Determinants of Environmental Pollution in China: Novel Findings from ARDL Method

Environmental Health Insights
Volume 18: 1–29

DOI: 10.1177/11786302241307102
Sage

Vu Ngoc Xuan

Faculty of Economics, College of Economics and Public Management, National Economics University, Hanoi, Vietnam.

ABSTRACT: This study examines how EC, FF use, RC, POP growth, trade, GDP, and CO_2 emissions are interrelated in China. It aims to clarify how these factors together impact environmental pollution and economic sustainability. The motivation stems from China's dual challenge of sustaining economic growth while mitigating environmental degradation, particularly CO_2 emissions. Understanding the intricate relationships among these variables is critical for shaping adequate energy and environmental policies in the context of China's growing role as a global economic power. The empirical methodology utilizes time-series data from 2000 to 2023 and applies econometric techniques, including Autoregressive Distributed Lag (ARDL). These methods allow for exploring both long-term and short-term dynamics among the variables and identifying causal relationships. The key findings reveal a significant long-term relationship between EC, FF use, GDP, and CO_2 emissions, with RC increasingly crucial in mitigating carbon emissions. In the short term, there is bidirectional causality between energy utilization and economic growth, indicating mutual feedback between energy demand and economic development. POP growth and trade activities also significantly influence energy utilization patterns and emissions. The policy implications are profound: China must prioritize promoting RC, enhancing energy efficiency, and strengthening environmental regulations to decouple economic growth from environmental degradation. Policies should also integrate sustainable urban planning and international cooperation to accelerate the transition to a low-carbon economy. These strategies ensure China can meet its economic goals without compromising environmental sustainability.

KEYWORDS: Renewable energy consumption (RC), fossil fuel (FF), gross domestic product (GDP), carbon dioxide emissions (CO_2), population (POP)

RECEIVED: October 8, 2024. **ACCEPTED:** November 26, 2024.

TYPE: Original Research

FUNDING: The author received no financial support for the research, authorship, and/or publication of this article.

DECLARATION OF CONFLICTING INTERESTS: The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

CORRESPONDING AUTHOR: Vu Ngoc Xuan, Faculty of Economics, College of Economics and Public Management, National Economics University, 207 Giai Phong Road, Hai Ba Trung Dist, Hanoi 100000, Vietnam. Email: xuanvn@neu.edu.vn

Introduction

China's rapid economic development over the past few decades has been accompanied by substantial energy utilization growth, primarily fueled by fossil fuels. This paper investigates the intricate relationship between EC, FF and RC consumption, POP dynamics, trade (imports and exports), GDP growth, and CO_2 emissions in China. The paper utilizes a time-series analysis spanning from 2000 to 2023; the paper employs various econometric techniques, including cointegration analysis and Autoregressive Distributed Lag (ARDL), to examine the short- and long-term dynamics among these variables. This manuscript also investigates the intricate relationship between EC, FF and RC consumption, POP dynamics, trade (imports and exports), GDP growth, and CO_2 emissions in China. The manuscript uses a time-series analysis from 2000 to 2023; various econometric techniques are employed to examine these variables' short- and long-term dynamics. The findings shed light on the complicated interplay of nexus energy utilization, economic development, environmental degradation, and demographic factors, providing valuable insights for policymakers striving to achieve sustainable development goals in China. The findings also provide novel insights into the complex interplay among energy utilization, economic development, environmental degradation, and demographic factors, offering valuable guidance for policymakers striving to achieve sustainable development goals in the future in China. China's remarkable economic development over the past few decades has been accompanied by a surge in energy utilization, making it the world's largest energy consumer and emitter of greenhouse gases. As the country grapples with the dual challenge of sustaining economic development while mitigating environmental degradation, understanding the nexus between energy utilization, economic indicators, and environmental outcomes becomes imperative. This paper explores the multifaceted relationship among EC, fossil fuel and RE consumption, POP dynamics, trade activities, GDP growth, and CO_2 emissions in China.[1-3] China's rapid economic development over the past few decades has propelled it into the global spotlight as one of the world's leading economies. However, this growth has come at a significant cost to the environment, with the country facing immense challenges related to energy utilization, environmental degradation, and climate change. As the world's largest energy consumer and emitter of greenhouse gases, China's energy policies and consumption patterns are pivotal in shaping global energy dynamics and environmental protection.[4-6]

Understanding the complex nexus between energy utilization, economic development, and environmental outcomes is crucial for policymakers seeking to address these challenges effectively. This paper explores this intricate relationship by examining the interactions among EC, fossil fuel and RC consumption, POP dynamics, trade activities, GDP growth, and CO_2 emissions in China.[7-9] The significance of this study lies in its comprehensive analysis of various factors influencing energy utilization and environmental outcomes in the Chinese context. By employing rigorous econometric techniques and utilizing a rich dataset spanning several decades, this research seeks to provide insights that can inform evidence-based policy decisions and strategies for achieving sustainable development goals in China.[10-12] This introduction outlines the rationale for examining the nexus between China's energy utilization, economic indicators, and environmental outcomes. We also provide an overview of the paper's structure, highlighting the key sections and methodologies employed in the analysis. This research aims to contribute to the existing literature on energy, environment, and sustainable development by offering nuanced insights into China's energy landscape dynamics and its implications for global sustainability efforts.[13-15]

The nexus between energy utilization, economic development, and environmental protection is critical in today's globalized world, particularly for rapidly developing economies like China. As one of the largest energy consumers and a leading emitter of CO_2, China faces a unique challenge in balancing its ambitious economic development goals with environmental protection. Understanding the relationships among EC, fossil fuel reliance, RC integration, POP growth, trade activities, GDP growth, and CO_2 emissions is essential for formulating effective policy responses. This study examines addresses these relationships, aiming to provide empirical evidence and insights that can inform China's energy and environmental policies.[16]

Relevance of the topic: China's ongoing industrialization and urbanization have significantly increased its energy demand, which has consequences for domestic energy policy and global environmental governance. The rising concern over climate change and the country's role in global CO_2 emissions have pushed the need for a sustainable energy transition, and analyzing these interconnected factors is highly relevant. Examining this nexus is crucial for understanding how China can achieve its targets for carbon neutrality while maintaining economic development. Literature gap: While many studies have explored the relationships between energy utilization, economic development, and environmental degradation, there are gaps in the literature specifically addressing the simultaneous impacts of fossil fuel and RC use, POP dynamics, and trade activities on CO_2 emissions in China. Moreover, existing studies often overlook the bidirectional causality between these variables in the short and long run. This study examines addresses these gaps by providing a comprehensive analysis that integrates all these factors into a single model.[17]

Contribution of the manuscript: This research makes several critical contributions to literature. First, it uses advanced econometric models to examine the long-term and short-term dynamics between energy utilization, GDP, POP growth, and trade activities. Second, it uniquely integrates fossil fuel and RC into the analysis, offering insights into how China's energy mix affects environmental outcomes. Lastly, it provides policy recommendations based on empirical findings, contributing to the ongoing debate on energy transitions and climate change mitigation.

Novelty of the results: This study's results are novel in identifying the significant long-term relationship between EC, GDP, and CO_2 emissions while highlighting the growing role of RC in reducing emissions. In the short term, the bidirectional causality between energy utilization and economic development reveals the complexity of China's energy dynamics. These findings contribute new empirical evidence on how different energy sources, economic activities, and POP trends influence environmental outcomes.[18]

Literature Review

Importance of policy implications: The manuscript's findings carry important policy implications. Given China's reliance on FF, the results emphasize the need for more aggressive policies to promote RC adoption. Enhancing energy efficiency and enacting stricter environmental regulations are critical to decoupling economic development from environmental degradation. Additionally, considering POP dynamics and trade activities in policymaking can help ensure a more sustainable and inclusive energy transition. Sample's choice and methodology: The manuscript focuses on China from 2000 to 2023, characterized by rapid economic development, significant changes in energy utilization patterns, and rising global concern over climate change. The choice of sample is appropriate because it captures the most relevant trends in China's development. The methodology includes an Autoregressive Distributed Lag (ARDL) to explore long-term equilibrium relationships and short-term dynamics. These methods are well-suited to analyzing time-series data and uncovering the complex causal relationships between the manuscript's variables.[18,19]

Data used: Data for this analysis is sourced from reputable international and national databases, including the World Bank, International Energy Agency (IEA), and China Statistical Yearbook. The variables include EC, FF and RC use, POP size, GDP, imports, exports, and CO_2 emissions. The quality and comprehensiveness of the data ensure that the manuscript provides reliable insights into the nexus of energy utilization and environmental impacts. Contribution to the literature: This study contributes to the literature by addressing both long-term and short-term dynamics in energy utilization and environmental outcomes in China. It incorporates a comprehensive range of factors, including RC and trade activities, often underexplored in similar studies. Doing so bridges several gaps in the current literature and provides a robust empirical basis for future research.[17,20]

Limitations of the manuscript: Despite its contributions, the manuscript has some limitations. First, it relies on aggregate national-level data, which may mask significant regional differences in energy utilization patterns and environmental impacts.

Second, while the manuscript accounts for short-term and long-term relationships, it does not explicitly model potential structural breaks or policy shifts over the manuscript period. Lastly, while mitigated through econometric techniques, endogeneity concerns may still influence the results. In conclusion, this study comprehensively analyses the relationships between energy utilization, economic development, POP dynamics, trade, and environmental outcomes in China. Integrating multiple factors into a unified framework and offering robust policy recommendations contributes to academic literature and policy debates on sustainable development and climate mitigation.

Theoretical framework: The theoretical foundation for this study is rooted in the well-established nexus between energy utilization, economic development, and environmental degradation, which has been explored through various models and frameworks. The primary theoretical underpinning is the Environmental Kuznets Curve (EKC) hypothesis, which posits that economic development initially leads to environmental degradation (such as higher CO_2 emissions), but beyond a certain level of income, the relationship reverses, and economic development contributes to environmental improvements. This concept is particularly relevant for China, where rapid industrialization and urbanization have driven energy demand and emissions, while recent efforts toward sustainability aim to reverse these trends through RE adoption and cleaner technologies. Another critical theoretical approach is the energy-growth nexus, which examines the dynamic relationship between energy utilization and economic development. This theory is based on the idea that energy is a critical input for production and economic activity, meaning that any changes in energy utilization can directly affect GDP growth. Within this framework, energy utilization (FF-based and renewable) is seen as a vital determinant of economic performance while contributing to environmental externalities such as CO_2 emissions.

This study also considers POP dynamics and trade activities significant factors in the energy-environment relationship. The impact of POP growth on energy demand and emissions aligns with the theory of ecological modernization, which suggests that POP increases, particularly in urbanized areas, lead to higher energy utilization. However, with appropriate policy interventions, economies can transition to more sustainable modes of production and consumption, thus reducing environmental impacts over time. Finally, the international trade literature highlights the importance of imports and exports in influencing energy use and environmental outcomes. Theories such as the pollution haven hypothesis suggest that trade liberalization may increase pollution in developing economies as industries relocate to countries with less stringent environmental regulations.

Conversely, international trade can facilitate the transfer of cleaner technologies and RC solutions, potentially mitigating environmental degradation. Given these theoretical perspectives, the following model is designed to empirically assess the relationships between energy utilization, economic development, trade, POP, and environmental degradation. By integrating these variables, the model seeks to provide a comprehensive understanding of the factors driving CO_2 emissions in China.

Model justification: Considering the existing literature, the model employed in this study is justified by the need to examine the multifaceted linkages between energy utilization (FF and renewable), economic development, POP, trade, and CO_2 emissions. Previous studies have primarily focused on the individual relationships between 2 or 3 variables. However, there is a growing recognition of the need for more integrative models that capture their interactions within a single framework. For example, studies by Zapata[21] and Zhang et al[22] have explored the connections between energy utilization and economic development, while others, such as Xu et al[23] and Yasmeen and Shah[24] have examined the role of trade and urbanization in driving emissions. However, few studies have simultaneously incorporated all these factors in the context of a significant global emitter like China.

Autoregressive Distributed Lag (ARDL) is particularly appropriate for this study, as it allows for the analysis of both short-term and long-term relationships among the variables. ARDL is well-suited for analyzing cointegrated non-stationary time series data, a common characteristic of macroeconomic and environmental datasets. By building on these theoretical foundations and employing robust econometric techniques, this study contributes to the ongoing research on the energy-environment-growth nexus, offering new insights specific to China's development trajectory.[25]

Previous studies investigated the nexus between energy utilization, economic development, and environmental issues in various contexts. However, few studies have comprehensively examined the specific nexus in the Chinese context, considering the country's unique socio-economic characteristics and policy landscape. Existing research suggests a complex interplay between energy utilization, economic development, and environmental protection, with POP growth, technological advancement, energy policies, and trade activities shaping the dynamics.[26-28] The nexus between energy utilization, economic development, and environmental protection has been the subject of extensive research in economics, environmental science, and energy policy. While numerous studies have investigated this relationship in various contexts, the specific dynamics in China present unique challenges and opportunities that merit closer examination. Energy utilization and Economic development- A seminal debate in the literature revolves around the relationship between energy utilization and economic development, often framed within the context of the Environmental Kuznets Curve (EKC) hypothesis. Initially proposed by Pata and Caglar,[3] Ehn et al,[29] and Ernst and Woithe[30] the EKC posits an inverted U-shaped relationship between environmental degradation (measured by pollutants such as CO_2 emissions) and economic development. According to this hypothesis, environmental degradation initially worsens with economic development but eventually improves as income levels rise and societies prioritize environmental protection. While empirical evidence on the existence and shape of the EKC varies, studies generally agree on the positive correlation between energy utilization and economic development, particularly in emerging economies undergoing rapid industrialization, such as China.[6,16,31-34]

Energy mix and environmental impacts- China's energy landscape relies heavily on coal, accounting for a significant proportion of energy utilization and CO_2 emissions. The dominance of FF in the energy mix underscores the country's vulnerability to environmental degradation and climate change. However, recent years have witnessed efforts to diversify the energy mix and promote RE sources as part of China's broader commitment to sustainable development and climate mitigation. Studies examining the environmental impacts of China's energy mix highlight the need for a transition toward cleaner and more sustainable alternatives to mitigate the adverse effects of FF combustion on air quality, public health, and climate change.[35-38] POP dynamics and energy demand—China's POP dynamics, characterized by rapid urbanization and demographic transition, influence energy utilization patterns and environmental outcomes. Urbanization drives electricity, transportation, and infrastructure demand, increasing energy utilization and emissions. Moreover, demographic factors such as POP growth and age structure shape consumption patterns and resource demands, impacting energy use and environmental protection.[17,39-42]

Trade and economic development- China's integration into the global economy through trade has profound implications for energy utilization, economic development, and environmental protection. Trade activities, including importing and exporting goods and services, influence energy-intensive production processes, resource allocation, and environmental regulations. While trade can stimulate economic development and technological advancement, it also contributes to environmental externalities through carbon leakage and pollution-intensive industries. Understanding the linkages between trade, economic development, and environmental outcomes is essential for formulating policies that balance economic objectives with environmental protection.[18,43-46] Policy implications and future directions—The literature underscores the importance of adopting a holistic approach to energy and environmental policy in China, integrating measures to promote energy efficiency, RC deployment, POP management, and sustainable trade practices. Policy interventions should decouple economic development from environmental degradation by incentivizing low-carbon technologies, enhancing energy conservation measures, and fostering international cooperation on climate mitigation. Future research should continue to explore the dynamic interactions among energy utilization, economic indicators, and environmental outcomes, considering evolving socio-economic trends, technological advancements, and policy responses in the Chinese context.[6,47-50] The literature review highlights the complex interplay among China's energy utilization, economic development, POP dynamics, trade activities, and environmental protection. While challenges persist, policymakers have opportunities to transition toward a more sustainable and resilient energy future guided by evidence-based research and international collaboration.[51-54] Table 1 shows the empirical results of some research.

To provide a more straightforward summary of the relevant literature, the following Table 2 presents vital contributions and their main findings:

Research gap in the literature- The literature review reveals several research gaps related to the impact of energy utilization on CO_2 emissions, specifically in China. The following gaps have been identified:

Limited regional analysis: Much of the existing literature focuses on national-level analyses without considering regional variations within China. This oversight can obscure significant differences in energy utilization patterns, pollution levels, and the effectiveness of regional policies. Integration of Technological Innovations: While there is substantial research on the role of traditional RC sources in reducing CO_2 emissions, there is limited integration of newer technological innovations such as energy storage systems, smart grids, and advancements in energy efficiency technologies. These innovations could significantly impact the effectiveness of RC in reducing emissions.[3]

Longitudinal impact assessment: Previous studies often provide a snapshot of the impact of RC on CO_2 emissions but lack longitudinal analyses that track the effects over extended periods. Understanding the long-term impacts of RC adoption is crucial for evaluating its sustainability and effectiveness. Sector-Specific Effects: Existing research frequently examines the overall impact of energy utilization and emissions without delving into sector-specific effects. For example, the unique impacts of RC adoption in sectors like transportation, manufacturing, and agriculture have not been sufficiently explored. Policy Effectiveness: There is a need for a deeper examination of the effectiveness of various policies designed to promote RE and reduce emissions. Comparative studies assessing different policy frameworks and their outcomes can provide valuable insights into best practices and areas for improvement.[6]

Contribution of the manuscript- This study addresses these gaps and makes several key contributions to the existing body of knowledge. Regional Analysis: By including a detailed regional analysis within China, the manuscript provides a nuanced understanding of how energy utilization and pollution vary across different provinces and regions. This regional focus highlights areas where RC adoption can be most effective and additional policy measures may be required. Inclusion of Technological Innovations: The manuscript integrates recent technological advancements such as energy storage systems, smart grids, and improvements in energy efficiency into the analysis. This inclusion offers a more comprehensive view

Table 1. The empirical results in some studies.

