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# Evaluating the Environmental Kuznets Curve: The Role of Renewable Energy, Economic Growth, Urban Density and Trade Openness on CO<sub>2</sub> Emissions. An Analysis for High-Income Countries Using the CS-ARDL Model

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## ABSTRACT

In view of the environmental challenges the world is currently facing, the objective of this research was to examine the short- and long-term effect of renewable energies on CO<sub>2</sub> emissions. In addition, to deepen the analysis, the Environmental Kuznet Curve (EKC) hypothesis, and the effects of urban population density and trade openness on CO<sub>2</sub> emissions in 30 high-income countries in the period 2000-2020 were evaluated. A cross-sectional autoregressive distributed lags model (CS-ARDL) and the Augmented Mean Group (AMG) model were estimated for robustness checks. The findings reveal that renewable energy consumption reduces CO<sub>2</sub> emissions in both the short and long term. Furthermore, there is strong evidence to support the EKC hypothesis. Finally, openness to trade was found to increase CO<sub>2</sub> emissions, while the relationship between urban density and CO<sub>2</sub> emissions is statistically non-significant. This information is expected to be crucial for the generation of public policies framed in sustainable development.

**Keywords:** CO<sub>2</sub> Emissions, Renewable Energies, Kuznet Hypothesis, Trade Openness, CS-ARDL

**JEL Classifications:** Q56, O13, F18

## 1. INTRODUCTION

In the dynamics of the modern economy, diversification of economic activities has positioned itself as a strategy to accelerate economic growth (Shabani, 2024). In this regard, energy consumption has become a key determinant of this process, mainly due to the intensification in the use of fossil fuels for the expansion of productive activities related to industrialization (Rahman et al., 2023). There is a significant body of literature supporting the growth through energy consumption hypothesis (Stern, 1993; Bowden and Payne, 2009; Tugcu et al., 2012). This pattern has led to a significant increase in energy demand, especially fossil energy, which accounts for about 80% of global energy consumption (Kim and Park, 2022; Acheampong et al., 2022; Zhou et al., 2023).

This situation has triggered a series of negative externalities, most notably an increase in greenhouse gas (GHG) emissions, which are responsible for environmental degradation and global warming (Bergougui, 2024). By 2022, GHG emissions reached a level of 53.8 Gt CO<sub>2</sub> eq, which means an increase of 2.3% compared to 2021, where 71.6% of these were carbon dioxide (CO<sub>2</sub>) emissions (Crippa et al., 2023). In 2023, global energy-related CO<sub>2</sub> emissions grew by 1.1%, achieving a historically high level of 37.4 billion tons (Gt) (IEA, 2024).

Unprecedented levels of CO<sub>2</sub> emissions in 2023 caused the global average temperature to exceed 14.9°C, surpassing the levels of 2016, where record highs in global temperature were recorded (Shabani, 2024). Therefore, these increasing trends in CO<sub>2</sub>

emissions have led to extreme weather conditions and increased likelihood of natural disasters (Liao et al., 2024), affecting the health and welfare of the population and causing significant losses in biodiversity (Pradhan et al., 2024; Huo et al., 2022). This scenario becomes even more critical under recent forecasts, where GHG emissions are estimated to increase by 52% by 2050 (Lin and Okoye, 2023), which would cause global temperatures to rise by 3-5°C by 2100 (Dasgupta et al., 2023). Thus, achieving the goals set in the Paris Agreement in 2015, specifically a temperature increase below 2°C above pre-industrial levels with zero CO<sub>2</sub> emissions by 2050, is far from being achieved (İnal et al., 2022).

In response to the challenges the world faces in relation to global warming, it is urgent to implement mechanisms to reduce GHG emissions. In this regard, developed and developing countries have traditionally implemented carbon taxes and different polluting activities to reduce emissions of these harmful gases (Wolde-Rufael and Mulat-Weldemeskel, 2021; 2023). However, despite evidence that environmental taxes help mitigate CO<sub>2</sub> emissions (Ulucak et al., 2020; Wolde-Rufael and Mulat-Weldemeskel, 2022), they are conditional on optimal tax rates, leading to uncertainty about their outcomes (Aydin and Esen, 2018; Rakpho et al., 2023). Moreover, their implementation has remained under debate, particularly because of their implications on the loss of efficiency of certain stakeholders that are dependent on fossil fuel-intensive activities, generating negative impacts at the socioeconomic level (Wang et al., 2016; Semet, 2024). For this reason, a consensus has been established in the global community to redirect efforts to encourage the transition to renewable energies, which will act as a mechanism to mitigate the detrimental effects of GHG emissions (Shabani, 2024).

The transition to renewable energies to address the climate crisis is not a recent topic, and has been debated for the last decades. Among the first researches to address this issue are the studies developed by Lysen (1989), Lee and Ryu (1991) and Wisniewski et al. (1995), where they highlight the potential of renewable energies to reduce CO<sub>2</sub> emissions. The initial rationale for this relationship is based on the Environmental Kuznet Curve (EKC) theory, whose hypothesis predicts an inverted U-shaped relationship between economic growth and environmental degradation (Stern, 2004). According to the EKC hypothesis, in the early stages of development, there is an increase in fossil energy consumption, which negatively affects environmental quality. However, in higher stages of development, where the use of clean energy and the adoption of technologies is promoted, environmental quality improves (Wolde-Rufael and Mulat-Weldemeskel, 2022). To date, various research continues to support the role of renewable energies in mitigating the environmental damage caused by CO<sub>2</sub> emissions from economic activities (Apergis et al., 2018; Khan et al., 2020; Jebli et al., 2020; Bergougui, 2024; Shabani, 2024).

However, despite the literature's interest in investigating the impact of renewable energy on environmental quality, most studies have focused their attention on developing countries, where they face major obstacles to the implementation of modern renewable energy sources, mainly in terms of accessibility and affordability (Briera and Lefèvre, 2024; Shabani, 2024). In contrast, few studies

have addressed this issue in high-income countries. Although these countries have made great progress in renewable energy, they also face significant challenges, especially as to whether renewable energy capacities can meet energy needs in a context of intensifying economic activities (Olabi et al., 2023). These challenges are compounded by technical and political concerns about environmental and socioeconomic consequences. For example, the environmental stress generated by the infrastructure required for the development of renewable energies or the loss of employment in conventional energy sectors (Olabi et al., 2023). Therefore, this study seeks to contribute to the literature and provide solid evidence to inform policy makers on the potential of promoting clean energy.

Thus, the objective of this research is to analyze the impact of renewable energies on the reduction of CO<sub>2</sub> emissions in high-income countries, bearing in mind that despite being home to 15% of the world's population, these countries produce 34.4% of the world's CO<sub>2</sub> emissions (Ritchie, 2023). In addition, countries such as Germany, the United States, Italy, and the United Kingdom have increased their production of CO<sub>2</sub> emissions (Huang et al., 2022). In this regard, the research contributes to the literature in three ways. First, it analyzes the magnitude of the impact of renewables to mitigate CO<sub>2</sub> emissions in the short and long term. Second, it investigates the relationship between economic growth and CO<sub>2</sub> emissions under the EKC hypothesis. Third, other determinants of CO<sub>2</sub> emissions are examined, mainly urban population density and trade openness. To meet the objectives, World Bank data from 30 high-income countries over the period 2000-2020 are used. In order to provide robust results, a sub-panel of the 15 main CO<sub>2</sub> emitting countries is established, allowing for a deeper analysis of magnitudes. Methodologically, a cross-sectional autoregressive distributed lags model (CS-ARDL) for panel data is used, which allows estimating short- and long-term relationships considering heterogeneity and cross-sectional dependence within the selected sample. Likewise, the Augmented Mean Group (AMG) technique is implemented to corroborate these results.

The research is structured as follows. Section 2 deals with the literature review, both theoretical and empirical. Section 3 describes the methodology. Section 4 presents the empirical findings and Section 5 develops the conclusions.

## 2. REVIEW OF THEORETICAL AND EMPIRICAL LITERATURE

### 2.1. Renewable Energy and CO<sub>2</sub> Emissions

In the face of increasing environmental deterioration caused by the intensive use of fossil fuels, renewable energies, such as wind, solar, and hydroelectric, have emerged as efficient alternatives to mitigate CO<sub>2</sub> emissions (Amer et al., 2024). There are several reasons for the negative impact of renewables on CO<sub>2</sub> emissions. First, renewable energies, thanks to their natural generation, do not release carbon dioxide into the atmosphere and, therefore, do not pollute the environment (Wang et al., 2024). Secondly, by substituting non-renewable energies, such as oil and gas, in productive activities, renewable energies promote energy

efficiency. This means that fossil fuel consumption is reduced while maintaining production levels, which promotes ecological sustainability (Wang et al., 2023a). Furthermore, the integration of renewables into energy systems encourages the development of green technologies, leading to higher levels of energy efficiency and ultimately to a significant reduction in CO<sub>2</sub> emissions (Song et al., 2024).

According to the theoretical implications, several empirical studies have examined the impact of renewable energies on CO<sub>2</sub> emissions under different temporal and spatial conditions. Based on a dynamic threshold panel for 67 countries between the period 1999 and 2019, Shabani (2024) finds that renewable energies have a negative impact on CO<sub>2</sub> emissions. In addition, he finds that human capital amplifies the effect of renewable energies, mainly in developed countries. In this line, Amer et al. (2024) by means of the feasible generalized least squares (FGLS) method found that non-renewable energies are positively associated with CO<sub>2</sub> emissions in the countries that make up the Gulf Cooperation Council (GCC) between 1995 and 2017. Conversely, renewables significantly mitigate CO<sub>2</sub> emissions. For 27 OECD countries between 2001 and 2020, Işık et al. (2024) evidence a negative correlation between renewables and CO<sub>2</sub> emissions. Li and Haneklaus (2022) applying a panel autoregressive distributed lags (ARDL) model for the G7 economies over the period 1979-2019, support the effect of renewable energies in reducing CO<sub>2</sub> emissions. More specifically, they find that for a 1% increase in clean energy consumption, CO<sub>2</sub> emissions are reduced by 0.33% in the short run and 0.099% in the long run. Similarly, Yang and Umar (2022) find that renewable energies reduce CO<sub>2</sub> emissions in G7 economies. In addition, they show that globalization is another determinant in mitigating these emissions, mainly because it promotes technology transfer in the context of clean energy.

Although previous studies, which have focused mainly on developed economies, reveal the important role that renewable energies play in environmental sustainability, it is important to examine the contribution of these energies in developing economies. In this regard, Yadav et al. (2024) examine the impact of good governance, renewable energy investment and green finance in BRICS countries (Brazil, Russia, India, China and South Africa) between 2000 and 2013. Using the cross-sectional autoregressive distributed lag autoregressive (CS-ARDL) model, the results show that investments in renewable energy reduce CO<sub>2</sub> emissions in the long run, and the effect is amplified when incorporating the development of green finance. In addition, several studies focusing on BRICS countries support the role of renewables in environmental sustainability (Adebayo and Samour, 2024; Khan et al., 2022a; Fu et al., 2021). However, Pata (2021) finds that the effect of renewables in BRICS countries is heterogeneous. According to the findings, these types of energies allow reducing environmental pollution in Brazil and China. Whereas, in Russia and India, these energies do not influence environmental pressure.

At the same time, several studies have addressed this issue in other regions of the world. For example, research such as Rahman and Alam (2022a), Amin et al. (2024), Zhang et al. (2023a,b) concur in

finding that renewable energies reduce CO<sub>2</sub> emissions in different regions of Asia, both in the short and long term. However, a heterogeneous effect persists. Alam and Hossain (2024), using the autoregressive distributed lags (ARDL) approach, show that increasing the use of renewable energy reduces CO<sub>2</sub> emissions in China in the short and long run. Complementing the ARDL model with the Granger causality approach of the Vector Error Correction (VEC) model, Chen et al. (2019) support the mitigating effect of renewable energy in China on CO<sub>2</sub> emissions. In contrast, Zaidi et al. (2018), using the ARDL model, find that renewable energy consumption has a non-significant impact on CO<sub>2</sub> emissions in a scenario where coal and natural gas are the main culprits of environmental degradation in Pakistan. This finding shows the obstacles Pakistan faces in relation to renewable energy adoption, with economic conditions being the main factor, followed by lack of access to credit, political instability and high investment risk (Shahzad et al., 2023).

