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Asymmetric Relationship Between Energy Consumption, Air Quality And Economic Growth In China

Çin'de Enerji Tüketimi, Hava Kalitesi ve Ekonomik Büyüme Arasındaki Asimetrik İlişki

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ÖZ

Erkekler ve kadınlar arasındaki önemli eşitsizliklerle birlikte, iş yerindeki cinsiyet eşitsizliği Asya'da önemli bir sorun olmaya devam etmektedir. Kadınlar için istihdamın nüfusa oranı 2024 yılında sadece %44,7 iken, bu oran erkekler için ortalama %73,5'tir. Kadınların istihdama katılımının %24,5, erkeklerin katılımının ise %75,3 olduğu Güney Asya, en eşitsiz bölgedir. Doğu ve Güneydoğu Asya'da kadın istihdam oranları sırasıyla %61,2 ve %55,8 ile daha yüksektir, ancak yine de %77'yi aşan erkek katılım oranının altındadır. Başlıca engeller arasında kültürel gelenekler, yetersiz çocuk bakım sistemi ve örgün eğitim ve istihdama sınırlı erişim yer almaktadır. Güney Asya'da bu eşitsizlikler yoksulluk ve eşitsizliği sürdürürken, Doğu ve Güneydoğu Asya'da maaş farklılıkları ve liderlik pozisyonlarında yetersiz temsil kapsayıcı ilerlemeyi engellemektedir. 2014 ve 2024 yılları arasında, sabit etkiler panel veri regresyon yaklaşımı ile, kentleşme, eğitim, ekonomik genişleme ve doğrudan yabancı yatırım (DYY) toplumsal cinsiyet eşitliğinin ilerletilmesinde önemli bir rol oynamıştır. Örneğin, Doğu Asya kentleşme ve eğitimdeki iyileşmeden faydalanmış olsa da, Güney Asya büyük yapısal ve kültürel engellerle karşılaşmaya devam etmektedir. Küçük iyileşmelere rağmen, kadınlar kayıt dışı ve güvencesiz işlerde aşırı temsil edilmeye devam etmekte, bu da ekonomik eşitsizliği artırmaktadır. Bu sorunların ele alınması için eğitimin yaygınlaştırılması, çocuk bakım sistemlerinin güçlendirilmesi, kadın girişimcilerin finansmana erişiminin artırılması ve eşit ücret yasalarının uygulanması gerekmektedir. Toplumsal cinsiyet uçurumunun kapatılması sadece ahlaki açıdan doğru değil, aynı zamanda kapsayıcı büyümeyi ve uzun vadeli bölgesel refahı desteklemek için ekonomik açıdan da önemlidir.

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A B S T R A C T

With significant inequalities between men and women, gender inequality in the workplace remains a significant issue in Asia. The employment-to-population ratio for women was only 44.7% in 2024, compared to an average of 73.5% for men. With women's participation at 24.5% and men's at 75.3%, South Asia is the most unequal area. In East and Southeast Asia, female employment rates are higher at 61.2% and 55.8%, respectively, but they are still below the male participation rate of more than 77%. Among the primary barriers are cultural customs, a subpar childcare system, and limited access to formal education and employment. In South Asia, these disparities perpetuate poverty and inequality, while in East and Southeast Asia, salary gaps and underrepresentation in leadership positions obstruct inclusive progress. Between 2014 and 2024, with fixed effects panel data regression approach, urbanization, education, economic expansion, and foreign direct investment (FDI) all had a significant role in advancing gender equality. For example, although East Asia has benefited from urbanization and improved education, South Asia continues to face major structural and cultural obstacles. Despite slight improvements, women continue to be overrepresented in informal and insecure jobs, which furthers economic inequality. Addressing these issues requires expanding education, strengthening childcare systems, enhancing access to financing for female entrepreneurs, and enforcing laws on equal pay. Closing the gender gap is not only morally right but also economically important to support inclusive growth and long-term regional prosperity.

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1. Introduction

China has become a country that attracts worldwide attention with its rapidly increasing energy consumption, striking economic growth rate and environmental impacts of this growth in recent years. In particular, the negative consequences on atmospheric quality have raised significant concerns about the sustainability of this growth. In this context, the complex relationships between energy consumption, air quality and economic growth are intensively discussed and studied in academic circles. This article aims to examine in depth the interaction of these policies with economic growth and their importance in terms of sustainability by addressing the effects of China's energy policies on air quality.

In recent years, the relationships between China's energy consumption, atmospheric quality, and economic development have been examined with increasing attention at both national and international levels. The relationships between energy consumption, atmospheric quality, and economic development in China have attracted intense attention in academic circles in recent years. As the largest energy consumer worldwide, China, along with its tremendous economic growth rate and increasing energy demand, significantly affects global atmospheric conditions and climate balances. In this context, a large part of academic studies addresses the interdependence between China's rapidly developing economy and increasing energy consumption and analyses the direct and indirect effects of changes in the energy sector on environmental pollution. In addition, the possible effects of practices aimed at increasing energy efficiency on economic growth are emphasized, the contribution of these policies to China's sustainable development goals is evaluated, and the reflections of initiatives to reduce carbon emissions on air quality, especially in big cities, are examined in detail. These studies also contribute to sustainability and climate change discussions at the international level by creating important reference points in both China's domestic policies and global environmental policies.

The expansion of China's energy sector and the rapid increase in industrial production have had serious negative effects on the country's air quality. In this process where industrialization and urbanization continue rapidly, increasing energy demand has further increased the pressure on atmospheric quality and brought environmental concerns to the fore. An increasingly questioned balance has been established between the advantages of economic growth and environmental health. In particular, the dramatic increase in the energy needs of the expanding industrial sectors and the rapidly growing population significantly determines China's economic policies and future directions. In this context, the intensive use of fossil fuels has caused the release of large amounts of pollutants into the atmosphere, which has led to serious deterioration of air quality, especially in densely populated urban areas. Air pollution not only threatens public health but also causes the ecological balance to deteriorate. All these challenges reveal that China's energy policies and sustainable economic growth goals have a direct impact on atmospheric quality. This situation necessitates China to re-evaluate its future energy strategies and economic development plans.

The industrial revolution and economic growth have negatively affected the environment and air quality by changing production and consumption habits. Increasing competition, non-renewable energy use and urbanization have accelerated air pollution and environmental degradation. This situation has not only damaged the ecosystem but has also caused the deaths of millions of people. For environmental sustainability, it is necessary to turn to renewable energy sources and increase environmentally friendly investments such as green finance. However, since such investments require large costs, political instability makes this process difficult(Çitil et al. 2023).

