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Exploring the dynamics of carbon emissions in China: Insights from ARDL and DOLS

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ABSTRACT

The research aims to justify the existence of the Environmental Kuznets Curve (EKC) hypothesis in China by analyzing key determinants of emissions and their influence on CO_2 production, including economic expansion, energy consumption, urbanization, trade openness, and renewable energy adoption. The study utilizes World Development Indicators data and employs econometric analysis using the Autoregressive Distributed Lag (ARDL) and Dynamic Ordinary Least Squares (DOLS) methods. These approaches were chosen to provide both long-term and short-term insights into the relationships between CO_2 emissions and their influencing variables. The empirical results confirm the EKC hypothesis in China, showing that CO_2 emissions rise with income up to a certain threshold and decline thereafter. Energy consumption, particularly coal use, is identified as the primary contributor to emissions. While trade openness is associated with increased emissions, the effect of urbanization on emissions is inconsistent. Renewable energy currently has a minimal impact due to its lower contribution compared to fossil fuels. The findings highlight the complex nature of reducing CO_2 emissions in a rapidly growing economy like China. Effective environmental policies are needed to achieve sustainable development. China should enhance renewable energy capabilities, implement structural changes in energy usage, and integrate environmental concerns into trade and urban development policies to support sustainable growth.

Contribution/Originality: This study uniquely combines ARDL and DOLS approaches to validate the EKC hypothesis for China, incorporating trade openness, renewable energy, and urbanization. It offers a comprehensive, updated econometric analysis using recent data, revealing nuanced impacts of urbanization and renewable energy adoption on emissions not fully explored in previous research. This study uniquely combines ARDL and DOLS approaches to validate the EKC hypothesis for China, incorporating trade openness, renewable energy, and urbanization. It offers a comprehensive, updated econometric analysis using recent data, revealing nuanced impacts of urbanization and renewable energy adoption on emissions not fully explored in previous research.

1. INTRODUCTION

The rapid economic progress of China over four decades has made it the world's second-largest economic power. The exceptional economic rise has resulted from industrialization alongside urbanization, together with rising energy usage. Recent Chinese economic achievements are reflected in the country's status as the world's biggest CO_2 emissions source, as it now produces approximately 30% of total global warming gases (Liu, Ur Rahman, Jóźwik, & Doğan, 2024). Millions of people have gained relief from poverty standards through economic development, but this progress has resulted in increased environmental concerns about sustainable solutions. Econometric research focused on China's economic growth, urbanization statistics, trade, and CO_2 emission patterns needs ARDL and Dynamic Ordinary Least Squares (DOLS) model applications to properly investigate this intricate relationship.

According to the Environmental Kuznets Curve hypothesis, pollution first increases, then decreases when economies reach a stage that enables sustainable investments along with strengthened environmental regulations (Shahani & Bansal, 2021). Research on the EKC hypothesis for China shows mixed results because some scholars support the inverted U-shaped assumption, yet others demonstrate increasing atmospheric pollution throughout national development (Avazdahandeh, 2024). High persistent emission levels in China raise doubts about whether economic growth alone will promote environmental sustainability or if new policies need to be established for carbon emission reduction.

Energy consumption leads to most CO_2 emissions in China because the country depends mostly on fossil fuels, especially coal (Liu, 2020). Despite significant investments in renewable energy sources, such as solar and wind power, coal still accounts for nearly 60% of China's electricity generation due to its affordability and energy security considerations (Shaari, Abdul Karim, & Zainol Abidin, 2020). Research establishes that China has achieved major growth in renewable energy installations, yet its total energy distribution remains overwhelmingly non-renewable, thus weakening its carbon emission reduction programs (Sobirov et al., 2024). Emissions continue to increase in China because its economic focus on industrial production generates high energy consumption (Zhai & Kong, 2024).

The expanding city populations serve as a primary factor behind escalating CO_2 emission levels. From the implementation of economic reforms in 1978 until 2013, China witnessed an explosive transformation in its urban population, which grew from 19.39% to 53.70%, according to Shahani and Bansal (2021). Urban migration patterns cause several environmental impacts because they drive higher power usage, demand more infrastructure development, and promote industrial economic systems (Zhai & Kong, 2024). Statistics confirm that urbanization generates substantial differences in emission levels between regions because the northern industrial areas of China have higher emission densities than their underdeveloped counterparts (Sobirov et al., 2024). Urbanization may boost energy efficiency and emission reduction, according to researchers, but China has not yet achieved this advancement (Shaari et al., 2020).

The emissions path of China depends significantly on its international trade policies and the advancement of globalization initiatives. China, which functions as the world's largest exporter, has attracted significant foreign direct investment and has developed into the nerve center of international supply chains (Liu et al., 2024). The Pollution Haven Hypothesis explains why China faces increasing pollution by suggesting that companies search for countries with weak environmental regulations to set up operations (Avazdahandeh, 2024). Varied research demonstrates that trade liberalization either degrades environmental quality or promotes cleaner production technology adoption, according to Shahani and Bansal (2021). The study investigates the lasting effects that openness to trade has on the CO_2 emissions released by China.

China has invested notable policy resources into developing solutions for climate change and reducing emission levels. The government signed agreements to reach carbon peak levels by 2030 and achieve carbon neutrality by 2060, which support the provisions of the Paris Agreement (Liu, 2020). China implemented the carbon trading system along with renewable energy subsidies and strengthened industrial regulations to meet its emission targets, according to Zhai and Kong (2024). These measures show limited effectiveness in reducing emissions because China maintains a significant dependence on heavy industry and export-related manufacturing (Shaari et al., 2020).

