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EMERGING SUSTAINABLE ENERGY TECHNOLOGIES TO COMBAT CLIMATE CHANGE: EVIDENCE USING NON-LINEAR ARDL ESTIMATION

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Annotation. Economies, either developed or developing, face problems in the form of climatic issues as they fail to restrict greenhouse gas emissions. The challenge increases as these emissions are due to high levels of consumption of non-renewable energy. Thus, in order to mitigate emissions, especially CO2, it is imperative to enhance the green energy share of the energy supply. Interestingly, scholars agree that public sector investment to raise renewable energy is significant, hence they hypothesize that investment is crucial for the technological advancement needed to increase sustainable energy production and supply. The circumstantial role of sustainable technology cannot be overlooked, as it boosts green energy supply and protects the environment. Because of climate complexities and rapid urbanization, a zero-carbon economy is not easy to achieve. To address the issues, countries must find effective ways to restrict carbon emissions, which is only possible if they are aware of the potential determinants of carbon emissions. Based on refined indicators, this study presents a comprehensive model to quantify the role of sustainable energy technologies in climate

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change in the context of China between 1991 and 2020. Through autoregressive distributed lag estimations, it reveals that renewable energy consumption and production, along with advanced technologies, are blessings for an economy trying to reduce carbon emissions. However, economic activity, rapid urbanization and industrial structures are responsible for high emissions. The findings suggest that certain target policies must be implemented to reduce carbon emissions. Also, there should be a proper platform to promote green technology at a regional level along with effective urban development strategies.

Keywords: sustainable energy technologies, renewable energy production, technology adoption, CO2 emissions, urbanization, industrialization, zero carbon economy.

JEL classification: Q56, Q54, O14, Q55, Q01.

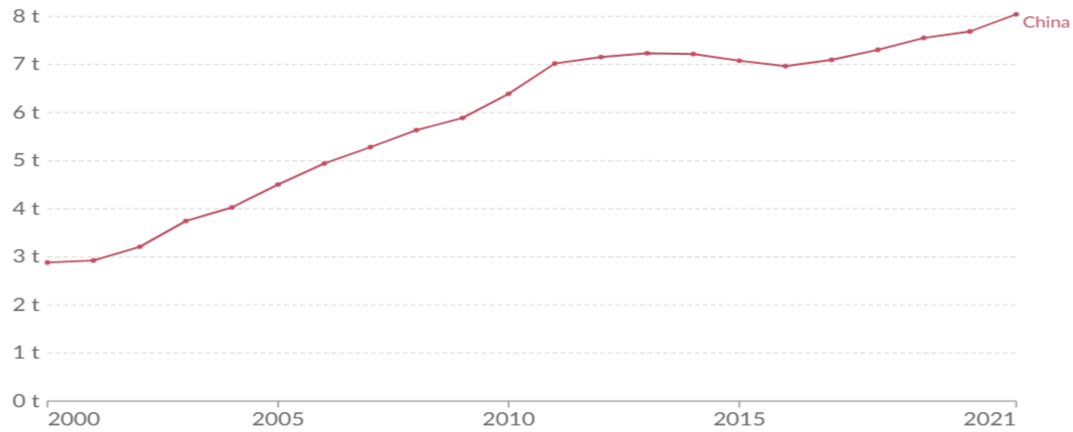
Introduction

Environmental pollution is rising, and therefore designing strategies for sustainable economies with zero-carbon energy sources is of paramount significance. Although the economy of China is world renowned for its achievements, due to resource shortages and high pollution it is difficult to maintain its traditional economic growth model (Paramati *et al.*, 2021). China, thus, has begun to transform its economic model and explore more sustainable ways to maintain growth. China has recently pledged to reduce its carbon emissions by 60-65% by 2030. The country is currently the largest carbon emitter in the world (Khattak *et al.*, 2022).

Urbanization and industrialization continue, meaning drastic changes to energy consumption and industrial structures (Sharif *et al.*, 2020; Sibuea *et al.*, 2021). Asia is repositioning itself in terms of energy consumption, which should result in environmental benefits. However, executing this transformation is a thorny issue due to difficulties achieving subsidy reforms for non-renewable energy and high supply risk for oil and gas. In 2017, energy related carbon emissions increased by 1.6%, and predictions are that this is likely to grow more in coming years, detracting from climate change objectives (Zhao *et al.*, 2021). Thus, it seems objective fact that the emission ratio might either remain unchanged or increase by 2040. Even with abundant studies, the issue of carbon emissions remains a burning topic for academics, economists, international organizations and governmental institutions (Ganda, 2019). Currently, the primary solution is green development, which not only reduces overall energy consumption but also minimizes harmful emissions, making it a meaningful proposition for economies, especially developing economies.