In the context of Africa, Acheampong et al. (2019) using panel techniques with fixed and random effects find that renewables contribute to mitigating CO<sub>2</sub> emissions in 46 countries in Sub-Saharan Africa. Along these lines, research such as Elom et al. (2024), Aquilas et al. (2024), Kwakwa (2023a,b) and Namahoro et al. (2022) support the ability of renewables to reduce CO<sub>2</sub> emissions in different regions of Africa. On the other hand, for the Latin American and Caribbean region, Koengkan and Fuinhas (2020) applying a panel model under the autoregressive distributed lags (PARDL) approach, find that renewable energies have a negative impact on CO<sub>2</sub> emissions in the short term of -0.0675 and in the long term of -0.0313. Similarly, the findings of Yuping et al. (2021), Raihan (2023), Raihan and Tuspekova (2022), and Nahrin et al. (2023), support the ability of renewables to promote environmental sustainability, mainly in countries dependent on non-renewable energy. In addition, Silva et al. (2021) mention that the levels of environmental degradation in Latin America and the Caribbean have a positive effect on the installed capacity of non-hydroelectric renewable energies, which reveals the pollution hotspots that the region faces.

On the other hand, the literature has also focused on investigating the effects of different renewable energy sources on CO<sub>2</sub> emissions. For the top ten European Union economies between the period 1991 and 2019, Mohsin et al. (2023) using quartile-on-quartile panel techniques find that hydropower consumption substantially reduces CO<sub>2</sub> emissions. Furthermore, Bello et al. (2018), applying Granger causality techniques under the Vector Error Correction Model (VECM) approach for Malaysian economy data between the period 1971 and 2016, evidences a significant reduction in environmental degradation due to hydropower use. However, the effects of this type of renewable energy can be asymmetric. For example, Bilgili et al. (2021), using the wevelet transformation model applied in the United States for the period 1980-2019, point out that hydropower increases CO<sub>2</sub> emissions in the short term, but reduces them in the long term. In addition, Güney (2022), analyzing data from 35 countries of different income levels between 2005 and 2018, find that increased solar energy use leads to a decrease in CO<sub>2</sub> emissions. Similarly, Yu et al. (2022), using data from the top ten solar consuming countries between 1991



and 2018 and applying the quartile-on-quartile model, report that with the exception of France, solar energy reduces CO<sub>2</sub> emissions. For wind power, Güney and Üstündağ (2022), sampling 37 countries for the period 2000-2019 using the Augmented Mean Group (AMG) method, found that a 1% increase in wind power consumption reduces CO<sub>2</sub> emissions by 0.018%.

Table 1 summarizes additional research on the link between renewable energies and CO<sub>2</sub> emissions.

In relation to the literature reviewed, the first hypothesis of the research is as follows:

#### Hypothesis 1

H1: Renewable energies have a negative impact on CO<sub>2</sub> emissions.

## 2.2. Economic Growth and CO<sub>2</sub> Emissions

The link between economic growth and environmental quality has been the subject of debate since the 1960s, initially addressed by the theory of natural resource extraction (Brock and Taylor, 2005). Since then, the literature has grown significantly and negative, positive and mixed effects of economic growth on CO<sub>2</sub> emissions have been reported. Regarding the negative effect, it is mentioned that higher economic growth is strongly associated with technological progress and innovation, which enables the adoption of better environmental practices that reduce CO<sub>2</sub> emissions (Hashmi and Alam, 2019). Thus, a rapid adoption of technologies within economic activities will promote higher environmental quality (Caglar et al., 2024). On the other hand, the positive effect is explained by the relationship between economic growth and natural resource utilization. In other words, as economic activities grow, the demand for raw materials increases, which in turn increases CO<sub>2</sub> emissions (Agboola et al., 2021). Thus, the

dilemma faced by public policy makers is to neglect conservation processes in order to achieve higher levels of economic growth.

Finally, the mixed effect is addressed by the Environmental Kuznet Curve (EKC) hypothesis. The EKC hypothesis, formulated by Grossman and Krueger (1991), postulates an inverted U-shaped relationship between per capita income and pollution. According to this hypothesis, environmental pollution increases up to a certain point as income increases; however, once a certain turning point is reached, pollution begins to decrease (Dinda, 2004). The central idea of the EKC hypothesis is the following: in the early stages of economic growth, natural resources are used intensively, which generates higher levels of environmental pollution. Moreover, at this stage, given the low level of per capita income, both the population and institutions tend to ignore the negative externalities of growth. However, as the economy develops and income increases, the environment becomes more highly valued. The productive structure, by incorporating technology, is redirected towards more environmentally sustainable models, which reduces environmental pressure (Leal and Marques, 2022).

As for the empirical studies, their main objective has been to verify the EKC hypothesis under different conditions and different econometric methodologies. In this regard, the research findings can be classified into three categories. First, a group of researches do not find strong evidence supporting the inverted U relationship between income level and CO<sub>2</sub> emissions (e.g., Islama et al., 2023; Kanlı and Küçükefe, 2023; Wencong et al., 2023). These findings suggest that economic growth can generate long-term environmental damage. Second, another group of research shows consistent results supporting the EKC hypothesis (e.g., Ridzuan et al., 2020; Wang et al., 2024; Zhang et al., 2022; Zhang et al., 2020). These results provide evidence that further economic

**Table 1: Additional empirical studies: Renewable energy and CO<sub>2</sub> emissions**

Authors	Country (ies), Data, Methodology	Endogenous variable	Independent variable (s)	Conclusion
Alam et al. (2023)	India; 1990Q1-2018Q4; econometric structural break technique.	CO <sub>2</sub> emissions; carbon footprint; carbon intensity.	Renewable energy Globalization Agricultural production Population density	Renewable energy $\xrightarrow{U}$ contamination atmospheric
Balsalobre-Lorente et al. (2023)	BRICS; 1995-2020; Fully Modified Least Squares (FMOLS) and Dynamic Least Squares (DOLS).	Carbon dioxide emissions per capita	Economic complexity index Renewable energy Foreign direct investment	Renewable energy $\xrightarrow{-}$ CO <sub>2</sub> emissions
Hoa et al. (2023)	Vietnam; 2000-2022; fixed effects panel data.	CO <sub>2</sub> emissions	High-tech innovations or exports Renewable energy consumption FDI inflows Economic growth	Renewable energy $\xrightarrow{-}$ CO <sub>2</sub> emissions
Phadkantha y Tansuchat (2023)	Thailand; 1990-2019; autoregressive distributed lag model (ARDL).	Carbon emissions per capita	Energy efficiency GDP per capita Renewable energy	Renewable energy $\xrightarrow{-}$ CO <sub>2</sub> emissions
Rahman et al. (2022c)	22 developed countries; 1990-2018; panel autoregressive nonlinear autoregressive distributed lag (NARDL).	Carbon emissions per capita	GDP per capita Renewable energy Research and Development Spending Export quality index	Renewable energy $\xrightarrow{-}$ CO <sub>2</sub> emissions

$\xrightarrow{U}$  U-shaped effect;  $\xrightarrow{-}$  negative effect

development promotes the transition to sustainability. Finally, a third group of studies find an N-shaped relationship between economic growth and CO<sub>2</sub> emissions; that is, in a first stage, economic growth is accompanied by environmental deterioration. In a second stage, further growth reduces CO<sub>2</sub> emissions until a threshold is reached which, when exceeded, environmental quality starts to worsen again (e.g., Ojaghlu et al., 2023; Fang and Gao, 2023; Fakher et al., 2023).

Table 2 summarizes additional research on the link between economic growth and CO<sub>2</sub> emissions.

In relation to the literature reviewed, the second hypothesis of the research is as follows:

#### Hypothesis 2

H2: Economic growth has an inverted U-shaped relationship with CO<sub>2</sub> emissions.

### 2.3. Urban Population Density and CO<sub>2</sub> Emissions

The theory that explores the relationship between population growth and environmental quality is limited despite the extensive debate that has been generated around this topic. However, it is possible to distinguish two classic approaches that have examined this link: the Malthusian theory and the Simon effect (Kruse-Andersen, 2023). The former, developed during the pre-industrial era, emphasizes that population growth negatively affects environmental quality. Population growth intensifies economic activities such as agriculture, resulting in increased exploitation of natural resources and the use of chemical fertilizers. These practices lead to increased deforestation, soil erosion and losses, and contamination of surface and groundwater (Cropper and Griffiths, 1994; Novotny, 1999; Maja and Ayano, 2021).

Consequently, an increase in population leads to an increase in production, worsening environmental damage. In addition, it implies the expansion of cities and changes in traffic modes, which aggravates air pollution (Lu et al., 2021). The second approach, described by Simon (1996), argues that an increase in population leads to higher levels of innovation due to the expansion and dissemination of knowledge. This situation would favor the development of environmentally friendly technology (Kruse-Andersen, 2023). Therefore, higher population growth would have positive effects on environmental quality (Bretschger, 2020).

Empirical studies to date have not provided conclusive evidence on the relationship between population density and environmental quality. These results can be classified into three different categories. First, some studies suggest that population density is associated with a reduction in environmental pollution (e.g., Chen et al., 2020; Wang et al., 2021). This effect could be explained by the fact that an increase in population promotes energy efficiency (Shao and Wang, 2023). Second, a different group evidences a positive effect of population density on CO<sub>2</sub> emissions (e.g., Rahman and Alam, 2021; Musah et al., 2021; Wang and Li, 2021). In this context, the growth of human activities has driven economic growth, exacerbating environmental damage. Finally, a third group reveals a mixed effect of population density on environmental quality. More precisely, they find evidence of an inverted U-shaped relationship, suggesting that in early stages an increase in population increases environmental degradation. However, there is an inflection point, where an increase in population improves environmental quality (e.g., Gierałowska et al., 2022; Latief et al., 2022).

Table 3 summarizes additional research on the link between population density and CO<sub>2</sub> emissions.

**Table 2: Additional empirical studies: Economic growth and CO<sub>2</sub> emissions**

Authors	Country (ies), Data, Methodology	Endogenous variable	Independent variable (s)	Conclusion
Wang et al. (2023b)	56 countries; 2003-2018; panel threshold regression.	Carbon dioxide emissions per capita	GDP per capita Income inequality Urbanization Renewable energy consumption Trade openness Industrial structure	Economic growth $\xrightarrow{N}$ CO <sub>2</sub> emissions
Mohammed et al. (2024)	EU-27; 1990-2019; Dynamic Ordinary Least Squares (DOLS) and Fully Modified Ordinary Least Squares (FMOLS).	CO <sub>2</sub> emissions - National total	Energy consumption GDP -market prices Population	Economic growth $\xrightarrow{\cap}$ CO <sub>2</sub> emissions
Ahmad et al. (2023)	G-11 countries; 1990-2018; cross-sectional autoregressive distributed lags (CS-ARDL).	CO <sub>2</sub> emissions	GDP Renewable energy Natural resources	Economic growth $\xrightarrow{\cap}$ CO <sub>2</sub> emissions
Bekun et al. (2021)	Block E7; 1995-2016; augmented mean group, the common correlated effects mean group estimator, Driscoll-Kraay and Dumitrescu and Hurlin causality analysis.	CO <sub>2</sub> emissions	Economic growth Renewable energy Institutional quality	Economic growth $\xrightarrow{\cap}$ CO <sub>2</sub> emissions

$\xrightarrow{N}$  N-shaped relationship,  $\xrightarrow{\cap}$  Inverted U ratio

In relation to the literature reviewed, the third hypothesis of the research is as follows:

#### Hypothesis 3

H3: Urban population density has a positive impact on CO<sub>2</sub> emissions.