This research uses economic and environmental variables to conduct an extensive investigation into CO_2 emission patterns in China by employing ARDL and DOLS models. The study utilizes both ARDL and DOLS models to examine short-term and long-term relationships between key economic and environmental variables. It investigates China's EKC pattern, the effectiveness of renewable energy adoption, the impacts of trade liberalization, and the contributions of population growth and urbanization to emissions (Liu et al., 2024).

This paper stands out because it analyzes emissions in China by utilizing different analytical methods. Research has mostly concentrated on single factors like economic expansion or energy consumption, while a thorough econometric analysis combining urban development, market liberalization approaches, and policy interventions remains underexamined (Avazdahandeh, 2024). This research seeks to bridge an academic and policy gap by providing insights that enable China to achieve its low-carbon economic transition. It will produce findings that extend their value to developing nations dealing with sustainability issues comparable to China's case, thus demonstrating broad boundary-transcending applicability.

The Chinese government has achieved substantial economic development, yet environmental issues continue to present severe pressures. The progressive pattern linking economic development to CO_2 emissions does not follow straightforward lines, so policymakers need to design comprehensive strategies that merge industry growth with environmental protection standards. Research will establish the underlying causes of China's emission patterns by providing specific guidance for attaining economic success through environmental protection initiatives. Research findings will benefit decision-makers, academic scholars, and stakeholders who focus on sustainable development, energy policy, and climate action within China and worldwide.

1.1. Contribution of the Study

This academic investigation presents important additions to carbon emission studies linked to economic expansion in China's development landscape, with environmental factors at play.

A comprehensive empirical examination of the Environmental Kuznets Curve (EKC) hypothesis occurs throughout the time period from 1990 to 2023 in China. The investigation provides insights into policy development regarding leveraging economic expansion to achieve sustainable environmental targets.

This research utilizes the combination of ARDL and DOLS methodologies to deliver improved results in tracing economic factors and CO_2 emissions both in short and extended time periods. The combination of these methods enables the proper management of endogeneity problems and generates enhanced observations about time delays while developing specific policy solutions.

The analysis combines trade openness and urbanization measurements as well as renewable energy utilization with established variables, including economic growth and energy consumption. The integrative strategy demonstrates how trade activities influence emission changes, with urbanization creating a detailed picture useful for governmental policy development.

Thid study establishes both tolerance levels and main factors leading to emissions enabling the identification of specific measures to promote economic growth together with environmental protection.

The research examines China specifically, but its analytical methods, together with its findings, will benefit developing countries working to manage trade-offs between economic development and environmental conservation. The study adds value for researchers who focus on China's environmental techniques because its findings apply to scholars and global audiences who study sustainable development practices.

2. LITERATURE REVIEW

2.1. Economic Growth and CO_2 Emissions: Testing the EKC Hypothesis

According to the Environmental Kuznets Curve hypothesis, carbon pollution rises as nations experience economic expansion until income levels reach a particular point, where emissions start to decrease. A number of researchers have validated the EKC hypothesis for China through diverse econometric model types such as ARDL and DOLS. A group of researchers found that China shows signs of reaching an inverted U-shaped relationship, which might lead to emission reduction when transitioning into a service-based economy (Liu, 2020). Research by Shahani and Bansal (2021) indicates that China remains below the EKC turning point, thus its emissions continue to grow alongside its economic development. The Peninsula has inconclusive empirical evidence, which demonstrates the need for new econometric studies using contemporary analytical methods.

China's dependence on energy-intensive industrial activities functions as the leading contributor to increases in emission quantities. Industrial development produces substantial carbon dioxide emissions in China, according to research studies, where steel production and cement manufacturing, along with other manufacturing operations, act as primary pollution sources (Sobirov et al., 2024). Some cases show that the decline in emissions fails to follow a consistent correlation with economic growth, exposing a contradiction against EKC ideas. Upon achieving prosperity through economic expansion, Chinese society has increased energy usage and faced environmental damage (Feng, Shang, Gao, An, & Han, 2023).

2.2. Energy Consumption and Carbon Emissions

The extraordinary Chinese economic expansion triggered immense power utilization that established China as the globe's leading energy consumption territory. Research shows that China continues to rely heavily on fossil fuels, mainly through coal, as its fuel source, consuming nearly 60% of the country's power generation capacity (Zhai & Kong, 2024). According to Liu et al. (2024) renewable energy investments show growth yet the coal sector transition has been delayed since people worry about energy security together with affordability concerns.

Among energy consumption elements in China, the rebound effect serves as an essential factor. The research indicates that better energy efficiency has failed to produce equivalent carbon emission reductions due to growing energy consumption patterns (Shaari et al., 2020). Although the rise of energy-efficient technologies exists, overall energy use continues to increase because the industrial sector and urban population numbers expand. The contradictory situation regarding technological progress and emission reduction warrants caution concerning its actual environmental benefits.

The energy consumption levels and emissions vary significantly across different regions of the country. Scientific evidence indicates that urban eastern China produces considerably greater amounts of CO_2 emissions compared to rural areas because of higher concentrations of industries and population (Liu et al., 2024). A comprehensive national emissions reduction strategy must consider varying energy consumption patterns across different regions.

2.3. Urbanization and CO_2 Emissions

Urbanization is the primary source of CO_2 emissions in China, with its urban population increasing from 19.39% in 1980 to 53.70% in 2013 (Avazdahandeh, 2024). The urban migration of people from rural areas causes increased energy usage, requiring greater industrial expansion and adding more transportation needs, which together result in higher emissions (Shahani & Bansal, 2021). Scientific evidence indicates that urbanization might decrease carbon emissions by enabling infrastructure improvements, superior waste handling, and green transit systems (Zhai & Kong, 2024). Existing empirical investigations demonstrate that urbanization has mostly intensified carbon emissions in highly industrialized areas (Feng et al., 2023).

