Harnessing Renewable Energy and Innovation for a Sustainable Future: An Empirical Analysis of Greenhouse Gas Emission Reductions

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Abstract

The unchecked absorption and emission of infiltrated radiation by greenhouse gas (GHG) emissions pose severe threats to human existence and future generations, endangering both living and non-living ecosystems. This study investigates the asymmetric impacts of environmental innovations advancements and renewable energy adoption on GHG emissions, using annual time-series data from China spanning 1990 to 2022. Employing both linear and nonlinear models, the analysis confirms cointegration among GHG emissions, renewable energy, environmental technologies, economic growth and annual freshwater availability, as evidenced by the bound's F-statistics. Notably, long-run asymmetry is observed, revealing that positive and negative shocks in environmental technology exhibit significant effects on GHG emissions over time. While environmental technology reduces GHG emissions growth under symmetric conditions, its impact becomes a significant driver of emissions once a threshold is surpassed. On the other hand, renewable energy adoption consistently mitigates emissions in both the short and long run, highlighting China's technological commitment to reducing its GHG footprint. Interestingly, annual freshwater availability exerts a negative and significant influence on emissions, emphasizing its role in environmental sustainability. These findings suggest that advancing environmental technology, coupled with renewable energy adoption, could accelerate China's trajectory toward achieving net-zero emissions, provided technological growth is managed beyond critical thresholds.

Keywords: GHG, renewables, annual freshwater, environmental innovations, asymmetric cointegration.

1. Introduction

The growing concern about environmental deterioration and the need for sustainable development has prompted societies worldwide to look into new techniques to minimize the negative impact of human activities on the environment. Over the last two decades, China's energy revolution has made significant progress, and the government-owned State Grid has emerged as a global leader in UHV (ultra-high voltage) electrical transmission engineering. It enables quick renewable energy delivery. However, in 2018, just 12.7% of China's primary energy consumption came from renewable sources. It is lagging the EU's 14.1% (Oxford Institute of Energy Studies, 2020). In addition, the Chinese government expanded its efforts to promote recycling and keep animals and waste out of the city. In July, the original national environmental funds established in China had already raised 88 billion CNY and were on

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course to surpass the "Big Fund" for China's chip sector as the country's second-largest national fund (Liu et al 2024; Kim et al 2024; Xinhua, 2020).

In this regard, technological innovation for eco-friendly products was identified as a critical approach for addressing environmental and sustainable development issues worldwide (Saqib et al., 2024; Mustafa et al 2022; Ahmed et al., 2020). Thus, technological innovation has emerged as a crucial factor for eco-friendly products in China. While industries have placed a significant emphasize on the implementation of advanced renewable energy technologies to develop eco-friendly alternatives for reducing their environmental consequences and encourage sustainable practice. Eco-friendly product plays a vital role in reducing environmental concerns and also resource consumption for the whole life cycle, from concept to disposal (Mustafa et al., 2022; Liang & Yang, 2019). For example, organic food, biodegradable packaging, electric vehicles, and renewable energy sources.

China, the world's second-largest economy and most populous nation, faces significant challenges in balancing rapid economic growth with environmental sustainability. Industrialization has caused severe environmental damage, including resource depletion, soil contamination, and air and water pollution. As the largest carbon emitter and consumer of natural resources (Luo et al., 2018), China is under immense pressure to adopt eco-friendly practices and reduce its environmental footprint. Technological innovation, government regulations and strategies, and shifting consumer preferences play a crucial role in driving economic growth and promoting the distribution of eco-friendly products in the country (Zeraibi et al., 2021).

This environmental concern pushes China to implement a policy framework that demonstrates its commitment to key objectives for technological innovation. In response, China has set specific goals, including reducing CO2 emissions, improving air quality, and strengthening eco-friendly energy sources. For example, the "Made in China 2025" initiative aims to position China at the forefront of high-tech industries, particularly in renewable energy, electric vehicles (EVs), and advanced manufacturing (Lin & Ma, 2022). This initiative emphasizes the development and application of advanced technologies to address environmental challenges and promote sustainable development.

Moreover, China has also invested a significant amount in research and development (R&D) initiatives to attain its objectives. This investment emphasizes renewable energy, waste management, population control and also energy efficiency. Besides this, China has developed many technological parks, incubation facilities, and innovation institutions to encourage collaboration among the government, businesses and universities for developing eco-friendly technologies (Anna Holzman and Nis Grunberg, 2021). Thus, China put efforts into achieving technological advancement, which has an adverse significant positive impact on the environment. Li et al. (2022) pointed out that the adoption of cleaner production technologies in the industrial sector of China will result in a considerable reduction in greenhouse gases and energy consumption. Likewise, Zhou et al. (2021) argue that incorporating eco-friendly technologies in the transportation sector might reduce carbon emissions and air pollution in China. Although China has progressively accelerated the initiatives but yet, there are barriers to the adoption and diffusion of eco-friendly technologies. While growing up, sustainable technology has considerable obstacles due to certain reasons including high initial cost, low awareness, limited finance, and also inadequate infrastructure. Thus, to address these concerns the multi-stakeholder policy is critical to encompass governments, industrial leaders, academic institutions, and consumers.

Unquestionably, major economies, such as China, can meet the growing demand of their populations through technological or environmental innovations that enhance economic expansion while minimizing environmental degradation. In addition to enhancing productivity and minimizing climate change, adopting environmentally friendly technical innovation for green and clean goods would reduce energy consumption (Sinha & Shahbaz, 2018; Bölük & Mert, 2015). Using renewable energy sources, energy transition, and financial development may help reduce reliance on fossil fuels, resulting in economic progress and environmental protection when sustainable development includes environmental innovation, energy transition, and financial growth.

Figure 1: Demonstrates emissions of carbon dioxide (kg PPP $ of GDP)

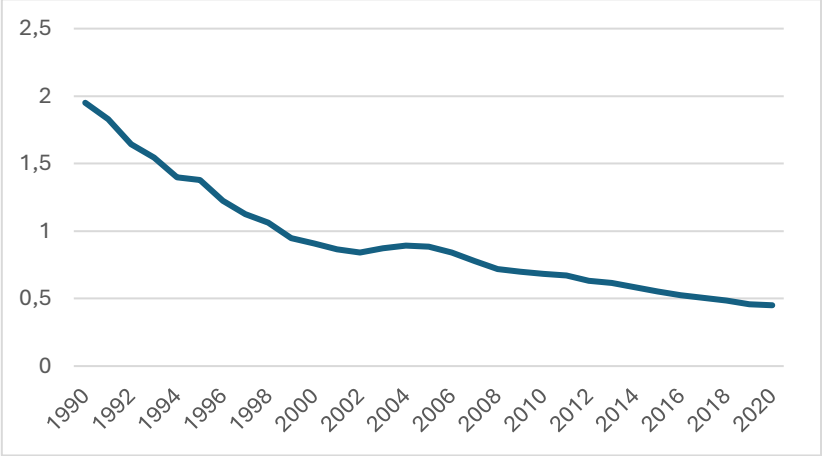
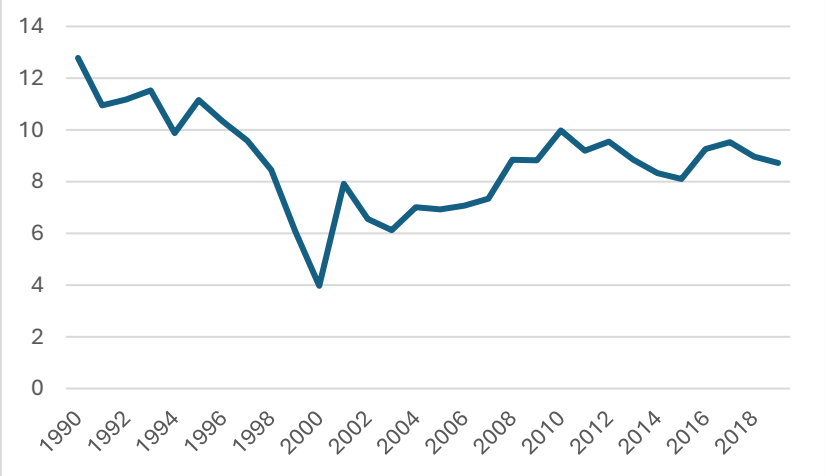