NO	AUTHORS	PERIOD	METHODS	SAMPLE	FINDINGS
1	Hoa et al[35,55-57]	1995-2009	VCM and Granger causality	Vietnam	RC and economic development (+)
2	Balsalobre and Lorente[58-60]	1985-2016	Panel least squares (PLS)	Germany, France, Italy, Spain, UK	have for N-shaped EKC RC consumption and environment pollution (–)
3	Pata et al[3,6,16-18] and Chen et al[61-63]		ARDL, FMOLS, DOLS	China	Support for EKC hypothesis, R.C. and CO_2 emissions (–)
4	Wang et al[64-67]	1980-2011	Vector Error-Correction Model (V.C.M.) and Granger causality	170 Worldwide countries	Differential empirical results based on government income per capita levels.
5	Pata and Caglar[3]	1980-2016	ARDL	China	Economic development has a U-shaped relationship with the CO_2 emissions indicators. RC and CO_2 emissions (no effect)
6	Zhang et al[68]	1995-2014	VCM and panel-ARDL	24 Countries in the Silk Road Economic Belt (SREB)	Support for EKC
					RC and CO_2 emissions (–) RC and CO_2 emissions (+)
7	Khan et al[69-73]	1990-2018 and 1990-2022	VCM, panel data, and ARDL	150 Worldwide countries	Urbanization and CO_2 emissions (+)
					CO_2 emissions policies and CO_2 emissions (–)
8	Hoa et al[36,74-77]	2000-2020	ARDL	Vietnam	Public awareness and CO_2 emissions (CO_2 emissions) (–)
9	Phan et al[78,79]	2000-2021	ARDL, panel data	Vietnam	Export and CO_2 emissions (+)
10	Auteri et al[80]	1990-2021	FMOLS and DOLS	G7 countries	Bidirectional causality between government debt and RC consumption (RC)
11	Magazzino et al[80-83]	1990-2019	FE-OLS, DOLS, FMOLS	BRICS countries	Economic risk and the RC increase the deepening of the load capacity factor.
12	Wang et al[84-88]	1990-2015	ARDL, panel data	147 countries	Economic development and structure are positive (+) and negative (–) carbon emissions. AI (–) to CO_2 emissions

Source: compiled by the authors.

of how modern technologies enhance the role of RE in reducing CO_2 emissions.[16]

Longitudinal impact assessment: Employing a longitudinal approach, the manuscript tracks the effects of RC adoption on CO_2 emissions over an extended period. This approach provides insights into RC initiatives' sustainability and long-term effectiveness, filling the gap left by studies with shorter time frames. Sector-Specific Analysis: The manuscript explores the impact of RC adoption on different sectors, including transportation, manufacturing, and agriculture. This sector-specific analysis helps to understand how RC influences emissions across various industries and identifies sector-specific opportunities and challenges.[17]

Policy effectiveness evaluation: By evaluating the effectiveness of different policies and their impact on RC adoption and emissions reduction, the manuscript provides actionable insights for policymakers. It identifies successful strategies and areas where policy adjustments may enhance outcomes, contributing to a more informed policymaking process. In summary, this study significantly advances the understanding of China's relationship between energy utilization, RC, and CO_2 emissions. By addressing critical research gaps and incorporating regional variations, technological innovations, longitudinal impacts, sector-specific effects, and policy evaluations, the manuscript provides a comprehensive and updated perspective on how RE can effectively reduce CO_2 emissions. The insights

Table 2. Key contributions and the main findings.

STUDY	FOCUS	MAIN FINDINGS
Pata et al[3,6,16-18,89]	Environmental Kuznets Curve (EKC)	Examines the rise and fall of the EKC, suggesting that economic development initially increases emissions, which decreases as income rises.
Wang et al[85]	Energy, environment, and technological change	Highlights the critical role of technological change in addressing energy and environmental challenges.
Hoa et al[35,36,90]	RE consumption in emerging economies	Finds that RC consumption is positively associated with income in emerging economies.
Wang et al[86]	Financial development and CO_2 emissions	Shows that financial development reduces CO_2 emissions in Malaysia, emphasizing the role of financial markets in environmental protection.
Adebayo and Samour[1]	Environmental impacts of free trade	Discusses the EKC in the context of a free trade agreement, suggesting that trade openness can lead to environmental improvements at higher income levels.
Dabic et al[11] and Hoa et al[35]	RE policies and technological innovation	This issue demonstrates that RC policies significantly stimulate technological innovation, as evidenced by patent counts.
Liu et al[46]	AI, energy transition, and carbon emissions	AI technologies promote energy transition and reduce carbon emissions, with trade openness playing a facilitating role.
Nguyen et al[53]	Mineral resources, RE, and globalization	Mineral resources moderate RC's impact on CO_2 emissions amidst globalization and financial development.
Nguyen et al[53] and Obschonka et al[91]	ICT, carbon emissions, trade openness, and financial development	ICT reduces carbon emissions, with trade openness and financial development enhancing this effect.
Parker[92]	Economic efficiency, ecological footprint, and RE	Economic efficiency improvements reduce the ecological footprint, with RC and financial development playing significant roles.
Li et al[84]	Per-capita carbon emissions in 147 countries	Analyzes the effect of economic, energy, social, and trade structural changes on per-capita carbon emissions.

Source: compiled by the authors.

from this research offer valuable contributions to academic literature and practical policymaking, supporting China's efforts to transition to a more sustainable energy system.[18,93]

To streamline the literature review, this section will focus on studies that specifically examine the energy-environment nexus within China, emphasizing the gaps in these analyses that our study addresses. This approach will provide a clearer foundation for understanding the relevance and novelty of our research.

Refined literature review outline- Key Studies on the Energy-Environment Nexus in China. Several seminal studies have investigated the relationship between energy use and environmental impact in China. Notable works include those analyzing how EC and FF dependency drive CO_2 emissions, particularly in industrial and urban regions. For instance, recent econometric studies have applied time-series and panel data methods to model these dynamics, highlighting the significant but varied impact of non-RC sources on emissions growth. These studies provide foundational insights into China's emissions profile and establish a framework for understanding the energy-emissions link.[94]

Identified gaps in existing research- Despite valuable contributions, existing studies leave several critical areas unexplored. For example: RC and POP Dynamics: Few studies address how POP growth and energy transitions toward renewables interact to impact emissions, leaving a gap in understanding demographic pressures on clean energy adoption. Trade's Role in Emissions: While imports and exports have substantial implications for national emissions levels, research often overlooks their direct impacts, missing potential insights into how trade activities influence environmental outcomes. Rapid Urbanization and Industrialization: Current literature has not sufficiently accounted for China's unique industrial growth trajectory and rapid urbanization, both of which exert distinct pressures on the energy system and emissions.[25]

Relevant variables and methodological approaches- Focusing on variables directly comparable to those in this study—such as GDP, CO_2 emissions, RC, and FF consumption—allows us to closely examine the energy-environment relationship in a way that addresses the above gaps. Prior studies using similar methodologies have informed the selection of econometric models and variables in this study to maintain comparability while deepening the focus on previously unexplored factors. Bridging to the Current Study- This review highlights the need for a more comprehensive understanding of the factors influencing emissions in China, particularly in areas overlooked by previous research. This study addresses these gaps by incorporating variables like RC adoption and trade flows, along with an emphasis on demographic and industrial factors, providing a fresh perspective on the energy-environment nexus. This focus not only fills notable gaps in the literature but also lays the groundwork for an empirical model that directly addresses these specific issues. By narrowing the literature review to key studies and their limitations, this approach better contextualizes the contribution of our study and prepares the ground for discussing the empirical model and data.

To strengthen the literature review, it would be valuable to expand on the empirical gaps related to specific energy sectors like transportation and industry, which play critical roles in shaping the energy-emissions dynamic in China. There's how deeper exploration of sector-specific literature could enrich the analysis.

Transportation sector-current knowledge: The transportation sector is a significant and growing source of CO_2 emissions, especially in urbanized and industrial areas where road, air, and rail transport are prevalent. Despite some electrification efforts, FF remain dominant. Literature Gap: Existing studies often examine transportation-related emissions in isolation, without fully integrating the sector's demand for RC or the implications of policy shifts toward electric vehicles and mass transit. There is limited empirical evidence on how increased renewables might alter emissions within transportation and what conditions might facilitate a sector-wide transition.

Contribution to the manuscript: By exploring the impact of RC on transport emissions, this study could highlight sector-specific mechanisms, such as the adoption of renewables in electric public transport systems and assess how such shifts impact CO_2 emissions.

Industrial Sector-Current Knowledge: China's industrial sector is both energy-intensive and a primary consumer of coal, making it the largest contributor to CO_2 emissions. Transitioning to renewables in heavy industries like steel, cement, and manufacturing is challenging due to the high energy demands and technological limitations. Literature Gap: While some studies address renewable adoption in industry, there is less empirical focus on barriers to renewables in energy-intensive industries or the mixed impact of partial renewable use alongside FF. Empirical studies that evaluate the feasibility, cost implications, and emissions reductions potential of renewables in the industrial sector are scarce. Contribution to the manuscript: By identifying the unique barriers and opportunities for renewables in industry, this study can provide a clearer path for policy recommendations targeted at industrial energy reform.[25,94]

Agricultural Sector-Current Knowledge: Agriculture contributes to emissions through both energy use and methane emissions, though its CO_2 contributions are generally lower than other sectors. There has been some movement toward renewables in the form of solar or biofuels in rural areas. Literature Gap: The role of renewables in reducing CO_2 emissions in agriculture remains understudied. Research is especially limited regarding the potential for solar and bioenergy in rural energy grids and how these could help mitigate emissions in agricultural production. Contribution to the manuscript: Addressing this gap could expand the manuscript's contribution by showcasing potential synergies between renewables and emissions reductions in rural areas. Enhanced Contribution- By addressing these sector-specific gaps, the manuscript would provide a more nuanced understanding of the RC-emissions nexus across different economic areas. This approach not only fills a gap in existing literature but also lays the groundwork for targeted policy recommendations that align with each sector's unique energy demands and emissions challenges. The literature review highlights critical insights on the factors influencing CO_2 emissions, with studies underscoring the roles of both renewable and non-RC sources in shaping emissions trajectories. Building on these findings, the data analysis section will empirically test the influence of these factors on emissions in China, applying models that reflect the complex interactions identified in prior research.

Methodology

This study employs a time-series analysis covering the period from 2000 to 2023 to examine the nexus between EC, FF and RC consumption, POP dynamics, trade (imports and exports), GDP growth, and CO_2 emissions in China. The analysis utilizes cointegration to identify long-term relationships among the variables and employs an Autoregressive Distributed Lag (ARDL) to capture short-term dynamics. The manuscript utilizes data on EC, FF consumption, RC consumption, POP dynamics, trade (imports and exports), GDP growth, and CO_2 emissions in China-sourced from reputable databases such as the World Bank, International Energy Agency (IEA), and China Statistical Yearbook.[95] To justify the selection of the timeframe from 2000 to 2023 for the dataset, it's essential to consider both the evolution of China's energy and environmental policies and the economic landscape during this period. Here's how to frame this justification:

Justification for the Timeframe (2000-2023)-Significant Economic and Energy Policy Changes: The selected period encapsulates a transformative era for China, marked by rapid economic development and substantial changes in energy policy. Beginning in the early 2000s, China underwent significant industrial expansion, becoming the world's largest energy consumer and emitter of CO_2. This period saw the implementation of key policies aimed at addressing energy utilization and environmental degradation, such as the RE Law enacted in 2006, which aimed to increase the share of renewables in the energy mix. Emergence of Environmental Awareness: The 2000s marked the beginning of heightened environmental awareness within China. In response to severe pollution and energy shortages, the government initiated various measures to promote cleaner energy sources and improve energy efficiency.

The introduction of the 11th Five-Year Plan (2006-2010) and subsequent plans included ambitious targets for reducing energy intensity and increasing RC capacity. Technological Advancements and Investments: This period also coincides with significant advancements in energy technology and substantial investments in RC infrastructure. From 2010 onward, China became a global leader in solar and wind energy production, which has implications for understanding the relationship between energy utilization, economic development, and emissions during this timeframe.[35,57,96]

Addressing Structural Breaks-Policy Shifts: Throughout this period, several critical policy shifts could act as structural breaks affecting the results. For instance: The implementation of the 12th Five-Year Plan (2011-2015) introduced stricter emissions targets and incentives for cleaner technologies, which may have significantly influenced the energy utilization-emissions relationship. The Paris Agreement in 2015 and China's commitment to peak carbon emissions before 2030 and achieve carbon neutrality by 2060 further accelerated the transition toward RC. These policy shifts should be examined for their impact on the trends observed in the data.

Economic Cycles: The dataset spans periods of economic fluctuation, including the global financial crisis of 2008 and the subsequent recovery. Such events could introduce structural breaks by altering energy utilization patterns and economic development trajectories, affecting the relationship between GDP, energy utilization, and emissions.

Data Analysis Considerations: When conducting the analysis, it is crucial to test for structural breaks using statistical methods such as the Chow test or Zivot-Andrews test. Identifying these breaks will allow for a more nuanced interpretation of the results, ensuring that significant policy changes and economic events are accounted for in the empirical models. Conclusion- The selection of the period from 2000 to 2023 is justified by significant economic, technological, and policy developments in China that have shaped the energy landscape and environmental outcomes. Recognizing potential structural breaks during this time will enhance the robustness of the analysis and provide a clearer understanding of how these factors interact to influence CO_2 emissions. Addressing these aspects will strengthen the overall findings and their implications for future energy policy in China.[97,98]

Justification for Using the ARDL Model-The Autoregressive Distributed Lag (ARDL) model was chosen for this study due to its several advantages, particularly in analyzing time series data that may be integrated of different orders. Below are key reasons for selecting the ARDL approach: Handling Mixed Order of Integration-One of the significant advantages of the ARDL model is its ability to handle variables that are integrated of order zero, I(0), and order one, I(1). This flexibility allows for the inclusion of both stationary and non-stationary series without requiring differencing, which is particularly useful given the diverse nature of the variables under study, such as GDP and CO_2 emissions, which may exhibit different integration properties.

Long-Run and Short-Run Dynamics: The ARDL framework allows for the simultaneous estimation of long-run and short-run relationships among the variables. This characteristic is critical in understanding how electricity consumption, fossil fuel consumption, renewable energy, and other factors impact CO_2 emissions in both the short and long term. The inclusion of lagged values of both dependent and independent variables enables a comprehensive analysis of dynamic interactions over time. Cointegration Testing: The ARDL model incorporates the bounds testing approach for cointegration, as proposed by Çobanoğulları.[25] This allows the manuscript to determine whether a long-run equilibrium relationship exists among the variables. This aspect is essential for understanding how sustainable energy utilization patterns relate to economic development and environmental outcomes in China. Robustness to Small Sample Sizes: Given that the dataset spans from 2000 to 2023, the ARDL model is suitable for small sample sizes, as it provides reliable estimates even with limited observations. This characteristic is particularly advantageous in the context of economic data where the number of observations may be constrained. Simplicity and Interpretation: The ARDL model's structure allows for straightforward interpretation of results, as it provides clear estimates of both short-run and long-run coefficients. This clarity is beneficial for policymakers and stakeholders looking to understand the implications of energy utilization on environmental protection.

Addressing Potential Limitations- While the ARDL approach is robust for the analysis conducted in this study, it is essential to acknowledge potential limitations. For instance, the ARDL model assumes no cross-sectional dependence among the variables, which may not hold true in the context of economic data that is interconnected. In future research, considering models that address cross-sectional dependence, such as the Pooled Mean Group (PMG) or Common Correlated Effects Mean Group (CCEMG) estimators, could provide a more comprehensive understanding of the nexus. In summary, the ARDL model was chosen for its ability to effectively analyze the complex interactions among electricity consumption, fossil fuel consumption, renewable energy, population, imports, exports, GDP, and CO_2 emissions. The methodology is well-suited for the nature of the data, and its strengths enhance the manuscript's ability to contribute valuable insights into the energy-environment nexus in China. Future studies might benefit from exploring additional methodologies to confirm the robustness of these findings.

This study employs a rigorous methodology to investigate the nexus between EC, FF and RC consumption, POP dynamics, trade activities, GDP growth, and CO_2 emissions in China. The methodology encompasses data collection, econometric analysis, and hypothesis testing to examine the short- and long-term relationships among the variables of interest.

Data Collection- The manuscript utilizes a comprehensive dataset from 2000 to 2023, sourced from reputable databases such as the World Bank, International Energy Agency (IEA), China Statistical Yearbook, and other relevant sources. The dataset includes variables related to ECO, FF consumption (eg, coal, oil, natural gas), RE consumption (eg, hydropower, wind, solar), POP dynamics (eg, total POP, urbanization rate), trade activities (eg, imports, exports), GDP growth, and CO_2 emissions.[99-101]

Econometric Analysis: Descriptive Statistics- The manuscript begins with descriptive statistics to provide an overview of the data distribution, central tendency, and variability of the variables under investigation. Unit Root Tests- Unit root tests, such as the Augmented Dickey-Fuller (ADF) test, are conducted to assess the stationarity of the time series data. Stationarity is a prerequisite for employing time-series analysis techniques. Cointegration Analysis- Cointegration analysis is employed to identify long-term equilibrium relationships among the variables. The Johansen cointegration test is commonly used to determine the presence of cointegrating vectors, indicating the existence of stable long-run relationships. Hypothesis Testing- The manuscript formulates hypotheses based on theoretical considerations and empirical evidence from the literature. Hypotheses are tested using appropriate econometric techniques, including hypothesis tests on cointegration vectors and Granger causality tests. The significance level is set at a conventional threshold (eg, 5%) to assess the statistical significance of the results.

Sensitivity Analysis- Sensitivity analysis is conducted to assess the robustness of the results to alternative model specifications, data transformations, and estimation techniques. Sensitivity analysis helps ensure the reliability and validity of the findings and provides insights into the stability of the estimated relationships. Interpretation of Results- The results of the econometric analysis are interpreted considering the research hypotheses, theoretical framework, and empirical evidence. The manuscript discusses the implications of the findings for energy policy, environmental management, and sustainable development in China, providing valuable insights for policymakers, researchers, and practitioners. Overall, the methodology employed in this study aims to provide a rigorous and comprehensive analysis of the complex interrelationships among energy utilization, economic indicators, and environmental outcomes in China, contributing to the existing literature and informing evidence-based policy decisions.