Emissions follow a direct correlation with the level of urbanization, which depends on income groups. Research evidence shows that wealthier city dwellers use energy at higher levels because they enhance household power consumption, buy cars, and engage in high-carbon emission practices (Liu et al., 2024). The reductions of urban emissions beyond technological solutions demand both behavioral transformations and strategic policy changes.

2.4. Trade Openness and CO_2 Emissions: Evidence from the Pollution Haven Hypothesis

The Chinese economic shift towards liberalized trade, combined with dependency on exports, has been a major driver behind China's rising CO_2 emissions. According to the Pollution Haven Hypothesis (PHH), weaker environmental regulations in targeted nations allow them to accept polluting industries, thus increasing nationwide emission levels (Liu et al., 2024). Several research documents establish China as a pollution center because the country implements flexible environmental regulations alongside low production expenses to attract foreign direct investment (FDI) from industries with high pollution exposure (Shaari et al., 2020).

Numerous scholars believe that trade accessibility results in environmental progress, as it enables the transfer of cleaner technology while fostering environmental consciousness (Zhai & Kong, 2024). Research data presents conflicting outcomes concerning short-term trade increases in CO_2 emissions since export-focused economies adopt cleaner technologies after a period to sustain their international standing (Feng et al., 2023).

Trade emissions depend primarily on the composition of exports that China manufactures. Studies show that producing electronic exports at higher values generates fewer carbon emissions than creating products from the steel and cement industries (Avazdahandeh, 2024). Trade-related emissions can potentially decrease when exports shift to avoid technology and carbon emissions.

2.5. The Role of Renewable Energy in Mitigating Carbon Emissions

The world acknowledges China as the top investor in renewable energy while it makes notable advancements across solar power, wind power, and hydroelectric generation (Liu, 2020). The rapid growth of green energy throughout the country fails to decrease China's extensive use of coal resources. Research indicates that China faces challenges with its renewable energy policies because they do not include effective enforcement tools, which impede the goal of major emission reductions (Shahani & Bansal, 2021).

There exists a primary obstacle to renewable energy adoption regarding connection to power grids. The power grid infrastructure in China shows limitations in accommodating intermittently generated renewable electricity, causing both curtailment problems and decreased operational efficiency, according to the study by Sobirov et al. (2024). Renewable energy facilities in China are primarily located in western areas, which face obstacles because eastern parts hold the country's highest energy consumption requirements. (Zhai & Kong, 2024).

Renewable energy adoption received some useful momentum through policy initiatives but did not achieve full success. The cost-competitiveness of renewables improved through carbon trading systems and clean energy technology subsidy programs, but coal remains dominant due to temporary economic benefits (Shaari et al., 2020). Low-carbon economy transition demands enforced regulations together with proper infrastructure development and economic incentives.

The research on carbon emissions throughout China demonstrates simultaneous relationships among economic growth, energy consumption, urbanization, trade activity, and renewable energy plan implementation. Multiple research studies find evidence for the EKC hypothesis, yet other studies demonstrate that China remains at the pollution generation stage. The present energy demand depends on fossil fuels, and renewable energy adoption has improved but has not yet reached levels necessary to reduce coal consumption. The process of urbanization has led to higher emissions, which future improvements in infrastructure and energy efficiency may help reduce in the coming decades. The process of trade liberalization benefits both manufacturing activities based on emissions-intensive industries and promotes the implementation of environmentally friendlier technologies. Achieving environmental sustainability during economic development requires stronger policies, improved enforcement systems, and technological progress.

3. DATA AND METHODS

The study analyzes CO_2 emission factors in China from 1990 to 2023 through an annual time series analysis. It examines CO_2 emissions per capita as the dependent variable, considering economic growth based on the EKC hypothesis and six independent factors, including energy use and urbanization, among others, as shown in Table 1. Zhang et al. (2023) establish the selected variables through a thorough analysis of research regarding the economic growth-energy consumption-environmental degradation nexus. The research applies the Autoregressive Distributed Lag (ARDL) bounds testing approach together with the Dynamic Ordinary Least Squares (DOLS) methodology.

3.1. Model and Data Sources

The data originates from the World Development Indicators (WDI) maintained by the World Bank, offering a collection of reliable macroeconomic and environmental measurement indicators. The following explanation details these variables.

Table 1. Data description.

Abbreviation	Description	Source
CO2_PC	Carbon dioxide (CO2) emissions excluding LULUCF per capita (t CO2e/capita)	WDI
GDPPCG	GDP per capita growth (Annual%)	WDI
EU	Energy use (kg of oil equivalent per capita)	WDI
UPG	Urban population growth (Annual%)	WDI
TRADE	Trade (% of GDP)	WDI
REC	Renewable energy consumption (% of total final energy consumption)	WDI
POP	Population density (People per sq. km of land area)	WDI

The functional form of the econometric model is:

$$CO2PC = f\ (GDPPCG, EU, UPG, TRADE, REC, POP)$$

The econometric model for the above functional form is given below:

$$CO2_t = \alpha_0 + \alpha_1 GDP_t + \alpha_2 EU_t + \alpha_3 UP_t + \alpha_4 TRADE_t + \alpha_5 REC_t + \alpha_6 POP_t + \varepsilon_t$$

Where:

α_0 is the intercept.

α_1, α_2, α_3, α_4, α_5, and α_6 are the long-run elasticities.

ε_t is the error term.