Institutional quality and political stability are key factors in combating environmental problems. Institutional quality reduces corruption, ensures more effective enforcement of environmental laws and reduces carbon emissions. Political stability encourages long-term environmental protection investments and supports the sustainability of natural resources. Therefore, strong institutions, stable management and innovative financial approaches should be used together to reduce environmental degradation (Çitil et al. 2023). Generally, investments in green activities are those that conserve natural resources, extend renewable energies, and cut carbon emissions. These investments have become vital not only for attaining sustainable economic development but also for improving air quality. The contribution of this study to the existing literature is carried out by assessing the impacts of green investment on air quality in two groups of European countries: a group of 15 developed and a group of 16 developing nations. Unlike earlier research, which used capital expenditure on the environment as a proxy, this study incorporates pure green investment values for a more appropriate analysis. The study also combines air quality and green investments under one umbrella to analyze dependency among them across countries at various development levels. The study aims to enrich understanding of the role green investments may play in supporting economic transformations toward environmental sustainability, using robust econometric methods. This will constitute a contribution from both policymakers' and future research perspectives (İlbasmış et al. 2023).

According to (Barut, Citil, et al. 2023), the logistics sector has become a rapidly growing area due to the increasing trade volumes and production with globalization. Logistics services are of critical importance in terms of efficiency, competitiveness and economic growth. However, since logistics activities are based on fossil fuel consumption, they lead to serious problems such as environmental pollution and depletion of natural resources. This situation has increased the importance of environmental sustainability and green logistics concepts. Green logistics aims to reduce the negative impacts of logistics operations on the environment and to adopt environmentally friendly methods such as the use of renewable energy sources and recyclable packaging. However, since the implementation of green logistics requires large investments and comprehensive transformations, different challenges arise depending on the development level of countries. This transformation is more complex, especially in low-income or developing countries. The relationship between economic indicators and green logistics performance is examined through direct and indirect effects. For example, factors such as foreign direct investment (FDI), R&D expenditures and international trade are important in terms of both logistics activities and their impacts on environmental sustainability. In this context, the relationship between economic development indicators and logistics activities and environmental impacts should be addressed separately for different country groups (Barut, Citil, et al. 2023).

However, the relationship between energy consumption and air quality is not as simple as it seems. Elements such as transformations in China's energy sector and investments in renewable energy sources bring with them the potential to improve air quality. In recent years, the country has been turning to green energy by developing policies to reduce carbon emissions. However, the effects and feasibility of these policies on economic growth are matters of critical examination. In particular, China has increased its commitment to environmentally friendly energy in line with environmental stewardship and carbon reduction goals. In this context, investments in clean energy sources such as solar, wind and hydroelectricity have been expanded and gained an important place in national energy production. Obtained empirical data supports the positive effects of these policies on air quality; For example, solar energy investments have provided significant improvements in air quality, while wind energy projects have played an important role in reducing regional air pollution. A study from IOPscience points out that accelerating the process of decarbonizing China's energy sector can save lives by improving air quality, and that synergistic control strategies for climate and air pollution are important in this process (Qian Luo et al., 2023).

Academic research conducted to understand the effects of China's green energy policies on air quality reveals that these strategies have significant environmental and health consequences. The positive effects of China's green energy policies on air quality have been demonstrated by numerous academic studies. These studies highlight that China's investments in renewable energy sources have resulted in visible improvements in air quality and the positive effects of these improvements on public health. For example, Xie et al. (2023) stated that the implementation of renewable energy projects in China provided significant reductions in health problems and premature deaths caused by air pollution. This research reveals that regionally varying air quality improvements are closely related to the fair distribution and implementation of investments in renewable energy.

In addition, another study on air quality standards applied in urban areas and the effects of these standards on green innovation shows that China's policies that encourage green innovation to make its industrial structure more sustainable have significantly improved air quality, especially in large cities (Zhang et al., 2023). In this study, it is emphasized that reshaping the industrial structure together with the promotion of green innovation plays a critical role in creating a cleaner air environment in cities.

China's green energy policies are considered an important step towards both improving air quality and reducing carbon emissions. However, more detailed studies are needed on the potential effects and feasibility of these policies on economic growth. At this point, China's transition to green energy needs to be carefully evaluated not only in terms of environmental sustainability but also in line with economic development goals. The long-term effects of green energy policies are critical for both protecting the environment and ensuring sustainable economic growth. Therefore, China's transition to green energy should be addressed strategically, both in internal dynamics and in the global context.

In case of examining the relationship between energy consumption, air quality and economic growth in China, it is vital to take a multifaceted approach. The purpose of this article is to understand these complex relationships and evaluate the effects of China's energy policies on air quality. It also aims to provide a framework for future research by furthering the debate on this important topic. The links between energy consumption, air quality and economic growth have been extensively discussed and investigated in the literature.

This article aims to comprehensively examine the effects of China's energy policies on air quality and economic growth, based on studies in the existing literature. The analysis aims to reveal in detail how energy consumption, air quality and economic growth interact with each other. In this regard, an in-depth evaluation will be presented to better understand the dynamics of these relationships by addressing various dimensions of energy policies and the environmental and economic consequences of these policies. By investigating in detail the complex connections between energy consumption and air quality, their relationship with economic growth, and the effects of energy policies on these factors, the article aims to expand knowledge on this subject and lay a solid foundation for future research. Thus, valuable information will be provided for policy makers and researchers by providing a clearer perspective on the environmental and economic consequences of China's energy policies.

The aim of this study is to examine the relationship between energy consumption, air quality and economic growth in more depth in the context of China. Understanding the dynamics between environmental sustainability and economic growth is of great importance, especially for developing countries. In this context, the study sought to answer the following questions:

A. What are the short-term and long-term asymmetric relationships between energy consumption, PM2.5 levels and economic growth?

B. How does urbanization interact in terms of its effects on energy consumption and air pollution?

C. What are the effects of fuel imports on air pollution and economic growth?

To answer these questions, long-term cointegration relationships were analyzed with ARDL and NARDL models. In addition, the Dynamic Conditional Correlation (DCC) model was used to understand the time-dependent relationship between variables. This approach allows for more effective analysis of nonlinear relationships in complex systems such as energy consumption, urbanization and economic growth.

Concomitantly, this paper tries to fill this literature gap by developing, within a nonlinear framework, a nuanced understanding of the asymmetric and nonlinear nexus that pervades energy consumption, air quality—as proxied by the levels of PM2.5—urbanisation, and economic growth for China. In fact, most of the previous related studies have considered the linear models, which do not recognise the complexity and dynamics of their interaction with each other and amongst themselves. Using sophisticated methodologies of analysis, like the Non-Linear Autoregressive Distributed Lag model and Dynamic Conditional Correlation, this study will be able to capture intricate and time-varying correlations that traditional models cannot cope with.

More precisely, the research contributes to the existing literature by exploring the dual impact of urbanisation on air quality and economic growth and, accordingly, the potential trade-offs and equilibria that exist or could emerge between environmental sustainability and economic development. Whereas most of these aspects have been focussed on separately in most of the literature, in this study they are integrated within a single framework, thus providing comprehensive analysis of the effects of urbanisation on economic and environmental outcomes.

Greater novelty is added to the research through a focus on China's rapid urbanisation, energy policies, and an unusual economic growth trajectory. Such phenomena have been pursued to date in general terms or across many countries without much attention being paid to the context specific to China and its implications for policy. Based on high-quality country-specific data from the period 2000–2020, this study feeds into developing more effective urban planning, energy policy, and environmental regulation strategies in China and similar rapidly developing economies.

