integration can reduce environmental pollution at an earlier income level in China. The findings that environmental quality improvement can start at a lower-than-expected income level in China empirically support the role of increasing renewable energy share in reducing environmental pollution. In this respect, the study makes original contributions to studies on China's sustainable growth process in terms of early transition and the impact of the energy mix. The results complement recent empirical research and offer a new perspective on China's transition to a green growth path.

This study has some limitations. First, this study is centred on China, which stands out among the most polluting countries, and developing countries are excluded from the scope. Considering that the dynamics of environmental deterioration can differ across countries, future research should focus on developing country cases. Second, this study is conducted over the period 1990–2022, due to data limitations. In future studies, it is essential to cover the pre-globalisation period to compare the pre- and post-globalisation period. Finally, this research focuses on mainland China and ignores differences in provinces of China. Future research focusing on China's provinces can allow for comparable results.

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