3.2. Econometric Methodology

Before performing ARDL estimation, it is necessary to conduct unit root tests because ARDL requires all variables to be I(0) or I(1). The Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests verify whether variables are at I(0) level or I(1) first difference properties (Pesaran, Shin, & Smith, 2001).

The ARDL model created by Pesaran, Shin, and Smith (1999) serves to detect possible long-run cointegrating relationships between the variables. The ARDL regression should be written as.

$$\Delta CO_2 = \beta_o + \sum_{i=1}^{p} \beta_1 \Delta CO_{2\,t-i}$$

$$+ \sum_{i=0}^{q1} \beta_2 \Delta GDP_{t-i}$$

$$+ \sum_{i=0}^{q1} \beta_3 \Delta EU_{t-i} + \sum_{i=0}^{q1} \beta_4 \Delta UP_{t-i} + \sum_{i=0}^{q1} \beta_5 \Delta TRADE_{t-i} + \sum_{i=0}^{q1} \beta_6 \Delta REC_{t-i} + \sum_{i=0}^{q1} \beta_7 \Delta POP_{t-i}$$

$$+ \lambda_1 CO_{2\,t-1} + \lambda_2 GDP_{t-1} + \lambda_3 EU_{t-1} + \lambda_4 UP_{t-1} + \lambda_5 TRADE_{t-1} + \lambda_6 REC_{t-1} + \epsilon_t$$

Where:

β_i are short-run coefficients.

λ_i are long-run coefficients.

ϵ_t is the error term.

The F-statistic is used to test the null hypothesis of no cointegration.

$$H_o: \lambda_1 = \lambda_{2=} \dots \dots \dots \dots \dots \dots = \lambda_7 = 0$$

If the calculated F-statistic exceeds the upper bound critical value, we reject H_0 and confirm the presence of long-run cointegration.

Once a long-run relationship is established, the error correction model (ECM) captures the short-run adjustment dynamics.

$$\Delta CO_2 = \gamma_o + \sum_{i=1}^{p} \gamma_1 \Delta CO_{2\,t-i}$$

$$+ \sum_{i=0}^{q1} \gamma_2 \Delta GDP_{t-i} + \sum_{i=0}^{q1} \gamma_3 \Delta EU_{t-i}$$

$$+ \sum_{i=0}^{q1} \gamma_4 \Delta UP_{t-i} + \sum_{i=0}^{q1} \gamma_5 \Delta TRADE_{\,t-i} + \sum_{i=0}^{q1} \gamma_6 \Delta REC_{\,t-i} + \sum_{i=0}^{q1} \gamma_7 \Delta POP_{t-i} + \eta ECM_{T-1} + \upsilon_t$$

Where ECM is the error correction term, measuring how quickly the system returns to equilibrium. A negative and significant η confirms adjustment toward the long-run equilibrium.

To ensure robust long-run estimates, the DOLS method is employed, correcting for endogeneity and autocorrelation (Stock & Watson, 1993).

$$CO_2 = \delta_o + \sum_{j=-k}^{k} \delta_1 \Delta GDP_{t-j} + \sum_{j=-k}^{k} \delta_2 \Delta EU_{t-j}$$

$$+ \sum_{j=-k}^{k} \delta_3 \Delta UP_{t-j} + \sum_{j=-k}^{k} \delta_4 \Delta TRADE_{\,t-j} + \sum_{j=-k}^{k} \delta_5 \Delta REC_{\,t-i} + \sum_{j=-k}^{k} \delta_6 \Delta POP_{\,t-j} + \mu_t$$

DOLS improves efficiency by including leads and lags of the first-differenced explanatory variables, reducing omitted variable bias.

3.3. Rationale for Time Span, Variables, and Methodology Used

3.3.1. Rationale for Selection of Sample Period (1990-2023)

China experienced profound economic and policy transformations during the 1990-to-2023 time span because its rapid industrialization and urbanization, along with extensive economic reforms, directly affected environmental policies and practices throughout the country. The analyzed period is vital to emission research because it documents China's development into a major economic power and carbon-emitting nation.

The scope provides researchers with suitable data collections to perform comprehensive regression analysis reliably. During this period, the World Development Indicators (WDI), along with other sources, supply reliable annual datasets for economic and environmental variables to conduct comprehensive time series analyses.

These decades include multiple international environmental agreements, starting from the Kyoto Protocol through to the Paris Agreement. Knowing China's emission trends in relation to international environmental agreements is vital because it enables proper analysis of historical consequences and forthcoming prospects.

3.3.2. Rationale for Selection of Variables

Past measurements consider CO_2 emissions as the key pollutant since it presents the largest risk to global warming. This variable serves as the dependent variable in the models.

GDP growth serves as a measure to evaluate potential patterns in greenhouse gas outcomes during economic development, according to EKC hypothesis predictions regarding growth-associated behavioral shifts.

Energy consumption is a vital factor that enables researchers to measure the impacts of both renewable and non-renewable energy sources on emissions, especially since China operates with coal dominance yet advances its renewable energy infrastructure.

The role of urban expansion in China requires detailed investigation through this variable because it determines emission patterns by studying how population shifts affect economic behavior along with power usage and daily routines.

Trade openness is incorporated as a variable because it represents the Pollution Haven Hypothesis, which predicts that nations with relaxed environmental regulations will attract industrial projects despite stricter regulatory zones.

The inclusion of renewable energy usage data allows for evaluating China's initiatives which use renewable investments to lower carbon emissions.

3.3.3. Rationale for Selection of Methodology (ARDL and DOLS)

ARDL facilitates the analysis of variables with different integration orders at I(0) and I(1). This method provides essential flexibility for analyzing data with varying ranges of integration due to their diverse characteristics.