This study adds dynamic correlation analyses in order to observe the changes in the framework of the STIRPAT and Kuznets Curve. The results will provide further detail on how environmental policies, technological advancement, and economic shocks such as the COVID-19 pandemic influence the interrelationships between energy use, air quality, and economic growth, hence setting new insights into the academic debate.

2. Literature review

Recent studies have explored the asymmetric relationship between energy consumption, air quality, and economic growth across various regions. Research indicates that the effects of positive and negative shocks to these variables differ in magnitude and direction (Jiang and Chen 2020); (Ha and Ngoc 2021). In China, positive shocks to air quality and energy consumption have a greater impact on economic development than negative shocks (Jiang and Chen 2020). Vietnam exhibits asymmetric effects of electricity and petroleum consumption on economic growth in both short and long run (Ha and Ngoc 2021). Pakistan demonstrates asymmetric co-integration between ecological footprint, energy consumption, and economic growth (Khan 2021). A global study of 85 countries reveals that positive shocks to energy use enhance growth in some regions while contracting it in others (Wajid et al. 2022). These findings emphasize the importance of considering asymmetries when formulating energy and environmental policies to maintain economic stability.

Many studies are available in the literature addressing the relationship between energy consumption, economic growth and air quality in China (Li et al., 2019; Jiang and Chen, 2020; Zeraibi et al., 2020; Zeeshan et al., 2021; Dong et al. ., 2021; Jiang et al., 2022; Ye and Tao, 2023). The details of these studies are as follows:

Li et al. (2019) used an innovative two-stage RIA model called "Modified Undesirable EBM Two Stage RIA" to analyse environmental, economic and health efficiencies in thirty-one major urban centres of China. The findings of the research revealed the need for higher GDP performance in each city; However, a steady improvement in environmental efficiency has been observed in most cities.

Jiang and Chen (2020) analysed the relationship between energy consumption, air quality and economic growth between 1990 and 2019 with the NARDL method. The study confirmed that there is a bidirectional and asymmetric relationship between these variables in both the short and long term. In particular, positive shocks in air quality and energy consumption have been found to have a greater impact on economic development than negative shocks.

Zeraibi et al (2020) investigated the potential effects of energy consumption and technological innovations on economic growth in China from 1980 to 2018 with the NARDL method. The results show a long-term relationship between these variables. Additionally, it has been determined that a 1% decrease in energy consumption will reduce economic growth by 12.5%.

Zeeshan et al (2021) examined the asymmetric relationships between household health expenditures, CO_2 emissions and environmental pollution in China during 1990-2019. The study revealed that there is an asymmetric relationship between CO_2 emissions and environmental pollution and household health expenditures. It has been observed that positive shocks increase health expenditures, while negative shocks decrease them.

Dong et al (2021) investigated the effects of air pollution on China's economic growth between 2002 and 2017. Research results show that air pollution has significant negative effects on China's macroeconomic growth.

Jiang et al (2022) examined the asymmetric relationship between renewable energy consumption and CO_2 emissions in China from 1990 to 2020. The results obtained confirmed the asymmetric effects of renewable energy on the environment in both the short and long term.

Finally, Ye and Tao (2023) evaluated economic development, air pollution, and health management data in 30 Chinese provinces between 2015 and 2020. The study's findings show that China's developed eastern provinces are more efficient in terms of economic development, healthcare production and air pollution control; On the other hand, it has been revealed that the central and western provinces have lower efficiency in terms of economic development.

(Barut, Kaya, et al. 2023) investigates the trade-off between economic growth and environmental sustainability for five fragile economies that suffer from enormous energy and sustainability challenges. Using PCA, it incorporates variables such as the financial inclusion index and human development into the framework of economic growth versus the environment. The second-generation panel analysis through Durbin-Hansen's cointegration test showed long-run relationships among the variables, and the augmented mean group estimator estimated related dynamics. Results confirm the pollution haven hypothesis due to fragile trade and environmental treaties. However, renewable energy and human development indices decrease environmental deterioration. This study considers energy transition, technological innovation, and financial inclusion as priorities within the UNSDGs, specifically Goals 11, 12, and 13, and draws some policy implications toward sustainable development for these economies.

(Anwar et al. 2024) examines the impact of policy uncertainty on environmental degradation in the Fragile Five economies (Brazil, India, Indonesia, South Africa, and Turkey) from 1996 to 2019, using Panel Quantile Regression analysis. The findings reveal that economic policy uncertainty and technological innovation increase environmental degradation, while financial development and renewable energy consumption reduce it. Additionally, the study confirms the Environmental Kuznets Curve (EKC) hypothesis, indicating that environmental degradation initially rises with economic growth but declines after reaching a certain income level. Based on these results, the study suggests integrated policy and environmental strategies to promote sustainable development in these economies.

Based on above studies, studies on China's energy consumption, economic growth, and air quality reveal several key insights. Research indicates that cities with higher GDP performance often show improvements in environmental efficiency. The relationship between energy consumption, air quality, and economic growth is complex and asymmetric, with positive changes in air quality and energy consumption generally having a more significant impact on economic growth compared to negative changes. A reduction in energy consumption is linked to a notable decrease in economic growth, emphasizing the trade-off between energy use and economic performance. Additionally, CO_2 emissions and environmental pollution have asymmetric effects on household health expenditures, with positive and negative shocks influencing health costs differently. Air pollution is consistently shown to have detrimental effects on economic growth, and renewable energy consumption impacts CO_2 emissions in an asymmetric manner. Finally, economically advanced regions demonstrate better efficiency in managing economic growth, health, and air quality compared to less developed regions.

There are many studies examining the relationship between variables such as energy consumption, economic growth, environment and air quality in both developed and developing countries. Rafindadi (2014) found in his study that economic growth increased energy demand in Germany. Additionally, financial development, capital use and trade openness have been observed to reduce energy demand. In their study covering the period 1970-2013, Rafindadi and Mika'Ilu (2019) found that energy demand in the UK increased with the development of financial markets, but began to decline after the markets reached their operational peak level. Research results show that global financial transactions flowing into the UK are putting indirect economic pressure on the country's electricity problems.

In their study covering the period 1981-2018, Ullah et al. (2020) found that a positive shock in public expenditure deteriorated environmental quality in Malaysia, UAE, Thailand, Indonesia, Turkey, Iran, India and China, but improved environmental quality in Japan. They observed that reducing public spending would improve environmental quality in these economies, while deteriorating environmental quality outside of Japan. Ampofo et al (2021) investigated asymmetric cointegration and causality relationships between economic growth, carbon emissions and energy consumption during the period 1972-2013. The results show that there is a non-linear cointegration relationship between variables in Bangladesh, Iran, Türkiye and Vietnam. Asymmetric causality results found a two-way causality relationship between carbon emissions and economic growth in Bangladesh and Turkey, and a unidirectional causality relationship between economic growth and carbon emissions in Egypt and South Korea. In their study considering the period 1965-2019, Adebayo et al. (2021) found that CO2 emissions triggered economic growth in South Korea. Kumari et al. (2021) analysed the impact of energy consumption and environmental quality on subjective well-being in G20 countries between 2006 and 2019 using a panel-corrected standard error (PCSE) model. The results show that renewable energy consumption and environmental quality, i.e. lower carbon emissions, increase subjective well-being in G20 countries.