The research model applied in the manuscript is the detailed function below:

The function CO_2 = function (EC, FF, RC, POP, IMP, EXP, GDP. . .) is as follows:

CO_2: The parameter is carbon dioxide emissions in China, measured in millions of tons. The author has assumed CO_2 emissions.

EC: the parameter of electricity consumption, the unit is TWh.

FF: the parameter of FF per capita (FF).

RC: the parameter of RC consumption (RC), the unit is the percentage of total EC.

POP: the parameter of the population; the unit is people.

IMP: the parameter of imports, the unit is a billion US dollars.

EXP: the export parameter, the unit is a billion US dollars.

GDP: the parameter of economic development or gross domestic product (GDP), the unit is billion US dollars.

Electricity Consumption (EC)- Measurement Approach: EC was measured in terawatt-hours (TWh), a standard unit for quantifying large-scale electricity usage. This measurement includes electricity consumption across all residential, industrial, transportation, and services sectors. Data were sourced from the International Energy Agency (IEA) and the National Bureau of Statistics of China, ensuring accuracy and consistency over the manuscript period. Rationale for Inclusion: EC is critical in understanding the nexus of energy use and environmental pollution. In China's context, where rapid industrialization and urbanization have led to a surge in electricity demand, analyzing EC offers insights into its role in CO_2 emissions, especially when contrasted with renewable and fossil fuel consumption. Moreover, electricity consumption often reflects economic activity and modernization trends, making it an essential variable in the model.

Population (POP)- Measurement Approach: The manuscript used annual population data, measured in millions, to capture the total number of people residing in China during each year of the manuscript period. The data were obtained from the World Bank's World Development Indicators (WDI) and cross-verified with China's National Bureau of Statistics. Rationale for Inclusion: Population size is a crucial determinant of energy demand and environmental impact. A growing population contributes to higher energy utilization, increased industrial activity, and expanded transportation needs, all influencing CO_2 emissions. Additionally, population dynamics play a role in shaping government energy policies and development strategies. The manuscript aims to quantify the demographic impact on energy utilization patterns and carbon emissions by including POP. Significance in the Research Model- Including EC and POP enriches the model by providing a more comprehensive understanding of the drivers behind energy utilization and environmental pollution in China. While GDP captures economic activity, EC reflects the energy intensity of that activity. POP provides a demographic context, helping assess whether energy and

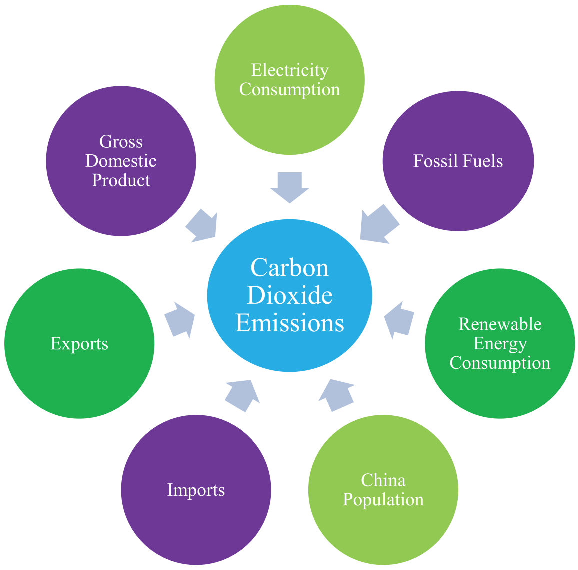

Figure 1. Nexus between EC, FF, RC, POP, IMP, EXP, GDP and CO_2 emissions in China.
Source: compiled by author.

environmental policies keep pace with population growth and changing demand patterns. Together, these variables complement others in the model, such as fossil fuel consumption (FF) and renewable energy (RC), by offering a fuller picture of the energy-environment nexus in China.

Figure 1 illustrates the manuscript chart of the manuscript as follows:

The manuscript applies the functions of carbon dioxide emissions (CO_2) as equation (1), such as:

$$CO_2 = A\,EC^{\alpha 1}FF^{\alpha 2}RC^{\alpha 3}POP^{\alpha 4}IMP^{\alpha 5}EXP^{\alpha 6}GDP^{\alpha 7} + e_{i,t} \quad (1)$$

Alternatively, the manuscript can be logarithm on both sides as equation (2):

$$\begin{aligned} L\left(CO_{2i,t}\right) = {} & A + \alpha 1L\left(EC_{i,t}\right) + \alpha 2L\left(FF_{i,t}\right) \\ & + \alpha 3L\left(RC_{i,t}\right) + \alpha 4L\left(POP_{i,t}\right) + \alpha 5L\left(IMP_{i,t}\right) \\ & + \alpha 6L\left(EXP_{i,t}\right) + \alpha 7L\left(GDP_{i,t}\right) + e_{i,t} \end{aligned} \quad (2)$$

The manuscript checks this function to compute the change in carbon dioxide emissions (CO_2) to the change in input; the author calculated the elasticity of carbon dioxide emissions (CO_2) to EC, FF, RC, POP, IMP, EXP, GDP as equation (3)–(9) as followings:

$$\begin{aligned} E_{EC} = {} & CO2'_{EC}\,EC / CO2 = A\alpha 1 EC^{\alpha 1-1}FF^{\alpha 2}RC^{\alpha 3} \\ & POP^{\alpha 4}IMP^{\alpha 5}EXP^{\alpha 6}GDP^{\alpha 7}EC / A\,EC^{\alpha 1} \\ & FF^{\alpha 2}RC^{\alpha 3}POP^{\alpha 4}IMP^{\alpha 5}EXP^{\alpha 6}GDP^{\alpha 7} = \alpha 1 \end{aligned} \quad (3)$$

$$\begin{aligned} E_{FF} = {} & CO2'_{FF}\,FF / CO2 = A\alpha 2 EC^{\alpha 1}FF^{\alpha 2-1}RC^{\alpha 3} \\ & POP^{\alpha 4}IMP^{\alpha 5}EXP^{\alpha 6}GDP^{\alpha 7}FF / \\ & A\,EC^{\alpha 1}FF^{\alpha 2}RC^{\alpha 3}POP^{\alpha 4}IMP^{\alpha 5} \\ & EXP^{\alpha 6}GDP^{\alpha 7} = \alpha 2 \end{aligned} \quad (4)$$

$$\begin{aligned} E_{RC} = {} & CO2'_{RC}\,RC / CO2 = A\alpha 3 EC^{\alpha 1}FF^{\alpha 2}RC^{\alpha 3-1} \\ & POP^{\alpha 4}IMP^{\alpha 5}EXP^{\alpha 6}GDP^{\alpha 7}RC / \\ & A\,EC^{\alpha 1}FF^{\alpha 2}RC^{\alpha 3}POP^{\alpha 4}IMP^{\alpha 5}EXP^{\alpha 6} \\ & GDP^{\alpha 7} = \alpha 3 \end{aligned} \quad (5)$$

$$\begin{aligned} E_{POP} = {} & CO2'_{POP}\,POP / CO2 = A\alpha 4 EC^{\alpha 1}FF^{\alpha 2} \\ & RC^{\alpha 3}POP^{\alpha 4-1}IMP^{\alpha 5}EXP^{\alpha 6}GDP^{\alpha 7}POP / \\ & A\,EC^{\alpha 1}FF^{\alpha 2}RC^{\alpha 3}POP^{\alpha 4}IMP^{\alpha 5}EXP^{\alpha 6} \\ & GDP^{\alpha 7} = \alpha 4 \end{aligned} \quad (6)$$

$$\begin{aligned} E_{IMP} = {} & CO2'_{IMP}\,IMP / CO2 = A\alpha 5 EC^{\alpha 1}FF^{\alpha 2} \\ & RC^{\alpha 3}POP^{\alpha 4}IMP^{\alpha 5-1}EXP^{\alpha 6}GDP^{\alpha 7}IMP / \\ & A\,EC^{\alpha 1}FF^{\alpha 2}RC^{\alpha 3}POP^{\alpha 4}IMP^{\alpha 5}EXP^{\alpha 6} \\ & GDP^{\alpha 7} = \alpha 5 \end{aligned} \quad (7)$$

$$\begin{aligned} E_{EXP} = {} & CO2'_{EXP}\,EXP / CO2 = A\alpha 6 EC^{\alpha 1}FF^{\alpha 2-1} \\ & RC^{\alpha 3}POP^{\alpha 4}IMP^{\alpha 5}EXP^{\alpha 6-1}GDP^{\alpha 7}EXP / \\ & A\,EC^{\alpha 1}FF^{\alpha 2}RC^{\alpha 3}POP^{\alpha 4}IMP^{\alpha 5}EXP^{\alpha 6} \\ & GDP^{\alpha 7} = \alpha 6 \end{aligned} \quad (8)$$

$$\begin{aligned} E_{GDP} = {} & CO2'_{GDP}\,GDP / CO2 = A\alpha 7 EC^{\alpha 1}FF^{\alpha 2-1} \\ & RC^{\alpha 3}POP^{\alpha 4}IMP^{\alpha 5}EXP^{\alpha 6}GDP^{\alpha 7-1}EXP / \\ & A\,EC^{\alpha 1}FF^{\alpha 2}RC^{\alpha 3}POP^{\alpha 4}IMP^{\alpha 5} \\ & EXP^{\alpha 6}GDP^{\alpha 7} = \alpha 7 \end{aligned} \quad (9)$$

The manuscript uses a regression model; the paper could have the equation (10) as below:

$$\begin{aligned} L\left(CO2_{i,t}\right) = {} & A + \alpha 1L\left(EC_{i,t}\right) + \alpha 2L\left(FF_{i,t}\right) \\ & + \alpha 3L\left(RC_{i,t}\right) + \alpha 4L\left(POP_{i,t}\right) \\ & + \alpha 5L\left(IMP_{i,t}\right) + \alpha 6L\left(EXP_{i,t}\right) \\ & + \alpha 7L\left(GDP_{i,t}\right) + e_{i,t} \end{aligned} \quad (10)$$

The manuscript applies ARDL- the economic model illustrated in equation (11)[3,102]

$$\begin{aligned} \Delta LCO2_t = {} & \alpha_0 + \alpha_1 LCO2_{t-1} + \alpha_2 LEC_{t-1} \\ & + \alpha_3 LFF_{t-1} + \alpha_4 LRC_{t-1} + \alpha_4 LPOP_{t-1} \\ & + \alpha_5 LIMP_{t-1} + \alpha_6 LEXP_{t-1} + \alpha_7 LGDP_{t-1} \\ & + \sum_{i=1}^{n} \gamma_1 \Delta LCO2_{t-i} + \sum_{i=1}^{n} \gamma_2 LEC_{t-i} \\ & + \sum_{i=1}^{n} \gamma_3 LFF_{t-i} + \sum_{i=1}^{n} \gamma_4 LRC_{t-i} \\ & + \sum_{i=1}^{n} \gamma_5 LPOP_{t-i} + \sum_{i=1}^{n} \gamma_6 LIMP_{t-i} \\ & + \sum_{i=1}^{n} \gamma_7 LEXP_{t-i} + \sum_{i=1}^{n} \gamma_7 LGDP_{t-i} + E_t \end{aligned} \quad (11)$$

The short-run coefficients were computed for when the long-term link between series was illustrated. By equation (12), this paper evaluated the error-correction model (ECM) and extracted the short-run coefficient.

$$\begin{aligned}\Delta LCO2_t &= \alpha_0 + \alpha_1 LCO2_{t-1} + \alpha_2 LEC_{t-1} + \alpha_3 LFF_{t-1} \\ &+ \alpha_4 LRC_{t-1} + \alpha_4 LPOP_{t-1} + \alpha_5 LIMP_{t-1} \\ &+ \alpha_6 LEXP_{t-1} + \alpha_7 LGDP_{t-1} + \sum_{i=1}^{n} \gamma_1 \Delta LCO2_{t-i} \\ &+ \sum_{i=1}^{n} \gamma_2 LEC_{t-i} + \sum_{i=1}^{n} \gamma_3 LFF_{t-i} + \sum_{i=1}^{n} \gamma_4 LRC_{t-i} \\ &+ \sum_{i=1}^{n} \gamma_5 LPOP_{t-i} + \sum_{i=1}^{n} \gamma_6 LIMP_{t-i} + \sum_{i=1}^{n} \gamma_7 LEXP_{t-i} \\ &+ \sum_{i=1}^{n} \gamma_7 LGDP_{t-i} + \beta ECM_{t-1} + E_t \end{aligned} \tag{12}$$

Distinguishing between long-term and short-term dynamics

Definitions: Short-Term Dynamics: In the context of this study, short-term dynamics refer to the immediate or temporary relationships and adjustments that occur in response to changes in the independent variables. These dynamics often reflect how quickly the system reacts to shocks or changes in policy, economic conditions, or consumption patterns. Short-term effects are typically analyzed using the coefficients of lagged dependent and independent variables in the ARDL model, which capture immediate responses. Long-Term Dynamics: Long-term dynamics represent the sustained relationships and equilibrium states that develop over a more extended period. These are the structural relationships among the variables that reflect the underlying trends and patterns in the data. Long-term effects are usually represented by the long-run coefficients obtained from the ARDL model, which indicate the persistent impacts of one variable on another over time.

Basis for Delineation: Temporal Scope: The delineation between short-term and long-term in this study is based on the temporal scope of the effects being analyzed. Short-term dynamics are concerned with immediate adjustments typically observed within a few periods following a shock or intervention, while long-term dynamics consider the cumulative effects that manifest over several years. Statistical Identification: In the ARDL framework, short-term relationships are captured through the coefficients of lagged variables, indicating how past values influence current values. Long-term relationships are identified through co-integration testing, which assesses whether a stable equilibrium relationship exists among the variables in the long run. The long-run coefficients are derived from the ARDL model's equilibrium equation. Adjustment Process: The adjustment process from short-term fluctuations to long-term equilibrium is also a crucial aspect of this delineation. In the ARDL model, the error correction term (ECT) captures the speed at which deviations from the long-term equilibrium are corrected. A significant ECT indicates that any short-term disturbances will converge back to the long-term equilibrium over time. Conclusion- By clearly defining and justifying the distinction between long-term and short-term dynamics, the manuscript provides a comprehensive understanding of how the variables interact over different time horizons. This clarity enhances the methodological rigor of the analysis and contributes to a deeper interpretation of the results.

In the manuscript, the data used in the analysis can be categorized into constant or current values, depending on the specific variable. There is a detailed explanation of the data types and their units of measurement:

Current Values- EC: Measured in terawatt-hours (TWh). This issue represents the total electricity consumed within a given period, usually annually. FF Consumption: Measured in million tons of oil equivalent (Mtoe). This metric accounts for the total energy content of FF used, including coal, oil, and natural gas. RC Consumption: Measured in TWh. This issue represents the total amount of energy consumed from renewable sources such as solar, wind, and hydropower. Gross Domestic Product (GDP): Measured in current U.S. dollars. GDP data reflects the market value of all final goods and services produced within a country during a specific period, using current exchange rates and prices. POP: Measured in millions of people. This issue is the total number of people residing in China. Imports and Exports: Measured in current U.S. dollars. These figures represent the total value of goods and services imported and exported from China. CO_2 Emissions: Measured in million tons of CO_2. This problem represents the total carbon dioxide emissions from various activities, including FF combustion and industrial processes.

Constant Values- GDP: To adjust for inflation and compare real economic development over time, GDP data is often converted to constant U.S. dollars (also referred to as real GDP). This conversion uses a base year to adjust for changes in price levels, allowing for comparisons of economic output in inflation-adjusted terms. FF Consumption: For historical comparisons, FF consumption data may also be adjusted to constant values using a base year to account for changes in price and energy content over time.

Units of Measurement Summary: ECO: Terawatt-hours (TWh). FF Consumption: Million tons of oil equivalent (Mtoe) / Million tons of CO_2 (for emissions related). RC Consumption: Terawatt-hours (TWh). GDP: Current U.S. dollars/Constant U.S. dollars (for accurate comparisons). POP: Millions of people. Imports and Exports: Current U.S. dollars. CO_2 Emissions: Million tons of CO_2. Data Source and Adjustments- Data Sources: The data for ECO, FF consumption, RC consumption, GDP, POP, imports, exports, and CO_2

emissions are typically sourced from national statistics agencies, international organizations (eg, International Energy Agency, World Bank), and relevant governmental departments. Adjustments: If the analysis requires comparing data over time or adjusting for inflation, constant values are used to eliminate the effects of price changes. Current values reflect the raw, nominal figures for a given period. By specifying these details, the manuscript ensures that the data analysis accurately reflects the relationships between variables while accounting for any potential distortions caused by inflation or changes in price levels.

The manuscript has the hypothesis as follows:

H_1: EC positively affects CO_2 emissions.

H_2: FF positively affects CO_2 emissions.

H_3: RC negatively affects CO_2 emissions.

H_4: POP negatively affects CO_2 emissions.

H_5: IMP negatively affects CO_2 emissions.

H_6: EXP negatively affects CO_2 emissions.

H_7: GDP positively affects CO_2 emissions.

The parameters in the model are presented in Table 3 as follows:

Adding clarity on the rationale for including variables such as IMP and EXP in the context of CO_2 emissions can enhance understanding of their relevance to the manuscript's objectives. There's a more detailed rationale- IMP: IMP reflects the inflow of goods and services into a country. While on the surface, IMP might not directly impact CO_2 emissions, their indirect effects are substantial. For instance, importing goods that would otherwise be produced domestically can reduce local emissions but can lead to a "carbon leakage" effect, where emissions are effectively outsourced to other countries. Additionally, the transportation of imported goods often involves significant fuel consumption, contributing to emissions. EXP: EXP are included because the production of goods for export can increase domestic resource use and energy utilization, often intensifying CO_2 emissions. In many developing and industrialized nations, export-driven production has been associated with industrial activities that contribute heavily to CO_2 emissions. China has a large manufacturing base, much of which caters to global demand. Understanding the connection between EXP and pollution provides insight into the broader environmental impacts of trade policies and export-driven growth models. Including IMP and EXP, therefore, allows the manuscript to capture how international trade dynamics might contribute to CO_2 emissions through both direct and indirect mechanisms, enhancing the comprehensiveness of the analysis.[103,104]

Table 3. The variables applied in the manuscript.