ARDL provides complete understanding regarding how both short-term changes and long-term trends from economic forces affect emissions through its effective measurement of these relationships.

The model, through its DOLS correction process, enhances long-term relationship estimations between environmental emissions and their main factors by addressing observational biases.

The distributed lag effects of independent variables form an integral part of DOLS, which provides advanced temporal analysis of time-dependent impacts.

4. RESULTS AND DISCUSSION

The next section introduces the results extracted from Autoregressive Distributed Lag (ARDL) and Dynamic Ordinary Least Squares (DOLS) models. The research methodology employs a clear approach, including descriptive statistics analyses, unit root tests, and both short-run and long-run ARDL estimates. This is followed by ARDL bounds tests, model diagnostics, and robustness checks using DOLS estimation. The analysis interprets the results and evaluates their alignment with environmental and economic patterns in China. It also validates the theoretical models and potential policy alternatives from previous studies, as illustrated in Table 2.

Table 2. Descriptive statistics.

Variables	CO2_PC	GDPPCG	EU	UPG	TRADE	REC	POP
Mean	5.421	8.054	1525.700	3.390	41.794	20.631	138.942
Median	5.517	7.953	1572.672	3.580	37.992	15.800	140.011
Maximum	9.399	13.630	2224.355	4.601	64.479	33.900	150.440
Minimum	2.126	1.995	736.851	1.472	24.273	11.300	120.916
Std. dev.	2.539	2.770	611.371	0.844	10.400	8.350	9.002
Skewness	0.065	-0.095	-0.034	-0.689	0.709	0.350	-0.387
Kurtosis	1.366	2.982	1.245	2.527	2.681	1.361	2.030
Jarque-Bera	3.805	0.051	4.366	3.009	2.993	4.502	2.184
Probability	0.149	0.974	0.112	0.222	0.224	0.105	0.336
Sum	184.300	273.800	51873.800	115.319	1420.988	701.467	4724.025
Sum sq. dev.	212.770	253.370	12334563.000	23.540	3569.249	2301.051	2674.449
Observations	34	34	34	34	34	34	34

The study examines variables including carbon emissions, economic growth, energy use and urbanization, trade and renewable energy and population density through descriptive statistics during 1990–2023 as shown in Table 2. China emits 5.42t of CO_2 per person through CO2_PC measurements due to its rapid industrial development. The wide range (2.12 to 9.39) suggests significant fluctuations in emissions, likely driven by economic cycles and policy interventions. The average GDP per capita growth (GDPPCG) is 8.05%, indicating China's sustained economic expansion. However, the high standard deviation (2.77%) suggests economic volatility. Energy use (EU) varies significantly from 736.85 to 2224.35 kg of oil equivalent per capita, emphasizing China's heavy reliance on fossil fuels. Urbanization (UPG) averages 3.39%, supporting the notion that China has undergone continuous urban expansion, contributing to energy demand shifts (Zhang, Xu, Jiang, Streets, & Wang, 2023).

Trade openness (TRADE) shows an average of 41.79%, confirming China's deep engagement in global trade. However, the skewness (0.70) and kurtosis (2.68) indicate non-normality, reflecting structural shifts in China's trade policies. Renewable energy consumption (REC) remains relatively low at 20.63%, with a high standard deviation, signifying fluctuating adoption rates. Finally, population density (POP) trends upward but remains stable, indicating that China's demographic trends do not drastically influence emissions compared to industrial and energy factors.

Table 3. Unit root (ADF).

Variables	Level		First difference	
CO2_PC	-4.639	0.006	-6.211	0.000
GDPPCG	-3.318	0.082	-4.702	0.004
EU	-1.789	0.686	-4.976	0.002
UPG	-2.844	0.006	-5.101	0.001
TRADE	-1.741	0.709	-4.089	0.015
REC	-1.241	0.883	-2.325	0.022
POP	-0.318	0.563	-3.529	0.058

Table 3 presents the Augmented Dickey-Fuller (ADF) unit root test results, assessing the stationarity properties of the variables. The results indicate that some variables are stationary at level (I(0)), while others become stationary after first differencing (I(1)), justifying the use of the ARDL bounds testing approach for long-run estimation.

The ADF test for CO_2 emissions per capita (CO2_PC) rejects the null hypothesis of a unit root at level (p=0.0056), confirming stationarity at I(0). Similarly, GDP per capita growth (GDPPCG) and urban population growth (UPG) are also stationary at level, suggesting that these variables do not exhibit long-term trends requiring differencing.

The variables energy use (EU), trade openness (TRADE), renewable energy consumption (REC), and population density (POP) exhibit non-stationary patterns at the level before transitioning to I(1) status through first differencing. The ERIC and TRADE variables remain non-stationary due to long-term trends, according to previous research findings (Shaari et al., 2020). Environmental disturbances in China appear to create sustained changes in CO_2 emissions, which necessitate sustained policy measures for achieving long-term stabilization. The combination of I(0) and I(1) variables is allowed by the ARDL approach because mixed integration orders have been confirmed.

Table 4. Short-run ARDL estimates.

