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Evaluating the Environmental Kuznets Curve: The Role of Renewable Energy, Economic Growth, Urban Density and Trade Openness on CO_2 Emissions. An Analysis for High-Income Countries Using the CS-ARDL Model

Juan Pablo Vallejo Mata[1], María Gabriela González Bautista[2], Luis Eduardo Solis Granda[1], Eduardo Germán Zurita Moreano[2]*

[1]Universidad Estatal de Milagro, Ecuador, [2]Universidad Nacional de Chimborazo, Ecuador. *Email: mggonzalez@unach.edu.ec

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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_2 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_2 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_2 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_2 emissions, while the relationship between urban density and CO_2 emissions is statistically non-significant. This information is expected to be crucial for the generation of public policies framed in sustainable development.

Keywords: CO_2 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_2 eq, which means an increase of 2.3% compared to 2021, where 71.6% of these were carbon dioxide (CO_2) emissions (Crippa et al., 2023). In 2023, global energy-related CO_2 emissions grew by 1.1%, achieving a historically high level of 37.4 billion tons (Gt) (IEA, 2024).

Unprecedented levels of CO_2 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_2

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_2 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_2 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_2 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_2 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_2 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_2 emissions (Ritchie, 2023). In addition, countries such as Germany, the United States, Italy, and the United Kingdom have increased their production of CO_2 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_2 emissions in the short and long term. Second, it investigates the relationship between economic growth and CO_2 emissions under the EKC hypothesis. Third, other determinants of CO_2 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_2 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_2 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_2 emissions (Amer et al., 2024). There are several reasons for the negative impact of renewables on CO_2 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_2 emissions (Song et al., 2024).

According to the theoretical implications, several empirical studies have examined the impact of renewable energies on CO_2 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_2 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 (FCLS) method found that non-renewable energies are positively associated with CO_2 emissions in the countries that make up the Gulf Cooperation Council (GCC) between 1995 and 2017. Conversely, renewables significantly mitigate CO_2 emissions. For 27 OECD countries between 2001 and 2020, Işık et al. (2024) evidence a negative correlation between renewables and CO_2 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_2 emissions. More specifically, they find that for a 1% increase in clean energy consumption, CO_2 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_2 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_2 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_2 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_2 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_2 emissions. In contrast, Zaidi et al. (2018), using the ARDL model, find that renewable energy consumption has a non-significant impact on CO_2 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_2 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_2 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_2 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_2 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_2 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_2 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_2 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_2 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_2 emissions by 0.018%.

Table 1 summarizes additional research on the link between renewable energies and CO_2 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_2 emissions.

2.2. Economic Growth and CO_2 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_2 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_2 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_2 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_2 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_2 emissions

Authors	Country (ies), Data, Methodology	Endogenous variable	Independent variable (s)	Conclusion
Alam et al. (2023)	India; 1990Q1-2018Q4; econometric structural break technique.	CO_2 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_2 emissions
Hoa et al. (2023)	Vietnam; 2000-2022; fixed effects panel data.	CO_2 emissions	High-tech innovations or exports Renewable energy consumption FDI inflows Economic growth	Renewable energy $\xrightarrow{-}$ CO_2 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_2 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_2 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_2 emissions; that is, in a first stage, economic growth is accompanied by environmental deterioration. In a second stage, further growth reduces CO_2 emissions until a threshold is reached which, when exceeded, environmental quality starts to worsen again (e.g., Ojaghlou et al., 2023; Fang and Gao, 2023; Fakher et al., 2023).

Table 2 summarizes additional research on the link between economic growth and CO_2 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_2 emissions.

2.3. Urban Population Density and CO_2 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_2 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., Gierałtowska et al., 2022; Latief et al., 2022).

Table 3 summarizes additional research on the link between population density and CO_2 emissions.

Table 2: Additional empirical studies: Economic growth and CO_2 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_2 emissions
Mohammed et al. (2024)	EU-27; 1990-2019; Dynamic Ordinary Least Squares (DOLS) and Fully Modified Ordinary Least Squares (FMOLS).	CO_2 emissions - National total	Energy consumption GDP -market prices Population	Economic growth $\xrightarrow{\cap}$ CO_2 emissions
Ahmad et al. (2023)	G-11 countries; 1990-2018; cross-sectional autoregressive distributed lags (CS-ARDL).	CO_2 emissions	GDP Renewable energy Natural resources	Economic growth $\xrightarrow{\cap}$ CO_2 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_2 emissions	Economic growth Renewable energy Institutional quality	Economic growth $\xrightarrow{\cap}$ CO_2 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_2 emissions.

2.4. Trade Openness and CO_2 Emissions

Given the complexity of trade openness, which involves a number of interactions between different factors, its relationship with CO_2 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_2 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_2 emissions. This relationship is framed in a model in which trade openness enables the transfer of green technology, allowing CO_2 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_2 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_2 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_2 emissions. In this context, the transition

Table 3: Additional empirical studies: Population density and CO_2 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_2 emissions	GDP per capita Unemployment rate Aging population Urbanization Life expectancy	Population density $\xrightarrow{+}$ CO_2 emissions
Mendonça et al. (2020)	Top 50 economies of the world; 1990-2015; hierarchical regression model.	CO_2 emissions	GDP Population growth Renewable energy	Population density $\xrightarrow{+}$ CO_2 emissions
Chen et al. (2023)	China; 2003-2019; spatial econometric models.	CO_2 emissions	Urbanization	Population density $\xrightarrow{\cap}$ CO_2 emissions