Figure 2: Development of environment-related technologies, % all technologies



Source: Author's Computation based on WDI data

Figure 1 depicts China's carbon dioxide emissions per kilogram of GDP during the last few decades. In contrast, Figure 2 illustrates technical innovation in environmental-related technologies as a fraction of all technologies. This understanding illuminates the relationship between technological innovation and environmental effects. China first focused on environmental challenges, but between 1990 and 1995, environmental technology development surged. However, the proportion fluctuated and declined in the years that followed until 1999. These technologies have advanced steadily since 2000, suggesting ongoing attempts to solve environmental concerns. The chart also shows that CO2 emissions kg per unit of GDP are decreasing, indicating that China is minimizing its carbon footprint. This decline shows that technological advancements in clean and green products have had a positive environmental impact by promoting more resource and greenhouse gas-efficient use.

The fundamental issue with this study is that while current studies in China and arguments emphasize the beneficial role of technical innovation in generating clean and green goods, there are substantial gaps and obstacles in identifying its environmental effect (Wang et al., 2021). The study dilemma mainly originated from a lack of studies and investigations of the ecological consequences related to technological innovation and also how this innovation makes the future sustainable. Moreover, yet a gap exists in inadequate extensive investigations into the factors that enable or prevent the essential implementation of eco-friendly technologies for reducing environmental deterioration (Jiang et al., 2022).

The novelty of this study is threefold. Firstly, by incorporating key control variables such as GDP and annual freshwater availability, this research extends beyond traditional analyses to provide a more comprehensive understanding of how these factors interact with environmental policy interventions in China. Secondly, it is novel by integrating these factors within a robust econometric framework by dissecting these factors into positive and negative partial sums in the context of a non-linear approach. Lastly, this is the first attempt to evaluate empirically the dynamic impact of the technological, renewables, and other control variables that could induce greenhouse gas emissions reduction. This way, we can fill a crucial gap in the existing literature on sustainable development pathways.

2. Literature Review

In this section, we critically analyze previous studies on the environmental impacts of technological innovation and renewables on greenhouse gas emissions and related issues in the context of China and other economies. Beginning with the general notion reported by Huo and Peng (2023) stating that fast economic expansion and industrialization have led to a deteriorating climate and depletion of resources. Extreme weather occurrences, such as floods and droughts, are among the negative consequences of ecological collapse, as is the extinction of species, flora, and fauna. It is expected that the situation will deteriorate if proper steps are not taken.

China has made significant economic growth, but environmental difficulties raise concerns about the country's long-term prosperity. To address environmental concerns, Chinese towns are moving toward low-carbon economies. China's green technology has dramatically benefited from national R&D programs; nevertheless, the "National High-Tech R&D Program" (863 Program) experienced significant growth in resources and environmental science projects between 2009 and 2013. Furthermore, China increased the equivalent percentage of the budget from 9.7% in 2012 to 14.8% in 2019, demonstrating China's commitment to clean and green technology innovation and its importance (Xu et al., 2023; Rivera Leon et al., 2020).

The Organization for Economic Cooperation and Development (OECD) reports that China's environmental parents climbed 60 times between 1990 and 2014 (OECD, 2018). Production also increased. China also holds the most top-tier patents in 2019 for three emerging green technologies: recycling, water purification, and waste management. Similarly, China is on track to become the world leader in renewable energy technology. Nonetheless, China's success in this field is alarmingly low, with only 2% of its wind energy patents in 2019 being classified as excellent (Stiftung, 2020). Nonetheless, China continues to have fewer environmentally friendly patents than other OECD countries. China's authorities must achieve a balance overall. Upholding substantial environmental restrictions and pushing for green technological developments to avoid compromising the present, frequently high base of a polluting business that sustains billions of Chinese people's means of livelihood.

The country has effectively decreased building footprints by shutting or relocating polluting companies, transportation, and energy sources. Investigation of these difficulties necessitates the use of cutting-edge technologies. Technology might significantly reduce the negative impact of industrial practices on environmental quality by encouraging the creation of clean and green goods (Herman & Hu, 2019). Clean technologies encompass a wide range of developments, such as energy-efficient manufacturing, waste management, and renewable energy systems (Song et al., 2022). However, these improvements cut pollutants and greenhouse gas emissions while also slowing resource depletion.

Dawkins et al. (2019) suggested that the environmental impact of eco-friendly (clean and green) products is intended to be as minimal as possible throughout their lifetime. Further, they are distinguished through greater energy efficiency, and environmentally friendly material procurement. Thus, adopting such products can encourage sustainable production and consumption attitudes that lead to a more significant environmentally conscious society (Xu et al., 2021). Zhang et al. (2022) emphasized that the carbon emissions have favorable relationship with green investments, natural resources, green technological investments, and economic growth in short and long-term. Nevertheless, the production production and consumption of eco-friendly goods and services promote green industries, employment opportunities, and economic growth (Fang, 2023; Abubakar et al., 2023).

Yun & Sun (2021) highlighted the adoption of electric automobiles to enhance air quality and also help to reduce greenhouse gas emissions from transportation. China's initiative for adopting eco-friendly technologies has potential to transform the country's economic structure and create more environmentally friendly sustainable society. Similar to this, Jiang et al. (2022) suggest that potential use of renewable energy helps to reduce long-term carbon emissions impacts. While waste management strategies and circular economic approaches have potential to reduce waste generation and increase resources efficiently (Wei et al., 2021). Thus, these technological advancements and development have had a significant positive impact on environment in China through preserving resources, reducing pollution, and promoting sustainable growth. Moreover, renewable energy sources transition can promote sustainable development, reduce pollution and reduce overall environmental impacts (Alola et al., 2019). In this regard, adopting renewable energy offers a several benefits including to reduce Lassen's reliance on non-renewable energy markets, allow for energy diversification, and lessen the impact of climate change.

According to Wang et al. (2021), multiple factors including GDP, human capital, economic globalization, and R&D (research and development) expenditure influence long-term green growth. Further, it has been put in attention that technological innovation promotes green growth. Su et al. (2021) employing CS-ARDL estimations to emphasize that there is considerable positive significant impact on energy consumption and monetary development on carbon dioxide (CO2) emissions, thus this suggest that using eco-friendly energy instead of conventional energy is a crucial step to reduce environmental pollution.

Theoretically, the EKC (environmental kusnets curve) is a crucial concept to understand clearly how technological innovation for clean and green products impacts environmental preservation. The hypothesis of EKC suggests that the countries that prioritize economic growth over environmental concerns are more likely to endure considerable pollution and ecological degradation in the early stage of economic development. Nevertheless, there are additional thresholds suppose when the quality of the environment gets better as economies rise and civilization becomes more developed (Sarkodie & Strezov, 2018).

Scholars in China mostly relied on the EKC theory to understand the potential link between economic growth, technological innovation, and environmental sustainability. Thus, the impact of economic growth and technological innovation on environmental quality has been thoroughly investigated in China. For instance, Ozkan et al. (2023) employed EKC theory in China and demonstrated the inverse U-shaped relationship between per-capita income and CO2 emissions. The study findings suggest that the adoption of eco-friendly technologies decreases environmental pollution as income per person increases. Another study by Zhang et al. (2023) explored that technological advancement has significantly impacted footprints in China. Furthermore, their findings emphasize the importance of innovation to support environmentally friendly production practices and eco-friendly products that show how technological innovation dramatically reduces carbon emissions.