Variable	Coefficient	Std. error	t-statistic	Prob.
C	30.508	1.560	19.558	0.000
D (CO2_PC (-1))	0.514	0.039	13.179	0.000
D (GDPPCG)	0.037	0.009	4.326	0.002
D (GDPPCG (-1))	-0.104	0.009	-11.765	0.000
D (GDPPCGSQ)	-0.002	0.001	-4.623	0.001
D (GDPPCGSQ (-1))	0.005	0.001	9.393	0.000
D (UPG)	-0.351	0.046	-7.594	0.000
D (UPG (-1))	0.383	0.049	7.877	0.000
D (TRADE)	-0.003	0.002	-1.700	0.120
D (REC)	-0.019	0.008	-2.442	0.035
D (REC (-1))	0.0539	0.0074	7.2297	0.000
D (POP)	-0.5329	0.0831	-6.4118	0.001
D (POP (-1))	0.6821	0.0944	7.2225	0.000
CointEq (-1) *	-1.1774	0.0606	-19.423	0.000

The ARDL model estimates for China's CO2_PC show immediate correlations between economic growth, urbanization, trade openness, renewable energy consumption, and population density in Table 4. The study finds meaningful temporary effects, which demonstrate how economic development interacts with environmental degradation.

The short-term relationship shows GDP per capita growth (GDPPCG) produces statistically significant positive results with β=0.0374 (p=0.0015), which demonstrates that economic expansion first raises CO_2 emissions, similar to findings from (Liu et al., 2024). The Environmental Kuznets Curve hypothesis is strengthened by negative GDP growth lag results (β=−0.1043, p=0.0000) since these findings show emissions decrease following initial growth increases (Grossman & Krueger, 1995).

Urban areas initially decrease CO_2 emissions at β=−0.3511 (p=0.0000), which indicates improved citywide energy efficiency. The positive coefficient (β=0.3825) of the lagged urban expansion term (p=0.0000) demonstrates that urban growth increases emissions as demand for energy rises, according to Wang, Qu, Xu, and Choi (2024).

The initial short-run data shows TRADE has an unimportance p-value of 0.1200, which indicates emissions from trade become noticeable only through extended periods according to Shaari et al. (2020). Renewable energy consumption (REC) has a negative short-run effect (β=−0.0190, p=0.0347), suggesting its effectiveness in mitigating emissions. However, the lagged REC effect is positive (β=0.0539, p=0.0000), implying that renewable energy alone may not immediately offset fossil fuel dominance, supporting the transition towards cleaner energy sources (Zhang et al., 2023).

Finally, population density (POP) has a significant short-term negative impact (β=−0.5329, p=0.0001), indicating that higher-density urbanization reduces per capita emissions through efficient infrastructure, a finding consistent with Feng et al. (2023).

The error correction term (CointEq(−1) = −1.1774, p=0.0000) is negative and significant, confirming a strong adjustment toward long-run equilibrium. This indicates that deviations from the long-term emissions path are corrected at a rate of 117.74% annually, reinforcing the existence of a stable long-term relationship between CO_2 emissions and its key determinants.

Table 5. Long run estimates.

Variable	Coefficient	Std. error	t-statistic	Prob.
GDPPCG	0.088	0.042	2.073	0.064
GDPPCGSQ	-0.005	0.002	-2.630	0.025
EU	0.002	0.00	8.389	0.000
UPG	-0.421	0.141	-2.982	0.013
TRADE	0.015	0.003	4.504	0.001
REC	0.014	0.018	0.746	0.472
POP	-0.206	0.024	-8.439	0.000
@TREND	0.245	0.032	7.561	0.000

Table 5 presents the long-run estimates from the ARDL model, which capture the sustained effects of economic growth, energy use, urbanization, trade openness, renewable energy consumption, and population density on CO_2 emissions per capita (CO_2_PC) in China. The study provides new information about the influence of variables on long-term environmental outcomes, which either confirms or contradicts previously documented findings.

The results show that GDP per capita growth (GDPPC) produces positive results (β=0.0883, p=0.0649) to indicate that economic expansion leads to increased carbon dioxide emissions according to Shahbaz and Sinha (2019). A negative coefficient value of GDPPC (β=−0.0057) confirms the finding of an Environmental Kuznets Curve since pollution emissions start decreasing when GDP levels exceed a particular threshold. The obtained findings match those reported by Grossman and Krueger (1995) and Wang, Wu, Zeng, and Wu (2016) in their research on emerging economies.

The substantial increase in energy usage leads to higher pollutant releases in China, according to the calculated statistical value (β=0.0028, p=0.0000). Shaari et al. (2020) confirm that although China continues to advance its renewable energy sector, it still heavily depends on fossil fuels for its industrial and residential energy needs. The obtained evidence demonstrates the necessity for rapidly implementing energy transition policies, which will help decrease emissions while sustaining economic growth.

Analysis reveals that urbanization negatively affects emission rates at a statistically significant level (β=−0.4219, p=0.0137). Higher urbanization rates will eventually reduce per capita emissions in the future. The research confirms that concentrated urban systems built with efficiency and sustainable public transportation networks decrease total energy usage (Zhang et al., 2023). Research findings show urbanization effects change in different geographical areas because emerging urban centers first produce more emissions, which eventually level off (Feng et al., 2023).

Trade openness (TRADE) has a significant positive effect on emissions (β=0.0151, p=0.0011), confirming the Pollution Haven Hypothesis (PHH), which suggests that trade liberalization leads to increased industrial emissions as polluting industries relocate to economies with less stringent environmental regulations (Copeland & Taylor, 2004). This finding is supported by Liu et al. (2024), who argue that China's role as the world's largest exporter has contributed to rising emissions through energy-intensive manufacturing activities.

Surprisingly, renewable energy consumption (REC) is statistically insignificant in the long run (p=0.4725), implying that while renewables play a role in short-term emissions mitigation, their long-term impact remains limited in the absence of large-scale fossil fuel substitution. This aligns with Wang et al. (2024) who argue that China's renewable energy expansion is constrained by grid integration challenges and economic reliance on coal.