Assamoi et al (2023) investigated the asymmetric effects between economic policy uncertainty (EPU) and environmental policy stringency (EPS) and carbon dioxide (CO2) emissions in China and the USA. They found that an improvement in EPU deteriorates environmental quality in both countries. They also find that a negative change in EPU reduces emissions in China but increases them in the United States. They found that a positive change in EPS reduces emissions, while a negative change increases environmental damage. Kirikkaleli et al (2023) examined the long-term asymmetric effects of energy efficiency on environmental quality in Ireland between 1990 and 2019. The results of the study confirm the economic theory that energy efficiency can promote sustainable green living and green technological growth. Mahapatra et al (2023) identified the long- and short-term asymmetric effects of energy efficiency on carbon emissions in India. Umair et al. (2023) investigated the effects of fossil fuel energy consumption, foreign exchange transfers, foreign direct investments and economic growth on environmental sustainability in the South Asian region during the period 1975-2020. The findings of ARDL models reveal that fossil fuel energy consumption and economic growth increase CO2 in the long run, while foreign exchange transfers and foreign direct investments reduce CO2. NARDL empirical findings show that positive foreign exchange transfers and negative foreign direct investment shocks reduce CO2, while positive and negative fossil fuel energy consumption shocks increase CO2. The table below show some studies on

Table 1. Summary of Selected studies

Authors	Country	Method Used	Findings
Rafindadi (2014)	Germany	ARDL bounds test and the VECM Granger causality	Economic growth increased energy demand. Financial development, capital utilization, and trade openness reduced energy demand.
Rafindadi and Mika'Ilu (2019)	United Kingdom	Bayer-Hanck combined cointegration test; the ARDL bounds testing approach to cointegration and the Johansen cointegration test	Energy demand increased with the development of financial markets but started to decline after reaching a peak level.
Ullah et al. (2020)	Malaysia, UAE, Thailand, Indonesia, Turkey, Iran, India, China, Japan	ARDL approach	Positive shocks in public expenditure deteriorated environmental quality in most countries, but improved it in Japan. Reducing public spending improved environmental quality, except in Japan.
Ampofo et al. (2021)	Bangladesh, Iran, Turkey, Vietnam, Egypt, South Korea	Asymmetric Cointegration and Causality	Bidirectional causality between carbon emissions and economic growth in Bangladesh and Turkey; unidirectional causality from economic growth to carbon emissions in Egypt and South Korea.
Adebayo et al. (2021)	South Korea	ARDL, and fully modified ordinary least squares (FMOLS) methods	CO2 emissions triggered economic growth.
Kumari et al. (2021)	G20 Countries	Panel-Corrected Standard Error (PCSE)	Renewable energy consumption and environmental quality, such as lower carbon emissions, enhance subjective wellbeing.
Assamoi et al. (2023)	China, USA	The nonlinear autoregressive distributed lag (NARDL) model and asymmetric cointegration test	Economic policy uncertainty worsens environmental quality in both countries. Negative changes in EPU reduce emissions in China but increase them in the US. Positive changes in EPS reduce emissions, while negative changes increase environmental damage.
Kirikkaleli et al. (2023)	Ireland	second-generation panel unit root, Westerlund cointegration, FMOLS, and DOLS	Energy efficiency supports sustainable green living and green technological growth.
Mahapatra et al. (2023)	India	panel SFA. Second, the NPARDL model	Identified long- and short-term asymmetric effects of energy efficiency on carbon emissions.
Umair et al.	South Asia	ARDL	Fossil fuel energy consumption and economic growth

Authors	Country	Method Used	Findings
(2023)			increase CO2 in the long run, while remittances and foreign direct investments reduce CO2. Positive remittances and negative FDI shocks reduce CO2; positive and negative fossil fuel energy consumption shocks increase CO2.
Wajid Ali, S. Nathaniel, I. Adekunle, B. Kumar (2022)	China	non-linear panel autoregressive distributed lag (ARDL)	positive shocks to energy use tend to have a growth-enhancing effect in ECO and the Next Eleven while in the rest of the regions, the effect is growth contraction
Ha, N. M., & Ngoc, B. H. (2020)	Vietnam	Non-linear panel autoregressive distributed lag (ARDL)	bi-directional causality between energy consumption and economic growth, supported the Feedback hypothesis
Khan et al (2020)	Pakistan	Non-linear panel autoregressive distributed lag (ARDL)	Asymmetric nexus between energy use and economic growth on environmental quality and Feedback effect noted between energy consumption and environmental quality
Jiang and Chen (2020)	China	Non-linear panel autoregressive distributed lag (ARDL)	The impacts of positive energy use changes and positive air quality changes on output are greater. Negative output shocks have more effects on energy use and air quality.

By authors

3. Methodology and Data

This study was conducted to contribute to a deeper understanding of the relationship between energy consumption, air quality and economic growth in China. For this purpose, the Non-Linear Autoregressive Distributed Lag (NARDL) model developed by (Shin, Yu, and Greenwood-Nimmo 2014) was used for asymmetric and non-linear cointegration analysis. The NARDL model has become a preferred analytical tool due to its ability to capture complex relationships. In additional, Traditional regression models often treat relationships in a linear fashion. However, in complex systems such as the economy and the environment, relationships are often non-linear. ARDL and NARDL models can help us analyse non-linear and asymmetric relationships more effectively. Also, following (Ojaghlou et al. 2023) Dynamic Conditional Correlation (DCC) model developed by (Engle 2002a) was used. The DCC model has the ability to capture the volatility and correlation structures of variables that change over time. In this way, we can better understand how volatility and correlation change over time. For this

The NARDL model uses the bounds test approach to test the long-run cointegration relationship between the variables, regardless of their stationarity levels. This approach is valid even for small sample sizes. By measuring asymmetric effects in both the short and long run, it can determine how variables respond to positive and negative shocks. In addition, the model can evaluate the causal relationship between the variables and reveal how the variables affect each other and the direction of interaction (Shin et al. 2014) and (Allen and McAleer 2021). This topic has been extensively studied in order to examine asymmetric dynamic relationships, especially on the basis of the STIRPAT and Kuznets curve framework. In this context, researchers such as (Ojaghlou and Ugurlu 2023), (Ojaghlou et al. 2023), (Mahmood, Alkhateeb, and Furqan 2020) and (Jiang and Chen 2020) have drawn attention to this method. In additional, following (Zhao and Zhang 2018) to test impact of urbanisation on energy consumption on China we set an NARDL model.

We use differential and annual time series data for variables such as Energy use EC (kg of oil equivalent per capita), real GDP per capita (LCU) and PM2.5 index (Micrograms per cubic metre), Annual change in primary energy consumption (%) in our analysis. Our dataset covers the period from 2000 to 2020 and includes data for China. These data were compiled using publicly available data from the OECD, the World Bank, and Our World in Data.