Figure 3. Conceptual Framework of the Study

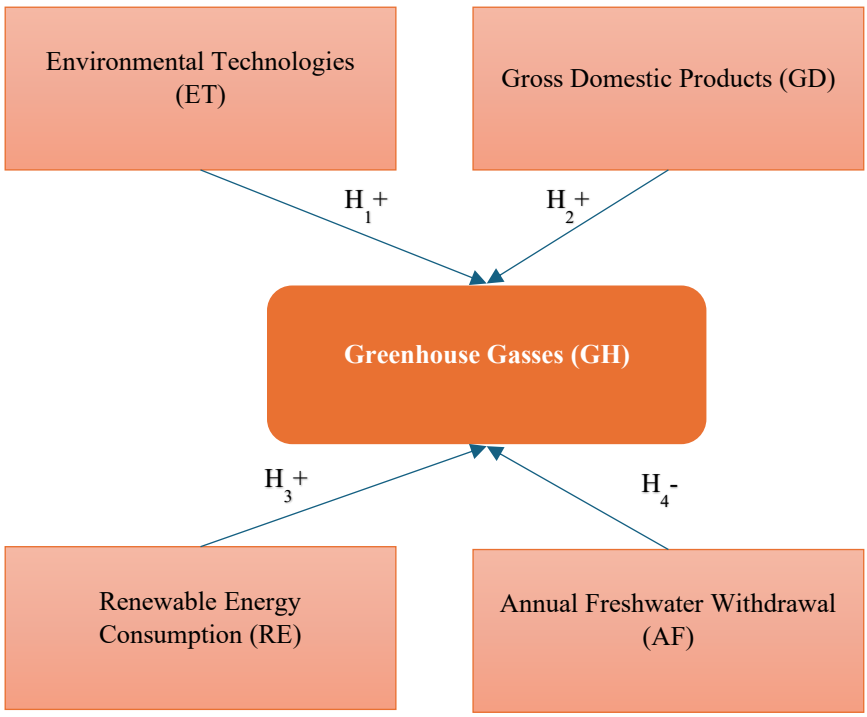


Figure 3 illustrates the study's conceptual framework. This conceptual framework appropriately reflects the link between the study's independent and dependent variables. This helps the researcher to understand how differences in independent factors may affect dependent factors. The framework also aids in the identification of potential confounding variables that may influence the study's results. In the framework used to express the proposed hypothesis, a positive sign indicates a favourable connection between independent and dependent variables. At the same time, the negative sign indicates a poor connection. Using this paradigm, researchers may quickly determine the direction of the link between variables.

2.1 Research Gap

Dissecting the effect of explanatory variables into positive and negative shocks is a recent empirical investigation, although there are large number of studies examining the nexus between environmental pollution proxy by carbon emissions and environmental innovations, a few addressed the issue of nonlinearity a gap this study fills. More extensive econometrics approaches are required to understand the true impact of innovations in moderating and reducing greenhouse gas emissions in the context of China. Thus, knowing these aspects is critical for identifying barriers and developing effective technical innovation strategies for

green and clean products. Despite China's large and quickly rising economy, there is a paucity of investigation into particular obstacles and possibilities in producing and implementing environmentally friendly technologies to reduce emissions. In-depth research in the context of China will yield significant insights into the country's particular situation and potential environmental remedies. Nevertheless, the literature only briefly mentions the practical consequences of environmental technology innovation for decision-makers and customers. This might include looking at public recommendations, company strategies, and changes in consumer behaviour that can encourage and assist the adoption of environmental-related technologies.

3. Material and Methods

3.1 Data Description

The study used a quantitative research approach to investigate and evaluate how the environmental technological adoption of green and clean products has influenced China's environmental quality. Secondary data for this study was gathered from the World Data Indicators (WDI) between 1990 and 2022. The study collects data on variables such as technological innovation in environmental-related equipment. Greenhouse gas emissions (GH) is the study's dependent variable, while environmental technologies (ET), gross domestic product (GD), renewable energy consumption (RE) and annual freshwater withdrawal (AF) are independent variables. Table 1 displays all variables under investigation.

Table 1. Variable Attributes

No	Variables	Measurement	Unit	Source
1	GH	Greenhouse Gases Emissions	kg per PPP $ of GDP	WDI
2	ET	Development of environment-related technologies or Technological Innovation	% all technologies	WDI
3	GD	Gross Domestic Products per capita	Current US$	WDI
4	RE	Renewable Energy Consumption	% of total final energy consumption	WDI
5	AF	Annual freshwater withdrawals, industry	% of total freshwater withdrawal	WDI

3.2 Model Specification

The model specification is very critical for any study, thus, selecting a model author should be more careful. Thus, the author employs several preliminary econometric tests to choose the model that fits with the nature of the data. The unit root test serves as the most widely accepted preliminary test check to determine the series that is stationarity at level, and first difference. Therefore, this study employs ARDL and NARDL models to empirically investigate the long-term and short-term relationship between dependent and independent variables with varying integration order.

$$GH_t = \delta_0 + \delta_1 ET_t + \delta_2 GD_t + \delta_3 RE_t + \delta_4 AF_t + \epsilon_t \quad (1)$$

Where:

GH is dependent variable; *ET* stands for Development of environment-related technologies or Technological Innovation. *GD* (Gross Domestic Product) is also considered an independent variable. The *RE* refers to the consumption of renewable energy as a percentage of total final

energy consumption. *AF* refers to Annual Freshwater Withdrawals from industries. Furthermore, β is the coefficient or slope of the variables, δ is the slope of control variables, and μ is an error in the model.

The ARDL method is more enduring and economical for small numbers of samples. Furthermore, it holds true whether the variables included in the model are simply I(0), merely I(1), or mutually cointegrated. However, the model fails in the presence of the I(2) series. The ARDL approach expresses the symmetric relationship between variables as follows:

$$\Delta GH_t = \beta_0 + \gamma GH_{t-1} + \rho_1 ET_{t-1} + \rho_2 GD_{t-1} + \rho_3 RE_{t-1} + \rho_4 AF_{t-1} + \sum_{i=0}^{q} \delta_1 GH_{t-1} \sum_{i=0}^{q} \delta_2 ET_{t-1} \sum_{i=0}^{q} \delta_3 GD_{t-1} \sum_{i=0}^{q} \delta_4 RE_{t-1} \sum_{i=0}^{q} \delta_5 AF_{t-1} + ECT_t + \mu_t .. (2)$$

The error correction model that captures the complex short-run dynamics is as follows:

$$\Delta GH_t = \sum_{i=0}^{q} \delta_1 GH_{t-i} \sum_{i=0}^{q} \delta_2 ET_{t-i} \sum_{i=0}^{q} \delta_3 GD_{t-i} \sum_{i=0}^{q} \delta_4 RE_{t-i} \sum_{i=0}^{q} \delta_5 AF_{t-i} + ECT_t + \mu_t .. (3)$$

Where Δ is the 1st difference operator, γ and ρ are the long-run parameters, β is a constant term, while δ represents the short-run parameters. q indicates the lags. ECT_{i-1} reflect the error correction factor in equation (3), which indicates the speed at which the model adjusts to long-run equilibrium after an economic shock. Thus, the ARDL model captures the relationship between greenhouse gas and environmental technologies, it does so under the explicit scenario that provides the linear and symmetrical relationship. Such presumptions do not align with the primary goal of this study, which is to explore China's GH asymmetric response to renewable energy or ecofriendly technologies trends. This study employs the non-linear Autoregressive distributed lag (NARDL) proposed by Shin et al (2014) model, an asymmetric extension of the linear ARDL to achieve its objective. To specify the NARDL model, the change in environmental innovations ΔET_{t-i} is decomposed into its positive and negative segments that are denoted by ΔET^+ and ΔET^- respectively. Segments are further stated as follows:

$$\Delta ET^+ = \sum_{i=1}^{t} \Delta ET^+ = \sum_{i=1}^{t} \max(\Delta ET_i, 0) .. (4)$$

$$\Delta ET^- = \sum_{i=1}^{t} \Delta ET^- = \sum_{i=1}^{t} \min(\Delta ET_i, 0) .. (5)$$