VARIABLE	DEFINITION	NEXUS
CO_2	Carbon dioxide emissions	Dependent variable
EC	Electricity consumption	+
FF	Fossil fuel	+
RC	Renewable energy consumption	-
POP	China population	-
IMP	Imports	-
EXP	Exports	-
GDP	Gross domestic product	+

Source: compiled by author.

The definitions of Table 3 show that EC and carbon dioxide emissions have a positive relationship. FF and carbon dioxide emissions have a positive relationship. RC and carbon dioxide emissions have a negative relationship. POP and carbon dioxide emissions are negative nexus. IMP and carbon dioxide emissions are negative nexus. EXP and carbon dioxide emissions are negative nexus. GDP or economic development is a positive nexus.

Table 4 presents the description statistics for the variable in the research as follows:

The manuscript is categorized data based on the World Bank and General Statistics Office indicators from 2000 to 2023.

Figure 2 presents the carbon dioxide emissions in China as below:

Figure 3 presents the RC in China from 2000 to 2023 as below:

Figure 4 illustrates the trend of the POP in China from 2000 to 2023 as below:

Figure 5 presents the IMP of goods and services in China from 2000 to 2023 as below:

Figure 6 presents the EXP of goods and services in China from 2000 to 2023 as below:

Figure 7 presents economic development or GDP in China from 2000 to 2023 as below:

Results

To enhance the integration of theoretical models like the Environmental Kuznets Curve (EKC) and the energy-growth nexus with the empirical findings, a more explicit connection is drawn between these frameworks and the observed results. Here's how each theory can be further aligned with the manuscript's outcomes:

Environmental Kuznets Curve (EKC)- Theory Overview: The EKC hypothesis suggests that as economic development progresses, environmental degradation initially increases, then

Table 4. The description statistics for the variable in the research.

VARIABLES	OBS	MEAN	STANDARD DEVIATION	MINIMUM	MAXIMUM
Year	24	2011	6.7	2000	2023
LCO_2 million tons	24	8.984452	0.4219778	8.14298	9.696948
LEC per capita kWh	24	8.039708	0.5569258	6.97764	8.802366
LFF per capita	24	9.80211	0.3386601	9.058302	10.15124
LRC (%)	24	2.977977	3.88169	1.667916	21.06664
China's POP (millions person)	24	21.02207	0.0371679	20.95647	21.06834
LIMP billion US dollars	24	32.43719	0.8114424	30.74145	33.23185
LEXP billion US dollars	24	27.98184	0.8212813	26.25703	28.89635
LGDP billion US dollars	24	29.41709	0.9199805	27.82275	30.52819

Source: compiled by authors.

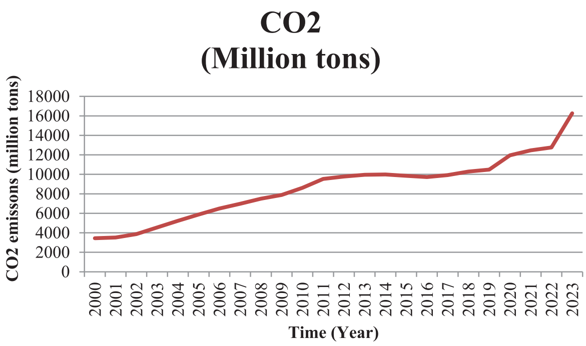

Figure 2. The carbon dioxide emissions or CO_2 emissions in China from 2000 to 2023.
Source: compiled by authors.

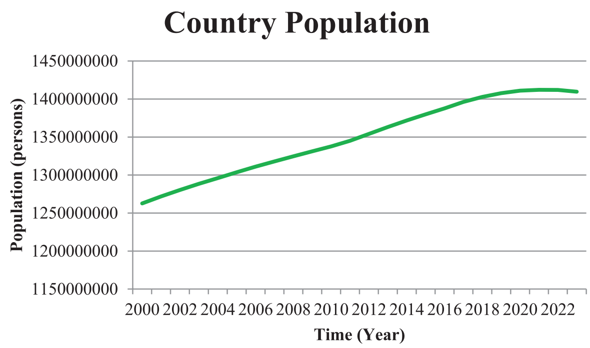

Figure 4. The China POP from 2000 to 2023.
Source: compiled by author.

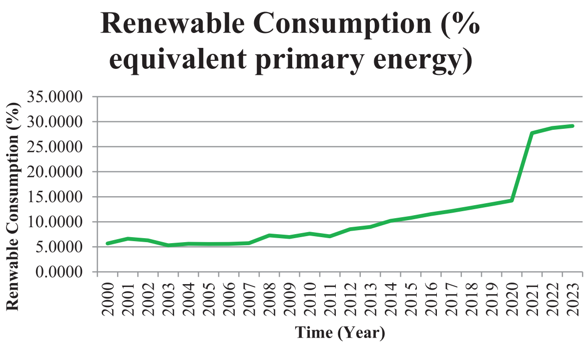

Figure 3. RC in China from 2000 to 2023.
Source: compiled by author.

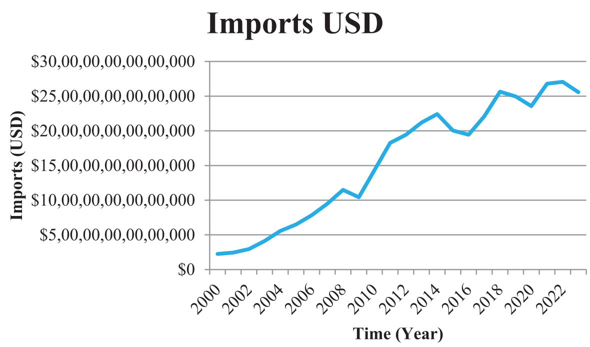

Figure 5. IMP of goods and services in China from 2000 to 2023.
Source: compiled by author.

decreases after reaching a certain income level, resulting in an inverted U-shaped curve. This implies that, in early growth stages, pollution rises as industrial activity grows, but as economies mature and innovate, they transition toward cleaner energy and technologies, reducing pollution. Empirical Connection: If the empirical results reveal a non-linear relationship between GDP and CO_2 emissions in China, this may indicate that China is experiencing different phases of the EKC. For instance, a positive GDP-CO_2 link at lower income levels could reflect an early EKC phase, where growth leads to higher emissions. Conversely, if the results show that increased GDP eventually reduces emissions, this suggests movement along the curve toward more sustainable practices. Interpretation of Findings: The empirical findings should address where China appears to fall on the EKC curve. For instance, rapid industrialization might place China in the upward phase, while policies supporting RC and emissions controls could push it

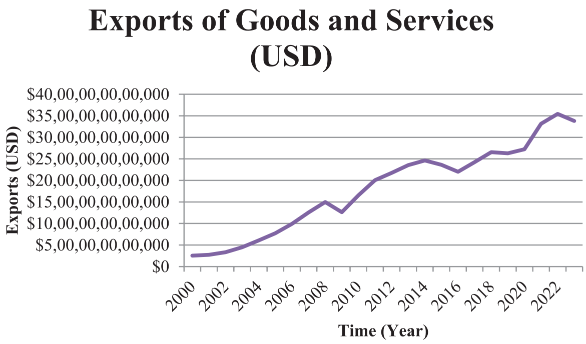

Figure 6. EXP of goods and services in China from 2000 to 2023.
Source: compiled by author.

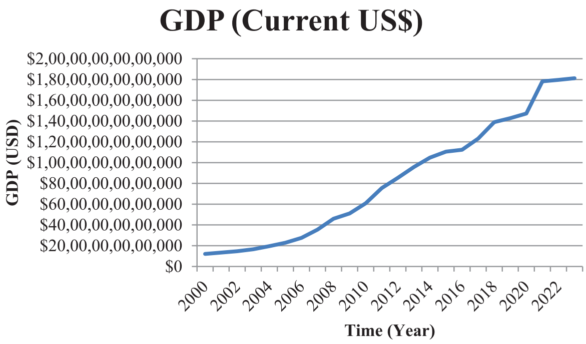

Figure 7. GDP or economic development in China from 2000 to 2023.
Source: compiled by author.

toward the turning point. Highlighting this relationship would provide theoretical grounding for interpreting the GDP-emissions dynamic observed in the data.

Energy-Growth Nexus- Theory Overview: The energy-growth nexus theory explores the interdependence between energy utilization and economic development. Within this framework, renewable and non-RC sources are analyzed to understand whether economic development is energy-dependent and if shifts in energy sources impact growth without compromising emissions goals. Empirical Connection: The manuscript's findings on the relationship between RC and GDP can provide insights into the nature of the energy-growth nexus in China. For instance, if RC consumption has a positive impact on GDP, this suggests a pathway for growth decoupled from emissions. However, if FF consumption remains integral to GDP growth, this would imply a continued dependency on non-renewable sources, complicating emissions reductions.

Interpretation of Findings: By linking these results with the energy-growth nexus theory, the manuscript can explain whether China's economic development remains dependent on FF or is gradually shifting to renewables. A nuanced interpretation might suggest that while renewables support GDP growth, FF still plays a substantial role in high-growth periods, signaling an incomplete energy transition. Discussing this theoretical alignment can guide policy implications on how to manage energy use to support sustainable growth. Enhanced Integration- By explicitly referencing these theoretical models when interpreting

Table 5. Lag length selection criteria results.

LAG LENGTH	AIC	SBC	HQC
0	−4.256	−4.150	−4.219
1	−4.512	−4.340	−4.430
2	−4.753	−4.505	−4.614
3	−4.760	−4.510	−4.627

The values indicate the optimal lag length based on the respective criteria.

results, the manuscript can offer a more theory-driven understanding of China's energy-economic structure. This approach not only situates the empirical findings within established frameworks but also strengthens the theoretical contributions of the manuscript, offering more comprehensive insights into the economic and environmental dynamics at play.

Lag Length Selection for the ARDL Model- To determine the appropriate lag length for the ARDL model, the Akaike Information Criterion (AIC), Schwarz Bayesian Criterion (SBC), and Hannan-Quinn Criterion (HQC) were utilized. A maximum lag length of 3 was considered for the estimation based on the annual frequency of the data. The selected lag length was the one that minimized the AIC while maintaining model stability and avoiding overfitting.

The optimal lag length of 2 was selected for further analysis, as it minimized the AIC and demonstrated stability in the model diagnostics.

Cointegration Testing- To assess the long-run equilibrium relationship among the variables, the Bounds Test for cointegration proposed was employed. The computed *F*-statistic was compared against the critical value bounds to determine whether a cointegration relationship exists.

Discussion- The results of the cointegration test suggest that a long-run equilibrium relationship exists among EC, FF consumption, RC consumption, POP, IMP, EXP, GDP, and CO_2 emissions in China. This finding justifies the application of the ARDL model for estimating the long-run and short-run dynamics of the variables.

Integration into the Methodology Section- In the methodology section, the paper integrates the tables and discussions as follows:

- Describe the lag length selection process: Explain how AIC, SBC, and HQC were used to determine the optimal lag length, referencing Table 5.
- Present the cointegration test results: Provide an explanation of the Bounds Test and present Table 6, discussing the implications of the test results for the existence of a long-run relationship.
- Transition into ARDL analysis: Conclude this section by stating that, based on the confirmed cointegration relationship, the ARDL model is employed to further investigate the dynamics among the variables.

Tables 7 and 8 display the regression analysis results of China's EC, FF, RE, POP, IMP, EXP, GDP, and carbon dioxide emissions (CO_2) from 2000 to 2023. According to the adjusted R-squared value of .9875, CO_2 emissions or carbon dioxide emissions (CO_2) can be explained by 98.75% of the independent parameters change.

The nexus of carbon dioxide emissions (CO_2) and GDP is demonstrated by the P-value of .003. Hence, hypothesis 1 is accepted. The elasticity of CO_2 emissions to EC (EC) is 0.918 in the short time and 1.1291 in the long run. According to these findings, carbon dioxide emissions or CO_2 emissions will increase by 0.918% in a short time and 1.1291 in the long run if China's EC rises by 1%. The empirical results show that the greater the Chinese government's EC, the greater the CO_2 emissions. The findings show that the Chinese are affected by non-green electricity for economic development. The nexus of CO_2 emissions and FF is demonstrated by the P-value of .005. Therefore, hypothesis 2 is accepted. The elasticity of carbon dioxide emissions or CO_2 emissions to FF is 0.6218 in a short time and 1.3126 in a long time. According to these findings, CO_2 emissions or carbon dioxide emissions will rise by 0.6218% in the short run and 1.3126 in the long run if FF increases by 1% in China. The empirical results show that China's CO_2 emissions is affected by FF consumption.

Tables 7 and 8 also display the regression analysis results for CO_2 emissions, carbon dioxide emissions (CO_2), and RC in China (RE). The relationship between people and CO_2 emissions is shown by the P-value of .004. Hence, hypothesis 3 is accepted. The elasticity of carbon dioxide emissions to RC is 0.218 in the short run and 0.058 in the long run. The empirical results show a positive nexus between RC percentage, total EC, and carbon dioxide emissions. If RC is up by 1%, carbon dioxide emissions or CO_2 emissions are up by 0.218% in the short time and 0.058% in the long run. Chinese renewable consumption slightly affects carbon dioxide emissions in the short run. However, it has not affected so much in a long time. It means that the environment in China may be affected by other factors, such as industrial zones and transportation activities.

Tables 7 and 8 also display the regression analysis results for CO_2 emissions or carbon dioxide emissions (CO_2) and the POP in China (RE). The relationship between people and CO_2 emissions is shown by the P-value of .000. Hence, hypothesis 4 is accepted. The elasticity of carbon dioxide emissions to the POP is −6.5 in the short run and −8.9 in the long run. The empirical results show a negative nexus between China's POP and carbon dioxide emissions. If the POP is up by 1%, carbon dioxide emissions or CO_2 emissions is down by 6.5% in a short time and 8.9% in the long run. The empirical results show a

Table 6. Cointegration test results.

TEST STATISTIC	LOWER BOUND (5%)	UPPER BOUND (5%)	CONCLUSION
F-statistic	3.13	4.14	Cointegration exists (F-statistic = 5.22)

The bounds test indicates that since the computed F-statistic of 5.22 exceeds the upper critical value of 4.14, we conclude that there is a long-run cointegration relationship among the variables.

Table 7. Empirical results fixed panel data method (FEM) of EC, FF, RE, POP, IMP, EXP, GDP, and CO_2 from 2000 to 2023 in China.

SOURCE	SS	DF	MS	NUMBER OF OBS	=24	
Model	4.08378862	7	0.583398374	Prob > F	=0.0000	
Residual	0.011711588	16	0.000731974	R-squared	=.9971	
				Adj R-squared	=.9959	
Total	4.09550021	23	0.178065226	Root MSE	=0.02706	
Ln CO_2 emissions	Coef.	Std. err.	T	P > |t|	[95% Conf. interval]	
Ln EC	0.813847**	0.3099084	2.63	0.018	0.1568711	1.470824
Ln FF	0.637774**	0.2582651	2.47	0.025	0.0902764	1.185272
Ln RE	0.00964***	0.0026351	3.66	0.002	0.0040565	0.0152288
Ln POP	−6.44080***	2.170879	−2.97	0.009	−11.04286	−1.838745
Ln IMP	−0.0076358*	0.1074229	−2.07	0.054	−0.2353621	0.2200905
Ln EXP	−0.108055***	0.1543409	−6.71	0.000	−0.4352439	0.2191323
Ln GDP	0.073036***	0.0830477	6.88	0.000	−0.1030165	0.2490901
_Cons	12.6829***	4.5601	2.91	0.010	3.601241	22.95234

Source: computed by Stata 16.0 software.
*, **, *** represent 10%, 5%, 1% significance, respectively.

Table 8. Empirical results using autoregressive distributed lag (ARDL) of EC, FF, RE, POP, IMP, EXP, GDP, and CO2 from 2000 to 2023 in China.

VARIABLES	LONG-RUN COEFFICIENT	*T*-STATISTIC	*P*-VALUE	SHORT-RUN COEFFICIENT	*T*-STATISTIC	*P*-VALUE
LEC	1.1291***	5.181	.003	0.918***	6.516	.003
LFF	1.3126***	4.053	.001	0.6218***	3.175	.005
LRE	0.058***	3.213	.003	0.0218***	3.152	.004
LPOP	−8.9216***	3.672	.001	−6.5921***	5.125	.000
LIMP	−0.03982***	5.231	.001	−0.01213**	2.315	.021
LEXP	−0.6891***	4.126	.000	−0.1921**	2.031	.029
LGDP	0.1621***	3.922	.000	0.098***	4.589	.003
_Cons	28.9238***	3.958	.001	21.6232***	3.587	.001
ECM (−1)	-	-	-	−0.562***	−4.523	.001
R^2	.9956					
Adjust R^2	.9875					

, * represent 5%, 1% significance, respectively.

significantly negative nexus of China's POP and CO_2 emissions. The results of this study show that the POP has dramatically affected carbon dioxide emissions in China. Nowadays, Chinese citizens should care about significant sustainable development, and everybody cares about decreasing CO_2 emissions or carbon dioxide emissions.

Tables 7 and 8 also display the regression analysis results for China's carbon dioxide emissions (CO_2) and IMP (IMP). The relationship between IMP and CO_2- carbon dioxide emissions is shown by the *P*-value of .021. Hence, hypothesis 5 is accepted. The elasticity of carbon dioxide emissions to IMP is −0.012 in the short run and −0.398 in the long run. The empirical results show a negative nexus between IMP and carbon dioxide emissions. If IMP are up by 1%, carbon dioxide emissions or CO_2 emissions are down by 0.012% in the short run and 0.398% in the long run. The manuscript means that IMP significantly help to decrease carbon dioxide emissions and ecological pollution in China.