In China, the climate has become more humid and warmer over the last 60 years. The total area of drought has lessened by nearly 65,000 square kilometres. This humidity leads to air and water pollution. Swift urbanization is partly responsible for climate change, and the urbanization rate has increased from 17.92% in 1978 to 58.5% in 2017, and is predicted to reach more than 76.0% by 2050 (Vu *et al.*, 2023. This increase leads to a decrease in urban land and more consumption of natural resources, including forests. The temperature is rising at an alarming rate, harmful to human well-being, and there is research showing that the death rate among older adults (>65) increases by 2.73% for every 1°C increase in temperature. The air quality in China is poor, with 235 of its 338 cities exceeding the national ambient air quality standard limit (Li *et al.*, 2024; Liguo *et al.*, 2022). Climate change in China is mainly due to the increase in industrial areas and continuous deforestation of trees which absorb the greenhouse gases (GHGs) responsible for warming. This increase in temperature causes drought, and the production of maize in

China has lessened by 2-32%. The pressure of the worsening climate has forced the government and industries to adopt new technologies to address these harmful changes. Firstly, a decrease in the consumption of fossil fuels is a basic measure to reduce GHG emissions. The latest sustainable energy technologies use renewable energy (RE) instead of fossil fuels (Lestari, Soewarno, 2024; Lin *et al.*, 2022).



Source: created by the authors.

Figure 1. **CO2 Emission in China**

China, since 2007, has been ranked first in the world for carbon emissions, making it an arduous task to reduce emissions. Many studies consider carbon reduction driving factors. Sustainable technologies are an effective solution, linking energy resources and renewable materials, and thereby lessening the use of natural resources and reducing harmful emissions (Hussain *et al.*, 2022; Raihan, Bari, 2024). Clean technologies are essential models for economies and firms. They can lead to a sharp decline in dirty fuel use and emissions. Studies affirm that energy saving technologies have the potential to reduce carbon emissions (Ulubeyli, Kazanci, 2018; Yerlikaya *et al.*, 2020). However, in the case of China, an absolute reduction is not easily achievable due to high population growth and complex energy infrastructure. The production of energy mainly relies on coal, and smooth transition once and for all is not easy. Carbon reduction is not a one-time process, but a continuous progression, only possible when constant change occurs in industrial structures and technological achievement (Gomes *et al.*, 2024; Wang *et al.*, 2021). It is imperative to study the simultaneous roles of energy consumption, sustainable technologies, industrialization and population growth on carbon emissions, which offers an interesting theoretical perspective and has practical significance for China.

This study uses various econometric methods to assess its constructs. Based on time series data, the paper presents an analysis focusing on the combined effects of energy consumption, sustainable technologies, industrialization and population growth on carbon emissions. We ensure reliable conclusions by administering a robustness test. The study makes multiple contributions. Firstly, conducting the research at country level, taking China as our study area, has great significance as China is responsible for high carbon emissions and energy consumption. Secondly, using multiple econometric methods and assessing the role of sustainable technologies, we explore the driving factors of carbon emissions and produce evidence at country level which is helpful for strategy development in accordance with local conditions. Although we only consider China as our study sample, evidence from the study is useful for global governance as climate change is not a country-specific issue. Learning from the case of China makes it easier to design certain targeted strategies to promote renewable technological progress for economies struggling with similar issues and facing serious pressure from international communities.

1. Literature Review

dependence on fossil fuels to generate power has increased. Fossil fuels are embedded in almost all daily activity, and as a result the GHG released from burning has reached a historically high level. The increase in GHG results in global warming and other climate change issues. The solution to these problems is RE, which almost has no effect on the environment has compared to the burning of fossil fuels (Bhuiyan *et al*., 2023; Khan *et al*., 2020b). Alola *et al*. (2019) assess whether RE consumption affects climate change in Europe, and propose an association. Charfeddine and Kahia (2019) investigate whether consumption of RE affects climate change and propose a positive relationship between the variables. The literature suggests that the role of governments is vital for controlling climate change by promoting renewable energy and educating populations them about the dangers of non-renewable energy and the benefits of renewable energy (Zhang, 2024).

Renewable energy is the key to a carbon-free future and meeting the goal of 2oC of warming. RE's share of the total energy consumption has increased from 19% to 65% between 2017 and the present. In the energy sector, RE production is at the centre of studies, because it is directly linked to the environment (Kamarudin *et al*., 2021; Kamran *et al*., 2024). In this context, Solaun and Cerdá (2019) assess whether RE production has any effect on climate change, and the results propose a strong impact. Most RE sources are climate condition driven. There are some barriers to renewable power plants. A shortage of recourses is the main barrier, as the power plants require specific weather and climate conditions which might change significantly in the future. Accordingly, Sarkodie *et al*. (2020) assess whether RE production impacts the climate, and show that RE production affects CO2 emissions. To reduce the speed of climate change, the emission of CO2 must be controlled, and therefore, a greater and more efficient use of renewable sources is required in the future. Hydroelectric generation has more than 1000GW of installed capacity, but an annual increase is needed. The world now understands the importance of the environment, and therefore people have started taking steps to address it. The conversion from non-renewable to RE is a big step towards a safer future. Gernaat *et al*. (2021) suggest that RE production impacts the climate, proposing an association between RE production and climate change.