As defined by Shin et al. (2014), the asymmetric cointegrating relationship between variables is specified.

$$\Delta GH_t = \beta_0 + \gamma GH_{t-1} + \rho_1 ET^+{}_{t-1} + \rho_2 ET^-{}_{t-1} + \rho_3 GD_{t-1} + \rho_4 RE_{t-1} + \rho_5 AF_{t-1} + \sum_{i=0}^{q} \delta_1 \Delta GH_{t-1} + \sum_{i=0}^{q} \delta_2 ET^+{}_{t-1} + \sum_{i=0}^{q} \delta_3 ET^-_{t-1} + \sum_{i=0}^{q} \delta_3 \Delta GD_{t-1} + \sum_{i=0}^{q} \delta_4 \Delta RE_{t-1} + \sum_{i=0}^{q} \delta_5 \Delta AF_{t-1} + ECT_t + \mu_t .. \quad (6)$$

The asymmetric error correction model is as follows:

$$\Delta GH_t = \sum_{i=0}^{q} \delta_1 \Delta GH_{t-1} + \sum_{i=0}^{q} \delta_2 ET^+{}_{t-1} + \sum_{i=0}^{q} \delta_3 ET^-_{t-1} + \sum_{i=0}^{q} \delta_3 \Delta GD_{t-1} + \sum_{i=0}^{q} \delta_4 \Delta RE_{t-1} + \sum_{i=0}^{q} \delta_5 \Delta AF_{t-1} + ECT_t + \mu_t .. (7)$$

Where Δ is the 1st difference operator, ρ^- and ρ^+ indicates the asymmetric parameters for long-term positive and negative environmental innovations, while δ^- and δ^+ shows the positive and negative deviation parameters in environmental technologies. ECT_{i-1} represents error correction term in the equation (7).

2. Results and Discussions

4.1 Preliminary Investigation Results

It is imperative to emphasize that the novelty of this study hinges on examining how environmental technological shocks impact greenhouse gas emissions, with a particular focus on whether linear or nonlinear relationships influence the nexus. This section is dedicated to three fundamental preliminary tests: the unit root status, the cointegration test, and the assessment of the adequacy and robustness of the estimated models. Panel 1a in Table 2 presents the results of the Kwiatkowski–Phillips–Schmidt–Shin (KPSS) unit root test, which tests the null hypothesis that the underlying series is trend-stationary, with the alternative hypothesis positing non-stationarity. The findings indicate that except for the renewable energy consumption series, which becomes stationary after first differencing, all other series are stationary at level. This leads to the conclusion that greenhouse gas emissions, environmentally related technologies, GDP per capita, and freshwater withdrawal are integrated of order zero. To complement the KPSS unit root test, we further assess whether the presence of structural breaks affects the decision to accept or reject the null hypothesis. This is achieved by employing the Zivot and Andrews (1992) unit root test, which accounts for structural breaks in both trend and intercept. The results are presented in Panel 1b, where the coefficients are reported alongside the actual year of the break. Notably, all variables are found to be stationary at levels using conventional significance levels. However, it is worth noting that the annual freshwater withdrawal series is only stationary at the 10% significance level, which we regard as a weak

outcome. Consequently, the series is differenced, and it becomes stationary at the 1% significance level.

Pesaran et al. (2001) provide a framework for modeling scenarios similar to the one at hand, where four variables are stationary at level, and one is stationary only after first differencing. Utilizing this framework, it is possible to identify a linear combination of all the variables, allowing for the testing of cointegration using a bound F-test. Following the implementation of both linear and nonlinear models, we tested for cointegration, and the results are reported in Panel 2. The estimation was guided by the Akaike Information Criterion (AIC) under an automatic lag selection procedure, resulting in optimal lags of 4 and 3 for the ARDL and NARDL models, respectively. The selected optimal models were ARDL (4,4,4,4,4) and NARDL (1,1,1,0,2). The null hypothesis of no level relationship was rejected at the 1% significance level for both the symmetric and asymmetric models. This indicates that greenhouse gas emissions, environmentally related technologies, GDP per capita, freshwater withdrawal, and renewable energy consumption, along with their respective lags, are interrelated and can affect each other in the long run.

Panel 3 presents the results of the diagnostic tests for the ARDL and NARDL estimates. We employed the Breusch-Pagan and Breusch-Godfrey tests to assess heteroskedasticity and serial correlation, respectively. In both cases, the test statistics were not statistically significant, leading us to fail to reject the null hypotheses of no serial correlation and homoscedasticity. To verify the normality of the residuals in the models, we used the Jarque-Bera statistic, which indicated that the residuals are normally distributed. Additionally, the Ramsey RESET test for specification error confirmed the correct functional form of the model at all conventional levels of significance. We also checked for the temporal consistency of the model parameters and the potential for structural breaks using cumulative sum (CUSUM) and cumulative sum of squares (CUSUMSQ) plots. As shown in the appendix, the lines remain consistent and within the confidence interval bounds, indicating stability at the 5% significance level. This suggests that the parameters are stable and consistent over the period covered by this study.

Table 1. Results of Preliminary Investigation

Panel 1a: KPSS Unit Root Test				
Variable	Test Statistics		Integration order	
	Level	Difference		
GH	0.116		I(0)	
ET	0.189		I(0)	
GD	0.010		I(0)	
AF	0.2859		I(0)	
RE	0.143*	0.271	I(1)	
Panel 1b: Zivot & Andrews Unit Root Test				
GH	-3.179*[2003]		I(0)	
ET	-4.098*[1998]		I(0)	
GD	-3.129**[2007]		I(0)	
AF	-3.041***[2017]	-3.673*(2016)	I(0)	
RE	-3.842*[2003]		I(0)	
Panel 2: Bound tests				
Method	Model		Lag	F-stat.
ARDL	ARDL(4,4,4,4,4)		4	9.060*
NARDL	NARDL(1,1,1,0,2)		3	15.519*
Panel 3: Diagnostic tests				

Test	ARDL	NARDL
Normality	0.837	0.846
BP Serial Correlation	6.477	0.320
BPG Hetero.	1.366	1.550
χ^2- Ramsey	0.589	0.036
CUSUM	Stable	Stable
CUSUM SQ	Stable	Stable

*,**,** denotes significant at 1%, 5% & 10% respectively. Values in [] are the structural break dates

Table 2. Long Run Impacts

Regressors	ARDL	NARDL
ET_{t-1}^{+}		0.056**(0.026)
ET_{t-1}^{-}		0.001(0.005)
ET	-0.009(0.011)	
GD	0.292*(0.068)	0.016(0.111)
AF	-0.013**(0.005)	-0.024*(0.008)
RE	-0.022*(0.007)	-0.035*(0.007)
Constant	14.352*(0.809)	16.545*(0.989)
Long-run Asymmetric Test	15.117*	

*,**,** denotes significant at 1%, 5% & 10% respectively. Values in () are the standard error

Table 3. Short Run Impacts

Regressors	ARDL	NARDL
ΔGH_{t-1}	0.791*(0.126)	
ΔET	0.002(0.001)	
ΔET_{t-1}^{+}		-0.007**(0.004)
ΔET_{t-1}^{-}		-0.018*(0.005)
ΔGD	-0.201*(0.050)	0.122*(0.028)
ΔAF	-0.007(0.004)	-0.001(0.002)
ΔRE	-0.006***(0.003)	
ECT	-1.022*(0.09)	-0.520*(0.043)
Short Run Asymmetric	1.090	