Table 2. shows our variables and sources:

Variables	Benchmark	Acronym	Source
GDP	Real GDP per capita (local Currency)	Y	World Bank
PM2.5	Particulate matter and the 2.5 refers to size	PM	OECD
change in primary energy	Annual change in primary energy consumption (%)	ECCH	Our World in Data*
Urbanization	Urban population (% of total population)	URB	World Bank
Fuel imports	Fuel imports (% of merchandise imports (mineral fuels, lubricants and related materials))	FIM	World Bank

***:**https://ourworldindata.org/explorers/energy?facet=none&country=CHN~IRN~TUR&Total+or+Breakdown=Total&Energy+or+Electricity=Primary+energy&Metric=Rel.+change+from+previous+year

4. Unit root test

Most time series are non-stationary and therefore the most of the can not be used directly. A common approach to modelling trends involves considering models that become stationary after some transformation(Mayoral n.d.)Stationarity means that statistical properties of a time series, such as mean, variance, and covariance, do not change over time. A non-stationary time series shows an unpredictable systematic structure and is not suitable for econometric analysis. Therefore, when working with time series, it is important to test for stationarity. Unit root tests test whether the coefficient in the autoregressive model of a time series is one. If the coefficient is one, it indicates the existence of a unit root and thus nonstationarity. Unit root tests can also be used to investigate long-run cointegration and causality relationships of time series (Hamilton 1989) and (Enders 2014). For this aim, Augmented Dickey-Fuller (ADF) test developed by (Dickey and Fuller 1979) and DF-GLS test developed by (Elliott, Rothenberg, and Stock 1996) have been used. The results is summarised in table 3.

Table 3: Unit Root Test Results

Variables	ADF	DF-GLS
Y	-4.320***	-9.791***
ΔY	-6.193***	-6.081***
ECCH	-2.66	-2.44
ΔECCH	-6.490***	-4.40***
PM2.5	-1.715	-1.306
ΔPM2.5	-5.107***	-5.413***
URB	-2.221	-2.381**
ΔURB	-4.82***	-3.61**

Note: .***,**,* Significance at the %1, %5 and %10 levels, respectively. ADF and DF-GLS test represent the Augmented Dickey and Fuller test and GLS-detrended Dickey-Fuller test of stationarity, respectively.

All variables are stationary at I(0) and I(1) levels, and none of them are stationary at I(2) levels, as seen in Table 2. In this context, all variables are stationary at the combination of I(0) and I(1) levels. Therefore, ARDL bound and NARDL model are considered as methods combining nonlinear and asymmetric error correction models using constructed partial sum decompositions to handle nonlinear long-run relationships. The mentioned models were developed by (Pesaran, Shin, and Smith 2001) and (Shin et al. 2014) respectively.

NARDL long-run relationship:

$$y_t = \beta^+ {x_t}^+ + \beta^- {x_t}^- + u_t$$

Where β^+, β^- are the asymmetric long-run parameters and x_t is a $k \times 1$ vector, and

$$x_t = x_0 + {x_t}^{POS} + {x_t}^{NEG}$$

Where ${x_t}^{POS}$ and ${x_t}^{NEG}$ are partial sum processes of positive and negative changes in x_t defined by

$${x_t}^+ = \sum_{j=1}^{t} \Delta x_j^+ = \sum_{j=1}^{t} max(\Delta x_j, 0), {x_t}^- = \sum_{j=1}^{t} \Delta x_j^- = \sum_{j=1}^{t} min(\Delta x_j, 0)$$

Error-correction form of the system is as follows:

$$\Delta y_t = \rho y_{t-1} + \theta^+ x_{t-1}^+ + \theta^- x_{t-1}^- + \sum_{j=1}^{p-1} \gamma_j \Delta y_{t-j} + \sum_{j=0}^{q} (\pi_j^+ \Delta x_{t-j}^+ + \pi_j^- \Delta x_{t-j}^-) + \varepsilon_t,$$

where null hypothesis:

$$\rho = \theta^+ = \theta^- = 0$$

The long-run steady state of the system can be expressed by asymmetric cumulative dynamic multipliers as follows:

$$m_h^+ = \sum_{j=0}^{h} \frac{\partial y_{t+j}}{\vartheta x_t^+} \quad m_h^- = \sum_{j=0}^{h} \frac{\partial y_{t+j}}{\vartheta x_t^-} \quad h = 0, 1, 2 \ldots$$

where m_h^+ and m_h^- tend toward the respective asymmetric long-run coefficients $\beta^+ = \theta^+ / -\rho$ and $\beta^- = \theta^- / -\rho$, respectively, as $h \to \infty$.

By analysing the positive and negative effects separately, the NARDL model can offer better suggestions on how to achieve the balance between economic activities and environmental quality. Following literature such as (Jiang and Chen 2020) and (Zhao and Zhang 2018) we set two NARDL model. The first model is used to analyse the relationship between PM2.5 concentration, income, financial developments, level of urbanization and the effects of past values. The main purpose of the model is to understand the dynamic relationships and possible asymmetry between these variables. The second model is used to analyse the relationship between income, changes in energy consumption, level of urbanization and the effects of past values. The purpose of the model is to understand the dynamic relationships and possible asymmetry between these variables. This type of analysis is important to understand the relationship of the economy to factors such as energy consumption and urbanization and the lags in this relationship. Both of those model help use to understand effect of urbanization and energy consumption effect on PM2.5 and economic activities and possıble trade-off between economic activities and PM2.5.

$$\Delta PM2.5_t = \alpha_0 + \sum_{q=1}^{p1} \alpha_{1q} \Delta PM2.5_{t-q} + \sum_{q=0}^{p2} \alpha_{2q} \Delta Y_{t-q} + \sum_{q=0}^{p3} \alpha_{3q} \Delta FIM_{t-q}^+ + \sum_{q=0}^{p4} \alpha_{4q} \Delta FIM_{t-q}^- + \sum_{q=0}^{p5} \alpha_{5q} \Delta URB_{t-q} + \beta_1 PM2.5_{t-1} + \beta_2 Y_{t-1} + \beta_3 FIM_{t-1}^+ + \beta_4 FIM_{t-1}^- + \beta_5 URB_{t-1} + \varepsilon_t \quad MODEL-I$$

$$\Delta Y_t = \alpha_0 + \sum_{q=1}^{p1} \alpha_{1q} \Delta Y_{t-q} + \sum_{q=0}^{p2} \alpha_{2q} \Delta ECCH_{t-q}^+ + \sum_{q=0}^{p3} \alpha_{3q} \Delta ECCH_{t-q}^- + \sum_{q=0}^{p4} \alpha_{4q} \Delta URB_{t-q} + \beta_1 Y_{t-1} + \beta_2 ECCH_{t-1}^+ + \beta_3 ECCH_{t-1}^- + \beta_4 URB_{t-1} + \varepsilon_t \quad Model-II$$

For Dynamic Correlation Model (DCC) developed by (Engle 2002a) has several advantages. Unconditional correlation methods often fail to capture relationships that change over time. However, the Dynamic Conditional Correlation method allows us to obtain results that are more realistic by better capturing the relationships that change over time. Likewise, relationships in variables can change frequently and sudden events can affect each other. Therefore, Dynamic Conditional

Correlation enables us to analyse more precisely, helping us to make more accurate effect of variable.