Extensive research has been conducted and empirical evidence collected on the association between technology and environmental quality. On the basis of the findings of a set of studies, technological innovation introduces advancements in technology that help countries restrict carbon emissions (Khan *et al*., 2020a). However, there are also studies which claim that technological innovation, even though it introduces energy-efficient technologies, is less significant at controlling harmful emissions (Bai *et al*., 2020; Sinha *et al*., 2020). Interestingly, scholars argue that, when renewable energy sources are introduced in technological development, they help in the betterment of environmental quality (He *et al*., 2023; Sohail *et al*., 2021). On the contrary, in countries relying on conventional energy resources, there is a possibility that, even with advancements in technology, the country may not be able to control pollution, causing environmental degradation. This is often the case in developing nations, especially those in Asia (Fuyane *et al*., 2021; Zhao *et al*., 2022).

Kuhl (2020) examine the relationship between adopting new technologies and climate change in the US and designs a mechanism to overcome the barriers to adopting new technology. Many technologies have been designed to manage water and land resources and the timing of crop seeding in response to climate change risk. Their adoption is based on case selection and regional selection. The results show that many farmers cope with severe or extreme weather by adopting new technologies which can save crops. Climate change is a major problem for smallholder households, affecting food security and income in southern African countries. Mutenje *et al*. (2019) examine how the adoption of technology in the agricultural sector protects households from the effects of climate change. Climate-smart agriculture (CSA) advancements involve interventions that increase economic efficiency. The empirical strategy of South African countries is CSA implementation, and, in general, the outcomes show that bundles containing each CSA methodology, soil and water preservation and grain vegetable broadening, create positive monetary advantages in terms of compensation for heterogeneous smallholders. Portability and vehicle automation are set to develop quickly over the decades. 15% of Americans were involved in on-request portability supervision in 2016. New technology has been designed to reduce climate change. Technology does not only mean software or hardware, but also methods and mechanisms. Jones & Leibowicz (2019) assess the concept of the shared automation vehicle (SVA), which could reduce ozone-depleting substance discharge by driving proficiently and speeding up the reception of elective fuel vehicles. In conclusion, the energy framework enhancement model investigates the likely commitment of SAVs to environmental change moderation actions, displaying incorporated power and transport areas and catching a rich arrangement of components through which SAVs impact CO2 discharge.

Econometric models of temperature impact on country-level GDP are progressively used to reduce worldwide temperature change harm. Newell *et al*. (2021) assess the relationship between GDP and climatic change. The major problem that climate change proposes is an increase in temperature, increasing power use to meet the electricity needs of hotter weather. Governments subsidize electricity for the well-being of people. The indicator selection methodology estimates that, by the year 2100, a 13oC increase could cause 23% global economic loss. Climate change poses a risk to the tourism sector, the chief source of income for more than 90 countries. Scott *et al*. (2019) assess the relationship between global tourism vulnerability and climate change. The World Travel and Tourism Council (WTTC) calculated the sectorial pledge to the worldwide economy in 2015 to be US$7.2 trillion, constituting 9.8% of global GDP and 9.1% of occupations around the world, around 284 million jobs. Climate change alters the natural environmental state. Food, security and the capacity to meet travel charges are other factors affected by climate change. Progress toward aggressive environmental targets normally depends on advancing monetary development, decreasing use of regular resources and decreasing GHG emissions. Ge & Lin (2021) assess the relationship between GDP, resource use and GHG emissions. Empirical studies of decoupling show that relative decoupling is useful for GHG and CO2 emissions. GHG emissions are increasing, changing the environment, and governments of developed countries such as the USA need to shift towards renewable technologies, which puts pressure on GDP. To conclude, large, rapid and absolute decreases in GHG emissions cannot be accomplished by decoupling (Chen *et al*., 2019; Qing *et al*., 2024).

Udemba (2022) assess whether the energy implications of industrialization have any impact on the climate. The results propose a direct association between industrialization and climate change. Adverse natural phenomena due to human activity have become an environmental concern due to fossil fuel combustion and deforestation. Opoku & Boachie (2020) investigate whether industrialization and foreign direct investment collectively impact the climate. The results propose that industrialization, economic mobility, territorial expansion, population growth, urban emergencies, and alteration of the global system all contribute to climate change. Rehman *et al*. (2021) investigate whether industrialization has any impact on the climate of Pakistan in a study conducted from 1971 to 2019. The results propose that an increase in industrialization increases carbon emissions in Pakistan.