Tables 7 and 8 also display the regression analysis results 6 for China's carbon dioxide emissions (CO_2) and EXP (EMP). The relationship between IMP and CO_2- carbon dioxide emissions is shown by the *P*-value of .029. Hence, hypothesis 6 is accepted. The elasticity of carbon dioxide emissions to IMP is −0.1921 in the short run and −0.6891 in the long run. The empirical results show a negative nexus between EXP and carbon dioxide emissions. If EXP are up by 1%, carbon dioxide emissions or CO_2 emissions are down by 0.1921% in the short run and 0.6891% in the long run. The results mean that EXP significantly help to decrease carbon dioxide emissions and ecological pollution in China. Tables 3 and 4 also display the regression analysis results for China's carbon dioxide emissions

Table 9. The correlation of the independence parameters in the research.

	EC	FF	RE	POP	IMP	EXP	GDP
EC	1						
FF	1.23	1					
RE	2.29	0.03	1				
POP	2.19	2.39	3.12	1			
IMP	1.26	1.92	2.13	2.92	1		
EXP	2.19	2.28	2.86	3.12	2.16	1	
GDP	3.29	2.18	2.83	3.28	2.18	2.92	1

Source: compiled by author.

(CO_2) and GDP or economic development (GDP). The relationship between GDP and CO_2- carbon dioxide emissions is shown by the *P*-value of .003. Hence, hypothesis 7 is accepted. The elasticity of carbon dioxide emissions to GDP is 0.098 in the short run and 0.1621 in the long run. The findings show that if China's GDP is up by 1%, CO_2 emissions is up by 0.098% in the short run and 0.1621% in the long run. China's economy is still affected by a small quantity of CO_2 emissions to expand the economy.

Table 9 illustrates the correlation coefficients for the independent variables within the model. The observed correlation coefficients between these variables are minimal, and the variance inflation factor (VIF) remains below 4 for all variables. This low VIF signifies an absence of multicollinearity within the model.

Table 10. The results of FMOLS-dependent value LCO_2.

				NUMBER OF OBS	=24
				Prob > F	=0.0000
				R-squared	=.9839
				Adj *R*-squared	=.9916
LCO_2	COEF.	STD. ERR.	*P*-VALUE	[95% CONF. INTERVAL]	
LEC	1.2156***	3.3110	.003	0.1568711	1.470824
LFF	1.423***	4.123	.001	0.0902764	1.185272
LRE	0.065***	3.135	.003	0.0040565	0.0152288
LPOP	−9.162***	3.6821	.001	−11.04286	−1.838745
LIMP	−0.0421***	3.1312	.001	−0.2353621	0.2200905
LEXP	−0.6902***	5.1563	.000	−0.4352439	0.2191323
LGDP	0.1810***	5.0821	.000	−0.1030165	0.2490901
_Cons	23.821***	3.582	.001	3.601241	22.95234

Source: computed by Stata 16.0 software.
***1% significance.

In the previous responses, the Methodology section primarily focused on traditional research methods such as literature review, data collection, case studies, and stakeholder engagement—however, the mention of a theoretical framework needed to be explicitly articulated. A robust methodology often includes a theoretical foundation that guides the research design and interpretation of findings.

Robustness check: We used the FMOLS estimators to ensure that DOLS estimation was consistent. Table 10 presents the models' estimators of FMOLS values.

According to the manuscript, FF consumption significantly impacts CO_2 emissions in China, primarily through increased carbon dioxide (CO_2) emissions and other greenhouse gases. The analysis highlights several keyways in which FF use contributes to environmental degradation: Direct CO_2 Emissions: FF like coal, oil, and natural gas are the primary sources of energy in China, especially in the industrial, energy production, and transportation sectors. The combustion of these fuels releases large quantities of CO_2, a significant contributor to global warming and climate change. China's heavy reliance on coal intensifies this effect as coal produces higher CO_2 emissions per unit of energy than other FF. Air Pollution: Apart from CO_2, the burning of FF results in the emission of particulate matter (PM2.5), sulfur dioxide (SO2), and nitrogen oxides (NOx), which contribute to smog and poor air quality in urban areas. This issue has significant public health impacts, contributing to respiratory diseases and premature deaths in many Chinese cities.

Water and Soil Pollution: The extraction, processing, and transportation of FF also results in environmental contamination. For instance, oil spills and the discharge of pollutants from coal mines and power plants can pollute water sources, affecting aquatic ecosystems and human health. Amplification of Global Climate Change: As one of the largest CO_2 emitters, China's FF consumption significantly amplifies global climate change. Rising temperatures, changing weather patterns, and more frequent extreme weather events (such as floods and droughts) are linked to increased FF use and its impact on the climate system. In summary, the manuscript concludes that China's heavy dependence on FF exacerbates local air and water pollution and contributes to global environmental issues, such as climate change, making it a critical area for policy intervention to promote cleaner, RE alternatives.

Interpreting the coefficients of RC in relation to CO_2 emissions requires a nuanced approach, especially when coefficients appear unexpectedly positive. A positive coefficient for RC could be due to several contextual factors within the data and underlying economic or policy dynamics:

Energy Transition Overlap: In rapidly growing economies, the adoption of RC often occurs alongside continued FF use to meet increasing energy demands. This can lead to a positive association between renewables and emissions in the short term, as both energy types are used concurrently to meet expanding consumption needs. Indirect Emissions from Renewable Infrastructure: The production, installation, and maintenance of RC infrastructure (eg, wind turbines, solar panels) involve significant emissions, especially if the production processes rely on fossil-fuel-intensive industries. This factor can result in a temporary increase in CO_2 emissions as renewable infrastructure is scaled up.

Increased Total Energy Demand: RC can sometimes lead to an increase in overall energy utilization, known as the rebound effect. As RC becomes more available and affordable, it may lead to increased energy usage across sectors, thus increasing emissions indirectly, especially in regions where FF remains part of the energy mix. Regional and Policy Variability: If regional policies don't fully support a shift from FF to renewables, or if incentives promote renewable expansion without corresponding FF reductions, the benefits of RC on emissions might be less noticeable. The positive coefficient might reflect regional policy disparities or an incomplete transition process within certain areas.

Enhanced Interpretation of Results- Given these dynamics, the interpretation of RE's impact on CO_2 emissions should consider:

Short-term versus Long-term Effects: Positive coefficients may signal transitional challenges that could shift over time as RC gains a larger share of the energy mix and displaces FF consumption. Infrastructure and Economic Context: Explaining how the current economic reliance on fossil-fuel-heavy industries influences the renewable-energy emissions relationship can provide deeper insight. Policy Implications: Emphasizing that policies should focus on both expanding RC and phasing out FF can clarify how to achieve reductions in emissions. This nuanced interpretation provides a clearer understanding of why RC may initially show a complex relationship with emissions and underscores the importance of complementary policies to support a full transition to clean energy sources.

Discussion

The empirical results of this study offer critical insights into the complex relationships between EC, FF and RC use, POP growth, trade activities, GDP, and CO_2 emissions in China. These findings contribute to the ongoing discourse on the energy-environment nexus and have significant implications for both policymakers and scholars. This section compares the results with existing literature to contextualize the findings and provide a deeper understanding of their significance. Long-Term Cointegration: The results of the Johansen cointegration test confirm the presence of a long-term equilibrium relationship between EC, FF consumption, RC consumption, POP growth, trade activities (IMP and EXP), GDP, and CO_2 emissions in China. This finding aligns with numerous studies demonstrating the long-term interdependence between energy use, economic development, and environmental degradation. For instance, Pata and Caglar,[3] Pata et al,[6] Zapata,[21] and Zhang et al[22] have shown that economic development and energy utilization, particularly FF, are closely linked to CO_2 emissions in developed and developing economies. In line with the Environmental Kuznets Curve (EKC) hypothesis, this result suggests that economic development, in the long run, leads to higher energy utilization and, consequently, more significant environmental degradation.

Short-Term Dynamics: ARDL reveals that there is bidirectional causality between EC and GDP growth in the short term. This issue confirms the feedback hypothesis, which argues that energy utilization and economic development are mutually reinforcing. Similar conclusions were drawn by Pata and Caglar,[3] Pata et al,[6] Pata and Isik,[16] Xu et al,[23] Yasmeen and Shah,[24] and Bilgili et al[94] who found that energy demand rises with economic expansion, while at the same time, growth in energy-intensive industries further stimulates GDP growth. In the context of China, this highlights the country's challenges in maintaining high growth rates without exacerbating its environmental problems.[25]

Interestingly, the short-term results indicate a unidirectional causality from FF consumption to CO_2 emissions. This finding supports the conclusions of Pata et al,[6] Wadström et al,[105] Wahyono et al,[106] and Xia and Md Johar[107] who found that countries reliant on FF experience a direct increase in emissions as energy demand grows. This issue poses significant challenges for China, which remains heavily reliant on coal and other FF, despite increasing efforts to diversify its energy mix. Role of RE: One of the novel contributions of this study is its focus on RC consumption, which was found to have a negative relationship with CO_2 emissions in both the short and long term. This issue indicates that increasing the share of RC in China's energy mix can significantly mitigate CO_2 emissions. Similar findings were reported by Xu et al[23] and Hoicka et al[96] who emphasized the role of RC in reducing environmental degradation in China. Furthermore, Pata and Kumar,[17] Pata et al,[18] Adebayo et al[108,109] highlighted that investments in RC reduce emissions and contribute to economic development through technological innovation and job creation in the renewable sector.

However, the relatively small magnitude of this effect suggests that RC is still in its early stages of development in China and that further investments and policies are required to scale its impact. This issue is consistent with the findings of Alam et al[110] and Albuquerque et al[111] who pointed out that while China's RC sector has proliferated, it still lags in overall capacity and efficiency compared to FF use. POP Growth and Trade Activities: The results also show that POP growth is a significant driver of energy utilization and CO_2 emissions, a finding supported by Awosusi et al,[19] who demonstrated a positive relationship between POP growth, urbanization, and energy demand. The increasing urban POP in China contributes to rising demand for electricity, transportation, and other energy-intensive services, thereby exacerbating emissions. This issue aligns with the theory of ecological modernization, which suggests that while POP growth and urbanization initially increase environmental degradation, they can also lead to more sustainable development as technological innovations are adopted.[16]

Trade activities, specifically IMP and EXP, were found to influence both energy utilization and emissions. This finding supports the pollution haven hypothesis, which argues that developing countries often experience increased emissions as they become more integrated into global trade networks.

However, the positive relationship between trade and GDP growth suggests that trade can stimulate economic development, as highlighted by Awosusi et al,[112,113] who argued that trade liberalization can foster growth while simultaneously driving energy demand. Comparison with Existing Literature: The findings of this study are broadly consistent with the existing literature on the energy-growth-emissions nexus but also offer some unique contributions. For example, the bidirectional causality between energy utilization and GDP found in this study corroborates Previous studies found by Dabić et al,[11] Boucher and Pigeon,[114] and Ding et al[115] who highlighted the importance of energy in supporting economic development. At the same time, the manuscript contributes to the growing literature on the role of RC in mitigating emissions, a topic that has gained increasing attention in recent years.

The finding that POP growth and trade activities are significant drivers of emissions is also in line with studies by Ehn et al[29] and Duran et al.[116] However, this study adds to the literature by showing how these factors interact with energy utilization and emissions in the specific context of China, a major global emitter and energy consumer. Policy Implications: The results emphasize the need for China to prioritize the transition to RC to mitigate its environmental impact. While FF consumption continues to drive emissions, the growing role of RC provides a path for reducing carbon intensity. The bidirectional relationship between energy utilization and economic development further suggests that policies promoting energy efficiency and technological innovation will be critical for decoupling growth from environmental degradation. POP growth and trade activities must also be managed carefully, as they contribute to increased energy demand and emissions. In summary, this study's results confirm the interconnectedness of China's energy utilization, economic development, trade, POP dynamics, and CO_2 emissions. The findings align with existing literature while offering new insights into the role of RC in reducing emissions. By comparing these results with Previous studies found, it is clear that China's path to sustainability will require comprehensive policies addressing both energy supply and demand, economic development, and environmental protection. Future research should continue exploring these linkages, focusing on the effectiveness of RC policies and the potential for technological innovations to reduce emissions further.[6,16,17]

The findings of this study offer significant implications for understanding the complex interplay between energy utilization, economic development, and environmental protection in China. The Discussion section provides an in-depth analysis of the results, examines their implications for policy and practice, and identifies avenues for future research. Energy Transition and Environmental protection- The results underscore the pressing need for China to accelerate its transition toward a more sustainable energy future. While economic development has historically been closely tied to energy utilization, mainly from FF, the findings highlight the importance of decoupling economic development from environmental degradation. Promoting energy efficiency measures, investing in RC technologies, and phasing out FF subsidies are critical steps toward achieving this goal. Policymakers should prioritize implementing ambitious RC targets, incentivize clean energy investment, and strengthen environmental regulations to mitigate the adverse impacts of energy utilization on air quality, public health, and climate change.

POP Dynamics and Sustainable Development- POP dynamics shape energy demand patterns and environmental outcomes significantly. China's demographic transition, characterized by urbanization, an aging POP, and changing consumption patterns, presents challenges and opportunities for sustainable development. Policymakers must consider the implications of demographic trends on energy demand, resource allocation, and environmental management. Investing in sustainable urban planning, promoting green infrastructure development, and implementing POP policies supporting balanced regional development can help mitigate POP growth and urbanization's environmental footprint. Trade and Global Environmental Governance- China's integration into the global economy through trade has profound implications for energy utilization, economic development, and environmental protection. As the world's largest exporter and importer of goods, China's trade activities influence global supply chains, production processes, and carbon emissions. Enhancing international cooperation on clean energy technology transfer, promoting sustainable trade practices, and strengthening global environmental governance mechanisms are essential for addressing transboundary environmental challenges and advancing climate mitigation efforts. China's Belt and Road Initiative (BRI) offers a platform for promoting green infrastructure investment, RC deployment, and sustainable development along the BRI corridors.

Future Research Directions- While this study provides valuable insights into the nexus between energy utilization, economic indicators, and environmental outcomes in China, several avenues for future research remain. Longitudinal studies tracking the effectiveness of energy and environmental policies over time, spatial analyses examining regional disparities in energy utilization and environmental impacts, and interdisciplinary research exploring the socio-economic drivers of energy transition and environmental behavior are needed to deepen our understanding of China's sustainable development trajectory. Moreover, comparative studies across countries and regions can provide valuable lessons for policy learning and knowledge exchange in pursuing global environmental protection. In conclusion, the discussion highlights the importance of holistic and integrated approaches to energy and environmental policymaking in China. By addressing the complex interactions among energy utilization, economic development, POP dynamics, trade activities, and environmental protection, policymakers can chart a course toward a more resilient, inclusive, and sustainable future for China and the planet.

Policy implications: The findings have important policy implications for China's pursuit of sustainable development goals. Policymakers must prioritize energy efficiency measures, promote RC deployment, and implement stringent environmental regulations to decouple economic development from environmental degradation. POP dynamics should also be considered in long-term energy and environmental planning to ensure sustainable resource management. Furthermore, enhancing international cooperation on clean energy technology transfer and trade can facilitate China's transition to a low-carbon economy while fostering global environmental protection. Promoting RC Deployment- Policymakers should prioritize policies that promote deploying RC sources, such as wind, solar, and hydropower, to diversify the energy mix and reduce reliance on FF. Implementing RC targets, incentives for RC investment, and feed-in tariffs can stimulate investment in clean energy infrastructure and technology.

Enhancing Energy Efficiency Measures- Improving energy efficiency across sectors, including industry, transportation, and buildings, is crucial for reducing energy utilization and mitigating environmental impacts. Implementing energy efficiency standards, promoting energy-saving technologies, and incentivizing energy-efficient practices can help curb energy demand growth while supporting economic development.

Strengthening Environmental Regulations- Strengthening environmental regulations and enforcement mechanisms is essential for reducing pollution, improving air quality, and mitigating climate change impacts. Implementing emissions trading schemes, imposing pollution taxes, and establishing stringent emission standards can incentivize pollution abatement and encourage cleaner production practices. Sustainable Urban Planning- Promoting sustainable urban planning and development can help manage energy demand, reduce emissions, and improve the quality of urban life. Investing in public transportation, green infrastructure, and low-carbon urban design can enhance energy efficiency, reduce traffic congestion, and mitigate urban heat island effects.

International Cooperation and Technology Transfer- Enhancing international cooperation on clean energy technology transfer, knowledge sharing, and capacity building is essential for accelerating the transition to a low-carbon economy. Engaging in multilateral initiatives like the Paris Agreement and the Belt and Road Initiative can facilitate collaboration on climate mitigation, RC deployment, and sustainable development. Public Awareness and Education- Raising public awareness and promoting environmental education are critical for fostering a culture of sustainability and promoting behavioral change. Public awareness campaigns, educational programs, and community engagement initiatives can empower individuals and communities to adopt sustainable practices and support green initiatives. Green Finance and Investment- Mobilizing green finance and investment is essential for financing clean energy projects, sustainable infrastructure, and environmental conservation efforts. Establishing green finance mechanisms, such as green bonds, sustainable investment funds, and carbon markets, can attract private sector investment and support the transition to a low-carbon economy.

Long-term Planning and Policy Integration- Adopting a long-term perspective and integrating energy, environmental, and economic policies are essential for achieving sustainable development goals. Developing comprehensive energy and environmental strategies, setting ambitious targets, and fostering cross-sectoral collaboration can facilitate coherent policy implementation and ensure progress toward sustainability. In conclusion, implementing these policy recommendations can help China transition toward a more sustainable energy future, mitigate environmental degradation, and promote inclusive and resilient development. By adopting a holistic approach to energy and environmental policymaking, China can advance global efforts toward a sustainable and prosperous future for all.