If covariance matrix written by

$$H_{ij,t} = R_{ij}\sqrt{H_{ii,t}H_{jj,t}}$$

Based on (Engle 2002b), R_t is taken as follows:

$$R_t = \mathrm{diag}(q_{11,t}^{\frac{1}{-2}} \ldots q_{NN,t}^{\frac{1}{-2}})\ Q_t\ \mathrm{diag}(q_{11,t}^{\frac{1}{-2}} \ldots q_{NN,t}^{\frac{1}{-2}})$$

and

$$Q_t = (1-\alpha-\beta)\overline{Q} + \alpha u_{t-1}u'_{t-1} + \beta Q_{t-1}$$

$$\rho_{12,t} = \frac{(1-\alpha-\beta)\overline{q_{12}} + \alpha u_{1,t-1}u_{2,t-1} + \beta q_{12,t-1}}{\sqrt{(1-\alpha-\beta)\overline{q_{11}} + \alpha u_{1,t-1}^2 + \beta q_{11,t-1}(1-\alpha-\beta)\overline{q_{22}} + \alpha u_{2,t-1}^2 + \beta q_{22,t-1}}}$$

According to (Engle and Sheppard 2001), if we have a positive definite Q_t, it means that R_t is of positive sign, and $\overline{Q}$ denotes the $N \times N$ unconditional variance matrix of u_t. Here, ρ values represent correlation coefficients, α and β coefficients represent variance model parameters and satisfy the conditions $\alpha \geq 0, \beta \geq 0$ and $\alpha + \beta < 1$.

Table 4: Results of the long-run test

Dependent variable: LPM2.5 **Model 1**		Dependent variable: LY Model 2	
Variables	Coefficients	Variables	Coefficients
$LFIM^{POS}$	-3.51*** (-3.94)	$ECCH^{POS}$	-0.020*** (-3.26)
$LFIM^{NEG}$	2.68 ***	$ECCH^{NEG}$	0.027*** (3.34)
LY	-4.387** (-3.59)	$LURB$	3.59*** (39.67)
$LURB$	8.468** (3.007)	-	-
Constant term	36.195** (2.897)	Constant term	-3.48*** (-10.08)
ECT*	-0.288*** (-3.82)	ECT**	-0.80*** (-4.03)
F-Bounds	54.83*** Upper Bound of 1%: 4.37	F-Bounds	11.02*** Upper Bound of 1%: 4.66
Prob. $\chi^2{}_{resid}$	> 0.05	Prob. $\chi^2{}_{resid}$	> 0.05
Prob. $\chi^2{}_{ARCH}$	> 0.05	Prob. $\chi^2{}_{ARCH}$	> 0.05
CUSUM	Fully stable	CUSUM	Fully stable
CUSUMSQ	Fully stable	CUSUMSQ	partially stable
Results	cointegrated	Results	cointegrated

Note: * $ECT = LPM2.5 - (-3.51(LFIM^{POS}) + 2.64(LFIM^{NEG}) - 4.38(LY) + 8.46(LURB) + 36.19)$

** $ECT = LY - (-0.020(ECCH^{POS} + 0.027(ECCH^{NEG}) + 3.59(LURB) - 3.4821)$

The model chosen to see the long-term relationship was determined as $ARDL(2,2,2,0,2)$. In this model, the constant term and its trend are considered as limited. According to the model results, the coefficients are examined to examine the long-term relationships of the dependent variable, LPM2.5.

Error term correction term (-0.288) in Model 1 and (-0.80) in Model 2. These terms are statistically significant and within the accepted range $(-1 < ECT < 0)$. F-bounds test results evaluates the long run relationship and stability of the model. Statistically significant results were obtained in both models.

Autocorrelation test $(\chi^2{}_{resid})$ and Autoregressive conditional heteroscedasticity (ARCH) test $(\chi^2{}_{ARCH})$,are above 0.05 significance level were obtained in both models, that show there is no problem of autocorrelation and heteroscedasticity in both models. Results of cumulative sum errors and stability tests of their squares. Full stability for Model 1 and partial stability results for Model 2. The results show that both models are "cointegrated", meaning they are in a long-term relationship

As table 3 shows, the estimated coefficient of $LFIM^{POS}$ is -3.511. Changes in positive fuel imports seem to have a reducing effect on air pollution (pm2.5) and the estimated coefficient of $LFIM^{NEG}$ is 2.68 which negative changes of fuel imports seem to have a increasing effect on air pollution (pm2.5). More fuel imports generally encourage the use of fuel sources. While in particular, in the case of China seems that the preference of cleaner fuels such as natural gas instead of fuels with high particle emissions such as coal contributes to the reduction of fine particulate matter (PM2.5) levels in the air. Combustion of natural gas releases less particulate matter and pollutants into the air compared to coal. In addition, the increase in fuel imports can be used to offset energy production in regions with less clean energy sources locally such as coal and woods. This can help favour less polluting fuel types and ultimately lower PM2.5 levels.

As expected urbanization increased PM2.5 emission, it general is due to increased energy consumption, intensive transportation, industrial activities, increase of residential and commercial areas, reduction in local green space. In model 2, Urbanization also has positive effect on output. It's generally because of increase in economic activity, access to human resources, technological progress, market access.

According to your findings, while the urbanization coefficient obtained in the model 1 examining the effect of urbanization on air pollution was 8.9, this coefficient was calculated as 3.59 in the second model measuring the effect on economic output\income. The coefficients obtained in both models are statistically significant. These results show that urbanization is effective on both air pollution and economic income.

The findings may suggest that the urbanization effect creates a balance between air pollution and economic income. This state of equilibrium may indicate that there is a complex relationship between environmental quality and economic growth. There may be several reasons for this phenomenon. The first, urbanization often leads to increased industrialization and trade (IMF. External Relations Dept. 1971). This can increase energy consumption and cause air pollution. On the other hand, economic growth and increased income may increase the possibility of investing in cleaner energy technologies and environmentally friendly production methods (Raihan and Tuspekova 2022), (Liu, Zhao, and Li 2023). In additional, as urbanization increases, the necessity of environmental protection and regulation becomes more evident. Air pollution can harm human health, which can increase healthcare costs (Li, Du, and Zhang 2020). Therefore, it is important to consider environmental factors in order for economic growth to be sustainable.

Well-designed urban planning and infrastructure can balance environmental sustainability and economic growth. Inadequate infrastructure, increased population and economic activity can lead to negative consequences such as air pollution and traffic congestion (Kalfas et al. 2023). On the other hand, technological progress can increase economic growth (Ayres 1996) while also reducing environmental impacts (Cheng et al. 2021). Innovations in clean energy sources and environmentally friendly production techniques can alleviate the negative relationship between air pollution and economic growth.