Urbanization is an important symbol of modernization and plays an indispensable role in the growth and advancement of contemporary economies and societies. People are moving to cities across the world, and the world's urban population surpassed the rural population for the first time in 2007 (Haberl *et al.*, 2020). The global urban population expanded from 1.35 billion to 4.22 billion between 1970 and 2018, while the urbanization rate climbed from 36.6% to 55.3%. Global urbanization is set to continue to accelerate. By 2050, the world's urban population might approach 6.6 billion, with an urbanization rate of 68%. Wang *et al*. (2020) investigate whether urbanization affects climate in the OECD nations, using an autoregressive distributed lag (ARDL) approach. The results propose an association between urbanization and climate change in the OECD economies. Since 1970, the world has seen tremendous urbanization expansion, and the cumulative CO2 emissions from human activities accounts for almost half the total since the Industrial Revolution. Currently, the top 600 cities in the world contain 20% of the world's population, generate 60% of GDP, and produce 70% of greenhouse gases. Anwar *et al*. (2020) assess whether urbanization affects the climate in East Asian economies. The results propose a direct association between urbanization and climate. Based on synchronous changes in urbanization development and carbon emissions, the literature claims that urbanization and carbon emissions have intrinsic linkages. As the world has focused on completing the urbanization process over the last few decades, the rise in carbon emissions has slowed. Accordingly, Cai *et al*. (2019) investigate the nexus between urbanization and climate in a study conducted in China and America, and the results propose an association.

Based on the literature synthesized above, we can conclude that most existing literature emphasizes either innovation and economic growth or innovation and environmental quality. Both are controversial in nature due to contradictory statements; hence, we fill a gap by exploring the association between sustainable technologies and carbon emissions along with the role of economic growth in the context of China. Therefore, the prime purpose of this study is to evaluate the related effect of sustainable technologies that majorly contribute to China's sustainable development. This evidence is crucial to the development of effective policies. Moreover, the study endeavours to determine the various renewable channels through which technological adoption influences the sustainability of a country. We investigate carbon emissions in order to be aware of the advancements in sustainable technologies through which we are able to identify whether sustainable technological advancement helps pollution reduction, ensuring its support of sustainable development goals.

2. Methodology

2.1 Theoretical Framework

Previous studies propose logical reasoning to justify the identification of carbon emissions through the IPAT model (Nelson *et al.*, 2018; Qamruzzaman, Jianguo, 2018). The theoretical lens of the IPAT model explains the relationships between environmental impact, technology, population and income. In the model, I represent pollution or environmental impact due to the sources such as population abbreviated as P, economic activity level, A, and technology, T, which represents the pollution amount per unit consumption. The model is further developed in the extended version introduced by Dietz and Rosa (1994;1997), a stochastic version known as the stochastic impacts by regression on population, affluence and technology (STIRPAT) model. The main benefit of the STIRPAT model is that it can be applied to test hypotheses empirically. Thus, the study frames the following equation based on the selection of variables:

$$PCCE_{it} = f(REP_{it}, REC_{it}, TAD_{it}, URB_{it}, GDP_{it}, IND_{it}) \text{ .... eq (1)}$$

The above model comes from the work of Shan *et al*. (2021). Equation 1 indicates that renewable energy production and consumption and technology adoption impact carbon emissions along with other dominant determinants such as urbanization, economic growth and industrialization, where:

PCCE = Per capita CO2 emission

t = Time period

REP = Renewable energy production

REC = Renewable energy consumption

TAD = Technology adoption

URB = Urbanization

GDP = Gross domestic product

IND = Industrialization

We use WDI and OECD as sources of data from 1991 to 2020. The article measures CO2 emissions in metric tons per capita. Emerging sustainable energy technologies are used as the study predictor and measured through electricity output and RE consumption. The rest of the variables are given in *Table 1*.

Table 1. Measurements of Variables

S#	Variable	Measurement
01	Climate Change	CO2 emissions (metric tons per capita)
02	Emerging Sustainable Energy Technologies	Renewable electricity output (% of total electricity output) Renewable energy consumption (% of total energy consumption)
03	Technology Adoption	High technology exports (% of manufactured exports)
04	Gross Domestic Product	GDP growth (annual %)
05	Urbanization	Urban population (% of total population)
06	Industrialization	Industry value added (% of GDP)

Source: WDI.

We use descriptives to study trends in the variables and a correlation matrix to examine the directional linkages among the variables. The study runs the augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) tests to check the unit root among the constructs. The equation for the tests is:

$$d(Y_t) = \alpha_0 + \beta t + \Upsilon Y_{t-1} + d(Y_t(-1)) + \mathcal{E}_t \qquad \text{eq (2)}$$

The study also runs the ARDL bound test to check the cointegration among the variables. The ADF and PP test results show that ARDL is suitable. A feature of the ARDL model is that it accounts for heteroscedasticity and autocorrelation issues. The ARDL equation is:

$$\Delta PCCE_t = \alpha_0 + \sum\delta_1\Delta PCCE_{t-1} + \sum\delta_2\Delta REP_{t-1} + \sum\delta_3\Delta REC_{t-1} + \sum\delta_4\Delta TA_{t-1} + \sum\delta_5\Delta GDP_{t-1} + \sum\delta_6\Delta URB_{t-1} + \sum\delta_7\Delta IND_{t-1} + \varphi_1 PCCE_{t-1} + \varphi_2 REP_{t-1} + \varphi_3 REC_{t-1} + \varphi_4 TA_{t-1} + \varphi_5 GDP_{t-1} + \varphi_6 URB_{t-1} + \varphi_7 IND_{t-1} + \mathcal{E}_t \quad \text{eq (3)}$$