## 2.4. Trade Openness and CO<sub>2</sub> Emissions

Given the complexity of trade openness, which involves a number of interactions between different factors, its relationship with CO<sub>2</sub> emissions could not be conclusively established (Zhang et al., 2023b). Arguments about the effects of trade openness on environmental quality are based on the “pollution paradise” hypothesis (PHH), described by Copeland and Taylor (2004). Under this approach, two types of effects can be distinguished. The first effect is a positive association between trade openness and CO<sub>2</sub> emissions. This is because governments seek to liberalize their economies and promote greater economic integration in order to achieve higher growth rates. Consequently, they implement strategies that reduce environmental regulations, which makes local companies more competitive internationally. In

addition, minimal or no environmental regulations in developing countries attract highly polluting foreign firms, which worsens environmental quality (Ragoubi and Mighri, 2021). The second effect is a negative relationship between trade openness and CO<sub>2</sub> emissions. This relationship is framed in a model in which trade openness enables the transfer of green technology, allowing CO<sub>2</sub> emissions to be neutralized (Liu et al., 2021).

In light of the theoretical basis, Table 4 summarizes additional research on the link between trade openness and CO<sub>2</sub> emissions.

In relation to the literature reviewed, the fourth hypothesis of the research is as follows:

#### Hypothesis 4

H4: Trade openness has a positive impact on CO<sub>2</sub> emissions.

In order to summarize and clarify the hypotheses established in this section, Figure 1 presents the theoretical framework that relates renewable energies, economic growth, urban population density and trade openness to CO<sub>2</sub> emissions. In this context, the transition

**Table 3: Additional empirical studies: Population density and CO<sub>2</sub> emissions**

Authors	Country (ies), Data, Methodology	Endogenous variable	Independent variable (s)	Conclusion
Pickson et al. (2024)	Different countries by income groups; 1993-2018; estimates including cross-sectional dependence.	CO <sub>2</sub> emissions	GDP per capita Unemployment rate Aging population Urbanization Life expectancy	Population density $\xrightarrow{+}$ CO <sub>2</sub> emissions
Mendonça et al. (2020)	Top 50 economies of the world; 1990-2015; hierarchical regression model.	CO <sub>2</sub> emissions	GDP Population growth Renewable energy	Population density $\xrightarrow{+}$ CO <sub>2</sub> emissions
Chen et al. (2023)	China; 2003-2019; spatial econometric models.	CO <sub>2</sub> emissions	Urbanization	Population density $\xrightarrow{\cap}$ CO <sub>2</sub> emissions

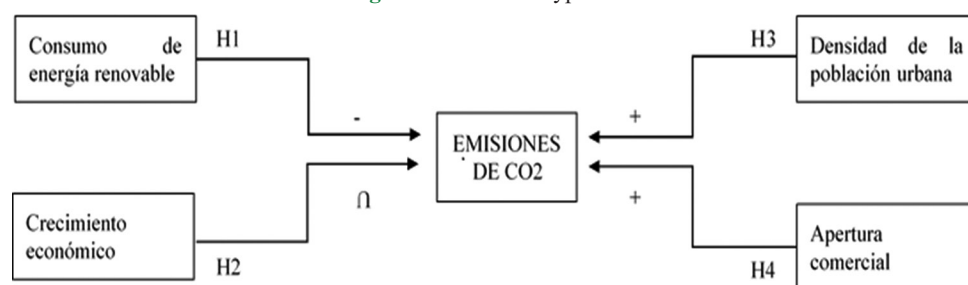
$\xrightarrow{+}$  Positive effect,  $\xrightarrow{\cap}$  Inverted U ratio

**Table 4: Additional empirical studies: Trade openness and CO<sub>2</sub> emissions**

Author	Country (ies), Data, Methodology	Endogenous variable	Independent variable (s)	Conclusion
Khan et al. (2022b)	176 countries; 2000-2019; panel ordinary least squares (OLS) and generalized method of moments.	CO <sub>2</sub> emissions per capita	Commercial openness Innovation, Institutional quality, Foreign direct investment Financial development Renewable and non-renewable energy consumption	Commercial opening $\xrightarrow{-}$ CO <sub>2</sub> emissions
Wenlong et al. (2023)	10 Asian countries; 1995-2018; cross-sectional augmented autoregressive distributed lag autoregressive (CS-ARDL) model.	Greenhouse gases	Energy efficiency Technological innovations Commercial openness Institutional quality	Commercial opening $\xrightarrow{+}$ greenhouse gases
Li et al. (2021)	China; 1989-2019; time series.	CO <sub>2</sub> emissions	Trade liberalization Export diversification Renewable electricity production	Commercial opening $\xrightarrow{-}$ CO <sub>2</sub> emissions

$\xrightarrow{+}$  Positive effect,  $\xrightarrow{-}$  Negative effect

Figure 1: Research hypothesis



to sustainable energies through the consumption of renewable energies to reduce CO<sub>2</sub> emissions is represented in Hypothesis 1. On the other hand, human and economic activities that affect the environment are addressed in Hypotheses 2, 3 and 4.

## 2.5. Limitations in the Literature

Although there is a variety of literature examining the effects of renewable energy on environmental quality, important limitations remain. First, much research has focused on developing countries or emerging economies, where the adoption of renewable energy remains a major challenge in terms of accessibility and affordability. While studies oriented to developed economies have shown a limited cross-section, which may generate ambiguity in the findings. Secondly, the heterogeneity present, mainly in studies covering large samples of countries, may generate inconsistencies due to the different economic, social, and even political contexts that may influence the relationship of variables. In light of these limitations, the present research seeks to contribute to the literature by examining the effect of renewable energies on CO<sub>2</sub> emissions in 30 high-income countries, which face other challenges regarding the potential of clean energy. Furthermore, to overcome possible biases due to unobserved heterogeneity, the panel is subdivided into the top 15 CO<sub>2</sub> emitting countries of this group, which allows for a deeper analysis of the magnitude of renewable energies.

## 3. METHODOLOGY

### 3.1. Description of Variables and Data

This paper uses panel data from 30 high-income countries, as classified by the World Bank, over the period 2000 to 2020 to examine the short- and long-term effects of renewables on CO<sub>2</sub> emissions (the countries included in the analysis are listed in Appendix A.1). The countries were selected because of the availability of information to construct a balanced panel and, especially, because of the challenges related to the capacity of renewable energies to meet the energy demand of economic activities in countries where the industrial structure is highly developed. The variables to be used were selected through the literature review described in section 2, and obtained from the World Bank database. The dependent variable is defined as CO<sub>2</sub> emissions per capita. As for the explanatory variables, these include renewable energy consumption per capita (Er), real Gross Domestic Product per capita (Ce) as an economic growth variable, the square of real Gross Domestic Product per capita (Ce2), to (in)validate the EKC hypothesis, urban population (U) and trade

openness (To). The description of each variable, including its unit of measurement and source, is presented in Table 5.

Following the work of Li and Hameklaus (2022) and Wang et al. (2023b), CO<sub>2</sub> emissions (metric tons per capita) from fossil fuel combustion, which includes solid, liquid and gaseous fuel combustion, and gas flaring, are used. In addition, CO<sub>2</sub> emissions per capita allow sizing the magnitude in relation to population size, which provides a better perspective on the environmental impact.

The percentage of renewable energy consumption shows the share of clean energy used, which allows us to measure its relative importance. Real GDP per capita and the square of this variable have been widely used in the literature to examine the EKC hypothesis, which describes a nonlinear relationship between economic growth and environmental quality (e.g. Ahmad et al., 2023; Zhang et al., 2020; Zhang et al., 2022). Regarding population density, urban population has traditionally been used, with the objective of capturing population agglomeration in an area conditioning environmental stress (e.g., Rahman and Alam, 2021). Finally, trade openness is measured as the sum of exports and imports as a percentage of GDP, which allows us to assess its impact on the overall economy.

Table 6 presents a summary of the descriptive statistics for each variable. The mean, median, standard deviation, minimum and maximum of each variable are found between columns (1) and (5). The average values of CO<sub>2</sub> emissions, renewable energy consumption, economic growth, urban population and trade openness during the study period are 8.62 (mt per capita), 17.27 (% total energy consumption), \$36,436.12, 98.43 (% total population) and 75.02 (% GDP), respectively. Of the variables analyzed, economic growth shows the greatest variability, with a minimum of US\$4,567.24 and a maximum of US\$112,417.9. In addition, a significant difference is also observed between the minimum and maximum values of CO<sub>2</sub> emissions, which reveals a possible heterogeneity in the panel structure. Column (6) presents the Levene's test to determine the variance stability of the series. The null hypothesis of the test is homogeneity of variance of the variables. It is observed that the P-values of all the variables are less than 5%, so the null hypothesis is rejected, and it is evident that the series are not stable in variance. Therefore, to stabilize the series, a logarithmic transformation is applied to all the variables (Box and Cox, 1964).

### 3.2. Model Construction

Following the methodological framework proposed by York et al. (2003) and applied by Amer et al. (2024) and Shabani



**Table 5: Description of variables**

Variable	Abbreviation	Description	Source
CO <sub>2</sub> Emissions	CO <sub>2</sub>	Carbon dioxide emissions (metric ton per capita)	World Bank Indicators (WDI)
Renewable energy consumption	Er	Renewable energy consumption (% of total final energy consumption)	
Economic growth	Ce	GDP per capita (constant \$ 2015)	
Economic growth squared	Ce <sub>2</sub>	GDP per capita squared (constant \$ 2015)	
Urban population	Urb	Urban area population (% total population)	
Trade openness	To	To Exports plus imports (% of GDP)	

**Table 6: Descriptive statistics of the variables**

Variable	Observations	Mean	Median	Standard deviation	Minimum	Maximum	Levene
		(1)	(2)	(3)	(4)	(5)	(6)
CO <sub>2</sub>	630	8.62	7.72	4.25	3	25.61	27.80***
Er	630	17.27	14.18	14.85	0.69	82.79	6.45***
Ce	630	36.436.12	36.039.52	21.287.01	4.567.24	112.417.9	22.67***
Ce2	630	1.78e+09	1.30e+09	2.17e+09	2.09e+07	1.26e+10	4.88***
Urb	630	75.02	78.16	13.12	50.75	98.08	9.67***
To	630	98.43	83.10	57.87	19.56	382.35	11.52***

\*\*\*P<0.01

(2024) to represent the environmental impacts derived from human activities, the empirical model to determine the effects of renewable energy consumption and other variables representative of human and economic activities, such as non-linear economic growth, trade openness and urban population density on CO<sub>2</sub> emissions is represented as follows:

$$CO_{2it} = f(Er_{it}, Ce_{it}, Ce2_{it}, Urb_{it}, To_{it}) \quad (1)$$

In equation (1),  $i$  denotes the country ( $i = 1, \dots, 30$ ) and  $t$  the period ( $t = 2000, \dots, 2020$ ). The dependent variable is the CO<sub>2</sub> emissions per capita ( $CO_{2it}$ ) of country  $i$  in period  $t$ . On the other hand, the independent variables include renewable energy consumption ( $Er_{it}$ ), economic growth ( $Ce_{it}$ ), squared economic growth ( $Ce2_{it}$ ), urban population density ( $Urb_{it}$ ) and trade openness ( $To_{it}$ ). The econometric extension of the model is expressed in equation (2), using the variables in their logarithmic form:

$$LnCO_{2it} = \beta_0 - \beta_1 LnEr_{it} + \beta_2 LnCe_{it} - \beta_3 LnCe2_{it} + \beta_4 LnUrb_{it} + \beta_5 LnTo_{it} + \mu_{it} \quad (2)$$

In equation (2),  $\beta_0$  corresponds to the model constant, and  $\beta_1, \dots, \beta_5$ , represent the partial elasticities to be estimated in relation to each independent variable, while  $\mu_{it}$  is the stochastic disturbance term. Based on the literature reviewed in Section 2, renewable energy consumption is expected to be negatively associated with CO<sub>2</sub> emissions. In addition, coefficients of  $\beta_2 > 0$  y  $\beta_3 < 0$ , re expected, which would be related to the EKC hypothesis. Finally, a positive relationship between urban population density and commercial openness with CO<sub>2</sub> emissions is expected.