*,**,** denotes significant at 1%, 5% & 10% respectively. Values in () are the standard errors

4.2 Long Run Impact

Table 2 quantifies the long-term impact of environmental technologies (ET), gross domestic product (GD), annual freshwater withdrawal (AF), and renewable energy (RE) on greenhouse gasses (GS) in China. Both ARDL and NARDL models provide comprehensives understanding on how each variable impacts greenhouse gases over time. Based on the results from both models, GDP exhibits a strong significant positive long-term impact on greenhouse gases with a (0.292*) coefficient in ARDL than the NARDL model. These results indicate that the economic expansion corresponds to a rise in emissions, which supports the Environmental Kuznets Curve theory (Ahmed et al., 2021). This theory argues that economic growth at first promotes environmental damage. The finding of this study is aligned with Liu et al. (2020), who suggest that economic growth frequently raises resource consumption and emissions in emerging economies like China due to better living standards of people. However, they rely on fossil fuel-powered appliances and technologies, which raises the critical concern related to the raise in the greenhouse gas emissions level in the atmosphere (Merlin & Chen, 2021).

In both models, renewable energy consumption comprises a relentlessly long-term substantial and adverse impact on greenhouse gas emissions, with a coefficient of (-0.022*) in ARDL and

(-0.035*) in the NARDL model. It, therefore, means that an extensive share of renewable energy consumption is more beneficial in mitigating emissions, complementing prior empirical research such as Ahmed et al. (2020), who suggested that renewables are critical for sustainable or environmentally friendly growth by reducing fossil fuel dependency.

Interestingly, environmental technologies persist negatively with greenhouse gas emissions in the ARDL model, also it is statistically significant at 5% level in the linear model, this suggests that these technologies have a limited direct impact on emission reduction. Although environmental technologies are very critical to environmental quality, these findings suggest that their influence might be indirect or it required marginalized government incentives to be beneficial; the same argument is highlighted by Akomolafe et al. (2024). When the effect is divide into two partial sum, the positive impact of environmental technology on greenhouse gas is significantly positive, while the negative shock from the environmental innovation is also significantly positive in the long run. Surprisingly, that is not the case in the short run, both partial sums are found to exert a negative impact on greenhouse gas emissions. This underscores the importance of monitoring the impact, the technologies themselves could have on the environment via emitting harmful gases. From the policy side, the adoption of eco-friendly technologies requires a consistent approach to sustain future threads concerning the environment.

The annual freshwater has a negative significant association with greenhouse gases with a higher coefficient (-0.024*) in the NARDL model than the ARDL model which shows (-0.013**). This triggers highly efficient freshwater management strategies that might reduce environmental tensions which are caused by polluted water for agriculture and industry manufacturing purposes. This argument is consistent with Pu & Fu (2018) and Xu et al. (2022), whose study highlights that water shortage may indirectly promote sustainable practices and innovation in eco-friendly technologies and innovations in developing nations.

The significant long-run asymmetry test in the NARDL model (15.117*) indicates that giving positive and negative shocks in environmental technologies affect emissions asymmetrically. This finding underscores the importance of maintaining continuous investment in eco-friendly technologies, as positive advancements have a lasting positive impact on emissions, while the absence of such investment does not directly increase emissions. The following section presents the short-run impacts of corresponding variables on greenhouse gas emissions in China.

4.3 Short Run Impact

The short-run impact of GDP on greenhouse gases is considerable and positive in the ARDL model with a coefficient of (0.791*); this indicates that intense growth in economies causes an increase in greenhouse gases. Similar to this, Hassan et al. (2021) found that short-term economic boosts consistently increase emissions due to sharp industrial activity and fossil fuel consumption in China. Contrary to the long-term, it is suggested that when technological advancement and governmental changes might enhance environmental quality, the immediate repercussions of economic growth often worsen environmental damage. This signals the concern related to “green growth” in emerging economies like China, which is experiencing significant industrial activities (Holzman & Grunberg, 2021).

Furthermore, renewable energy consumption presents a strong significant impact on emissions, as reported by both ARDL and NARDL models with (-0.201* and -0.122*) coefficients; this finding suggests that even in the short term, an increase in renewables quickly reduces greenhouse gas emissions. This result confirms Ahmed et al. (2020), who argued that switching to renewable energy adoption and consumption is more crucial for both short- and long-term emission reductions in emerging economies. The negative association in both models further suggest that renewables are more successful in reducing emissions in the short run, emphasizing that policies that accelerate renewable energy deployment could provide immediate environmental benefits. Though it is proved in many studies that conventional energy consumption has negative impact on greenhouse gases, this could be minimized by advancing technological innovation in clean energy initiatives. Therefore, to achieve this, public and private sectors should contribute to the industrial modernization of the energy sector. Technological innovation/adoption might be widely utilized if they are properly and appropriately harnessed to facilitate the orderly and well-organized utilization of natural resources.

In the short run for both models, the impact of environmental technologies on emissions is not statistically significant, which highlights that environmental technologies have potential, but it takes time to manifest and requires compatible integration into industrial and societal practice. This conclusion is more aligned with Hassan et al. (2024), who found that the adoption of friendly environmental technologies is often hampered by factors such as initial costs, awareness, and regulatory backing. This pushes the significance of government incentives that stimulate quick adoption and deployment of green technology/green growth for sustainability since the short-term impacts on emissions are limited when adoption is slow and partial.

Similar to long run, freshwater withdrawal exhibits adverse significant short-run impact on green gases with (-0.007**), indicating that greater attention to water usage critically reduces emissions immediately in China. Sha et al. (2021) have also similar suggestion that effective resources management might result in immediate reductions in environmental pressure. In the short term. Policies that limit excessive water usage are more likely to promote sustainable behaviour despite indirectly restricting activities that may lead to emissions. Meanwhile, it is essential to emphasize the fact the short-term limits could only be beneficial in implementing temporary modifications rather than delivering a comprehensive, long-term solution.

Concluding this, the error correction term (ECT) is negative and statistically significant, confirming self adjustment of the equilibrium in case of distortion in the system.

Table 4. Robustness Test Results

Regressors	FMOLS	DOLS
ET	0.001(0.004)	0.004(0.0041)
GD	0.250*(0.017)	0.319*(0.031)
AF	-0.010*(0.003)	-0.012*(0.003)
RE	-0.026*(0.003)	-0.019*(0.003)
Constant	14.579*(0.251)	13.885*(0.353)

*,**,** denotes significant at 1%, 5% & 10% respectively. Values in () are the standard error

Table 5. Quantile Regression Results

Regressors	25th Quantile	50th Quantile	75th Quantile
ET	-0.003(0.006)	-0.002(0.004)	0.003(0.003)
GD	0.250*(0.022)	0.227*(0.028)	0.241*(0.028)

AF	-0.010*(0.003)	-0.011**(0.005)	-0.008(0.005)
RE	-0.026*(0.004)	-0.029*(0.004)	-0.026*(0.004)
Constant	14.597*(0.324)	14.887*(0.404)	14.620*(0.417)

*,**,** denotes significant at 1%, 5% & 10% respectively. Values in () are the standard error

4.4 Robustness Results

The fully modified OLS (FMOLS), dynamic OLS (DOLS) and quantile regression are presented in this section as robustness check to reinforce our findings. Table 4 displays the results of FMOLS and DOLS, while Table 5 shows the quantile regression results in 3 scenarios: 25th Quantile, 50th Quantile and 75th Quantile. These models analyze the stability of results across various predictions of greenhouse gas emissions. The consistent, significant results for GDP and renewable energy confirm the robustness of the finding in the study's primary models, reinforcing that GDP has a positive impact on emissions with (0.25*) in FMOLS and (0.319*) in DOLS. In contrast, the renewable energy usage was consistently found to have adverse effects with (-0.026*) in FMOLS and (-0.019*) in DOLS. These study's robustness findings suggest that irrespective of estimation strategies, confirming the idea that economic expansion might strain the environment unless accompanied by green activities (Xie & Jamaani, 2022).