For clear understanding of time-varying relationship between variables Dynamic correlation of variable (DCC) are tested. The DCC model is used to capture how conditional correlations change over time. This is suitable for analysing datasets with variable correlations over time, such as financial data. Table 5 shows coefficients of DCC model:

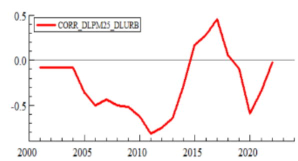
Table 5: coefficients of DCC

Variables	Coefficient
α	0.681
β	0.318
ρ_{21}	−0.415
ρ_{31}	−0.953
ρ_{41}	−0.080
ρ_{32}	0.410
ρ_{42}	−0.255
ρ_{43}	0.088

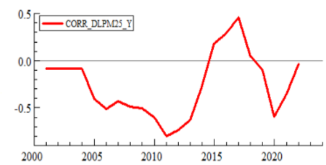
In the DCC model, the alpha (α) parameter represents its own volatility threshold for each data. This parameter is used to regulate the volatility of each series. The alpha condition usually takes a value between 0 and 1, and this value determines the effectiveness of volatility forecasts. The larger the alpha, the more weight the volatility estimates give to historical data. In the DCC model, the beta (β) parameter represents the relationship between two entities. This parameter determines how the correlation of two assets changes dynamically. The beta condition also usually takes a value between 0 and 1. High beta values indicate that the correlation of two assets is changing more rapidly, while low beta values may indicate a slower changing correlation. Based on results of DCC model, α and β (parameters of the DCC model) are not negative, and their sum is less than one ($\alpha + \beta < 1$). Graph 1 shows DCC between the variables.

Graph 1: DCC

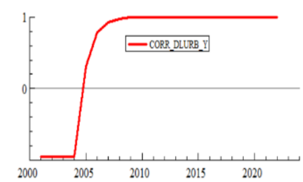
DCC between urbanization and PM2.5



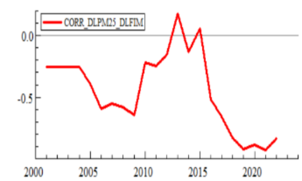
DCC between income and PM2.5



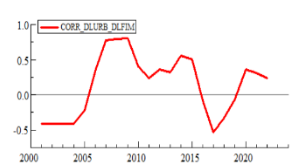
DCC between urbanization and income



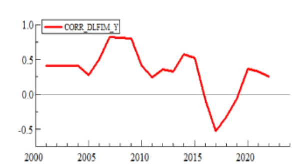
DCC between Fuel imports and PM2.5



DCC between urbanization and Fuel imports



DCC between income and Fuel imports



The relationship between urbanization and PM2.5 (Particulate Matter) examined with the aid of the DCC model is generally negative. The negative correlation observed especially after 2004 continued to increase until 2011. Since 2011, the correlation has decreased and continued until 2015. Between 2015 and 2018, the correlation turned positive, but changed to negative again between 2018 and 2021. These observations show that the relationship between urbanization and PM2.5 exhibits a complex dynamic over time. A negative correlation may indicate that air pollution decreases with increasing urbanization. This can be interpreted as higher urbanization levels encourage the adoption of more effective environmental policies and the use of cleaner production methods. However, the decrease in the negative correlation observed after 2011 and even its return to positive may suggest that different factors were effective in this process. Factors such as economic growth, industrialization and energy consumption can affect air pollution levels, and the interaction of these factors with urbanization may change.

The positive correlation period between 2015 and 2018 may indicate that an increase in economic growth and/or energy consumption in a given period may increase air pollution. However, the re-observation of negative correlation in the 2018-2021 period could possibly reflect the impact of environmental policy measures and the shift to clean energy technologies. However, income (output) has strong DCC with urbanization so that after 2005, the correlation turned to full positive. The positive correlation between urbanization and income occurs because cities are rich in economic, educational and social opportunities. Cities are often places where people can maximize their skills and abilities and have access to a variety of job and educational opportunities, which increases their income levels. That why DCC between DCC between income and PM2.5 is so similar to DCC between urbanization and PM2.5.

The Dynamic Conditional Correlation (DCC) between fuel imports and PM2.5 (Particulate Matter) is generally negative. However, it was observed that the correlation turned weakly positive in the short term between 2013 and 2015. In addition, there was a strong correlation between 2019-2021; It is thought that this situation may have resulted from the COVID-19 outbreak. It has been observed that the level of air pollution increases as fuel imports increase. Intensive use of fossil fuels can contribute to air pollution, especially in the industrial and transportation sectors. Therefore, the negative correlation between fuel imports and PM2.5 may reflect the fundamental relationship between increased fuel use and reduced air quality. It is thought that the strong correlation between 2019-2021 may have resulted from the COVID-19 outbreak. With the effect of the epidemic, economic activities were restricted, transportation decreased and production activities stopped in many countries. Energy consumption and fuel imports may have also decreased during this period, resulting in reductions in air pollution levels. In this context, it is thought that the economic recession and restrictions caused by the COVID-19 pandemic may have affected the relationship between fuel consumption and air pollution.

The Dynamic Conditional Correlation (DCC) between urbanization and fuel imports between 2000 and 2005 is negative. However, it turns positive after 2005 and continues to be positive until 2016. DCC between 2016-2019 turns negative and turns positive again during the COVID-19 outbreak.

Urbanization and Energy Use: Negative DCC between 2000-2005 may reflect the dynamics of the relationship between urbanization and fuel imports. Urbanization may have increased during this period, but energy efficiency and the use of alternative energy sources may still be limited. Therefore, there may be a link between increased urbanization and energy demand, which could explain the negative correlation.

Positive DCC after 2005 may reflect the impact of the relationship between economic growth and energy demand. Economic growth often increases energy demand. In this period of rapid urbanization, the increasing energy need may also increase fuel imports. Negative DCC during 2016-2019 may reflect the impact of economic factors and certain policy decisions. Factors such as energy policies and the management of fuel imports can affect energy demand and imports. The period of the COVID-19 pandemic is characterized by economic restrictions and reduced mobility. This may lead to a decrease in energy demand. Stay-at-home policies and a decrease in industrial activities during the epidemic may also affect energy imports. However, economic recovery efforts and an increase in energy demand after the partial shutdown may cause the positive correlation to reappear.

Dynamic Conditional Correlation (DCC) between Income and Fuel Imports shows a very similar pattern as DCC between Urbanization and Fuel Imports. In both cases, especially economic growth and energy demand factors are effective. The negative correlation in the 2000-2005 period may be due to low energy efficiency and limited use of alternative energy sources. The positive correlation after 2005 can be explained by economic growth and increased energy demand. Similarly, the negative correlation in the 2016-2019 period may have occurred due to the impact of economic and policy factors. The positive correlation during the COVID-19 epidemic period can be explained by the recovery efforts following the economic restrictions, increasing energy demand. These results show that economic dynamics and policy decisions similarly affect the relationship between income and fuel imports.