### 3.3. Econometric Strategy

Based on Ahmad et al. (2023) and Li and Hameklaus (2022), to analyze the short- and long-term effects of renewable energy consumption, economic growth, urban population density and trade openness on CO<sub>2</sub> emissions, the cross-sectional autoregressive distributed lag autoregressive (CS-ARDL) panel model is

employed. Following Uddin et al. (2023), preliminary analyses, such as tests for cross-sectional dependence, homogeneity of slopes, stationarity and co-integration, must be performed for its estimation. The purpose of these tests is to determine the suitability of the CS-ARDL model, which due to its characteristics is robust to cross-sectional dependence and mixed integration orders, I(0) and I(1). In addition, robustness checks are performed by applying the Augmented Mean Group (AMG) technique, which is recognized for its efficiency against cross-sectional dependence and slope heterogeneity problems (Eberhardt and Bond, 2009).

This procedure will be applied to the full panel of 30 high-income countries, as well as to the sub-panel of the top 15 CO<sub>2</sub> emitting countries, selected for having the highest average CO<sub>2</sub> emissions during the period of analysis.

#### 3.3.1. Tests for cross-sectional dependence and homogeneity of slopes

Several studies that have examined the various determinants of CO<sub>2</sub> emissions based on macroeconomic components in panel data have highlighted the importance of addressing cross-sectional dependence of errors to avoid inconsistent estimates (Yadav et al., 2024). Following Perone (2024), this study employs Pesaran's CD test, which is described as a simple diagnostic test applicable to different panel data structures (Pesaran, 2021). The specification of this test is described in equation (3) (Pesaran, 2021, 19):

$$CD = \sqrt{\frac{2T}{N(N-1)}} \left( \sum_{i=1}^{N-1} \sum_{j=i+1}^N \hat{p}_{ij} \right) \quad (3)$$

Where,  $T$  represents the time dimension,  $N$  the cross sections of the panel, and  $\hat{p}_{ij}$  is the pairwise correlation of the residuals between sections  $i$  and  $j$ , which denote the study units.

Furthermore, given the possible heterogeneity in the panel data, it is crucial to complement the cross-sectional dependence analysis

with tests of slope homogeneity. In this regard, the Swamy (SH) slope homogeneity test for panel data with multiple observations in cross-section and time section, presented by Pesaran and Yamagata (2008), is employed.

### 3.3.2. Unit root and cointegration tests

Determining the stationarity of the series is a prerequisite for estimating long-run relationships in order to avoid possible biases in the estimation (Li and Haneklaus, 2022). However, first-generation unit root tests, by assuming cross-sectional independence (Rahman et al., 2023), may lead to incorrect inferences about the order of integration of the variables. For this reason, second-generation unit root tests, which consider cross-sectional dependence, are employed. Specifically, the Im Pesaran and Shin (CIPS) and the cross-sectional augmented Dicky Fuller (CADF) tests are employed (Im et al., 2003; Pesaran, 2007). Under the specification of equation (4), the CADF test is determined:

$$\Delta V_{it} = \varphi_i + \varphi_i V_{it-1} + \varphi_i \bar{K}_{t-1} + \sum_{i=0}^p \varphi_{il} \Delta \bar{V}_{t-1} + \sum_{i=0}^p \varphi_{il} \Delta V_{t-1} + e_{it} \quad (4)$$

Where,  $\bar{K}_{t-1}$  y  $\Delta \bar{V}_{t-1}$  represents the cross-sectional average. Meanwhile, the CIPS test is expressed in equation (5).

$$CIPS(N, T) = N^{-1} \sum_{i=1}^N t_i(N, T) \quad (5)$$

Once the order of integration of the variables has been determined, the existence of equilibrium relationships in the long run (cointegration) is verified. For this purpose, the Pedroni (2001) and Kao and Chiang (2001) cointegration tests are used to provide robust results.

### 3.3.3. Cross-Sectional Autoregressive Distributed Lagged Autoregressive Panel Model (CS-ARDL)

To estimate the short- and long-term relationships between renewable energy consumption and CO<sub>2</sub> emissions, the cross-sectional autoregressive distributed lag autoregressive (CS-ARDL) panel model, proposed by Chudik and Pesaran (2015), is employed. Several studies opt for the CS-ARDL model due to its different advantages, especially for its characteristics of dealing with series with a mixed order of integration, I(0) or I(1). Moreover, this technique is robust to endogeneity problems, panel heterogeneity, and cross-sectional dependence (Kassouri and Alola, 2023; Uddin et al., 2023). Thus, the CS-ARDL model is expressed in equation (6).

$$\Delta CO2_{it} = \delta_i + \sum_{g=1}^p \bar{\delta}_{it} \Delta CO2_{i,t-1} + \sum_{g=0}^q \bar{\delta}_{it} \Delta X_{i,t-1} + \sum_{g=1}^w \bar{\delta}_{it} \bar{CS}_{i,t-1} + \mu_{it} \quad (6)$$

In equation (6),  $CO2_{it}$  represents CO<sub>2</sub> emissions in country  $i$  (1,...,30) in year  $t$  (2000,...,2020).  $X_{it}$  is the vector of the independent variables in their logarithmic form ( $LnEr$ ,  $LnCe$ ,  $LnCe2$ ,  $LnUrb$ ,  $LnTo$ ),  $\bar{CS}_i$  represents the cross-sectional mean  $p$ ,  $q$ ,  $w$ , are the optimal lags and  $\mu_{it}$  is the stochastic perturbation term.

### 3.3.4. Robustness checks

To corroborate the results of the CS-ARDL model, the Augmented Mean Group (AMG) technique (Eberhardt and Bond, 2009) is applied. This technique is used to address cross-sectional dependence, so its complementarity with the CS-ARDL model allows to generate consistent results. The AMG estimator is more efficient compared to the group mean (MG), as it allows the coefficients to vary in both cross-section and time, making the estimates more reliable (Hwang and Díez, 2024).

## 4. EMPIRICAL FINDINGS AND DISCUSSION OF RESULTS

### 4.1. Preliminary Estimates to the CS-ARDL Model

Initially, the cross-sectional dependence (CD) test of Pesaran (2021) and the slope homogeneity (SH) test of Pesaran and Yamagata (2008) are used as preliminary stringency tests. The results of the CD test for both the full panel and the subpanel are shown in Table 7. These results indicate significance at 1% for both panels, which allows us to reject the null hypothesis of cross-sectional independence. In addition, Table 8 presents the results of the SH test, where the null hypothesis refers to the slope coefficients being homogeneous. Since the  $\Delta$  and  $\Delta_{Adj}$ . Values are significant at 1% for both panels, it is determined that there is sufficient evidence to point to the presence of slope heterogeneity in the series.

Subsequent to the cross-sectional dependence and slope homogeneity tests, second generation stationarity tests are performed, given their characteristics of considering cross-sectional dependence. Specifically, the CIPS and CADF tests introduced by Im et al. (2003) and Pesaran (2007) are used. The null hypothesis is that the variables are not stationary for both tests. The results of the stationarity tests are presented in Table 9. For the full panel, the results of the CIPS and CADF tests show that renewables are stationary at I(0) levels, while the rest of the variables are stationary at I(1) first differences. Regarding the subpanel, both tests show that all variables are stationary in first differences or integrated of order I(1).

Once the order of integration of the series has been determined, it is essential to determine the existence of long-run equilibrium

Table 7: Cross-sectional dependence test

Variables	Pasaran CD	
	Full panel	Subpanel
Ln CO <sub>2</sub>	24.09***	11.72***
LnRe	4.13***	0.051
LnCe	13.54***	5.17***
LnCe2	13.04***	4.98***
LnUrb	5.51***	1.20
LnOt	21.28***	5.88***

\*\*\*P<0.01

Table 8: Homogeneity of slope test

	Full panel	Subpanel
$\Delta$	10.43***	6.62***
$\Delta_{Adj}$	13.46***	8.54***

\*\*\*P<0.01

**Table 9: Stationarity tests**

State of variables	Variables	Full panel		Subpanel	
		CIPS	CADF	CIPS	CADF
In levels	Ln CO <sub>2</sub>	-1.83	-1.68	-1.66	-1.55
	LnRe	-2.38***	-2.17***	-1.91	-2.03
	LnCe	-1.66	-1.75	-1.42	-1.51
	LnCe2	-1.61	-1.72	-1.40	-1.49
	LnUrb	-1.53	-1.73	-0.97	-1.27
	LnOt	-1.63	-1.84	-1.90	-1.91
In first differences	Ln CO <sub>2</sub>	-4.21***	-3.15***	-4.23***	-4.23***
	LnRe	-	-	-4.06***	-4.06***
	LnCe	-2.87***	-2.08**	-2.71***	-2.71***
	LnCe2	-2.86***	-2.07**	-2.71***	-2.71***
	LnUrb	-2.40***	-2.41***	-2.35**	-2.35**
	LnOt	-3.12***	-2.51***	-3.54***	-3.54***

\*\*\*P<0.01, \*\*P<0.05, \*P<0.1

relationships between the variables (cointegration). For this purpose, the Pedroni (2001) and Kao and Chiang (2001) cointegration tests are used. The complementarity of both tests is adequate to determine cointegration, both in heterogeneous and homogeneous panels (Rahman et al., 2023). The null hypothesis of these tests is that there is no cointegration. The results are presented in Table 10. The statistics of both alternative cointegration tests show significance levels of 1% and 5% for both panels, which is evidence of the existence of a long-run equilibrium relationship between variables.

## 4.2. Estimation of Short and Long-run Relationships: Cross-Sectional Autoregressive Distributed Lagged Autoregressive Model (CS-ARDL)

From preliminary tests, it has been determined that there is cross-sectional dependence, heterogeneity of slopes, the variables present a mixed order of integration between I(0) and I(1) and that they cointegrate. These results indicate that the selection of the CS-ARDL model is suitable for examining the short- and long-term relationships between renewable energy and CO<sub>2</sub> emissions.

Table 11 presents the short-run and long-run effects of the explanatory variables on CO<sub>2</sub> emissions of high-income countries. First, the error correction term ( $ECT_{-1}$ ) is negative and significant in both panels, confirming the existence of long-run equilibrium relationships. For the full panel, we find that, in both the short and long run, a 1% increase in renewable energy consumption is associated with a reduction in CO<sub>2</sub> emissions of 0.397% and 0.36%, respectively. This association is consistent in the subpanel, where renewable energy consumption is also significant in reducing CO<sub>2</sub> emissions; however, their coefficients are of smaller magnitude, 0.22% and 0.19%, respectively. This difference in magnitudes can be explained by the different levels of CO<sub>2</sub> emissions intensity among countries. In countries with higher CO<sub>2</sub> levels, the mitigation capacity of renewable energies is reduced. Thus, renewable energies emerge as a potential alternative to neutralize CO<sub>2</sub> emissions from human and economic activities (Balsalobre-Lorente et al., 2023).