Additionally, across the models, the negative association for renewable energy has been seen, this emphasis is its efficacy in decreasing emissions and supporting prior studies by (Bhattacharya et al., 2017; Nguyen & Kakinaka) whose findings revealed that renewables are more critical to sustainable development pathways. Notably, the insignificance of environmental technologies in both FMOLS and DOLS models might highlight challenges with quick impact. These technologies require a supportive legislative environment to deliver significant reductions in emissions (Mngumi et al., 2022). This robustness analysis, therefore, supports the broader significance of renewable energy and regulated economic integration and development while addressing limits in the short-run impacts of environmental technologies an area of imminent concern to policymakers in China as it pushes to achieve net zero emissions.

Table 5 presents the results of quantile regression; these quantile results show that although economic growth raises emissions in all scenarios, renewable energy is uniformly beneficial in reducing greenhouse gas emissions. Despite this, resource management through freshwater withdrawal persist a strong significant impact in lowering emissions, this also indicates that policy integration approaches could be required in higher scenarios to achieve environmental objectives in China.

3. Conclusions and Implications

China is one of the fastest-growing economies in the world, yet the country faces dynamic challenges in maintaining environmental quality. The industrial growth has sparked further discussions on the topic. This study analyzes the complex dynamics between economic development, environmental technologies, renewable energy consumption, and greenhouse gas emissions in China by considering both linear and nonlinear dimensions. We found evidence of long-run asymmetric cointegration among the variables of the study. In the long run, the findings reveal that although GDP growth has a significant positive impact on emissions, renewable energy emerges as an effective short- and long-term option for emission reduction

across many scenarios. China is currently transforming its economic structure, accelerating its growth rate, and changing its development mode. To achieve a high-quality environment, China must promote technical innovation for clean and green products. This will allow for a more accurate assessment of green growth potential and support high-quality economic development. Furthermore, annual freshwater withdrawal has a conditional impact, contributing more significantly in low-emission environments. This suggests that resource efficiency methods have varying degrees of influence depending on emission intensity.

Additionally, the findings indicate that to achieve long-term economic development, emerging economies like China should prioritise renewable energy deployment and implement policies that promote effective resource management. Policymakers should consider establishing incentives for adopting beneficial environmental technologies, especially if the immediate impact on emissions is modest. Quantile-specific policies could also help target high-emission situations more effectively by tailoring solutions to emission intensities. In some cases, governments are motivated by the potential to expand markets and create economic opportunities while driving the transition to green growth.

The key limitation of this study lies in the inability to obtain high-frequency data with a large time span. Additionally, the study focuses primarily on China; future research should expand to include a panel of Asian and Pacific countries, incorporating additional variables to moderate the long-term effects of innovations on greenhouse gas emissions.

References

Abubakar, A. B., Muhammad, M., & Mensah, S. (2023). Response of fiscal efforts to oil price dynamics. *Resources Policy*, *81*, 103353. https://doi.org/10.1016/j.resourpol.2023.103353

Ahmad, M., Muslija, A., & Satrovic, E. (2021). Does economic prosperity lead to environmental sustainability in developing economies? Environmental Kuznets curve theory. *Environmental Science and Pollution Research*, *28*(18), 22588-22601.

Ahmed, K., Bhattacharya, M., Qazi, A. Q., & Long, W. (2016). Energy consumption in China and underlying factors in a changing landscape: empirical evidence since the reform period. *Renewable and Sustainable Energy Reviews*, *58*, 224-234.

Ahmed, Z., Wang, Z., Mahmood, F., Hafeez, M., & Ali, N. (2019). Does globalization increase the ecological footprint? Empirical evidence from Malaysia. *Environmental Science and Pollution Research*, *26*, 18565-18582.

Ahmed, Z., Zafar, M., & Ali, S. (2020). Linking urbanization, human capital, and the ecological footprint in G7 countries: An empirical analysis. *Sustainable Cities and Society*, *55*, 102064. https://doi.org/10.1016/j.scs.2020.102064

Akomolafe, O. O., Olorunsogo, T., Anyanwu, E. C., Osasona, F., Ogugua, J. O., & Daraojimba, O. H. (2024). Air quality and public health: a review of urban pollution sources and mitigation measures. *Engineering Science & Technology Journal*, *5*(2), 259-271.

Alola, A. A., Bekun, F. V., & Sarkodie, S. A. (2019). Dynamic impact of trade policy, economic growth, fertility rate, renewable and non-renewable energy consumption on ecological footprint in Europe. *Science of the Total Environment*, *685*, 702–709. https://doi.org/10.1016/j.scitotenv.2019.05.139

Anna Holzman & Nis Grunberg. (2021, January 7). *"Greening" China: An analysis of Beijing's sustainable development strategies*. *Merics*.

https://merics.org/en/report/greening-china-analysis-beijings-sustainable-development-strategies

Bertelsmann Stiftung (2020). "Weltklassepatente in Zukunftstechnologien – Die Innovationskraft Ostasiens, Nordamerikas und Europas" (World class patents – The innovative strength of East Asia, North America and Europe). https://www.bertelsmann-stiftung.de/en/publications/publication/did/weltklassepatente-in-zukunftstechnologien. Accessed: December 11, 2020.

Bhattacharya, M., Churchill, S. A., & Paramati, S. R. (2017). The dynamic impact of renewable energy and institutions on economic output and CO2 emissions across regions. *Renewable Energy*, *111*, 157–167. https://doi.org/10.1016/j.renene.2017.03.102

Bölük, G., & Mert, M. (2015). The renewable energy, growth and environmental Kuznets curve in Turkey: An ARDL approach. *Renewable & Sustainable Energy Reviews*, *52*, 587–595. https://doi.org/10.1016/j.rser.2015.07.138

Dawkins, E., André, K., Axelsson, K., Benoist, L., Swartling, Å. G., & Persson, Å. (2019). Advancing sustainable consumption at the local government level: A literature review. *Journal of Cleaner Production*, *231*, 1450–1462. https://doi.org/10.1016/j.jclepro.2019.05.176

Doğan, B., Balsalobre-Lorente, D., & Nasir, M. (2020). European commitment to COP21 and the role of energy consumption, FDI, trade and economic complexity in sustaining economic growth. *Journal of Environmental Management*, *273*, 111146. https://doi.org/10.1016/j.jenvman.2020.111146

Dogan, E., & Seker, F. (2016). Determinants of CO2 emissions in the European Union: The role of renewable and non-renewable energy. *Renewable Energy*, *94*, 429–439. https://doi.org/10.1016/j.renene.2016.03.078

Fang, Z. (2023). Assessing the impact of renewable energy investment, green technology innovation, and industrialisation on sustainable development: A case study of China. *Renewable Energy*, *205*, 772–782. https://doi.org/10.1016/j.renene.2023.01.014

Gujarati, D. N. (2021). *Essentials of econometrics*. Sage Publications.

Hassan, S. A., Haq, I., Khattak, E. A., Nassani, A. A., Zaman, K., & Haffar, M. (2024). Transitioning from gridlock to sustainability: advancing transport strategies for eco-friendly solutions in high-income countries. *Environmental Science and Pollution Research*, 1-24.

Hassan, S. T., Zhu, B., Lee, C. C., Ahmad, P., & Sadiq, M. (2021). Asymmetric impacts of public service "transportation" on the environmental pollution in China. *Environmental Impact Assessment Review*, *91*, 106660.