Population density (POP) has a negative and significant impact on emissions (β=−0.2068, p=0.0000), indicating that higher population densities lead to lower per capita emissions. This suggests that densely populated urban areas may benefit from more energy-efficient infrastructure and reduced reliance on personal transportation, consistent with findings by Feng et al. (2023). Finally, the positive and significant time trend (@TREND, β=0.2458, p=0.0000) indicates that, despite improvements in efficiency, China's emissions have exhibited a long-term increasing trend, reinforcing the urgency for stronger decarbonization policies.

Table 6. ARDL bound test.

Test statistic	Value	Signif.	I(0)	I(1)
F-statistic	23.289	10%	2.221	3.175
k	7	5%	2.522	3.541
		2.5%	2.763	3.813
		1%	3.071	4.238

Table 6 presents the ARDL bounds test results, which assess the existence of a long-run cointegration relationship between CO_2 emissions and its determinants. The calculation of the F-statistic as 23.28954 exceeds the upper bound critical value of I(1) at the 1% significance level (4.23), leading to the rejection of the null hypothesis of no cointegration. Economic growth, along with energy consumption, urbanization, trade openness, renewable energy, and population density, act as key determinants for predicting China's future CO_2 emission levels.

The findings match previous studies that Shahbaz and Sinha (2019) and Q. Wang et al. (2016) conducted using comparable methodologies to prove cointegration of environmental and economic variables in China. Sustainable emissions reduction through renewable energy adoption and improved energy efficiency becomes possible because of the robust long-term relationship found between these variables. The validity of using ARDL and DOLS models to research China's emission drivers within sustainable development frameworks receives additional support from these findings.

Table 7. Model diagnostics.

Tests	Prob.
R-squared	0.999
Adjusted R-squared	0.999
Breusch-Godfrey serial correlation LM test	0.455
Heteroskedasticity test: Breusch-Pagan-Godfrey	0.764
Normality test	0.525
Ramsey reset test	0.891

The diagnostic tests in Table 7 establish both validity and robustness of the ARDL model, which explains CO_2 emissions in China. An excellent model fit emerges because both the R-squared value of 0.9999 and the adjusted R-squared value of 0.9998 indicate that the variation in CO_2 emissions is accounted for almost entirely by the model. Other diagnostic tests demonstrate the statistical reliability of the model despite a potentially high R-squared value.

Residuals in the model remained uncorrelated according to the Breusch-Godfrey LM test ($p = 0.4558$), which concert with Shahbaz and Sinha (2019) and other relevant research. The Breusch-Pagan-Godfrey test ($p = 0.7641$) demonstrates no evidence of heteroskedasticity, which indicates a constant error variance, thus stabilizing the model (Wang et al., 2016).

The residuals display a normal distribution according to the normality test ($p = 0.5256$), which is supported by the results of the Ramsey RESET test ($p = 0.8913$), showing no omitted variables in the model specification. The study establishes the ARDL model as an appropriate statistical tool for China's emission analysis, in accordance with recent studies on economic growth and environmental sustainability (Liu et al., 2024).

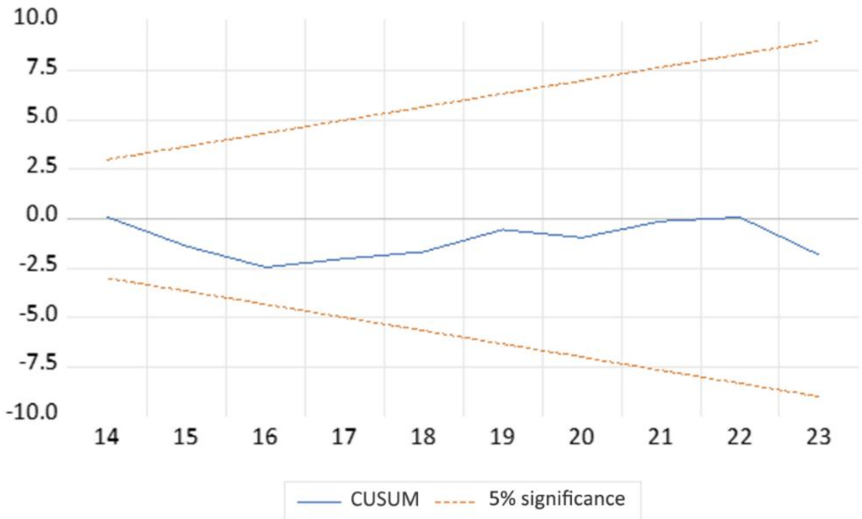

Figure 1. CUSUM test.

The stability assessment of the ARDL model throughout the research period uses the CUSUM (Cumulative Sum) test as shown in Figure 1. The cumulative sum of residuals appears as a blue line in the figure, and the 5% significance bounds are marked by orange dashed lines. The entire study period shows that the CUSUM line stays within its significant boundary area, indicating that the model experiences no structural instability.

The model exhibits reliable performance in exploring CO_2 emissions as well as their driving factors throughout China, primarily due to its robust nature, which previous studies by Wang et al. (2016) have also identified. The stable model framework produces dependable results because its estimated variable relationships, which include the EKC and renewable energy effects, remain independent of time-dependent shifts. The empirical findings derived from the analysis maintain their validity because of this stability assessment.