In addition, the results indicate that economic growth has a positive and significant effect, both in the short and long term, on CO<sub>2</sub> emissions. A 1% increase in economic growth generates a substantial increase in per capita CO<sub>2</sub> emissions of 30.52% and 28.97%, respectively in the full panel. This effect, as expected,

**Table 10: Cointegration test**

Test	Full panel	Subpanel
Pedroni test		
Modified Phillips-Perron t	3.21***	2.68***
Phillips-Perron t	-3.44***	-0.97
Augmented Dickey-Fuller t	-2.82***	-0.06
Kao test		
Dickey-Fuller t	3.84***	3.07***
Augmented Dickey-Fuller t	3.06***	2.17**
Unadjusted Dickey-Fuller t	3.74***	3.09***

\*\*\*P<0.01, \*\*P<0.05, \*P<0.1

**Table 11: Short- and long-term effects. CS-ARDL**

Variables	Full panel	Subpanel
	Short-term	
LnCO <sub>2-1</sub>	-0.12** (0.05)	-0.11 (0.08)
LnRe	-0.397*** (0.10)	-0.22*** (0.08)
LnCe	30.52* (16.36)	50.86** (21.882)
LnCe2	-1.40* (0.77)	-2.32** (1.00)
LnUrb	-3.37 (10.66)	5.31 (18.64)
LnOt	0.25*** (0.09)	0.14 (0.097)
ECT <sub>-1</sub>	-1.12*** (0.05)	-1.11*** (0.08)
<b>A largo plazo</b>		
LnRe	-0.36*** (0.10)	-0.19*** (0.06)
LnCe	28.97** (14.73)	56.04** (24.18)
LnCe2	-1.33* (0.69)	-2.53** (1.08)
LnUrb	1.35 (8.32)	10.05 (15.76)
LnOt	0.23*** (0.09)	0.14 (0.1)

\*\*\*P<0.01, \*\*P<0.05, \*P<0.1. Error estándar entre paréntesis

is of greater magnitude in the top 15 CO<sub>2</sub> emitting countries, where the coefficients reach values of 50.86% and 56.04%. Similar effects were found by Li and Haneklaus (2021; 2022) and Tchouto (2023). On the other hand, the estimated coefficient of

squared economic growth for both panels, short and long term, is negative at 5% and 10% significance levels. These findings show a non-linear relationship between economic growth and CO<sub>2</sub> emissions, providing evidence to support the EKC hypothesis in high-income countries. Thus, it is confirmed that the initial stages of economic growth generate high environmental degradation. However, there is a maximum threshold beyond which the growth process reaches adequate levels of development to mitigate environmental damage.

The impact of urban population density on CO<sub>2</sub> emissions, both in the full panel and in the subpanel, in the long term is positive, but not significant. Despite the statistical weakness, this positive direction aligns with other research (Ridwan et al., 2024; Pickson et al., 2024; Mendonça et al., 2020). Thus, the pressures of increasing urban density could generate environmental stress.

Trade openness is an important driver of CO<sub>2</sub> emissions. According to the full panel results, in the long square, a 1% increase in trade openness leads to an increase in CO<sub>2</sub> emissions by 0.23%. In the subpanel, the positive effect persists, although it is not statistically significant. Moreover, these impacts are consistent in the short run. This finding is aligned with the work of Li and Haneklaus (2021) and Wenlong et al. (2023).

### 4.3. Robustness Check

To provide robustness evidence and confirm the results of the CS-ARDL model, the Augmented Mean Group (AMG) model, used as a complementary technique in the presence of cross-sectional dependence (Wenlong et al., 2023), is employed. The results of the AMG model are presented in Table 12. The findings are consistent, where the mitigating effect of renewable energies on CO<sub>2</sub> emissions, the nonlinear inverted U-shaped relationship between economic growth and environmental damage, and the positive direction of trade openness on CO<sub>2</sub> emissions are confirmed. Regarding urban density, the non-significance persists, which is in line with the theoretical ambiguity, where there is no conclusive effect.

### 4.4. Discussion of Results

Table 13 presents a summary of the findings in relation to the hypotheses described in section 2.

This research provides a dynamic analysis to examine the short- and long-term effects of renewable energy consumption, economic growth, urban population density and trade openness on CO<sub>2</sub> emissions in high-income countries. The first finding reveals the negative impact of renewable energy consumption on CO<sub>2</sub> emissions, which supports hypothesis H1. This finding is consistent with previous literature (e.g., Shabani, 2024; Amer et al., 2024; Işık et al., 2024; Yang and Umar, 2022) and can be explained by several well-documented reasons. Renewable energies, given their natural characteristics, do not generate harmful emissions to the environment, thus mitigating greenhouse gas emissions from burning fossil fuels (Wang et al., 2024). In addition, they encourage investments in technological innovation, thus contributing to generate structural changes at the economic and social level by channeling resources towards more energy-efficient sectors (Nepal et al., 2024). Renewable energy generation

**Table 12: Robustness estimation, AMG**

Variables	Full panel	Subpanel
		Coefficients
LnRe	−0.31*** (0.08)	−0.21*** (0.07)
LnCe	26.35* (13.83)	34.19 (23.34)
LnCe2	−1.17* (0.63)	−1.48 (1.04)
LnUrb	−10.65 (12.63)	−29.32 (21.41)
LnOt	0.12*** (0.03)	0.14** (0.04)
C_d_p	0.96*** (0.18)	0.89*** (0.32)
Const	−0.05*** (0.013)	0.014 (0.015)

\*\*\*P<0.01, \*\*P<0.05, \*P<0.1. Error estándar entre paréntesis

**Table 13: Summary of results and validation of hypotheses**

Null Hypothesis <sup>a</sup>	Finding	Conclusion
H1 Renewable energies have a negative impact on CO <sub>2</sub> emissions.	Er $\xrightarrow{-}$ CO <sub>2</sub>	Does not reject H1
H2 Economic growth has an inverted U-shaped relationship with CO <sub>2</sub> emissions	Ce $\xrightarrow{\cap}$ CO <sub>2</sub>	Does not reject H2
H3 Urban population density has a positive impact on CO <sub>2</sub> emissions	Urb $\xrightarrow{NON}$ CO <sub>2</sub>	Not conclusive
H4 Openness to trade has a positive impact on CO <sub>2</sub> emissions	To $\xrightarrow{+}$ CO <sub>2</sub>	Does not reject H4

Findings:  $\xrightarrow{-}$  negative effect,  $\xrightarrow{\cap}$  inverted U relationship,  $\xrightarrow{NON}$  non-significant effect,  $\xrightarrow{+}$  positive relationship

can also reduce dependence on net oil imports (Adekoya et al., 2022), thus increasing energy security and independence. Finally, developed countries are characterized by higher levels of education, which positively influences the acceptance and use of renewable energies and, at the same time, has generated cultural changes towards environmental conservation (Shabani, 2024). Consequently, the potential of renewable energies, mainly solar, wind and hydroelectric, to replace conventional energies is reflected in the efforts of public policy makers to seek technical and financial mechanisms for their adaptation (Nassar et al., 2024).

Another relevant finding is the nonlinear inverted U-shaped relationship between economic growth and CO<sub>2</sub> emissions. This finding supports the results of previous Environmental Kuznet Curve (EKC) studies (Ridzuan et al., 2020; Wang et al., 2024; Zhang et al., 2022) and contradicts others (Islama et al., 2023; Kanlı and Küçükefe, 2023). In line with Li and Haneklaus (2021; 2022) and Tchouto (2023), substantial impacts of economic growth on CO<sub>2</sub> emissions are revealed, mainly in major polluting countries. The explanation for this effect lies in energy intensity patterns driven by economic activities, especially industrialization (Rahman et al., 2023). In the early stages of structural change, factors of production are shifted to higher intensity sectors, such as manufacturing. Therefore, as industrialization grows, the use



of non-renewable energy increases, impacting environmental degradation (Rahman and Alam, 2022b).

However, as economic growth accelerates, technology incorporation and energy efficiency expand, which helps reduce CO<sub>2</sub> emissions intensity (Rahman et al., 2023).

Regarding urban population density, it has not been possible to find statistically significant evidence to validate or invalidate hypothesis H3, so its effect in high-income countries is inconclusive. However, the relationship in the long term shows a positive association, which was expected in relation to previous literature (Pickson et al., 2024; Mendonça et al., 2020). Higher population density, especially in areas of high agglomeration, may increase CO<sub>2</sub> emissions due to the intensification of economic activities such as agriculture or the expansion of cities, which aggravate environmental damage (Cropper and Griffiths, 1994; Lu et al., 2021).

Finally, it is evident that trade openness leads to an increase in CO<sub>2</sub> emissions in high-income countries in the short and long term. Following Li and Haneklaus (2021), increased international trade causes productive capacity to expand, leading to an increase in imports which would cause a considerable increase in CO<sub>2</sub> emissions.

## 5. CONCLUSIONS AND POLICY IMPLICATIONS

Global warming is a topic of great interest due to the environmental challenges the world is currently facing. Various economic, social, political and institutional factors condition the sustainable development agenda, making it essential to broaden empirical analyses. In this context, the present study contributes to the literature by comprehensively examining relevant factors affecting environmental quality. The short- and long-term effects of renewable energy consumption, economic growth, urban population density, and trade openness on CO<sub>2</sub> emissions have been investigated.

Based on the studies of Li and Haneklaus (2021), Wang et al. (2023b) and Ahmad et al. (2023), four hypotheses were constructed. First, an inverse relationship between renewable energy consumption with CO<sub>2</sub> emissions was proposed. Second, a nonlinear inverted U-shaped relationship between economic growth and CO<sub>2</sub> emissions was proposed. Third, a positive relationship of urban density and trade openness with CO<sub>2</sub> emissions was considered. To evaluate these hypotheses, a cross-sectional autoregressive distributed lagged model (CS-ARDL) was estimated for 30 high-income countries over the period 2000 to 2020. The specified model was adequate due to its ability to handle the presence of cross-sectional dependence, slope heterogeneity, mixed order stationarity and cointegration. In addition, an Augmented Mean Group (AMG) estimator was applied to corroborate the results.

The research findings revealed that renewable energy consumption has a significant negative effect on CO<sub>2</sub> emissions in both the short

and long term. Specifically, it was estimated that a 1% increase in renewable energy consumption reduces CO<sub>2</sub> emissions by 0.36% in the long term. This result highlights the potential of renewable energies, such as solar, wind and hydroelectric, to promote environmental sustainability. Consequently, the costs inherent to the implementation of clean energies are justified in different scenarios, and their potential impact on boosting energy efficiency makes their ability to meet energy demand feasible.

Another relevant finding was the non-linear inverted U-shaped association between economic growth and CO<sub>2</sub> emissions, validating the ECK hypothesis, both in the short and long term, presented by Grossman and Krueger (1991). It became evident that in the early stages of economic growth, an increase in the level of per capita income is accompanied by environmental degradation. However, when a maximum threshold is reached, the process of economic growth reaches a point of development where changes in the productive structure are generated, environmentally friendly technologies are incorporated and environmental concerns grow, resulting in a decrease in CO<sub>2</sub> emissions.

It was also found that trade liberalization increases CO<sub>2</sub> emissions in the short and long term by 0.25% and 0.23%, respectively. This result indicates that the growing trends of international trade activities cause productive capacities to increase, generating a greater intensification in the use of raw materials and traditional energies, which would affect environmental quality. On the other hand, this impact reveals that international trade does not promote the transfer of efficient technology to act as a mitigator of CO<sub>2</sub> emissions, which is worrisome in view of the high rates of world globalization. Finally, insufficient evidence was found to determine the impacts of urbanization, so further studies on this relationship are needed.

### 5.1. Policy Implications

The research findings offer crucial information for the generation of public policies to promote environmental sustainability. First, renewable energies are a viable alternative to mitigate the negative effects of human and economic activities on the environment, especially in the most polluting countries. Therefore, public policies should be generated to encourage the consumption of renewable energies. Furthermore, in order to promote greater accessibility to this type of energy, it is urgent to increase investment in infrastructure, taking advantage of the climatic conditions of each country. To this end, it is important to generate partnerships between the public and private sectors to make this sector self-sufficient over time.