Herman, K. S., & Hu, X. (2019). Induced innovation in clean energy technologies from foreign environmental policy stringency? *Technological Forecasting and Social Change*, *147*, 198–207. https://doi.org/10.1016/j.techfore.2019.07.006

Holzman, A., & Grunberg, N. (2021, January 7). "Greening" China: An analysis of Beijing's sustainable development strategies. *Merics*. Retrieved from https://merics.org/en/report/greening-china-analysis-beijings-sustainable-development-strategies

Huo, J., & Peng, C. (2023). Depletion of natural resources and environmental quality: Prospects of energy use, energy imports, and economic growth hindrances. *Resources Policy*, *86*, 104049.

Jiang, D., Shu, H., Fan, Y., Dong, Y., & Li, H. (2022). Influence of renewable energy and natural resources on climate change: The role of green innovation in China. *Frontiers in Environmental Science*, *10*. https://doi.org/10.3389/fenvs.2022.966656

Johansen, S. (1995). Likelihood-Based inference in cointegrated vector autoregressive models. In *Oxford University Press eBooks*. https://doi.org/10.1093/0198774508.001.0001

Johansen, S., & Juselius, K. (2009). MAXIMUM LIKELIHOOD ESTIMATION AND INFERENCE ON COINTEGRATION - WITH APPLICATIONS TO THE DEMAND FOR MONEY. *Oxford Bulletin of Economics and Statistics*, *52*(2), 169–210. https://doi.org/10.1111/j.1468-0084.1990.mp52002003.x

Kassens, A. L. (2019). Theory vs. practice: Teaching undergraduate econometrics. *The Journal of Economic Education*, *50*(4), 367-370.

Kim, Y., & Rho, S. (2024). The US–China Chip War, Economy–Security Nexus, and Asia. *Journal of Chinese Political Science*, 1-28.

Li, Z., Wu, B., Wang, D., & Tang, M. (2022). Government mandatory energy-biased technological progress and enterprises' environmental performance: Evidence from a quasi-natural experiment of cleaner production standards in China. *Energy Policy*, *162*, 112779. https://doi.org/10.1016/j.enpol.2022.112779

Liang, W., & Yang, M. (2019). Urbanization, economic growth, and environmental pollution: Evidence from China. *Sustainable Computing: Informatics and Systems*, *21*, 1–9. https://doi.org/10.1016/j.suscom.2018.11.007

Lin, B., & Ma, R. (2022). How does digital finance influence green technology innovation in China? Evidence from the financing constraints perspective. *Journal of Environmental Management*, *320*, 115833. https://doi.org/10.1016/j.jenvman.2022.115833

Liu, X., Sun, T., Feng, Q., & Zhang, D. (2020). Dynamic environmental regulation threshold effect of technical progress on China's environmental pollution. *Journal of Cleaner Production*, *272*, 122780.

Liu, X. (2024). Coalition Building and Sino–US Competition in the Digital Era. *The Chinese Journal of International Politics*, *17*(4), 425-448.

Luo, W., Bai, H., Jing, Q., Liu, T., & Xu, H. (2018). Urbanization-induced ecological degradation in Midwestern China: An analysis based on an improved ecological footprint model. *Resources Conservation and Recycling*, *137*, 113–125. https://doi.org/10.1016/j.resconrec.2018.05.015

Merlin, M. L., & Chen, Y. (2021). Analysis of the factors affecting electricity consumption in DR Congo using fully modified ordinary least square (FMOLS), dynamic ordinary least square (DOLS) and canonical cointegrating regression (CCR) estimation approach. *Energy*, *232*, 121025. https://doi.org/10.1016/j.energy.2021.121025

Mngumi, F., Shaorong, S., Shair, F., & Waqas, M. (2022). Does green finance mitigate the effects of climate variability: role of renewable energy investment and infrastructure. *Environmental Science and Pollution Research International*, *29*(39), 59287.

Mustafa, S., Hao, T., Jamil, K., Qiao, Y., & Nawaz, M. (2022). Role of eco-friendly products in the revival of developing countries' economies and achieving a sustainable green economy. *Frontiers in Environmental Science*, *10*, 955245.

Nguyen, K. H., & Kakinaka, M. (2019). Renewable energy consumption, carbon emissions, and development stages: Some evidence from panel cointegration analysis. *Renewable energy*, *132*, 1049-1057.

OECD (2018). "China's Progress Towards Green Growth." https://www.oecd.org/env/country-reviews/PR-China-Green-Growth-Progress-Report-2018.pdf. Accessed: December 11, 2020.

Oxford Institute for Energy Studies. (2020). "Current Direction for Renewable Energy in China." Oxford: University of Oxford.

Phillips, P. C., & Perron, P. (1988). Testing for a unit root in time series regression. *Biometrika*, *75*(2), 335–346. https://doi.org/10.1093/biomet/75.2.335

Pu, Z., & Fu, J. (2018). Economic growth, environmental sustainability and China mayors' promotion. *Journal of Cleaner Production*, *172*, 454-465.

Qin-Hua, W., Qu, J., Bao, W., Wang, P., & Yang, T. (2019). Green technology innovation development in China in 1990–2015. *Science of the Total Environment*, *696*, 134008. https://doi.org/10.1016/j.scitotenv.2019.134008

Rivera Leon, Lorena et al. (2020). "Measuring innovation in energy technologies: green patents as captured by WIPO's International Patent Classification (IPC) green inventory." World Intellectual Property Organization. https://www.wipo.int/edocs/pubdocs/en/wipo_pub_econstat_wp_44.pdf. Accessed: December 11, 2020.

Saqib, N., Usman, M., Ozturk, I., & Sharif, A. (2024). Harnessing the synergistic impacts of environmental innovations, financial development, green growth, and ecological footprint through the lens of SDGs policies for countries exhibiting high ecological footprints. *Energy Policy*, *184*, 113863.

Sha, A., Liu, Z., Jiang, W., Qi, L., Hu, L., Jiao, W., & Barbieri, D. M. (2021). Advances and development trends in eco-friendly pavements. *Journal of Road Engineering*, *1*, 1-42.

Shahbaz, M., Solarin, S. A., Sbia, R., & Bibi, S. (2015). Does energy intensity contribute to CO2 emissions? A trivariate analysis in selected African countries. *Ecological Indicators*, *50*, 215–224. https://doi.org/10.1016/j.ecolind.2014.11.007

Shen, Y., Su, Z., Malik, M. I., Umar, M., Khan, Z., & Khan, M. S. (2021). Does green investment, financial development and natural resources rent limit carbon emissions? A provincial panel analysis of China. *Science of the Total Environment*, *755*, 142538. https://doi.org/10.1016/j.scitotenv.2020.142538

Sinha, A., & Shahbaz, M. (2018). Estimation of Environmental Kuznets Curve for CO2 emission: Role of renewable energy generation in India. *Renewable Energy*, *119*, 703–711. https://doi.org/10.1016/j.renene.2017.12.058

Song, S., Zhang, L., & Ma, Y. (2022). Evaluating the impacts of technological progress on agricultural energy consumption and carbon emissions based on multi-scenario analysis. *Environmental Science and Pollution Research*, *30*(6), 16673–16686. https://doi.org/10.1007/s11356-022-23376-z

Song, W., & Yu, H. (2017). Green Innovation Strategy and Green Innovation: The roles of green Creativity and Green Organizational Identity. *Corporate Social Responsibility and Environmental Management*, *25*(2), 135–150. https://doi.org/10.1002/csr.1445

Su, C., Yuan, X., Tao, R., & Umar, M. (2021). Can new energy vehicles help to achieve carbon neutrality targets? *Journal of Environmental Management*, *297*, 113348. https://doi.org/10.1016/j.jenvman.2021.113348

The Oxford Institute for Energy Studies (2020). "Current Direction for Renewable Energy in China." Oxford: University of Oxford.