Several studies in the literature complement the findings of this research and have, as such, constrained the relationships examined. For instance, Rafindadi (2014) and Rafindadi & Mika'Ilu (2019) established the significant impacts of financial development and economic activities on energy demand, complementary to the emphasis of this study on the economic determinants of energy and environmental dynamics. Ampofo et al. (2021) and Adebayo et al. (2021) proved that carbon emissions and economic growth have a bidirectional causality direction in selected countries, which corroborates the interconnectivity from the present study. Assamoi et al. (2023) and Umair et al. (2023) further find asymmetric impacts of policy and energy consumption changes on environmental quality, supporting the current study for nonlinear relationships. Moreover, the asymmetries of both the short and long run in the impact of energy and economic factors on emissions have been exposed by Mahapatra et al. (2023) and Jiang and Chen (2020)—further supporting the nuanced results which have been developed here. Comparisons are thus brought forth by strength in the results of this study but place them in a wider empirical context.

Results from this analysis provide tremendous insight into the complex nexus of economic growth, energy demand, financial development, and environmental quality. This study was therefore able to capture the short- and long-run dynamics that might exist, together with asymmetries, using newly developed econometric approaches like ARDL and NARDL in analysing these crucial linkages.

The findings indicate that energy demand is indeed positively affected by economic growth—a precept that has been reiterated by trends observed by Rafindadi (2014) in Germany. This trips off a connotation that energy needs increase with the increasing economies, which are reflected by industrialisation and rising consumption patterns. However, this decline in energy demand after a peak level is consistent with the findings of Rafindadi and Mika'Ilu (2019) for the UK, implying that beyond a threshold level, technological changes, efficiency in the use of energy, and structural transformations within the economy alleviate dependence on energy-intensive processes.

More importantly, this asymmetric relationship—in which the positive shocks of economic variables like financial development have different effects than negative ones—found support in Assamoi et al. (2023). Their work reported asymmetric effects of economic policy uncertainty on emissions in China and the USA. This parallel underlines the consideration of nonlinearities that need to be done in policy design, most especially in energy- and environment-related ones.

The interrelation of public spending with environmental quality has, therefore, somewhat agreed with the findings of Ullah et al. (2020). As much as this study confirms that increased public expenditure can degrade environmental quality in certain contexts, it also highlights that strategic reduction or efficient allocation of public funds can mitigate environmental damage. By such duality, a nexus of budget policy towards sustainable development is picked up for greener growth.

In fact, this bidirectional causality among carbon emissions and economic growth in Turkey supports the results of Ampofo et al. (2021) and reiterates the Feedback Hypothesis for similar economies. This, therefore, presents causality that means policy measures put in place to reduce emissions have to consider their potential effects on economic performance and vice versa.

These findings also contribute to the growing body of literature that points to renewable energy and environmental factors due to the development of technology. For instance, Kumari et al. (2021) concluded that renewable energy consumption is positive for subjective well-being and environmental quality. The current findings extend this conclusion by pointing out that policies of encouraging the use of renewable energy are essential as the economy grows and energy needs change.

These results have multifold implications: first, that energy-efficient technologies and renewable energy are to be pursued by policymakers if the economy is to realise unprecedented economic growth with limited harm to the environment; second, financial markets should be used to incentivise green investments in such a way that economic development gradually achieves its environmental objectives; lastly, fiscal policies should be designed to enforce sustainable public spending behaviour since interaction between government spending and environmental quality has thus far acted as a linchpin.

These findings form a basis for further research on region-specific and sectoral dynamics of the subject matter, especially by expanding the dataset into more countries or even time periods. Future studies should try to incorporate institutional factors like governance quality and policy stability that may shape such relationships.

The integration of the foregoing aspects allows the study to contribute to a better understanding of the nexus between economic-environment-energy and contributes to evidence-based policymaking in a more effective way.

This study, while contributing valuable insights, has certain limitations that warrant consideration. One significant limitation is the reliance on a restricted dataset that includes a limited number of countries and time periods. This constrains the ability to generalise the findings across different regions with diverse economic structures, energy consumption patterns, and environmental policies. Furthermore, the methodological approach, though robust in employing ARDL and NARDL models, does not account for cross-sectional dependencies among countries, which are increasingly relevant in a globally interconnected economy. The analysis also excludes the potential role of institutional factors such as governance quality, policy stability, and international agreements, which could significantly influence the nexus between energy, environment, and economic growth. Additionally, the study focuses on broad variables like energy demand and environmental quality without incorporating more detailed or disaggregated data, potentially oversimplifying complex interactions.

To address these issues, future research should expand the geographical and temporal scope to include more countries, particularly those from low- and middle-income regions, while also extending the time horizon to cover more recent developments. Incorporating advanced econometric techniques, such as methods that account for cross-sectional dependencies, could provide a more nuanced understanding of the interconnections between variables. Including institutional factors, such as governance quality and compliance with international environmental agreements, would enrich the analysis and enhance its policy relevance. Sector-specific investigations, particularly within industries like manufacturing, transportation, and agriculture, could reveal unique dynamics that broad analyses might overlook.

Furthermore, integrating technological innovation into future studies would provide valuable insights into the role of advancements in renewable energy and energy efficiency in shaping the observed relationships. The inclusion of demographic, cultural, and social factors could also enhance the understanding of societal responses to energy and environmental challenges. Finally, exploring feedback effects using causality-based methods, such as Granger Causality or Structural Equation Modelling, would provide deeper insights into the bidirectional relationships between economic growth and environmental quality. By addressing these areas, future research can build on the current study's findings, offering more comprehensive guidance for policymakers and stakeholders.

5. Conclusions

This study aimed to conduct an in-depth analysis of the relationships between energy consumption, air quality, and economic growth in China. The Non-Linear Autoregressive Distributed Lag (NARDL) model developed by Shin, Yu, and Greenwood-Nimmo (2014) was used as the preferred analytical tool to capture these complex relationships. The results have shown that China's green energy policies have made a significant contribution to improving air quality and reducing carbon emissions.

The relationship between energy consumption and air quality is closely associated with China's rapidly growing industrial sectors and increasing population. This has led to a significant rise in the intensive use of fossil fuels and the amount of pollutants emitted into the atmosphere. Particularly in major cities, the deterioration in air quality has raised serious concerns about health issues and environmental impacts. China's energy policies and economic growth objectives have a direct and decisive impact on air quality.

Our findings may suggest a balance between urbanization and air pollution. This equilibrium situation demonstrates a complex relationship between environmental quality and economic growth. Urbanization often accompanies increased industrialization and trade, while economic growth and rising incomes can increase the likelihood of investment in clean energy technologies and environmentally friendly production methods. However, as urbanization increases, the need for environmental protection and regulation becomes more pronounced, and considering environmental factors becomes critical for sustainable economic growth.

The findings of our study indicate that the relationship between urbanization and PM2.5 exhibits a complex dynamic over time. A negative correlation may indicate that air pollution decreases with increasing urbanization, while a positive correlation period suggests that an increase in economic growth and/or energy consumption within a specific timeframe may increase air pollution.

As a result, China's green energy policies have had positive effects on air quality, but the impacts and feasibility of these policies on economic growth should be carefully assessed. In this context, future studies are expected to help us better understand the complex relationships between urbanization, economic growth, and environmental quality, and to identify effective policies for sustainable development.

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