The intention is to examine the asymmetric linkage between urbanization, GDP, industrialization and CO2 emissions. Thus, the nonlinear function is established as:

$$PCCE = f\ (REP, REC, TA, GDP^+, GDP^-, URB^+, URB^-, IND^+, IND^-) \quad \text{eq (4)}$$

Hence, the empirical model is:

$$PCCE_t = \alpha_0 + \beta_1 REP_t + \beta_2 REC_t + \beta_3 TA_t + \beta_4 {GDP_t}^+ + \beta_5 {GDP_t}^- + \beta_6 {URB_t}^+ + \beta_7 {URB_t}^- + \beta_8 {IND_t}^+ + \beta_9 {IND_t}^- + e_t \quad \text{eq (5)}$$

The article also investigates the nonlinear association of urbanization, GDP, industrialization and CO2 emissions. The equations given below show the partial sum of positive and negative changes in urbanization, GDP and industrialization:

$$GDP^+ = \sum_{i=1}^{t} \Delta GDP_i^+ = \sum_{i=1}^{t} \max\ (\Delta GDP_i\ 0) \quad \text{eq } \mathbf{(6)}$$

$$GDP^- = \sum_{i=1}^{t} \Delta GDP_i^- = \sum_{i=1}^{t} \min\ (\Delta GDP_i\ 0) \quad \text{eq } \mathbf{(7)}$$

$$URB^+ = \sum_{i=1}^{t} \Delta URB_i^+ = \sum_{i=1}^{t} \max\ (\Delta URB_i\ 0) \quad \text{eq } \mathbf{(8)}$$

$$URB^- = \sum_{i=1}^{t} \Delta URB_i^- = \sum_{i=1}^{t} \min\ (\Delta URB_i\ 0) \quad \text{eq } \mathbf{(9)}$$

$$IND^+ = \sum_{i=1}^{t} \Delta IND_i^+ = \sum_{i=1}^{t} \max\ (\Delta IND_i\ 0) \quad \text{eq } \mathbf{(10)}$$

$$IND^- = \sum_{i=1}^{t} \Delta IND_i^- = \sum_{i=1}^{t} \min\ (\Delta IND_i\ 0) \quad \text{eq } \mathbf{(11)}$$

Therefore, using these asymmetric associations in urbanization, GDP and industrialization, the study establishes the nonlinear ARDL model equation:

$$\Delta PCCE_t = \alpha_0 + \sum\delta_1\Delta PCCE_{t-1} + \sum\delta_2\Delta REP_{t-1} + \sum\delta_3\Delta REC_{t-1} + \sum\delta_4\Delta TA_{t-1} + \sum\delta_5\Delta GDP_{t-1}^+ + \sum\delta_6\Delta GDP_{t-1}^- + \sum\delta_7\Delta URB_{t-1}^+ + \sum\delta_8\Delta URB_{t-1}^- + \sum\delta_9\Delta IND_{t-1}^+ + \sum\delta_{10}\Delta IND_{t-1}^- + \varphi_1 PCCE_{t-1} + \varphi_2 REP_{t-1} + \varphi_3 REC_{t-1} + \varphi_4 TA_{t-1} + \varphi_5 GDP_{t-1}^+ + \varphi_6 GDP_{t-1}^- + \varphi_7 URB_{t-1}^+ + \varphi_8 URB_{t-1}^- + \varphi_9 IND_{t-1}^+ + \varphi_{10} IND_{t-1}^- + \mathcal{E}_t \quad \text{eq } \mathbf{(12)}$$

3. The Theoretical Framework

The results quoted in *Table 2* indicate that the mean value of PCCE is 4.761, while REP is 18.277%, REC is 20.243% and the TA mean value is 30.575%. The GDP mean value is

9.289% followed by URB at 43.577%, and IND at 44.394%. From *Table 2*, it is clear that the average IND is higher, meaning that industrialisation trends are greater in the targeted economy. We can also see that TA is more volatile than REC. However, REC displays more deviation than REP, PCCE or GDP.

Table 2. Measurements of Variables

Variable	Obs	Mean	Std. Dev.	Min	Max
PCCE	30	4.761	2.186	2.001	8.262
REP	30	18.277	1.972	15.037	23.927
REC	30	20.243	9.063	6.007	33.258
TA	30	30.575	.595	29.364	32.124
GDP	30	9.289	2.646	2.348	14.231
URB	30	43.577	10.775	27.312	61.428
IND	30	44.394	2.902	37.821	47.557

Source: own calculations.

Table 3 shows that RE production, RE consumption and technology adoption have a negative nexus with CO2 emissions, while urbanization, GDP and industrialization have a positive impact on CO2 emissions in China. If REP increases by 1%, PCCE sees a decline of 0.504%, shown by the negative sign. A decline of 1% reduces REC to 0.976% and TA to 0.431%. Contrastingly, a GDP increment leads to a 0.563% rise in carbon emissions, while in the case of urbanization it is 0.981%. Lastly, due to the positive correlation, when IND increases by 1%, PCCE sees a rise of 0.542%.