Secondly, there is the possibility of sustainable economic growth patterns. However, it is important that these processes generate a channeling of resources towards more energy-efficient sectors that allow for an integral development with nature. In this way, public planning must be strengthened and induced to redesign environmental control mechanisms. In addition, it is important to promote the optimization of public finances and increase resources for research and technological development in universities, and make them a competitive advantage in the immediate future.

## 5.2. Limitations of the Research

Although this research has tried to comprehensively address some environmental constraints, it has some limitations that can serve as a starting point for further research. First, the research has focused on evaluating the direct effect of renewable energies on CO<sub>2</sub> emissions. In this sense, possible research can assess indirect effects through various channels, such as energy efficiency, technological development or green finance. Secondly, the research has omitted variables that may affect the intensity of CO<sub>2</sub> emissions. Given this, it is possible to evaluate the direct and indirect effects of other economic, social and political variables, such as globalization indexes, human capital or institutional quality. In addition, since no conclusive evidence was found on the relationship between urban population density and CO<sub>2</sub> emissions, further studies can be carried out on other population dimensions, both in urban and rural areas.

On the other hand, the evidence of panel heterogeneity can be addressed with samples in sub-panels, where more similar structures are contemplated and which allow to deepen the scope of the different variables on the environment. Finally, this study evaluated short- and long-term effects. However, the relationships between the variables under study are complex, so it is possible to use alternative econometric techniques, such as Vector Autoregressive and Moving Average models, which allow verifying dynamic interactions over time.

## REFERENCES

- Acheampong, A.O., Adams, S., Boateng, E. (2019), Do globalization and renewable energy contribute to carbon emissions mitigation in Sub-Saharan Africa? *Science of The Total Environment*, 677, 436-446.
- Acheampong, A.O., Boateng, E., Amponsah, M. (2022), Econometric analysis of the economic growth-energy consumption nexus in emerging economies: The role of globalization. In: Shahbaz, M., Tiwari, A.K., Sinha, A., editors. *Energy-Growth Nexus in an Era of Globalization*. Netherlands: Elsevier. p105-148.
- Adebayo, T.S., Samour, A. (2024), Renewable energy, fiscal policy and load capacity factor in BRICS countries: Novel findings from panel nonlinear ARDL model. *Environment, Development and Sustainability*, 26, 4365-4389.
- Adekoya, O.B., Oliyide, J.A., Fasanya, I.O. (2022), Renewable and non-renewable energy consumption - Ecological footprint nexus in net-oil exporting and net-oil importing countries: Policy implications for a sustainable environment. *Renewable Energy*, 189, 524-534.
- Agboola, M.O., Bekun, F.V., Joshua, U. (2021), Pathway to environmental sustainability: Nexus between economic growth, energy consumption, CO<sub>2</sub> emission, oil rent and total natural resources rent in Saudi Arabia. *Resources Policy*, 74, 102380.
- Ahmad, M., Dai, J., Mehmood, U., Houran, M.A. (2023), Renewable energy transition, resource richness, economic growth, and environmental quality: Assessing the role of financial globalization. *Renewable Energy*, 216, 119000.
- Alam, M.B., Hossain, M.S. (2024), Investigating the connections between China's economic growth, use of renewable energy, and research and development concerning CO<sub>2</sub> emissions: An ARDL bound test approach. *Technological Forecasting and Social Change*, 201, 123220.
- Alam, M.S., Duraisamy, P., Siddik, A.B., Murshed, M., Mahmood, H., Palanisamy, M., Kirikkaleli, D. (2023), The impacts of globalization, renewable energy, and agriculture on CO<sub>2</sub> emissions in India: Contextual evidence using a novel composite carbon emission-related atmospheric quality index. *Gondwana Research*, 119, 384-401.
- Amer, E.A., Meyad, E.M., Meyad, A.M., Mohsin, A. (2024), Impacts of renewable and disaggregated non-renewable energy consumption on CO<sub>2</sub> emissions in GCC countries: A STIRPAT model analysis. *Heliyon*, 10(9), e30154.
- Amin, N., Shabbir, M.S., Abbass, K. (2024), Renewable energy consumption and its impact on environmental quality: A pathway for achieving sustainable development goals in ASEAN countries. *Energy and Environment*, 35(2), 644-662.
- Apergis, N., Jebli, M.B., Youssef, S.B. (2018), Does renewable energy consumption and health expenditures decrease carbon dioxide emissions? Evidence for sub-Saharan Africa countries. *Renewable Energy*, 127, 1011-1016.
- Aquilas, N.A., Ngangnchi, F.H., Mbella, M.E. (2024), Industrialization and environmental sustainability in Africa: The moderating effects of renewable and non-renewable energy consumption. *Heliyon*, 10, e25681.
- Aydin, C., Esen, Ö. (2018), Reducing CO<sub>2</sub> emissions in the EU member states: Do environmental taxes work? *Journal of Environmental Planning and Management*, 16(13), 2396-2420.
- Balsalobre-Lorente, D., Parente, C.C., Leitão, N.C., Cantos-Cantos, J.M. (2023), The influence of economic complexity processes and renewable energy on CO<sub>2</sub> emissions of BRICS. What about industry 4.0? *Resources Policy*, 82, 103547.
- Bekun, F.V., Gyamfi, B.A., Onifade, S.T., Agboola, M.O. (2021), Beyond the environmental Kuznets Curve in E7 economies: Accounting for the combined impacts of institutional quality and renewables. *Journal of Cleaner Production*, 314, 127924.
- Bello, M.O., Solarin, S.A., Yen, Y.Y. (2018), The impact of electricity consumption on CO<sub>2</sub> emission, carbon footprint, water footprint and ecological footprint: The role of hydropower in an emerging economy. *Journal of Environmental Management*, 219, 218-230.
- Bergougui, B. (2024), Moving toward environmental mitigation in Algeria: Asymmetric impact of fossil fuel energy, renewable energy and technological innovation on CO<sub>2</sub> emissions. *Energy Strategy Reviews*, 51, 101281.
- Bilgili, F., Lorente, D.B., Kuşkaya, S., Ünlü, F., Gençoğlu, P., Rosha, P. (2021), The role of hydropower energy in the level of CO<sub>2</sub> emissions: An application of continuous wavelet transform. *Renewable Energy*, 178, 283-294.
- Bowden, N., Payne, J.E. (2009), The causal relationship between U.S. energy consumption and real output: A disaggregated analysis. *Journal of Policy Modeling*, 31(2), 180-188.
- Box, G.E., Cox, D.R. (1964), An analysis of transformations. *Journal of the Royal Statistical Society: Series B (Methodological)*, 26(2), 211-243.
- Bretschger, L. (2020), Malthus in the light of climate change. *European Economic Review*, 127, 103477.
- Briera, T., Lefèvre, J. (2024), Reducing the cost of capital through international climate finance to accelerate the renewable energy transition in developing countries. *Energy Policy*, 188, 114104.
- Brock, W.A., Taylor, M.S. (2005), Chapter 28 - Economic growth and the environment: A review of theory and empirics. In: Aghion, P., Durlauf, S.N., editors. *Handbook of Economic Growth*. Netherlands: Elsevier. p1749-1821.
- Caglar, A.E., Daştan, M., Rej, S. (2024), A new look at China's environmental quality: how does environmental sustainability respond to the asymmetrical behavior of the competitive industrial sector? *International Journal of Sustainable Development and World Ecology*, 31(1), 6-28.

- Chen, C., Qin, Y., Gao, Y. (2023), Does new urbanization affect CO<sub>2</sub> emissions in China: A spatial econometric analysis. *Sustainable Cities and Society*, 96, 104687.
- Chen, J., Wang, B., Huang, S., Song, M. (2020), The influence of increased population density in China on air pollution. *Science of The Total Environment*, 735, 139456.
- Chen, Y., Wang, Z., Zhong, Z. (2019), CO<sub>2</sub> emissions, economic growth, renewable and non-renewable energy production and foreign trade in China. *Renewable Energy*, 131, 208-216.
- Chudik, A., Pesaran, M.H. (2015), Common correlated effects estimation of heterogeneous dynamic panel data models with weakly exogenous regressors. *Journal of Econometrics*, 188(2), 393-420.
- Copeland, B.R., Taylor, M.S. (2004), Trade, growth, and the environment. *Journal of Economic Literature*, 42(1), 7-71.
- Crippa, M., Guizzardi, D., Pagani, F., Banja, M., Muntean, M., Schaaf, E., Becker, W., Monforti-Ferrario, F.,...& Quadrelli Branco, A. (2023), GHG Emissions of All World Countries. Luxembourg: Publications Office of the European Union.
- Cropper, M., Griffiths, C. (1994), The interaction of population growth and environmental quality. *The American Economic Review*, 84(2), 250-254.
- Dasgupta, S., Lall, S., Wheeler, D. (2023), Subways and CO<sub>2</sub> emissions: A global analysis with satellite data. *Science of The Total Environment*, 883, 163691.
- Dinda, S. (2004), Environmental kuznets curve hypothesis: A survey. *Ecological Economics*, 49(4), 431-455.
- Eberhardt, M., Bond, S. (2009), Cross-section Dependence in Nonstationary Panel Models: A Novel Estimator. MPRA Paper 17692. Germany: University Library of Munich. Available from: [https://mpra.ub.uni-muenchen.de/17692/1/MPRA\\_paper\\_17692.pdf](https://mpra.ub.uni-muenchen.de/17692/1/MPRA_paper_17692.pdf) [Last accessed on 2 2024 May 02].
- Elom, C.O., Onyeneke, R.U., Ankrah, D.A., Deffor, E.W., Ayerakwa, H.M., Uwaleke, C.C. (2024), Achieving carbon neutrality in Africa is possible: The impact of education, employment, and renewable energy consumption on carbon emissions. *Carbon Research*, 3, 24.
- Fakher, H.A., Ahmed, Z., Acheampong, A.O., Nathaniel, S.P. (2023), Renewable energy, nonrenewable energy, and environmental quality nexus: An investigation of the N-shaped Environmental Kuznets Curve based on six environmental indicators. *Energy*, 263, 125660.
- Fang, X., Gao, S. (2023), An empirical study on relationship between island ecological environment and socio-economic development from perspective of environmental Kuznets curve (EKC). *Ocean and Coastal Management*, 244, 106819.
- Fu, Q., Álvarez-Otero, S., Sial, M.S., Comite, U., Zheng, P., Samad, S., Oláh, J. (2021), Impact of renewable energy on economic growth and CO<sub>2</sub> emissions-evidence from BRICS countries. *Processes*, 9(8), 1281.
- Gieraltowska, U., Asyngier, R., Nakonieczny, J., Salahodjaev, R. (2022), Renewable energy, urbanization, and CO<sub>2</sub> emissions: A global test. *Energies*, 15(9), 3390.
- Grossman, G.M., Krueger, A.B. (1991), Environmental Impacts of a North American Free Trade Agreement. NEER Working Paper No 3914. p1-57.
- Güney, T. (2022), Solar energy, governance and CO<sub>2</sub> emissions. *Renewable Energy*, 184, 791-798.
- Güney, T., Üstündağ, E. (2022), Wind energy and CO<sub>2</sub> emissions: AMG estimations for selected countries. *Environmental Science and Pollution Research*, 29, 21303-21313.
- Hashmi, R., Alam, K. (2019), Dynamic relationship among environmental regulation, innovation, CO<sub>2</sub> emissions, population, and economic growth in OECD countries: A panel investigation. *Journal of Cleaner Production*, 231, 1100-1109.
- Hoa, P.X., Xuan, V.N., Thu, N.T. (2023), Nexus of innovation, renewable consumption, FDI, growth and CO<sub>2</sub> emissions: The case of Vietnam. *Journal of Open Innovation: Technology, Market, and Complexity*, 9(3), 100100.
- Huang, Y., Haseeb, M., Usman, M., Ozturk, I. (2022), Dynamic association between ICT, renewable energy, economic complexity and ecological footprint: Is there any difference between E-7 (developing) and G-7 (developed) countries? *Technology in Society*, 68, 101853.
- Huo, C., Hameed, J., Sharif, A., Albasher, G., Alamri, O., Alsultan, N., Baig, N.U.A. (2022), Recent scenario and nexus of globalization to CO<sub>2</sub> emissions: Evidence from wavelet and Quantile on Quantile Regression approach. *Environmental Research*, 212(Part A), 113067.
- Hwang, Y.K., Díez, Á.S. (2024), Renewable energy transition and green growth nexus in Latin America. *Renewable and Sustainable Energy Reviews*, 198, 114431.
- IEA. (2024), CO<sub>2</sub> Emissions in 2023. A New Record High, but is There Light at the End of the Tunnel? Paris: IEA. Available from: <https://www.iea.org/reports/co2-emissions-in-2023>
- Im, K.S., Pesaran, M., Shin, Y. (2003), Testing for unit roots in heterogeneous panels. *Journal of Econometrics*, 115(1), 53-74.
- İnal, V., Addi, H.M., Çakmak, E.E., Torusdağ, M., Çalışkan, M. (2022), The nexus between renewable energy, CO<sub>2</sub> emissions, and economic growth: Empirical evidence from African oil-producing countries. *Energy Reports*, 8, 1634-1643.
- İşık, C., Bulut, U., Ongan, S., Islam, H., Irfan, M. (2024), Exploring how economic growth, renewable energy, internet usage, and mineral rents influence CO<sub>2</sub> emissions: A panel quantile regression analysis for 27 OECD countries. *Resources Policy*, 92, 105025.
- Islama, M.M., Alam, M.M., Ahmed, F., Al-Amin, A.Q. (2023), Economic growth and environmental pollution nexus in Bangladesh: Revisiting the environmental Kuznets curve hypothesis. *International Journal of Environmental Studies*, 80(1), 68-92.
- Jebli, M.B., Farhani, S., Guesmi, K. (2020), Renewable energy, CO<sub>2</sub> emissions and value added: Empirical evidence from countries with different income levels. *Structural Change and Economic Dynamics*, 53, 402-410.
- Kanlı, N.K., Küçükefe, B. (2023), Is the environmental Kuznets curve hypothesis valid? A global analysis for carbon dioxide emissions. *Environment, Development and Sustainability*, 25, 2339-2367.
- Kao, C., Chiang, M.H. (2001), On the estimation and inference of a cointegrated regression in panel data. In: Baltagi, B., Fomby, T., Carter Hill, R., editors. *Nonstationary Panels, Panel Cointegration, and Dynamic Panels (Advances in Econometrics)*. Vol. 15. Bingley: Emerald Group Publishing Limited. p179-222.
- Kassouri, Y., Alola, A.A. (2023), Examining the interaction of technology adoption-diffusion and sectoral emission intensity in developing and emerging countries. *Journal of Cleaner Production*, 405, 136920.
- Khan, H., Weili, L., Khan, I. (2022a), Examining the effect of information and communication technology, innovations, and renewable energy consumption on CO<sub>2</sub> emission: Evidence from BRICS countries. *Environmental Science and Pollution Research*, 29, 47696-47712.
- Khan, H., Weili, L., Khan, I. (2022b), Environmental innovation, trade openness and quality institutions: An integrated investigation about environmental sustainability. *Environment, Development and Sustainability*, 24, 3832-3862.
- Khan, Z., Ali, S., Umar, M., Kirikkaleli D., Jiao, Z. (2020), Consumption-based carbon emissions and International trade in G7 countries: The role of Environmental innovation and Renewable energy. *Science of the Total Environment*, 730, 138945.
- Kim, D., Park, Y.J. (2022), Nonlinear causality between energy consumption and economic growth by timescale. *Energy Strategy Reviews*, 44, 100949.
- Koengkan, M., Fuinhas, J.A. (2020), Exploring the effect of the renewable energy transition on CO<sub>2</sub> emissions of Latin American and Caribbean countries. *International Journal of Sustainable Energy*, 39(6), 515-538.