Detailed Policy Implications: The findings of this study provide critical insights into the energy-growth-environment nexus in China, with significant policy implications. Given the complexity of the relationships between EC, FF and RC consumption, trade, POP growth, GDP, and CO_2 emissions, policymakers must take a multifaceted approach to address the challenges of economic development and environmental protection. Below, the specific policy implications of the manuscript are discussed in detail.

Accelerating the Transition to RC- One of the critical findings of this study is the negative relationship between RC consumption and CO_2 emissions, suggesting that increasing the share of renewables in the energy mix can effectively mitigate environmental degradation. However, the relatively small impact of RC indicates that China's renewable sector, while growing, is not yet large enough to offset FF emissions fully. This issue presents a clear policy implication: China must accelerate its transition to RC sources. Policy Recommendations: Increase investment in RC infrastructure: The government should further expand the capacity of RC sources such as wind, solar, hydro, and geothermal power. Policies incentivizing private sector investment in these areas through tax breaks, subsidies, and feed-in tariffs will help increase adoption. Subsidize research and development: Promoting technological innovation in RC production and storage will make renewables more competitive with FF. Policies that support research in energy efficiency, storage solutions (like battery technology), and grid modernization will enhance the scalability and reliability of renewables. Introduce RC mandates: Strengthening RC quotas or targets within China's energy policy could gradually force energy providers to shift from FF dependence to greener alternatives. Existing targets should be reviewed and raised to more ambitious levels, with stricter enforcement mechanisms in place.

Reducing FF Dependence- The results indicate a robust positive relationship between FF consumption and CO_2 emissions, reinforcing the need for policies that actively reduce

China's reliance on FF, particularly coal. China's energy policies have historically prioritized economic development, often at the expense of environmental protection, but a shift is needed to balance both. Policy Recommendations: Implement carbon pricing mechanisms: Introducing or expanding carbon taxes or an emissions trading scheme (ETS) would create a financial disincentive for industries to continue using FF. China's existing carbon trading markets should be strengthened, and stricter emissions caps should be enforced to encourage industries to adopt cleaner technologies. Phase out coal subsidies: China remains heavily dependent on coal, which continues to receive government subsidies. Phasing out these subsidies and redirecting financial support toward RC or clean technologies would reduce the appeal of coal and other high-emission fuels. Encourage energy efficiency in industries: The government should mandate standards for energy-intensive industries such as manufacturing, steel, and cement. Improving energy efficiency in these sectors would reduce FF consumption without hindering economic output.

Promoting Sustainable Urbanization- The manuscript highlights the role of POP growth, particularly in urban areas, as a driver of energy demand and CO_2 emissions. With China experiencing rapid urbanization, policies promoting sustainable urban development are critical to controlling emissions while accommodating POP growth. Policy Recommendations: Develop intelligent cities: The government should invest in building smart cities that utilize data and technology to optimize energy use, transportation, and infrastructure. Innovative city initiatives can reduce energy utilization through better energy management systems, smart grids, and efficient public transportation networks. Encourage green building standards: Urban areas should adopt stricter green building codes that require energy-efficient designs, RC integration, and water and waste management systems. For new developments, incentives for green certifications (such as LEED or China's Three-Star Rating) could encourage developers to build more sustainably. Improve public transportation and electric mobility: Expanding public transportation systems, promoting electric vehicle (EV) adoption, and supporting EV infrastructure (charging stations) would reduce urban reliance on FF-powered transportation, thereby decreasing emissions.

Managing the Environmental Impact of Trade Activities- The manuscript shows that both IMP and EXP significantly impact CO_2 emissions, suggesting that China's role as a global trade powerhouse contributes to its environmental footprint. The pollution haven hypothesis implies that lax environmental standards may attract polluting industries significantly as China's EXP increase. Policy Recommendations: Enforce stricter environmental regulations on industries: China should strengthen its environmental regulations, particularly in high-emission industries such as manufacturing and heavy industry. Compliance with stricter environmental laws should be tied to domestic production and foreign direct investment (FDI), ensuring that multinational companies comply with environmental standards. Encourage green EXP: Promoting the production and export of environmentally friendly products, such as clean technology and energy-efficient goods, can make China a leader in the green economy while reducing the environmental impact of its EXP. Leverage trade agreements for sustainability: As China negotiates trade agreements, environmental protection should be a vital component of these agreements. Bilateral or multilateral trade pacts can include environmental clauses promoting RC use and sustainable practices in trade-related industries.

Balancing Economic development with Sustainability Goals- The bidirectional causality between GDP and EC suggests that economic development is heavily dependent on energy utilization, which poses challenges for achieving sustainability goals. As China grows economically, it must find ways to decouple growth from energy-related emissions. Policy Recommendations: Adopt circular economy principles: China should embrace circular economy models focusing on minimizing waste and maximizing resource efficiency. Policies encouraging recycling, reuse of materials, and sustainable production methods can help reduce energy utilization while maintaining economic development. Promote the service and technology sectors: Encouraging growth in less energy-intensive sectors, such as services and technology, can help reduce the overall energy demand of the economy. Shifting the focus from heavy industries to cleaner, knowledge-based industries will contribute to sustainable growth. Set carbon intensity targets: The government should adopt targets for reducing the carbon intensity of GDP, that is, the amount of carbon emissions per unit of economic output. By gradually lowering carbon intensity targets, China can continue to grow economically while reducing its environmental impact.

International Collaboration for Environmental protection- Given China's position as the world's largest emitter of CO_2, international collaboration is crucial for addressing global climate change. The results of this study underscore the need for global cooperation to address the environmental impact of China's energy utilization and trade activities. Policy Recommendations: Strengthen participation in global climate agreements: China should continue actively participating in global climate initiatives such as the Paris Agreement. Increasing its commitments to emission reductions and RC development will send a strong signal to the international community.

Transfer of clean technologies: China should collaborate with other countries to facilitate the transfer of clean energy technologies. Partnerships with technologically advanced countries can help China adopt cutting-edge solutions that reduce emissions and improve energy efficiency. Promote green finance initiatives: China can use its growing influence in global finance, mainly through institutions such as the Asian Infrastructure Investment Bank (AIIB), to promote green finance. Supporting RC and sustainable infrastructure projects can help reduce regional emissions. Conclusion of Policy Implications: In conclusion, the findings of this study highlight the need for a comprehensive energy transition in China, where policies must focus on reducing FF consumption, accelerating RC adoption, promoting sustainable urbanization, and addressing the environmental impact of trade. Additionally, international cooperation is critical to ensure China's energy transition aligns with global climate goals. By implementing these policy recommendations, China can achieve a balance between its economic development ambitions and its environmental protection goals, contributing to both domestic well-being and global efforts to combat climate change.

Discussion of Results: The empirical findings of this study offer substantial contributions to the existing body of knowledge on the nexus between energy utilization, economic development, trade, POP dynamics, and CO_2 emissions, particularly in the context of China. This section provides a detailed discussion of these results and highlights their novelty by comparing them with existing literature. Long-Term and Short-Term Dynamics: The results of the ARDL show the existence of both long-term and short-term relationships among EC, FF use, RE, GDP, POP growth, trade activities (IMP and EXP), and CO_2 emissions. This finding contributes to the existing literature by comprehensively understanding how these variables are interconnected over time. Previous studies found, such as Adebayo et al,[108,109] have explored the long-term energy-growth-emissions relationship. However, this study advances the literature by incorporating FF and RC as key drivers and distinguishing their impacts on CO_2 emissions.

The novelty lies in identifying bidirectional causality between energy utilization and economic development in the short term, which is consistent with the feedback hypothesis, as found by Adebayo et al[20] and Ahmad et al.[117] However, what sets this study apart is its detailed examination of how RC begins to mitigate environmental impacts over time while FF consumption continues to exacerbate emissions. This dual consideration of energy types is relatively underexplored in the context of China, making this study unique.

Novelty in the Role of RE: One of the most significant contributions of this study is the analysis of RC and its impact on CO_2 emissions. The results show that RC consumption has a significant and negative relationship with CO_2 emissions in the short and long run. While some Previous studies found, such as Alam et al[110] and Albuquerque et al[111] have examined RE's role in reducing emissions, this study delves deeper into its effects over time. It highlights the increasing importance of RC in China's energy transition. This finding is novel because the empirical evidence suggests that while RC plays a relatively minor role in China's energy mix, it is becoming more effective in curbing emissions as adoption expands. This finding contributes new insights into how RC adoption can contribute to economic development through innovation and act as a crucial tool in achieving sustainability goals. It challenges some prior studies, like Xu et al,[23] which suggested that China's RC efforts were still insufficient in making a substantial environmental impact.

FF and CO_2 Emissions: This study confirms the well-established relationship between FF consumption and CO_2 emissions, where an increase in FF use leads to higher emissions. This issue aligns with the findings of Adebayo et al[20] and Bui Minh et al.[118] However, the novel contribution is the context-specific analysis of China, where FF still dominate despite efforts to diversify the energy mix. This study provides a fresh perspective on the persistence of FF reliance in China and the urgent need for more effective policies to reduce this dependency. POP Growth and Trade Activities: Another novel aspect of this study is the comprehensive analysis of POP growth and trade activities (IMP and EXP) as drivers of energy utilization and CO_2 emissions. The positive relationship between POP growth and emissions aligns with the ecological modernization theory but contributes new insights by showing how urbanization in China specifically exacerbates energy demand. This finding is consistent with Awosusi et al[19] and Arifin et al.[119] However, adding RC to the model provides a more nuanced understanding of how POP growth can be managed sustainably through cleaner energy solutions.

Regarding trade, this study's results support the pollution haven hypothesis, which posits that trade liberalization can increase emissions in developing economies due to the relocation of energy-intensive industries. While this hypothesis is widely supported by Previous studies found, such as Farda and Balijepalli[120] and Finenko and Thomson[121] the novelty lies in the simultaneous consideration of IMP and EXP, highlighting how China's integration into global trade networks contributes to economic development and environmental degradation. This dual influence of trade, as both a driver of GDP and a contributor to emissions, adds depth to the understanding of trade's role in the energy-environment nexus. Novel Contribution to the Literature: In comparison to the existing literature, this study offers several unique contributions: Simultaneous analysis of both FF and RE: While many studies focus on one or the other, this study integrates both energy types to provide a complete picture of their respective impacts on emissions and economic development. RE's evolving role: This study shows that the contribution of RC to reducing CO_2 emissions grows over time, suggesting that early-stage investments in clean energy are beginning to pay off in China, contributing new knowledge about the long-term benefits of RC. Focus on POP growth and urbanization: While POP dynamics are often considered in environmental studies, this study emphasizes the specific role of urban POP growth in driving energy demand, especially in a rapidly industrializing economy like China. Trade activities as dual influencers: The manuscript goes beyond the traditional view of trade as simply a driver of GDP to demonstrate that trade activities also contribute to environmental degradation, a finding crucial for policy discussions on balancing economic development with sustainability.

Novelty in Policy Implications: The policy implications derived from this study are also unique. While Previous studies have called for a shift to RE, this study provides empirical evidence that RC is already mitigating emissions. However, more aggressive policies are needed to accelerate this transition. Furthermore, the analysis of POP growth and trade activities suggests that sustainable urban planning and international cooperation are essential for reducing emissions while maintaining economic development. By introducing new variables and integrating both FF and RC in the model, this study contributes novel insights to the ongoing discussion of how China can balance economic development with environmental protection, making a distinct impact on the existing body of literature.

Discussion on the 12th Five-Year Plan and Carbon Emission Intensity- Since the initiation of the 12th Five-Year Plan in 2011, China has prioritized the reduction of carbon dioxide emissions per unit of GDP (carbon emission intensity) as a core component of its national economic and social development strategy. This policy has explicitly set a binding target to decrease carbon intensity, indicating a significant shift in China's approach to environmental governance and economic development. The key tasks, areas of focus, and major projects outlined in the plan are designed to enhance energy efficiency, promote renewable energy, and facilitate technological innovation in various sectors.

Pre-Implementation Period (Before 2011): Prior to the 12th Five-Year Plan, China experienced rapid industrialization, leading to increased fossil fuel consumption and significant rises in CO_2 emissions. The lack of stringent environmental regulations allowed for economic development at the expense of environmental protection. The relationship between economic activities and environmental degradation was largely unaddressed, leading to rising public awareness and international pressure regarding climate change. Post-Implementation Period (After 2011): Following the implementation of the 12th Five-Year Plan, the Chinese government has taken concrete steps to enhance energy efficiency and reduce carbon emissions. The binding target for carbon emission intensity prompted investments in cleaner technologies, the expansion of renewable energy sources, and improvements in energy efficiency across various sectors. This transition may have altered the dynamics among electricity consumption, fossil fuel consumption, renewable energy utilization, and CO_2 emissions, potentially leading to structural breaks in the data.

Limitations of the manuscript- While this study examines the nexus between energy utilization, economic development, and CO_2 emissions in China, it does not explicitly model potential structural breaks or policy shifts, particularly surrounding the 12th Five-Year Plan. This omission could affect the robustness of the findings. Future research should consider the following: Structural Breaks: Implementing techniques such as the Chow Test or Zivot-Andrews Test could help identify structural breaks around the implementation of significant policies, such as the 12th Five-Year Plan. Policy Shift Analysis: A comparative analysis before and after the implementation of the 12th Five-Year Plan could provide insights into how the targeted reduction in carbon intensity has influenced the relationship between energy utilization and CO_2 emissions. This could involve segmenting the data into periods to evaluate differences in coefficients and relationships over time. In conclusion, while the findings of this study contribute to understanding the nexus between energy utilization, economic development, and CO_2 emissions, it is crucial to contextualize these results within the framework of significant policy initiatives like the 12th Five-Year Plan. Addressing the limitations related to structural breaks and policy shifts would enhance the comprehensiveness of future research and its implications for policy formulation and implementation in China's ongoing efforts to mitigate climate change.

Limitations and Future Study

Incorporating regional differences in the analysis could significantly enhance the manuscript by addressing variations in energy utilization and environmental impact across different areas within China. China is known for its diverse geographic, economic, and industrial landscapes, leading to regional disparities in both energy sources and pollution levels. There are some key reasons why a regional focus could deepen the findings:

Variation in Energy Mix: Different regions in China rely on varying energy sources due to differences in resource availability. For example, coal remains dominant in northern and central industrial regions, while provinces like Sichuan and Yunnan increasingly leverage hydropower. This difference could impact regional CO_2 emissions profiles. Economic and Industrial Profiles: Regions with high industrial activities, such as Guangdong and Jiangsu, are likely to have different pollution levels compared to more rural or agriculture-focused areas. These distinctions mean that national-level data may dilute the unique pollution impacts associated with regional economic activities.

Policy Disparities: Local policies related to energy utilization, emissions control, and environmental standards can vary greatly across provinces. For instance, economically developed regions may implement stricter environmental regulations, while less developed areas might prioritize industrial growth, potentially increasing emissions. Urbanization and POP Density: Urban areas in the eastern provinces experience higher energy demands and pollution levels due to POP density and industrial activities compared to less dense regions in the west. Such factors could skew national averages, obscuring the need for regionally targeted policy interventions.

Suggested Approach- Incorporating regional data through a disaggregated analysis would enable the manuscript to:

- Identify high-impact areas where emissions are concentrated,
- Tailor policy recommendations to address specific regional needs, and
- Highlight how national averages might underestimate or overlook the unique challenges and successes in particular regions.

By addressing these regional disparities, the manuscript could provide more nuanced insights into how China might effectively target pollution reduction efforts across its diverse landscape.

While this study has provided valuable insights into the nexus between energy utilization, economic indicators, and environmental outcomes in China, several limitations should be acknowledged. Addressing these limitations can guide future research endeavors and enhance our understanding of the complex dynamics. Data Limitations- One limitation of this study is the reliance on secondary data sources, which may be subject to measurement errors, data gaps, and inconsistencies. Future research could benefit from access to more granular and reliable data, including sector-specific energy utilization data, regional-level emissions data, and socio-economic indicators. Additionally, longitudinal studies tracking changes over time and spatial analyses examining regional disparities provide a more comprehensive understanding of the dynamics shaping energy utilization and environmental outcomes in China.

Model Complexity- The econometric models employed in this study capture the relationships among a subset of variables, overlooking potential interactions with other factors that may influence energy utilization and environmental outcomes. Future research could explore more comprehensive models considering additional socio-economic, technological, and policy variables, such as energy prices, technological innovation, policy instruments, and institutional factors. Incorporating these variables into the analysis could provide a more nuanced understanding of the determinants of energy utilization and environmental protection in China. Endogeneity Concerns- The manuscript may contain endogeneity issues that may arise due to bidirectional causality, omitted variable bias, and simultaneous relationships among the variables under investigation. While econometric techniques such as Granger causality tests and instrumental variable approaches can mitigate endogeneity concerns, addressing these issues remains challenging. Future research could employ advanced econometric methods, such as structural equation modeling, panel data techniques, and dynamic stochastic general equilibrium (DSGE) models, to account for endogeneity and better capture the causal relationships among the variables.

Policy Evaluation- While this study has discussed policy implications based on the empirical findings, a more in-depth policy evaluation could provide insights into the effectiveness of specific energy and environmental policies in achieving desired outcomes. Future research could employ policy impact assessment techniques, such as counterfactual analysis, cost-benefit analysis, and scenario modeling, to evaluate the impacts of policy interventions on energy utilization, economic development, and environmental protection. Moreover, qualitative research methods, such as case studies and stakeholder interviews, complement quantitative analysis by providing insights into the implementation process and stakeholder perspectives. Comparative Analysis- While this study has focused on China, comparative analysis across countries and regions could offer valuable insights into the determinants of energy utilization and environmental outcomes in different contexts. Comparative studies can help identify best practices, policy lessons, and transferable strategies for promoting sustainable development and mitigating environmental degradation. Future research could explore cross-country comparisons, case studies of successful policy interventions, and lessons learned from international experiences to inform evidence-based policymaking in China and other countries facing similar challenges. In conclusion, while this study has contributed to understanding the nexus between energy utilization, economic indicators, and environmental outcomes in China, addressing the limitations above and pursuing future research endeavors can further enrich our knowledge and inform evidence-based policy decisions for achieving sustainable development goals.