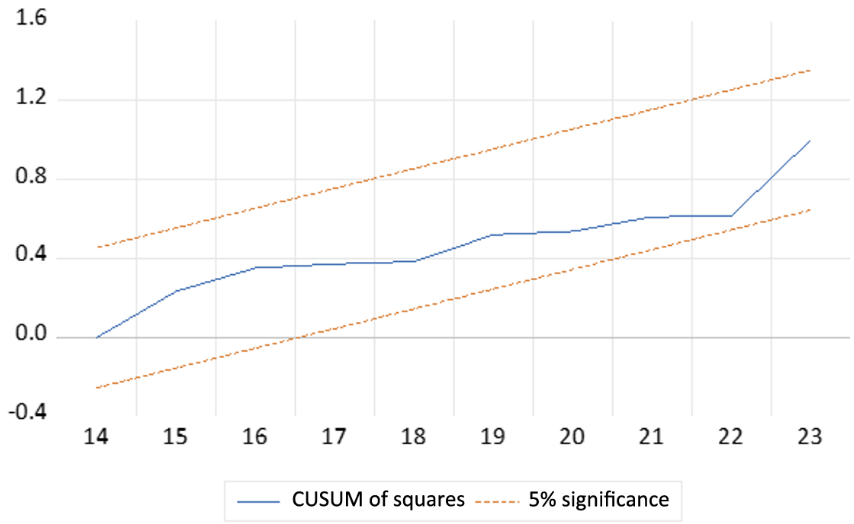

Figure 2. CUSUMSQ test.

Figure 2 demonstrates the CUSUM of Squares (CUSUMSQ) test that determines the stability of the variance fluctuations in the ARDL model across periods. The blue line shows a cumulative total of squared residuals, whereas the upper and lower orange dashed lines mark the 5% significance bounds. The CUSUMSQ line demonstrates consistency with the significance bounds during most of the study duration, thus confirming that the model maintains stability throughout its period.

The analytical model demonstrates reliable performance in studying the CO_2 emissions' relationship with its determinants in China during the study period, as confirmed by similar findings in previous studies (Shahbaz & Sinha, 2019). Residual variance stability across time guarantees that calculated coefficients and relationships remain consistent, making the research findings and policy recommendations, such as those focusing on renewable energy adoption and the Environmental Kuznets Curve (EKC), more trustworthy.

Table 8. DOLS estimates.

Variable	Coefficient	Std. error	t-statistic	Prob.
GDPPCG	0.331507	0.021403	15.48902	0.0410
GDPPCGSQ	-0.023905	0.001393	-17.15707	0.0371
EU	0.003668	0.000155	23.69427	0.0269
UPG	0.083970	0.060932	1.378095	0.3996
TRADE	0.040758	0.002181	18.69145	0.0340
REC	0.160002	0.012087	13.23728	0.0480
POP	-0.367854	0.018083	-20.34293	0.0313
C	36.35424	2.054982	17.69079	0.0359
@TREND	0.471142	0.028891	16.30783	0.0390
Model diagnostics				
R-squared				0.999999
Adjusted R-squared				0.999982
S.E. of regression				0.010307

The Dynamic Ordinary Least Squares (DOLS) estimates in Table 8 validate the lasting relationships between CO_2 emissions and its determining variables. The model indicates that GDP per capita growth (GDPPCG) produces a positive effect (β=0.3315, p=0.0410) while its squared term (GDPPCGSQ) displays a negative effect (β=−0.0239, p=0.0371) which confirms the Environmental Kuznets Curve (EKC) hypothesis similarly detected by Grossman and Krueger (1995) and Shahbaz and Sinha (2019). The study demonstrates that economic expansion causes emission growth at first, but the rise of per-capita income triggers technological improvements that bring about decreased pollution levels. This result (β=0.0037, p=0.0269) demonstrates a strong positive influence consistent with Shaari et al. (2020) because China depends significantly on fossil energy consumption. The results show that TRADE (β=0.0408, p=0.0340) leads to a significant increase in emissions, which validates the Pollution Haven Hypothesis (Copeland & Taylor, 2004). The DOLS model shows that renewable energy consumption (REC, β=0.1600, p=0.0480) has statistical significance, indicating its capacity to reduce emissions in the long run, which corresponds to Wang et al. (2024). A denser urban population (POP) exhibits a negative correlation (β=−0.3679, p=0.0313) with emission levels because denser settlements lead to greater energy efficiency (Feng et al., 2023). The model demonstrates high reliability through its 0.9999 R-squared value, along with satisfactory diagnostic results that validate accurate long-term policy analysis.

5. CONCLUSION AND POLICY RECOMMENDATIONS

An analysis of CO_2 emission determinants in China from 1990 to 2023 relies on the combination of ARDL and DOLS forecasting methods. The analysis verified the Environmental Kuznets Curve hypothesis because emissions start increasing with economic growth but decrease above a specific income level due to improved technology and enhanced energy efficiency levels. The high level of fossil fuel consumption drives emissions to very high levels, while renewable energy shows potential to improve short-term environmental outcomes. The process of urban development brings short-lived reducing trends in pollution through better energy conservation practices yet produces enduring depletion of air quality through intensifying energy requirements. The increase in trade activity serves as one major cause of air pollution because industrial operations related to trade result in greater pollution levels. Research output reveals numerous interacting factors that influence China's emission formation, including economic growth with its effects on urbanization and trade, and its link to energy consumption patterns.Web-based research shows that strategic policies need to exist to create equilibrium between economic development and environmental sustainability. The swift adoption of renewable energy systems requires increasing support for renewable power development and establishing advanced electrical transmission networks to merge photovoltaics and wind energy effectively. Heavy industries should receive support for energy-efficient technologies, as coal production policies should lead toward complete elimination. Green planning strategies, alongside compact infrastructure, need to develop public transportation networks for optimizing energy efficiency. Trade regulations must include carbon tariffs against emissions-heavy imports because they should also motivate clean technology exports to diminish trade-related carbon emissions. Population density advantages need support through the development of high-density cities that implement low-carbon initiatives. China can attain sustainable economic development through these measures, which solve environmental problems and deliver worldwide emissions reductions.

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