- Kruse-Andersen, P.K. (2023), Directed technical change, environmental sustainability, and population growth. *Journal of Environmental Economics and Management*, 122, 102885.
- Kwakwa, P.A. (2023b), Sectoral growth and carbon dioxide emission in Africa: Can renewable energy mitigate the effect? *Research in Globalization*, 6, 100130.
- Kwakwa, P.A. (2023a), Climate change mitigation role of renewable energy consumption: Does institutional quality matter in the case of reducing Africa's carbon dioxide emissions? *Journal of Environmental Management*, 342, 118234.
- Latief, R., Sattar, U., Javeed, S.A., Gull, A.A., Pei, Y. (2022), The environmental effects of urbanization, education, and green innovation in the union for Mediterranean countries: Evidence from quantile regression model. *Energies*, 15, 5456.
- Leal, P.H., Marques, A.C. (2022), The evolution of the environmental Kuznets curve hypothesis assessment: A literature review under a critical analysis perspective. *Heliyon*, 8(11), e11521.
- Lee, H., Ryu, J.C. (1991), Energy and CO<sub>2</sub> emissions in Korea: Long-term scenarios and related policies. *Energy Policy*, 19(10), 926-933.
- Li, B., Haneklaus, N. (2021), The role of renewable energy, fossil fuel consumption, urbanization and economic growth on CO<sub>2</sub> emissions in China. *Energy Reports*, 7(7), 783-791.
- Li, B., Haneklaus, N. (2022), Reducing CO<sub>2</sub> emissions in G7 countries: The role of clean energy consumption, trade openness and urbanization. *Energy Reports*, 8(4), 704-713.
- Li, M., Ahmad, M., Fareed, Z., Hassan, T., Kirikkaleli, D. (2021), Role of trade openness, export diversification, and renewable electricity output in realizing carbon neutrality dream of China. *Journal of Environmental Management*, 297, 113419.
- Liao, W., Liu, D., Xue, Y., Wu, Y., Xue, F., Chang, K. (2024), Power generation expansion planning considering natural disaster scenarios under carbon emission trajectory constraints. *Applied Energy*, 361, 122832.
- Lin, B., Okoye, J.O. (2023), Towards renewable energy generation and low greenhouse gas emission in high-income countries: Performance of financial development and governance. *Renewable Energy*, 215, 118931.
- Liu, X., Wahab, S., Hussain, M., Sun, Y., Kirikkaleli, D. (2021), China carbon neutrality target: Revisiting FDI-trade-innovation nexus with carbon emissions. *Journal of Environmental Management*, 294, 113043.
- Lu, J., Bin Li, H.L., Al-Barakani, A. (2021), Expansion of city scale, traffic modes, traffic congestion, and air pollution. *Cities*, 108, 102974.
- Lysen, E.H. (1989), The potential of renewable energy to reduce CO<sub>2</sub> emissions. In: Okken, P., Swart, R., Zwerver, S., editors. *Climate and Energy: The Feasibility of Controlling CO<sub>2</sub> Emissions*. Dordrecht: Springer. p78-94.
- Maja, M.M., Ayano, S.F. (2021), The impact of population growth on natural resources and farmers' capacity to adapt to climate change in low-income countries. *Earth Systems and Environment*, 5, 271-283.
- Mendonça, A.K., Barni, G., Moro, M.F., Bornia, A.C., Kupek, E., Fernandes, L. (2020), Hierarchical modeling of the 50 largest economies to verify the impact of GDP, population and renewable energy generation in CO<sub>2</sub> emissions. *Sustainable Production and Consumption*, 22, 58-67.
- Mohammed, S., Gill, A.R., Ghosal, K., Al-Dalahmeh, M., Alsafadi, K., Szabó, S., Oláh, J., Alkerdi, J., Ocwa, A., Harsanyi, E. (2024), Assessment of the environmental kuznets curve within EU-27: Steps toward environmental sustainability (1990-2019). *Environmental Science and Ecotechnology*, 18, 100312.
- Mohsin, M., Orynassarov, D., Anser, M.K., Oskenbayev, Y. (2023), Does hydropower energy help to reduce CO<sub>2</sub> emissions in European Union countries? evidence from quantile estimation. *Environmental Development*, 45, 100794.
- Musah, M., Kong, Y., Mensah, I.A., Antwi, S.K., Donkor, M. (2021), The connection between urbanization and carbon emissions: A panel evidence from West Africa. *Environment, Development and Sustainability*, 23, 11525-11552.
- Nahrin, R., Rahman, M.H., Majumder, S.C., Esquivias, M.A. (2023), Economic growth and pollution nexus in Mexico, Colombia, and Venezuela (G-3 countries): The role of renewable energy in carbon dioxide emissions. *Energies*, 16(3), 1076.
- Namahoro, J., Wu, Q., Zhou, N., Xue, S. (2022), Impact of energy intensity, renewable energy, and economic growth on CO<sub>2</sub> emissions: Evidence from Africa across regions and income levels. *Renewable and Sustainable Energy Reviews*, 147, 111233.
- Nassar, Y.F., El-Khozondar, H.J., Elnaggar, M., El-Batta, F.F., El-Khozondar, R.J., Alsadi, S.Y. (2024), Renewable energy potential in the State of Palestine: Proposals for sustainability. *Renewable Energy Focus*, 49, 100576.
- Nepal, R., Liu, Y., Wang, J., Dong, K. (2024), How does green finance promote renewable energy technology innovation? A quasi-natural experiment perspective. *Energy Economics*, 134, 107576.
- Novotny, V. (1999), Diffuse pollution from agriculture - A worldwide outlook. *Water Science and Technology*, 39(3), 1-13.
- Ojaghlo, M., Ugurlu, E., Kadlubek, M., Thalassinis, E. (2023), Economic activities and management issues for the environment: An environmental kuznets curve (EKC) and STIRPAT analysis in Turkey. *Resources*, 12(5), 57.
- Olabi, A., Elsaid, K., Obaideen, K., Abdelkareem, M.A., Rezk, H., Wilberforce, T., Maghrabie, H.M., Sayed, E.T. (2023), Renewable energy systems: Comparisons, challenges and barriers, sustainability indicators, and the contribution to UN sustainable development goals. *International Journal of Thermofluids*, 20, 100498.
- Pata, U.K. (2021), Linking renewable energy, globalization, agriculture, CO<sub>2</sub> emissions and ecological footprint in BRIC countries: A sustainability perspective. *Renewable Energy*, 173, 197-208.
- Pedroni, P. (2001), Fully modified OLS for heterogeneous cointegrated panels. In: Baltagi, B., Fomby, T., Carter Hill, R., editors. *Nonstationary Panels, Panel Cointegration, and Dynamic Panels (Advances in Econometrics)*. Vol. 15. Leeds: Emerald Group Publishing Limited. p93-130.
- Perone, G. (2024), The relationship between renewable energy production and CO<sub>2</sub> emissions in 27 OECD countries: A panel cointegration and Granger non-causality approach. *Journal of Cleaner Production*, 434, 139655.
- Pesaran, M.H. (2007), A simple panel unit root test in the presence of cross-section dependence. *Journal of Applied Econometrics*, 22(2), 265-312.
- Pesaran, M.H. (2021), General diagnostic tests for cross-sectional dependence in panels. *Empirical Economics*, 60, 13-50.
- Pesaran, M.H., Yamagata, T. (2008) Testing slope homogeneity in large panels. *Journal of Econometrics*, 142(1), 50-93.
- Phadkantha, R., Tansuchat, R. (202), Dynamic impacts of energy efficiency, economic growth, and renewable energy consumption on carbon emissions: Evidence from Markov Switching model. *Energy Reports*, 9(12), 332-336.
- Pickson, R.B., Gui, P., Jian, L., Boateng, E. (2024), Do population-related factors matter for carbon emissions? Lessons from different income groups of countries. *Urban Climate*, 55, 101934.
- Pradhan, R.P., Nair, M.S., Hall, J.H., Bennett, S.E. (2024), Planetary health issues in the developing world: Dynamics between transportation systems, sustainable economic development, and CO<sub>2</sub> emissions. *Journal of Cleaner Production*, 449, 140842.
- Ragoubi, H., Mighri, Z. (2021), Spillover effects of trade openness on CO<sub>2</sub> emissions in middle-income countries: A spatial panel data approach.