Table 3. Matrix of Correlations

Variable	PCCE	REP	REC	TA	GDP	URB	IND
PCCE	1.000						
REP	-0.504	1.000					
REC	-0.976	-0.365	1.000				
TA	-0.431	0.107	-0.425	1.000			
GDP	0.563	-0.545	0.471	-0.278	1.000		
URB	0.981	0.475	-0.957	0.426	-0.634	1.000	
IND	0.542	-0.586	0.414	-0.193	0.688	-0.594	1.000

Source: own calculations.

The next move is to assess carbon emissions, renewable energy consumption, renewable energy production, technological adoption, economic growth, urbanization and industrialization stationarity. This helps researchers make decisions about the suitability of the cointegration approach. The study employs the ADF test, which is popularly used to handle single unspecified structural breaks in sequential data, to address the issue. The test is applied to check whether the variables under study are stationary at level or first difference or both. The ADF and PP unit root tests might under or over-reject the null hypothesis problem of low explanatory power. ADF addresses these problems via high explanatory power. Thus, it offers consistent findings regarding time series structural break presence. *Table 3* reveals that PCCE, REP, URB and IND are stationary at level. In contrast, REC, TA and GDP are stationary at first difference. *Table 5* reveals a calculated f-statistic value of 4.185, along with the lower and upper bound values of critical f-statistics, thus cointegration exists.

Table 4. Unit Root Test

	ADF		PP	
Series	Level	First difference	Level	First difference
PCCE	-3.902***	-6.909***	-3.902***	-4.902***
REP	-2.994***	-6.190***	-2.092***	-6.015***
REC	-1.176	-4.543***	-1.092	-4.922**
TA	-1.172	-4.907***	-1.128	-5.268***
GDP	-1.111	-6.276***	-1.195	-5.192***
URB	-2.152***	-5.272***	-4.102***	-5.294***
IND	-3.291***	-7.902***	-5.636***	-8.108***

Source: own calculations.

Table 5. Bound Test of Nonlinear ARDL

	F-statistic	Lower Bound	Upper Bound	Decision
Linear ARDL	0.549	2.292	2.102	No Co-integration
Asymmetric ARDL	4.185	2.421	2.929	Co-integration

Source: own calculations.

Table 6. Nonlinear ARDL Results

Variable	Coefficient	Std. Err.	t-statistic
C	0.390	0.029	1.448
PCCE (-1)	0.281	0.032	-8.781
REP (-1)	-1.929	0.529	-3.647
REC (-1)	-1.202	0.410	-2.932
TA (-1)	-0.383	0.101	3.792
GDP-P (-1)	0.532	0.192	2.771
GDP-N (-1)	0.823	0.297	2.771
URB-P (-1)	0.102	0.022	4.636
URB-N (-1)	0.521	0.201	2.592
IND-P (-1)	1.820	0.529	3.440
IND-N (-1)	0.928	0.322	2.882
Adj. R Square	0.502		
F-statistic	47.201		
Prob.(F-statistic)	0.002		

Source: own calculations.

The nonlinear ARDL results show that GDP, urbanization and industrialization have an asymmetric association with CO2 emissions. Since REP and PCCE share a positive and significant relationship, a 1% rise in REP leads to a 1.929% decline in PCCE. The consumption of renewable energy reduces carbon emissions, as the statistics in Table 6 reveal. When REC increases by 1%, PCCE sees a decline of 1.2020%. Technological adoption is also a blessing for the Chinese economy as it decreases carbon emissions by 0.383%. Contrastingly, economic activity leads to a sharp rise in carbon emissions, which is 0.532%. The positive and significant relationship of urbanization and industrialization also indicates that they are culprits and pollute the environment.

4. Discussion

The current article investigates the impact of sustainable energy technologies such as RE production and consumption on CO2 emissions. It also examines the impact of technology adoption, urbanization, GDP and industrialization on CO2 emissions in China. The results reveal that RE production has a negative association with CO2 emissions. The Chinese economy emits CO2 emissions in large amounts. An increase in RE production, such as the generation of bioenergy, geothermal power, solar power and hydroelectric power, reduces CO2 emissions from economic practices in China. With reduced CO2 emissions, temperature levels can be controlled, and weather patterns can be restrained from being disturbed. These results are in line with Chen (2024), who show that, in countries where RE production is preferred, there are fewer drivers of climate change, because RE production, such as energy production from green natural resources, require carbon in large amounts and temperature from the air. These results are also in line with Sinha & Shahbaz (2019), who state that RE production is a source of clean energy which discourages the reliance on fossil fuels to run technologies for social and economic purposes, reducing CO2 emissions and saving the planet from climate change.