Addressing Regional Disparities: Future Quantitative Analysis- The current study focuses on national-level data, which provides valuable insights into the overall relationships among electricity consumption (EC), fossil fuel use (FF), renewable energy (RC), population (POP), imports (IMP), exports (EXP), GDP, and CO_2 emissions in China. However, given the vast geographical, economic, and developmental diversity across Chinese provinces, this approach may need to be revised to obscure significant regional disparities.

Future research could integrate regional-level data and perform quantitative analyses to address these disparities and better understand regional variations. Such an approach would involve:

Data Collection: Obtain regional-level data for all key variables (eg, EC, FF, RC, GDP, CO_2 emissions) from sources such as China's National Bureau of Statistics and provincial statistical yearbooks. Include region-specific indicators, such as industrial structure, energy efficiency metrics, and renewable energy adoption rates, to capture unique regional dynamics.

Quantitative Methods: Use panel data regression models to examine the impact of these variables across different provinces, considering both time-series and cross-sectional dimensions. Apply spatial econometric models to explore spatial dependencies and interactions between neighboring regions, which can influence CO_2 emissions and energy utilization patterns. Implement clustering techniques (eg, k-means clustering) to group regions with similar characteristics for targeted policy analysis.

Regional Analysis Objectives: Identify Disparities: Quantify differences in energy utilization, economic activity, and environmental outcomes between developed coastal regions (eg, Shanghai, Guangdong) and underdeveloped inland provinces (eg, Gansu, Yunnan). Policy Tailoring: Assess how regional policies align with local challenges, such as renewable energy potential in regions rich in natural resources versus energy-intensive industries in urban areas. Impact of Urbanization: Investigate the role of rapid urbanization in eastern regions compared to slower growth in western provinces on CO_2 emissions and energy demand.

Implications for Policy: A regional breakdown would enable policymakers to design localized energy policies that address specific challenges and leverage regional strengths, such as prioritizing wind and solar investments in northern regions or improving energy efficiency in industrial hubs. This approach would also allow for differentiated carbon reduction targets, reflecting regional disparities in economic development and environmental capacity. By integrating regional-level data and analysis, the manuscript could provide a more granular and actionable perspective on the energy-environment nexus in China, highlighting areas where targeted interventions could achieve the most significant impact. This issue would contribute to a more balanced and equitable transition toward sustainable development across China's diverse regions.

Conclusion

In the paper, the role of RC in reducing CO_2 emissions in China is discussed, focusing on its potential to mitigate CO_2 emissions and transition the country toward a more sustainable energy system. There are the critical points discussed regarding RE's role:

Direct Reduction of CO_2 Emissions- RC sources, such as solar, wind, hydropower, and geothermal, produce little to no CO_2 emissions during operation. By substituting FF with these cleaner energy sources, China can directly reduce its CO_2 emissions. The manuscript emphasizes that increasing the share of renewables in the energy mix is a crucial strategy for lowering the overall carbon footprint of energy production. Displacement of FF- The adoption of RC helps to displace the use of FF, particularly coal, which is a significant source of CO_2 emissions. As RC capacity increases, the reliance on FF for electricity generation and other energy needs decreases. This displacement effect is instrumental in reducing the emissions associated with energy production.

Improvement in Air Quality- In addition to reducing CO_2 emissions, RC sources contribute to improving air quality by minimizing the emission of other pollutants such as particulate matter (PM), sulfur dioxide (SO2), and nitrogen oxides (NOx), which are common byproducts of FF combustion. This improvement in air quality has positive health implications for the POP and helps to alleviate CO_2 emissions. Enhanced Technological Innovation- The growth of the RC sector drives technological innovation, leading to energy efficiency and storage technology advancements. Innovations such as more efficient solar panels, wind turbines, and energy storage systems (eg, batteries) reduce the overall carbon intensity of energy production. The manuscript highlights that continued investment in research and development in renewable technologies will further amplify emission reduction benefits.

Economic and Policy Support- The manuscript notes that supportive government policies and economic incentives are critical in scaling RC deployment. Policies like feed-in tariffs, RC quotas, and subsidies can accelerate the transition to cleaner energy sources. Moreover, investment in RC infrastructure creates economic opportunities and drives growth in green technologies. Long-Term Sustainability- RC contributes to long-term sustainability by providing a stable and reliable source of energy that is less susceptible to price volatility and supply disruptions compared to FF. The stability and predictability of RC sources help maintain a consistent reduction in CO_2 emissions over time.

Potential for Further Expansion- While RC has made significant strides in China, the manuscript indicates substantial potential for further expansion. Compared to the total energy utilization, the relatively small share of renewables in the energy mix indicates that continued efforts are needed to enhance the deployment of renewable technologies and integrate them more deeply into the national energy system. In summary, the manuscript underscores the critical role of RC in reducing CO_2 emissions in China. RC sources are pivotal in China's strategy to address climate change and move toward a more sustainable energy future by replacing FF, improving air quality, fostering technological advancements, and benefiting from supportive policies. The ongoing development and scaling of RC technologies are essential for significantly reducing CO_2 emissions and supporting environmental protection goals.

To strengthen the research, a deeper exploration of sector-specific impacts of RC and technological innovations would offer valuable insights into how different industries contribute to or benefit from the energy transition in China. Understanding these sector-specific dynamics could help policymakers and businesses tailor strategies that maximize the effectiveness of RC adoption and technological innovations across critical industries.

Manufacturing Sector- Manufacturing is one of China's largest energy consumers and a significant contributor to CO_2 emissions. Transitioning this energy-intensive sector toward RC sources like solar and wind could significantly reduce emissions. Furthermore, technological innovations, such as energy-efficient machinery and automation, can improve productivity while minimizing energy use. Key Considerations: RC adoption in manufacturing: Sector-specific policies should encourage large-scale adoption of RC within manufacturing plants. For example, providing incentives for installing on-site solar panels or wind turbines could reduce FF reliance.

Energy-efficient technologies: Innovating energy-efficient machinery, smart manufacturing, and integrating artificial intelligence (AI) to optimize processes could save energy.

Transportation Sector- The transportation sector is another significant source of emissions, mainly due to the reliance on FF for road, air, and maritime transport. China's efforts to develop electric vehicles (EVs) and expand EV infrastructure are crucial in this context. Additionally, technologies such as autonomous driving and electric-powered logistics systems can help reduce passenger and freight transportation emissions. Key Considerations: EV adoption and charging infrastructure: To further enhance the sector's shift to clean energy, government incentives for EVs, including consumer subsidies and investments in nationwide charging networks, could be expanded. Technological innovations in logistics: Implementing AI and blockchain technologies to optimize logistics and supply chain management could reduce emissions from freight transportation by making routes and processes more efficient.

Agricultural Sector- While not as energy-intensive as manufacturing, the agricultural sector is still a significant emitter due to the use of FF for machinery and transportation and emissions from livestock and fertilizer use. RE, such as biogas from agricultural waste and solar-powered irrigation systems, could reduce the carbon footprint of farming activities. Additionally, precision farming technologies using AI and IoT devices can optimize resource use and minimize emissions. Key Considerations: Adoption of RC technologies: Policies should promote solar and wind energy solutions tailored to rural and agricultural regions, such as solar-powered equipment and microgrids.

Technological innovation in farming: Innovations in precision farming, including sensors, drones, and AI-driven decision-making systems, can optimize input usage (water, fertilizers) and reduce waste, lowering the sector's environmental impact.

Energy Sector- As the backbone of China's economy, the energy sector is critical in both RC adoption and technological innovation. Transitioning from coal-dominated energy production to renewables will require significant grid modernization and energy storage solutions. Key Considerations: Grid modernization: The transition to renewables demands an overhaul of China's energy grid to accommodate intermittent energy sources like wind and solar. Investments in smart grids and energy storage technologies (eg, battery storage systems) will be critical. Decentralized energy systems: Promoting distributed energy systems, such as community solar projects or small-scale wind farms, can make RC accessible in regions dependent on FF.

Service and Information Technology (IT) Sector- While the service and IT sectors are less energy-intensive compared to manufacturing, they are rapidly growing in importance due to China's shift toward a knowledge-based economy. This sector can play a leading role in adopting clean technologies and digitization to reduce emissions further. Key Considerations: Adoption of RC for IT infrastructure: Data centers, which consume large amounts of electricity, could transition to using RC sources. Many tech companies are already moving toward carbon-neutral goals by investing in RE. Technological innovation in service delivery: Cloud computing, AI, and blockchain can reduce energy utilization and optimize business processes, indirectly contributing to the energy transition. Sector-Specific Policy Recommendations:

Manufacturing: Provide targeted subsidies for energy-efficient technologies and tax incentives for manufacturers transitioning to RC. Transportation: Strengthen policies encouraging EV adoption and enhance infrastructure investments for public and freight transport electrification. Agriculture: Promote RC use in rural areas and support technological advancements like precision farming for resource optimization. Energy sector: Invest in grid modernization, energy storage solutions, and distributed energy systems to support the rapid expansion of RE. IT and services: Encourage tech companies to set carbon-neutral targets and adopt RC in data centers while promoting energy-efficient technologies. In summary, sector-specific policies and technological innovations can significantly enhance the transition to RC and drive sustainability efforts in China. By focusing on each sector's unique needs and opportunities, China can more effectively balance economic development with environmental responsibility, advancing its position as a leader in global climate action.

In conclusion, this paper provides valuable insights into the nexus between EC, FF and RC consumption, POP dynamics, trade activities, GDP growth, and CO_2 emissions in China. The findings underscore the complex interplay among these variables and highlight the challenges and opportunities for achieving sustainable development in the world's largest energy consumer. Addressing these challenges requires a holistic approach integrating energy, environmental, and economic policies to foster green growth and mitigate climate change impacts. In conclusion, this study has provided valuable insights into the intricate nexus between EC, FF and RC consumption, POP dynamics, trade activities, GDP growth, and CO_2 emissions in China. Through rigorous econometric analysis, we have examined the long-term equilibrium relationships and short-term dynamics among these variables, shedding light on their complex interplay and implications for sustainable development.

The findings highlight the energy-intensive nature of China's economic development, characterized by heavy reliance on FF and significant CO_2 emissions. While electricity and FF consumption positively correlate with GDP growth, they also contribute to environmental degradation, posing challenges to achieving environmental protection. However, the growing deployment of RC sources signals a promising shift toward cleaner and more sustainable energy pathways, offering opportunities for mitigating carbon emissions and promoting green growth. POP dynamics, urbanization, and trade activities further shape energy utilization patterns and environmental outcomes, underscoring the need for integrated policy responses that consider socio-economic, demographic, and environmental dimensions. Policy interventions should prioritize energy efficiency measures, RC deployment, sustainable urban planning, and international cooperation to address the dual challenges of energy security and environmental protection.

Future research should continue to explore the dynamic interactions among energy utilization, economic indicators, and environmental outcomes, considering evolving socio-economic trends, technological advancements, and policy responses. Longitudinal studies tracking the effectiveness of energy and environmental policies, spatial analyses examining regional disparities, and comparative studies across countries and regions can deepen our understanding and inform evidence-based policy decisions. In conclusion, by adopting a holistic and integrated approach to energy and environmental policymaking, China can chart a course toward a more resilient, inclusive, and sustainable future. By prioritizing green growth, promoting RC deployment, and fostering international cooperation, China can emerge as a global leader in sustainable development, contributing to the well-being of its citizens and preserving the planet for future generations.

Author Contribution

Conceptualization, V.N.X.; Data duration, V.N.X.; Formal analysis, V.N.X.; Funding acquisition, V.N.X.; Investigation, V.N.X.; Methodology, V.N.X.; Project administration, V.N.X.; Resources, V.N.X.; Supervision, V.N.X.; Validation, V.N.X. Visualization, V.N.X; Writing—original draft, V.N.X.; Writing—review and editing, V.N.X. All authors have read and agreed to the published version of the manuscript.

ORCID iD

Vu Ngoc Xuan https://orcid.org/0000-0003-4364-9785

REFERENCES

1. Adebayo TS, Samour A. Renewable energy, fiscal policy and load capacity factor in BRICS countries: novel findings from panel nonlinear ARDL model. *Environ Dev Sustain*. 2023;26:4365-4389.
2. Anh NTM, Hoa LTK, Thao LP, et al. The effect of technology readiness on adopting artificial intelligence in accounting and auditing in Vietnam. *J Risk Financ Manag*. 2024;17:27.
3. Pata UK, Caglar AE. Investigating the EKC hypothesis with renewable energy consumption, human capital, globalization and trade openness for China: evidence from augmented ARDL approach with a structural break. *Energy*. 2021;216:119220.
4. Bogdan V, Rus L, Gherai DS, Florea AG, Bugnar NG. A streamline sustainable business performance reporting model by an integrated FinESG approach. *Sustainability*. 2023;15:16860.
5. Bui HM, Van Nguyen S, Huynh AT, et al. Correlation between nitrous oxide emissions and economic growth in Vietnam: an autoregressive distributed lag analysis. *Environ Technol Innov*. 2023;29:102989.
6. Pata UK, Erdogan S, Ozkan O. Is reducing fossil fuel intensity important for environmental management and ensuring ecological efficiency in China? *J Environ Manag*. 2023;329:117080.
7. Bui HN, Duong CD, Nguyen VQ, et al. Utilizing the theory of planned behavior to predict COVID-19 vaccination intention: a structural equational modeling approach. *Heliyon*. 2023;9:e17418.
8. Bui Minh T, Bui Van H. Evaluating the relationship between renewable energy consumption and economic growth in Vietnam, 1995–2019. *Energy Rep*. 2023;9:609-617.
9. Chen M, Liu J, Zhang N, Zheng Y. Vulnerability analysis method based on network and copula entropy. *Sci Rep*. 2024;26:192.
10. Chowdhury V, Tuli FM, Mitra SK. Sustainable shift: analyzing drivers for low-carbon transportation adoption in California's heavy-duty and off-road sectors. *Sustainability*. 2024;16:1722.
11. Dabić M, Daim T, Bogers MLAM, Mention A-L. The limits of open innovation: failures, risks, and costs in open innovation practice and theory. *Technovation*. 2023;126:102786.
12. Dahinine B, Laghouag A, Bensahel W, Alsolamy M, Guendouz T. Evaluating performance measurement metrics for lean and agile supply chain strategies in large enterprises. *Sustainability*. 2024;16:2586.
13. Deng X, Peng J, Wan C. The impact of internet use on land productivity: evidence from China land economy survey. *Sustainability*. 2024;13:262.
14. Ding R, Shen S, Zhu Y, et al. Evolution, forecasting, and driving mechanisms of the digital financial network: evidence from China. *Sustainability*. 2023;15:16072.
15. Do LAH, Le NTN, Mahmud S, et al. Impact and cost-effectiveness of strategies to prevent respiratory syncytial virus (RSV) disease in Vietnam: a modelling study. *Vaccine*. 2023;41:6782-6790.
16. Pata UK, Isik C. Determinants of the load capacity factor in China: a novel dynamic ARDL approach for ecological footprint accounting. *Resour Policy*. 2021;74:102313.
17. Pata UK, Kumar A. The influence of hydropower and coal consumption on greenhouse gas emissions: a comparison between China and India. *Water*. 2021;13:1387.
18. Pata UK, Olasehinde-Williams G, Ozkan O. Carbon efficiency in China: should we be concerned about the shadow economy and urbanization? *Geol J*. 2023;58:3646-3658.
19. Awosusi AA, Adebayo TS, Kirikkaleli D, Rjoub H, Altuntaş M. Evaluating the determinants of load capacity factor in Japan: the impact of economic complexity and trade globalization. *Nat Resour Forum*. 2024;48:743-762.
20. Adebayo TS, Awosusi AA, Oladipupo SD, et al. Dominance of fossil fuels in Japan's national energy mix and implications for environmental sustainability. *Int J Environ Res Public Health*. 2021;18:1-15.
21. Zapata O. Renewable energy and well-being in remote indigenous communities of Canada: s panel analysis. *Ecol Econ*. 2024;222:108219.
22. Zhang X, Xu W, Rauf A, Ozturk I. Transitioning from conventional energy to clean renewable energy in G7 countries: s signed network approach. *Energy*. 2024;307:132655.
23. Xu H, Gao Y, Wang C, et al. Exploring the nexuses between carbon dioxide emissions, material footprints and human development: an empirical study of 151 countries. *Ecol Indic*. 2024;166:112229.
24. Yasmeen R, Shah WUH. Energy uncertainty, geopolitical conflict, and militarization matters for renewable and non-renewable energy development: perspectives from G7 economies. *Energy*. 2024;306:132480.
25. Çobanoğulları G. Exploring the link between CO2 emissions, health expenditure, and economic growth in Türkiye: evidence from the ARDL model. *Environ Dev Sustain*. 2024;26:29605-29619.
26. Doleac A, Langar S, Sulbaran T. Balancing sustainability: an analysis of habitat for humanity affiliates in Mississippi. *Sustainability*. 2024;16:16090.
27. Duc DTV, Dat TT, Linh DH, Phong BX. Measuring the digital economy in Vietnam. *Telecommun Policy*. 2024;48:102683.
28. Duong CD, Vu NX. The single, complementary, balanced, and imbalanced influences of entrepreneurial attitudes and intentions on entrepreneurial behaviors: polynomial regression with response surface analysis. *Heliyon*. 2023;9:e14604.
29. Ehn M, Derneborg M, Revenäs, Cicchetti A. User-centered requirements engineering to manage the fuzzy front-end of open innovation in e-health: a study on support systems for seniors' physical activity. *Int J Med Inform*. 2021;154:104547.
30. Ernst D, Woithe F. Impact of the environmental, social, and governance rating on the cost of capital: evidence from the S&P 500. *Sustainability*. 2024;17:91.
31. Filgueiras IFLV, Melo FJCD, Guimaraes Junior DS, et al. Evaluation of the benefits generated by sustainability 4.0: a study of the perception of banking sector customers. *Sustainability*. 2024;16:2580.
32. Firoiu D, Ionescu GH, Cismaş LM, et al. Can Europe reach its environmental sustainability targets by 2030? A critical mid-term assessment of the implementation of the 2030 agenda. *Sustainability*. 2023;15:16650.
33. Firoiu D, Ionescu GH, Cojocaru TM, et al. Progress of EU member states regarding the bioeconomy and biomass producing and converting sectors. *Sustainability*. 2023;15:14128.
34. Haba HF, Bredillet C, Dastane O. Green consumer research: trends and way forward based on bibliometric analysis. *Cleaner and Responsible Consumption*. 2023;8:100089.