- Regional Science Policy and Practice, 13(3), 835-878.
- Rahman, M.M., Alam, K. (2021), Clean energy, population density, urbanization and environmental pollution nexus: Evidence from Bangladesh. *Renewable Energy*, 172, 1063-1072.
- Rahman, M.M., Alam, K. (2022a), Effects of corruption, technological innovation, globalisation, and renewable energy on carbon emissions in Asian countries. *Utilities Policy*, 79, 101448.
- Rahman, M.M., Alam, K. (2022b), Impact of industrialization and non-renewable energy on environmental pollution in Australia: Do renewable energy and financial development play a mitigating role? *Renewable Energy*, 195, 203-213.
- Rahman, M.M., Alam, K., Velayutham, E. (2022c), Reduction of CO<sub>2</sub> emissions: The role of renewable energy, technological innovation and export quality. *Energy Reports*, 8, 2793-2805.
- Rahman, M.M., Khan, Z., Khan, S., Tariq, M. (2023), How is energy intensity affected by industrialisation, trade openness and financial development? A dynamic analysis for the panel of newly industrialized countries. *Energy Strategy Reviews*, 49, 101182.
- Raihan, A. (2023), The influences of renewable energy, globalization, technological innovations, and forests on emission reduction in Colombia. *Innovation and Green Development*, 2(4), 100071.
- Raihan, A., Tuspekova, A. (2022), The nexus between economic growth, renewable energy use, agricultural land expansion, and carbon emissions: New insights from Peru. *Energy Nexus*, 6, 100067.
- Rakpho, P., Chitksame, T., Kaewsompong, N. (2023), The effect of environmental taxes and economic growth on carbon emission in G7 countries applying panel kink regression. *Energy Reports*, 9(10), 1384-1391.
- Ridwan, M., Urbee, A.J., Voumik, L.C., Das, M.K., Rashid, M., Esquivias, M.A. (2024), Investigating the environmental Kuznets curve hypothesis with urbanization, industrialization, and service sector for six South Asian Countries: Fresh evidence from Driscoll Kraay standard error. *Research in Globalization*, 8, 100223.
- Ridzuan, N.H., Marwan, N.F., Khalid, N., Ali, M.H., Tseng, M.L. (2020), Effects of agriculture, renewable energy, and economic growth on carbon dioxide emissions: Evidence of the environmental Kuznets curve. *Resources, Conservation and Recycling*, 160, 104879.
- Ritchie, H. (2023), Global Inequalities in CO<sub>2</sub> emissions. Available from: <https://ourworldindata.org/inequality-co2> [Last accessed on 2024 Jan 29].
- Semet, R. (2024), Coordinating social equity and emissions: Challenges in carbon tax policy. *Energy Policy*, 185, 113954.
- Shabani, Z.D. (2024), Renewable energy and CO<sub>2</sub> emissions: Does human capital matter? *Energy Reports*, 11, 3474-3491.
- Shahzad, K., Abdul, D., Umar, M., Safi, A., Maqsood, S., Baseer, A., Lu, B. (2023), Analysis of obstacles to adoption of solar energy in emerging economies using spherical fuzzy AHP decision support system: A case of Pakistan. *Energy Reports*, 10, 381-395.
- Shao, J., Wang, L. (2023), Can new-type urbanization improve the green total factor energy efficiency? Evidence from China. *Energy*, 262, 125499.
- Silva, N., Fuinhas, J.A., Koengkan, M. (2021), Assessing the advancement of new renewable energy sources in Latin American and Caribbean countries. *Energy*, 237, 121611.
- Simon, J.L. (1996), *The Ultimate Resource 2*. Princeton: Princeton University Press.
- Song, A., Rasool, Z., Nazar, R., Anser, M.K. (2024), Towards a greener future: How green technology innovation and energy efficiency are transforming sustainability. *Energy*, 290, 129891.
- Stern, D.I. (1993), Energy and economic growth in the USA: A multivariate approach. *Energy Economics*, 15(2), 137-150.
- Stern, D.I. (2004), Environmental kuznets curve. *Encyclopedia of Energy*, 517-525.
- Tchouto, J.E. (2023), An empirical assessment on the leveraging evidence of economic complexity under environmental kuznets curve hypothesis: A comparative analysis between Nordic and Non-Nordic European countries. *Innovation and Green Development*, 2(4), 100074.
- Tugcu, C.T., Ozturk, I., Aslan, A. (2012), Renewable and non-renewable energy consumption and economic growth relationship revisited: Evidence from G7 countries. *Energy Economics*, 34(6), 1942-1950.
- Uddin, I., Ahmad, M., Ismailov, D., Balbaa, M.E., Akhmedov, A., Khasanov, S., Haq, M.U. (2023), Enhancing institutional quality to boost economic development in developing nations: New insights from CS-ARDL approach. *Research in Globalization*, 7, 100137.
- Ulucak, R., Danish, Kassouri, Y. (2020), An assessment of the environmental sustainability corridor: Investigating the non-linear effects of environmental taxation on CO<sub>2</sub> emissions. *Sustainable Development*, 28(4), 1010-1018.
- Wang, Q., Hubacek, K., Feng, K., Wei, Y.M., Liang, Q.M. (2016), Distributional effects of carbon taxation. *Applied Energy*, 184, 1123-1131.
- Wang, Q., Li, L. (2021), The effects of population aging, life expectancy, unemployment rate, population density, per capita GDP, urbanization on per capita carbon emissions. *Sustainable Production and Consumption*, 28, 760-774.
- Wang, Q., Sun, Z., Guo, J., Li, R. (2023a), The more effective option to combat environmental degradation: Energy efficiency vs. renewable energy vs. natural gas? *Energy*, 2023, 128512.
- Wang, Q., Yang, T., Li, R. (2023b), Does income inequality reshape the environmental Kuznets curve (EKC) hypothesis? A nonlinear panel data analysis. *Environmental Research*, 216, 114575.
- Wang, S., Zafar, M.W., Vasbieva, D.G., Yurtkuran, S. (2024), Economic growth, nuclear energy, renewable energy, and environmental quality: Investigating the environmental Kuznets curve and load capacity curve hypothesis. *Gondwana Research*, 129, 490-504.
- Wang, W.Z., Liu, L.C., Liao, H., Wei, Y.M. (2021), Impacts of urbanization on carbon emissions: An empirical analysis from OECD countries. *Energy Policy*, 151, 112171.
- Wencong, L., Kasimov, I., Saydaliev, H.B. (2023), Foreign direct investment and renewable energy: Examining the environmental Kuznets curve in resource-rich transition economies. *Renewable Energy*, 208, 301-310.
- Wenlong, Z., Tien, N.H., Sibghatullah, A., Asih, D., Soelton, M., Ramli, Y. (2023), Impact of energy efficiency, technology innovation, institutional quality, and trade openness on greenhouse gas emissions in ten Asian economies. *Environmental Science and Pollution Research*, 30, 43024-43039.
- Wisniewski, G., Rogulska, M., Grzybek, A., Pietruszko, S.M. (1995), The role of renewable energy in carbon dioxide emission reduction in Poland. *Applied Energy*, 52(2), 291-298.
- Wolde-Rufael, Y., Mulat-Weldemeskel, E. (2021), Do environmental taxes and environmental stringency policies reduce CO<sub>2</sub> emissions? Evidence from 7 emerging economies. *Environmental Science and Pollution Research*, 28, 22392-22408.
- Wolde-Rufael, Y., Mulat-Weldemeskel, E. (2022), The moderating role of environmental tax and renewable energy in CO<sub>2</sub> emissions in Latin America and Caribbean countries: Evidence from method of moments quantile regression. *Environmental Challenges*, 6, 100412.
- Wolde-Rufael, Y., Mulat-Weldemeskel, E. (2023), Effectiveness of environmental taxes and environmental stringent policies on CO<sub>2</sub> emissions: The European experience. *Environment, Development and Sustainability*, 25, 5211-5239.
- Yadav, A., Gyamfi, B.A., Asongu, S.A., Behera, D.K. (2024), The role of green finance and governance effectiveness in the impact of renewable energy investment on CO<sub>2</sub> emissions in BRICS economies.

Journal of Environmental Management, 358, 120906.

Yang, S., Umar, M. (2022), How globalization is reshaping the environmental quality in G7 economies in the presence of renewable energy initiatives? *Renewable Energy*, 193, 128-135.

York, R., Rosa, E.A., Dietz, T. (2003), STIRPAT, IPAT and ImPACT: Analytic tools for unpacking the driving forces of environmental impacts. *Ecological Economics*, 46(3), 351-365.

Yu, J., Tang, Y.M., Chau, K.Y., Nazar, R., Ali, S., Iqbal, W. (2022), Role of solar-based renewable energy in mitigating CO<sub>2</sub> emissions: Evidence from quantile-on-quantile estimation. *Renewable Energy*, 182, 216-226.

Yuping, L., Ramzan, M., Xincheng, L., Murshed, M., Awosusi, A.A., Bah, S.I., Adebayo, T.S. (2021), Determinants of carbon emissions in Argentina: The roles of renewable energy consumption and globalization. *Energy Reports*, 7, 4747-4760.

Zaidi, S., Danish, Hou, F., Mirza, F. (2018), The role of renewable and non-renewable energy consumption in CO<sub>2</sub> emissions: A disaggregate analysis of Pakistan. *Environmental Science and Pollution Research*, 25, 31616-31629.

Zhang, J., Alharthi, M., Abbas, Q., Li, W., Mohsin, M., Jamal, K., Taghizadeh-Hesary, F. (2020), Reassessing the environmental kuznets curve in relation to energy efficiency and economic growth. *Sustainability*, 12(20), 8346.

Zhang, S., Kaikun, W., Yastrubskiy, M., Huang, C. (2023b), Carbon emissions from international trade and consumption: Assessing the role of cumulative risk for EU and Chinese economic development. *Energy Strategy Reviews*, 50, 101219.

Zhang, T., Yin, J., Li, Z., Jin, Y., Ali, A., Jiang, B. (2023a), A dynamic relationship between renewable energy consumption, non-renewable energy consumption, economic growth and CO<sub>2</sub> emissions: Evidence from Asian emerging economies. *Frontiers in Environmental Science*, 10, 1-17.

Zhang, Z., Bashir, T., Song, J., Aziz, S., Yahya, G., Bashir, S., Zamir, A. (2022), The effects of Environmental Kuznets Curve toward environmental pollution, energy consumption on sustainable economic growth through moderate role of technological innovation. *Environmental Science and Pollution Research*, 29, 405-416.

Zhou, X., Xie, F., Li, H., Zheng, C., Zhao, X. (2023), Understanding inter-term fossil energy consumption pathways in China based on sustainable development goals. *Geoscience Frontiers*, 2023, 101687.

APPENDIX

Appendix A.1

Table 14 presents in detail the 30 high-income countries selected for the study.

Table 14: High-income countries used in the research

Australia*	Islandia	Polonia*
Austria*	Irlanda*	Portugal
Bélgica*	Israel*	Rumania
Canadá*	Italia	República Eslovaca
Croacia	Japón*	Eslovenia
Dinamarca*	Corea, Rep.*	España
Estonia*	Lituania	Suecia
Francia	Luxemburgo*	Suiza
Alemania*	Países Bajos*	Reino Unido
Hungría	Nueva Zelanda	Estados Unidos*

\*Sub-panel of countries with the highest average CO<sub>2</sub> emissions