The results reveal that RE consumption has a negative association with CO2 emissions. The increasing trend of using RE sources for infrastructure, transport services and internal and external operations of various sorts in China significantly reduces CO2 emissions. These results are supported by Kirikkaleli *et al*. (2022), who show that the consumption of clean energy, such as solar power, wind power, biomass and biofuel, does not create any harmful substances, such as CO2, as by-products of the production process. So, the use of RE reduces climate change. These results are also supported by Hanif (2018), who shows that climate change is mostly linked to CO2 emissions and the use of technologies fuelled by non-renewable energy. The replacement of non-renewable energy with RE helps run business technologies without CO2 emissions and climate change. Hence, RE consumption plays a crucial role in combating climate change.

The results reveal that technology adoption has a negative association with CO2 emissions, implying that when more people have the intention and capacity to acquire and adopt technologies to facilitate tasks or do something new, there may be adoption of energy-efficient technologies that could run on RE or consume only a small amount of energy. Thus, there could be a reduction in CO2 emissions and climate change. These results agree with Fu *et al*. (2018), who focus on the adoption of innovative technologies for reducing climate change. The study states that, to produce renewable energy and apply it to business practice, firms need generators, energy storage systems, transformers and technologies with specific requirements of voltage power. Firms' tendencies to acquire technologies results in clean energy generation and use in business practice, reducing CO2 emissions and climate change. These results also agree with Chau *et al*. (2022) and Dessì *et al*. (2021), who reveal that the rapid adoption of energy-efficient technologies promotes the optimal use of energy, so that the same output can be generated with less energy, resulting in reduced CO2 emissions and ensuring climate safety.

The results reveal that urbanization has a positive association with CO2 emissions. In rural areas, people mostly rely on fossil fuel combustion for household chores and the activities involved in their professions. Urbanization does not create environmental awareness in people, and they do not initiate measures to reduce environmental damage. They cannot reduce their use of fossil fuels for energy purposes or prevent CO2 emissions. These results are in line with Ahmed *et al*. (2019) and Chen *et al*. (2023), who show that people living in cities have no awareness of innovations in technology or resources. Urbanization, with its lack of awareness of ecologically friendly innovations, makes people reduce unclean energy combustion and its adverse environmental impacts. So, urbanization reduces CO2 emissions and controls climate change. The results are also in line with Ali *et al*. (2019) and Zhang *et al*. (2023) , highlighting that urbanization increases CO2 emissions. People do not have easy access to clean energy sources or ecologically friendly technologies in urban areas.

The results reveal that GDP growth has a positive association with CO2 emissions. With the increase in GDP growth in China, there is an increase in levels of investment, technological advancement, human capital improvement and financial development. These factors increase CO2 emissions due to the high level of operational and production activities. These results are in line with Magazzino *et al*. (2021), who examine GDP's role in CO2 emissions. The study implies that, if a country records a high GDP growth rate, economic units can afford energy-efficient technologies, and a specialized labour force can be hired. So, GDP increase reduces CO2 emissions and protects the environment, but at a very minimum level. The results reveal that industrialization has a positive association with CO2 emissions. Industrialization is one of the significant sources of CO2 emissions in China. It is a way to achieve technological and financial development, produce clean energy, and build awareness among the general public of the circumstances, but an increase in industrialization fails to control CO2 emissions. These results are supported by Mentel *et al*. (2022), who reveal that industrialization opens the way to achieving higher economic development, comprising human capital improvement, financial development, and technological advancement, which are all sources of increased CO2 emissions.

4.1 Policy Implications

The current study has great significance for economies across the world. It addresses the global issue of environmental pollution, a serious hurdle to achieving sustainable economic development and a healthy and prosperous world. It describes the causes of CO2 emissions and climate change and their impacts on human life in various spheres, in order to develop awareness in the reader and, in the end, describe ways to combat CO2 emissions and climate change. Thus, it provides a path to sustainable economic development and a healthy and prosperous world. This study is a set of guidelines for governments, environmental regulatory authorities and economists in China and other countries, showing that they should perform efficiently in their field by forming and executing specific policies. The study suggests that governments should issue policies to promote RE, such as wind energy, solar power, bioenergy and geothermal power, to meet their needs for energy and, with the help of economists, make RE production and consumption policies which reduce CO2 emissions and fight climate change. This article provides guidelines to policymakers relating to policy development regarding CO2 emissions and climate change using sustainable energy technologies. This study suggests that, by implementing favourable fiscal, monetary, trade and regulatory policies, citizens should be encouraged to employ energy-efficient technologies and minimize climate change through reduced CO2 emissions. Moreover, the study suggests that urbanization, GDP growth and industrialization should be managed in ways that reduce CO2 and climate change through effective policymaking.