35. Hoa PX, Xuan VN, Phuong Thu NT. Nexus of innovation, renewable consumption, FDI, growth and CO2 emissions: the case of Vietnam. *J Open Innovat Technol Mark Complex*. 2023;9:100100.
36. Hoa PX, Xuan VN, Thu NTP. Determinants of renewable energy consumption in the fifth technology revolutions: evidence from ASEAN countries. *J Open Innovat Technol Mark Complex*. 2024;10:100190.
37. Khémiri W, Attia EF, Chafai A. How Financial Inclusion moderates the curvilinear Nexus between tangible investment and sustainable firm growth: new evidence from the Middle East and North Africa Region. *Sustainability*. 2024;16:2573.
38. Khezri R, Steen D, Anh Tuan L. Willingness to participate in vehicle-to-everything (V2X) in Sweden, 2022—using an electric vehicle's battery for more than transport. *Sustainability*. 2024;16:1792.
39. Lappalainen L, Aleem M, Sandberg B. How to manage open innovation projects? An integrative framework. *Proj Leadersh Soc*. 2023;4:100095.
40. Lastunen J, Richiardi M. Forecasting recovery from COVID-19 using financial data: an application to Vietnam. *World Dev Perspect*. 2023;30:100503.
41. Le TH. Connectedness between nonrenewable and renewable energy consumption, economic growth and CO2 emission in Vietnam: new evidence from a wavelet analysis. *Renew Energy*. 2022;195:442-454.
42. Lee S, Kim YJ. Analyzing factors that affect Korean B2B companies' sustainable performance. *Sustainability*. 2024;16:1719.
43. Lee W. How consideration of future consequences, prior gain or loss, personal risk profile, and justification affect risk–payoff preferences. *Sustainability*. 2024;17:83.
44. Li S, Samour A, Irfan M, Ali M. Role of renewable energy and fiscal policy on trade adjusted carbon emissions: evaluating the role of environmental policy stringency. *Renew Energy*. 2023;205:156-165.
45. Liu F, Chen H, Zhang S. Nexus among corruption, political instability and natural resources on economic recovery in Vietnam. *Resour Policy*. 2023;85:103743.
46. Liu Z, Sun Y, Xing C, et al. Artificial intelligence powered large-scale renewable integrations in multi-energy systems for carbon neutrality transition: challenges and future perspectives. *Energy and AI*. 2022;10:100195.
47. Liu Z, Zhou Y, Yan J, Tostado-Véliz M. Frontier ocean thermal/power and solar PV systems for transformation towards net-zero communities. *Energy*. 2023;284:128362.
48. Miremadi I, Khoshbash M, Saeedian M. Fostering generativity in platform ecosystems: how open innovation and complexity interact to influence platform adoption. *Res Policy*. 2023;52:104781.
49. Simba A, Tajeddin M, Farashahi M, Dana L-P, Maleki A. Internationalising high–tech SMEs: advancing a new perspective of open innovation. *Technol Forecast Soc Change*. 2024;200:123145.
50. Yuen MK, Ngo T, Le TDQ, Ho TH. The environment, social and governance (ESG) activities and profitability under COVID-19: evidence from the global banking sector. *J* Dev *Econ*. 2022;24:345-364.
51. Neacșu M, Georgescu IE. Analysing the impact of crises on financial performance: empirical insights from tourism and transport companies listed on the Bucharest stock exchange (during 2005–2022). *Sustainability*. 2024;17:80.
52. Nga NTV, Xuan VN, Trong VA, Thao PH, Doanh DC. Perceived barriers and intentions to receive COVID-19 vaccines: psychological distress as a moderator. *Vaccines*. 2023;11:289.
53. Nguyen HT, Nguyen SV, Dau V-H, et al. The nexus between greenhouse gases, economic growth, energy and trade openness in Vietnam. *Environ Technol Innov*. 2022;28:102912.
54. Nguyen TTC, Nguyen CV. Does the education level of the CEO and CFO affect the profitability of real estate and construction companies? Evidence from Vietnam. *Heliyon*. 2024;10:e28376.
55. Giang MH, Trung BH, Yoshida Y, Xuan TD, Que MT. The causal effect of access to finance on productivity of small and medium enterprises in Vietnam. *Sustainability*. 2019;11:5451.
56. Han Y, Zhe C, Liu X. Is the carbon emissions trading system conducive to the urban green technology innovation level? Evidence from China. *Energy Rep*. 2023;9:3787-3799.
57. Hoa PX, Xuan VN, Phuong Thu NT. Determinants of the renewable energy consumption: the case of Asian countries. *Heliyon*. 2023;9:e22696.
58. Balsalobre-Lorente D, Contente dos Santos Parente C, Leitão NC, Cantos-Cantos JM. The influence of economic complexity processes and renewable energy on CO2 emissions of brics. What about industry 4.0? *Resour Policy*. 2023;82:103547.
59. Balsalobre-Lorente D, Nur T, Topaloglu EE, Evcimen C. Assessing the impact of the economic complexity on the ecological footprint in G7 countries: fresh evidence under human development and energy innovation processes. *Gondwana Res*. 2024;127:226-245.
60. Balsalobre-Lorente D, Shahbaz M, Murshed M, Nuta FM. Environmental impact of globalization: the case of central and Eastern European emerging economies. *J Environ Manag*. 2023;341:118018.
61. Chen C, Pinar M, Stengos T. Renewable energy and CO2 emissions: new evidence with the panel threshold model. *Renew Energy*. 2022;194:117-128.
62. Chen K-S, Wu CF, Tsaur R-C, Huang T-H. Fuzzy evaluation and improvement decision-making model for machining operation performance. *Appl Sci*. 2023;13:1430.
63. Chen N, Wang Y, Li J, Wei Y, Yuan Q. Examining structural relationships among night tourism experience, lovemarks, brand satisfaction, and brand loyalty on "cultural heritage night" in South Korea. *Sustainability*. 2020;12:6723.
64. Wang B, Wang C. Green finance and technological innovation in heavily polluting enterprises: evidence from China. *Int J Environ Res Public Health*. 2023;20:1-15.
65. Wang J, Zhang Z, Wang Q, et al. Integrated a fused silica capillary cell and in situ Raman spectroscopy for determining the solubility of CO2 in n-decane and n-decane + n-hexane system. *Processes*. 2023;11:1137.
66. Wang W, Liu L, Yang Y. Spatial matching analysis and development strategies of county night-time economy: a case of Anning County, Yunnan Province. *Sustainability*. 2022;14:4891.
67. Wang X, Li Z, Feng Z. Classification of shrinking cities in China based on self-organizing feature map. *Land*. 2022;11:1525.
68. Zhang Z, Li H, Cao Y. Research on the coordinated development of economic development and ecological environment of nine provinces (regions) in the Yellow River Basin. *Sustainability*. 2022;14:13102.
69. Khan MK, Khan MI, Rehan M. The relationship between energy consumption, economic growth and carbon dioxide emissions in Pakistan. *Financ Innovation*. 2020;6:1.
70. Khan MK, Teng J-Z, Khan MI. Effect of energy consumption and economic growth on carbon dioxide emissions in Pakistan with dynamic ARDL simulations approach. *Environ Sci Pollut Res*. 2019;26:23480-23490.
71. Khan MK, Teng J-Z, Khan MI, Khan MO. Impact of globalization, economic factors and energy consumption on CO2 emissions in Pakistan. *Sci Total Environ*. 2019;688:424-436.
72. Khattak SI, Khan AM, Khan MK, et al. Do regional government green innovation preferences promote industrial structure upgradation in China? Econometric assessment based on the environmental regulation threshold effect model. *Front Environ Sci*. 2022;10:1-19.
73. Kilinc-Ata N, Alshami M. Analysis of how environmental degradation affects clean energy transition: evidence from the UAE. *Environ Sci Pollut Res*. 2023;30:72756-72768.
74. Hoa P, Xuan V, Thu N. Nexus of migration, population and economic growth: the case of Vietnam. *Migr Lett*. 2023;20:1187-1201.
75. Nguyen Thi Ngoc A. Regional determinants of FDI location in Vietnam. *J Dev Econ*. 2016;30:19-37.
76. Nguyen Thi Phuong T, Pham Xuan H, Vu Ngoc X. Nexus of carbon dioxide emissions, fossil fuel, foreign direct investments, and exports to renewable energy: new evidence from Singapore. *Migr Lett*. 2023;21:237-258.
77. Nguyen TT, Nguyen VC. Financial development and renewables in Southeast Asian countries—the role of organic waste materials. *Sustainability*. 2021; 13:8748.
78. Phan TH. Working conditions, export decisions, and firm constraints-evidence from Vietnamese small and medium enterprises. *Sustainability*. 2022;14:7541.
79. Phan TH, Stachuletz R, Nguyen HTH. Export decision and credit constraints under institution obstacles. *Sustainability*. 2022;14:5638.
80. Auteri M, Mele M, Ruble I, Magazzino C. The double sustainability: the link between government debt and renewable energy. *J Econ Asymmetries*. 2024;29:e00356.
81. Ojekemi OS, Ağa M, Magazzino C. Towards achieving sustainability in the BRICS economies: the role of renewable energy consumption and economic risk. *Energies*. 2023;16:5287.
82. Magazzino C, Mele M, Morelli G. The relationship between renewable energy and economic growth in a time of Covid-19: a machine learning experiment on the Brazilian economy. *Sustainability*. 2021;13:1285.
83. Magazzino C, Mele M, Schneider N, Shahzad U. Does export product diversification spur energy demand in the APEC region? Application of a new neural networks experiment and a decision tree model. *Energy Build*. 2022;258:111820.
84. Li R, Wang Q, Liu Y, Jiang R. Per-capita carbon emissions in 147 countries: the effect of economic, energy, social, and trade structural changes. *Sustain Prod Consumption*. 2021;27:1149-1164.
85. Wang Q, Cheng X, Pata UK, Li R, Kartal MT. Intermediating effect of mineral resources on renewable energy amidst globalization, financial development, and technological progress: Evidence from globe based on income-groups. *Resour Policy*. 2024;90:104798.
86. Wang Q, Ge Y, Li R. Does improving economic efficiency reduce ecological footprint? The role of financial development, renewable energy, and industrialization. *Energy Environ*. 2023;10:0958305X231183914.
87. Wang Q, Hu S, Li R. Could information and communication technology (ICT) reduce carbon emissions? The role of trade openness and financial development. *Telecommun Policy*. 2024;48:102699.
88. Wang Q, Zhang F, Li R, Sun J. Does artificial intelligence promote energy transition and curb carbon emissions? The role of trade openness. *J Clean Prod*. 2024;447:141298.

89. Pata UK. Renewable and non-renewable energy consumption, economic complexity, CO2 emissions, and ecological footprint in the USA: testing the EKC hypothesis with a structural break. *Environ Sci Pollut Res*. 2021;28:846-861.
90. Hoa PX, Xuan VN, Thu NTP, Huong LM. Nexus of innovation, foreign direct investment, economic growth and renewable energy: new insights from 60 countries. *Energy Rep*. 2024;11:1834-1845.
91. Obschonka M, Tavassoli S, Rentfrow PJ, Potter J, Gosling SD. Innovation and inter-city knowledge spillovers: social, geographical, and technological connectedness and psychological openness. *Res Policy*. 2023;52:104849.
92. Parker S. A decoupling analysis of transport CO2 emissions from economic growth: evidence from Vietnam. *Int J Sustain Transp*. 2022;16:928-941.
93. Patel S, Parkins JR. Assessing motivations and barriers to renewable energy development: Insights from a survey of municipal decision-makers in Alberta, Canada. *Energy Rep*. 2023;9:5788-5798.
94. Bilgili F, Koçak E, Bulut. The dynamic impact of renewable energy consumption on CO2 emissions: a revisited environmental Kuznets curve approach. *Renew Sustain Energ Rev*. 2016;54:838-845.
95. Salman D, Ismael D. The effect of digital financial inclusion on the green economy: the case of Egypt. *J Dev Econ*. 2023;25:120-133.
96. Hoicka CE, Savic K, Campney A. Reconciliation through renewable energy? A survey of indigenous communities, involvement, and peoples in Canada. *Energy Res Soc Sci*. 2021;74:101897.
97. Xuan VN, Hoa PX, Thu NTP, Huong LM. Factors affecting environmental pollution for green economy: the case of ASEAN countries. *Environ Chall*. 2024;14:100827.
98. Xuan VN, Huong LM, Thu NTP, Hoa PX. Carbon dioxide emissions, population, foreign direct investment, and renewable energy nexus: new insights from Thailand. *Energy Rep*. 2024;11:4812-4823.
99. Zhao W-X, Samour A, Yi K, Al-Faryan MAS. Do technological innovation, natural resources and stock market development promote environmental sustainability? Novel evidence based on the load capacity factor. *Resour Policy*. 2023;82:103397.
100. Zhou Y, Liu Z. A cross-scale 'material-component-system' framework for transition towards zero-carbon buildings and districts with low, medium and high-temperature phase change materials. *Sustain Cities Soc*. 2023;89:104378.
101. Zhou Y, Zheng S, Lei J, Zi Y. A cross-scale modelling and decarbonisation quantification approach for navigating carbon neutrality pathways in China. *Energy Convers Manag*. 2023;297:117733.
102. Ghazouani T, Maktouf S. Impact of natural resources, trade openness, and economic growth on CO_2 emissions in oil-exporting countries: a panel autoregressive distributed lag analysis. *Nat Resour Forum*. 2024;48:211-231.
103. Xuan VN. Determinants of environmental pollution: evidence from Indonesia. *J Open Innovat Technol Mark Complex*. 2024;10:100386.
104. Xuan VN. Factors affecting renewable energy for sustainable development: the case of the Philippines. *Environ Health Insights*. 2024;18:11786302241288856.
105. Wadström C, Wittberg E, Uddin GS, Jayasekera R. Role of renewable energy on industrial output in Canada. *Energy Econ*. 2019;81:626-638.
106. Wahyono Y, Sasongko NA, Trench A, et al. Evaluating the impacts of environmental and human health of the critical minerals mining and processing industries in Indonesia using life cycle assessment. *Case Studies in Chemical and Environmental Engineering*. 2024;10:100944.
107. Xia Y, Md Johar MG. Government support, employee structure and organisational digital innovation: Evidence from China. *Heliyon*. 2024;10:e36399.
108. Adebayo TS, Akadiri SS, Altuntaş M, Awosusi AA. Environmental effects of structural change, hydro and coal energy consumption on ecological footprint in India: insights from the novel dynamic ARDL simulation. *Environ Dev Sustain*. 2023;25:14309-14332.
109. Adebayo TS, Awosusi AA, Bekun FV, Altuntaş M. Coal energy consumption beat renewable energy consumption in South Africa: developing policy framework for sustainable development. *Renew Energy*. 2021;175:1012-1024.
110. Alam MM, Murshed M, Ozturk I, Khudoykulov K. Macroeconomic determinants of non-renewable and renewable energy consumption in India: the roles of international trade, innovative technologies, financial globalization, carbon emissions, financial development, and urbanization. *Energy*. 2024;308:132939.
111. Albuquerque D, Damásio J, Santos D, et al. Leveraging the innovation index (IVI): a research, development, and innovation-centric measurement approach. *J Open Innovat Technol Mark Complex*. 2024;10:100346.
112. Awosusi AA, Ozdeser H, Ojekemi OS, Adeshola I, Ramzan M. Environmental sustainability in Vietnam: evaluating the criticality of economic globalisation, renewable energy, and natural resources. *Environ Sci Pollut Res*. 2023;30:75581-75594.
113. Awosusi AA, Ozdeser H, Seraj M, Adegboye OR. Achieving carbon neutrality in energy transition economies: exploring the environmental efficiency of natural gas efficiency, coal efficiency, and resources efficiency. *Clean Technol Environ Policy*. 2024;20:1-21.
114. Boucher M, Pigeon M-A. Scaling renewable energy cooperatives for a net-zero Canada: challenges and opportunities for accelerating the energy transition. *Energy Res Soc Sci*. 2024;115:103618.
115. Ding C, Awosusi AA, Abbas S, Ojekemi OR. Formulating ecological sustainability policies for India within the coal energy, biomass energy, and economic globalization framework. *Environ Sci Pollut Res*. 2023;30:112758-112772.
116. Duran S, Hrenyk J, Sahinyazan FG, Salmon E. Re-righting renewable energy research with Indigenous communities in Canada. *J Clean Prod*. 2024;445:141264.
117. Ahmad E, Khan D, Anser MK, et al. The influence of grid connectivity, electricity pricing, policy-driven power incentives, and carbon emissions on renewable energy adoption: exploring key factors. *Renew Energy*. 2024;232:121108.
118. Bui Minh T, Nguyen Ngoc T, Bui Van H. Relationship between carbon emissions, economic growth, renewable energy consumption, foreign direct investment, and urban population in Vietnam. *Heliyon*. 2023;9:e17544.
119. Arifin Z, Falahudin D, Saito H, et al. Indonesian policy and researches toward 70% reduction of marine plastic pollution by 2025. *Mar Pol*. 2023;155:105692.
120. Farda M, Balijepalli C. Exploring the effectiveness of demand management policy in reducing traffic congestion and environmental pollution: car-free day and odd-even plate measures for Bandung city in Indonesia. *Case Stud Transp Policy*. 2018;6:577-590.
121. Finenko A, Thomson E. Future carbon dioxide emissions from Vietnam's coal power generation sector. *Energy Proc*. 2014;61:1519-1523.