Wang, H., Cui, H., & Zhao, Q. (2021). Effect of green technology innovation on green total factor productivity in China: Evidence from spatial durbin model analysis. *Journal of Cleaner Production*, *288*, 125624. https://doi.org/10.1016/j.jclepro.2020.125624

Wang, K., Umar, M., Akram, R., & Caglar, E. (2021). Is technological innovation making world "Greener"? An evidence from changing growth story of China. *Technological Forecasting and Social Change*, *165*, 120516. https://doi.org/10.1016/j.techfore.2020.120516

Wei, Y., Ding, S., & Konwar, Z. (2021). The two faces of FDI in environmental performance: a meta-analysis of empirical evidence in China. *Journal of Chinese Economic and Business Studies*, *20*(1), 65–94. https://doi.org/10.1080/14765284.2021.1943735

Wooldridge, J. M. (2015). *Introductory econometrics: A modern approach*. Cengage learning.

Xie, P., & Jamaani, F. (2022). Does green innovation, energy productivity and environmental taxes limit carbon emissions in developed economies: Implications for sustainable development. *Structural Change and Economic Dynamics*, *63*, 66-78.

Xinhua (2020). "国家绿色发展基金扬帆起航，传递中国坚定绿色发展信心" (National Green Development Fund sets sail, conveying China's confidence in firm green development). July 17. http://www.xinhuanet.com/fortune/2020-07/17/c_1126251635.htm. Accessed: December 11, 2020.

Xinhua. (2020). 国家绿色发展基金扬帆起航，传递中国坚定绿色发展信心 (National Green Development Fund sets sail, conveying China's confidence in firm green development). July 17. Retrieved from http://www.xinhuanet.com/fortune/2020-07/17/c_1126251635.htm

Xu, X., Hou, P., & Liu, Y. (2022). The impact of heterogeneous environmental regulations on the technology innovation of urban green energy: A study based on the panel threshold model. *Green Financ*, *4*, 115-136.

Yan, X., & Sun, S. (2021). Impact of electric vehicle development on China's energy consumption and greenhouse gas emissions. *Clean Technologies and Environmental Policy*, *23*(10), 2909–2925. https://doi.org/10.1007/s10098-021-02209-6

Zeraibi, A., Balsalobre-Lorente, D., & Murshed, M. (2021). The influences of renewable electricity generation, technological innovation, financial development, and economic growth on ecological footprints in ASEAN-5 countries. *Environmental Science and Pollution Research, 28(37),* 51003–51021. https://doi.org/10.1007/s11356-021-14301-x

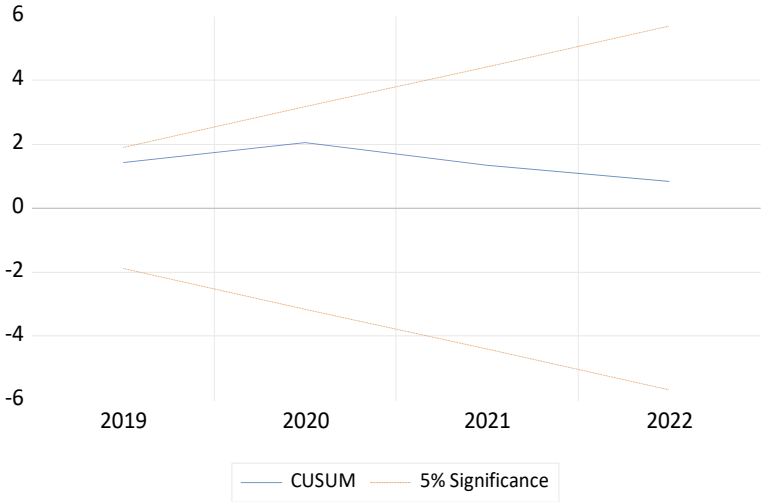
Zeraibi, A., Balsalobre-Lorente, D., & Murshed, M. (2021). The influences of renewable electricity generation, technological innovation, financial development, and economic growth on ecological footprints in ASEAN-5 countries. *Environmental Science and Pollution Research*, *28*(37), 51003–51021. https://doi.org/10.1007/s11356-021-14301-x

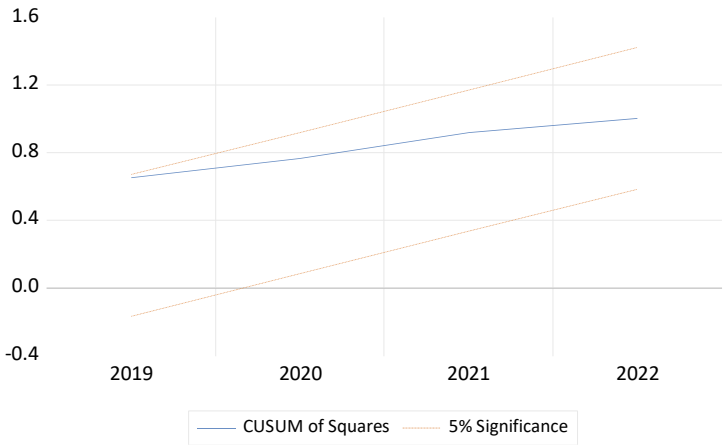
Zhang, H., Shao, Y., Han, X., & Chang, H. (2022). A road towards ecological development in China: The nexus between green investment, natural resources, green technology innovation, and economic growth. *Resources Policy*, *77*, 102746. https://doi.org/10.1016/j.resourpol.2022.102746

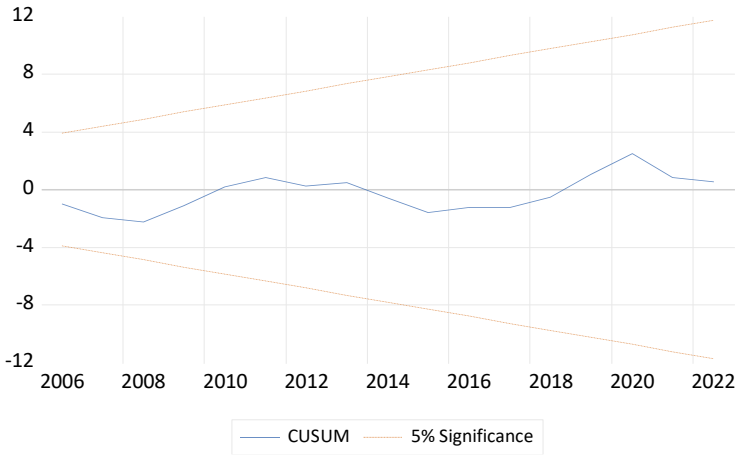
Zhang, Q., Adebayo, T. S., Ibrahim, R. L., & Al-Faryan, M. A. S. (2023). Do the asymmetric effects of technological innovation amidst renewable and nonrenewable energy make or mar carbon neutrality targets?. *International Journal of Sustainable Development & World Ecology*, *30*(1), 68-80.

Zhou, Y., Wei, T., Chen, S., Wang, S., & Qiu, R. (2021). Pathways to a more efficient and cleaner energy system in Guangdong-Hong Kong-Macao Greater Bay Area: A system-based simulation during 2015-2035. *Resources Conservation and Recycling*, *174*, 105835. https://doi.org/10.1016/j.resconrec.2021.105835

Appendix


6
4
2
0
-2
-4
-6
2019
2020
2021
2022
CUSUM
5% Significance


1.6
1.2
0.8
0.4
0.0
-0.4
2019
2020
2021
2022
CUSUM of Squares
5% Significance


12
8
4
0
-4
-8
-12
2006
2008
2010
2012
2014
2016
2018
2020
2022
CUSUM
5% Significance