The Chinese government should offer guidance and support to industries in terms of technological innovation. The government should also upgrade the scale of technology and its expenditure. The positive impact of renewable technologies on carbon emissions shows that sustainable and clean technologies actively respond to climate complexities. This indicates that we must take notice of innovation effectiveness in sustainable technologies and how it would be helpful for carbon reduction. There is a need for funding to promote innovation in clean technologies. The findings help in developing policies where innovation investment must be prioritized in terms of R&D investment and fiscal spending on technology and science. Investment innovation is essential to promote sustainable technology in various ways. Technological innovation is an effective way for organizations to enhance their competitive characteristics, however this is costly, highly risky and has uncertain outcomes. As a result, innovation investment from organizations is always less than the socially optimal level. The government, as a prime promoter of national innovation and has the potential to optimize the technological level via technology related expenditure, R&D projects, government level subsidies, carbon taxes etc. This shows that fiscal spending on science and technology can be an effective solution to address issues pertaining to R&D procedures, which can only be solved by government resource allocation. This is why government institutions must take full measures to guide firms and show support for clean energy technological innovation. Meanwhile, the government is supposed to spend the maximum on science and technology and divert attention to those provinces where carbon emissions are high and the innovation level is low. This would help narrow the gap of technology across regions.

There is also a need to make the role of energy prices rational, while encouraging technological innovation. This is an essential factor for renewable energy development, especially in the case of China. The reason is that, due to the low price of conventional energy resources, the country consumes large amounts of coal. This practice not only hinders the goal of low-carbon energy development but also creates difficulties in the technological progress of renewable energy. Thus, it is advised that the government design an energy price mechanism and impose heavy taxes on traditional energy resources, while offering subsidies for renewable energy. It is also imperative to explore potential energy price mechanisms and their role in the promotion of clean technology.

Conclusions

China started to show progress towards its low-carbon goal after the COP21 conference. The present study attempts to take a step towards a zero-carbon goal by exploring the roles of RE production, RE consumption, technology adoption, urbanization, GDP growth and industrialization in combating climate change. The quantitative empirical data proves a negative role of RE production, RE consumption, technology adoption, urbanization, GDP growth and industrialization in CO2 emission and, thereby, their positive role in combating climate change. The results show that RE production provides enhanced clean energy reserves and reduces CO2 emissions, controlling climate change. RE replaces fossil fuels for energy purposes in economic practice, thereby reducing CO2 emissions. The results show that adopting environmentally friendly technologies for relevant economic activities reduces CO2 emissions in various businesses. The study concludes that urbanization, increased GDP growth and industrialization enhance knowledge, technological advancement and human capital development, providing access to essential resources for accelerating sustainable energy production and consumption, but enhancing CO2 emissions.

Limitations and Future Recommendations

The present study assesses the role of only a limited number of factors, RE production, RE consumption, technology adoption, urbanization, GDP growth and industrialization, in combating climate change. Many other factors, such as corporate social responsibility, green finance, energy import, etc., have strong influences on climate change but are not under consideration here. For a comprehensive study, future authors must consider more factors. In this study, CO2 emissions alone, instead of all GHG emissions, are taken to measure climate change. In future research, GHG emissions should be considered. The data for this study come from the Chinese economy, which has specific particulars regarding its geography, population, economic expansion and environment, and therefore may not be generalizable. Future scholars could analyse the roles of RE production, RE consumption, technology adoption, urbanization, GDP growth and industrialization in combating climate change in other countries.

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NAUJOS TVARIOS ENERGIJOS TECHNOLOGIJOS KLIMATO KAITAI STABDYTI: ĮRODYMAI TAIKANT NETIESINĮ ARDL METODĄ

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Santrauka. Ekonomikos, tiek išsivysčiusios, tiek tokios, kurios vystosi, susiduria su klimato problemomis, nes nepavyksta apriboti šiltnamio efektą sukeliančių dujų išmetimo. Ši problema tampa dar sudėtingesnė dėl didelio neatsinaujinančios energijos suvartojimo lygio, todėl siekiama sumažinti išmetimą, ypač CO2, ir padidinti žaliosios energijos dalį energijos tiekime. Mokslininkai sutaria, kad viešojo sektoriaus investicijos į atsinaujinančią energiją yra svarbios, todėl jie daro prielaidą, kad investicijos yra būtinos technologinei pažangai siekiant padidinti tvarios energijos gamybą ir tiekimą. Negalima pamiršti tvarių technologijų vaidmens, kuris svarbus didinant žaliosios energijos tiekimą ir saugant aplinką. Siekiant spręsti šias problemas, šalys turi rasti veiksmingus būdus, kaip apriboti anglies dioksido išmetimą. Tai įmanoma tik tuo atveju, jei jos yra informuotos apie galimus išmetimo veiksnius. Šiame tyrime naudojamasi rafinuotais rodikliais ir pristatomas išsamus modelis, skirtas įvertinti tvarių energijos technologijų vaidmenį klimato kaitoje Kinijoje 1991–2020 m. laikotarpiu. Siūloma įgyvendinti tam tikras tikslines politikos priemones siekiant sumažinti išmetimą. Taip pat turėtų būti sukurta platforma, skirta skatinti žaliąsias technologijas regioniniu lygiu šalia veiksmingų miesto plėtros strategijų.

Reikšminiai žodžiai: tvarios energijos technologijos; atsinaujinanti energijos gamyba; technologijų pritaikymas; CO2 emisija; urbanizacija; industrializacija; nulinė anglies dioksido emisijos ekonomika.