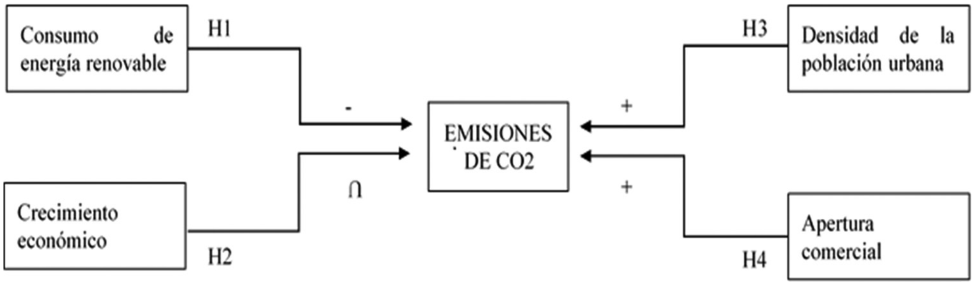
$\xrightarrow{+}$ Positive effect, $\xrightarrow{\cap}$ Inverted U ratio

Table 4: Additional empirical studies: Trade openness and CO_2 emissions

Author	Country (ies), Data, Methodology ís (es), Datos, Metodología	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_2 emissions per capita	Commercial openness Innovation, Institutional quality, Foreign direct investment Financial development Renewable and non-renewable energy consumption	Commercial opening $\xrightarrow{-}$ CO_2 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_2 emissions	Trade liberalization Export diversification Renewable electricity production	Commercial opening $\xrightarrow{-}$ CO_2 emissions

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

Figure 1: Research hypothesis



to sustainable energies through the consumption of renewable energies to reduce CO_2 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_2 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_2 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_2 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_2 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_2 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_2 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_2 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_2 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_2 Emissions	CO_2	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_2	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 (1)	Median (2)	Standard deviation (3)	Minimum (4)	Maximum (5)	Levene (6)
CO_2	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 CO2 emissions is represented as follows:

$$CO2_{it} = f\,(Er_{it}, Ce_{it}, Ce2_{it}, Urb_{it}, To_{it}) \qquad (1)$$

In equation (1), *i* enotes the country (i = 1,…,30) and *t* the period ($t = 2000,\ldots 2020$). The dependent variable is the CO_2 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:

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

In equation (2), β_0 corresponds to the model constant, and $\beta_1,\ldots,\beta_5$, represent the partial elasticities to be estimated in relation to each independent variable, while μ_{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_2 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_2 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_2 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_2 emitting countries, selected for having the highest average CO_2 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_2 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):

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

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 Pasaran 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:

$$\Delta V_{it} = \varphi_i + \varphi_i V_{it-1} + \varphi_i \bar{K}_{t-1} + \sum\nolimits_{i=0}^{p} \varphi_{iI} \Delta \bar{V}_{t-1} + \sum\nolimits_{i=0}^{p} \varphi_{iI} \Delta V_{t-I} + e_{it} \tag{4}$$

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).

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

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_2 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).

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

In equation (6), $CO2_{i,t}$ represents CO_2 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*), $\overline{CS}_i$, represents the cross-sectional mean p, q, w, are the optimal lags and μ_{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 Δ and Δ_{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_2	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
Δ	10.43***	6.62***
Δ_{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_2	−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_2	−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.

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

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_2 emissions.

Table 11 presents the short-run and long-run effects of the explanatory variables on CO_2 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_2 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_2 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_2 emissions intensity among countries. In countries with higher CO_2 levels, the mitigation capacity of renewable energies is reduced. Thus, renewable energies emerge as a potential alternative to neutralize CO_2 emissions from human and economic activities (Balsalobre-Lorente et al., 2023).

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

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

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

In addition, the results indicate that economic growth has a positive and significant effect, both in the short and long term, on CO_2 emissions. A 1% increase in economic growth generates a substantial increase in per capita CO_2 emissions of 30.52% and 28.97%, respectively in the full panel. This effect, as expected, is of greater magnitude in the top 15 CO_2 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_2 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_2 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_2 emissions. According to the full panel results, in the long square, a 1% increase in trade openness leads to an increase in CO_2 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_2 emissions, the nonlinear inverted U-shaped relationship between economic growth and environmental damage, and the positive direction of trade openness on CO_2 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_2 emissions in high-income countries. The first finding reveals the negative impact of renewable energy consumption on CO_2 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 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).

Table 12: Robustness estimation, AMG

Variables	Full panel	Subpanel
	Coefficients	
LnRe	−0.31***	−0.21***
	(0.08)	(0.07)
LnCe	26.35*	34.19
	(13.83)	(23.34)
LnCe2	−1.17*	−1.48
	(0.63)	(1.04)
LnUrb	−10.65	−29.32
	(12.63)	(21.41)
LnOt	0.12***	0.14**
	(0.03)	(0.04)
C_d_p	0.96***	0.89***
	(0.18)	(0.32)
Const	−0.05***	0.014
	(0.013)	(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 Hypothesisa		Finding	Conclusion
H1	Renewable energies have a negative impact on CO_2 emissions.	$Er \xrightarrow{-} CO_2$	Does not reject H1
H2	Economic growth has an inverted U-shaped relationship with CO_2 emissions	$Ce \xrightarrow{\cap} CO_2$	Does not reject H2
H3	Urban population density has a positive impact on CO_2 emissions	$Urb \xrightarrow{NON} CO_2$	Not conclusive
H4	Openness to trade has a positive impact on CO_2 emissions	$To \xrightarrow{-} CO_2$	Does not reject H4

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

Another relevant finding is the nonlinear inverted U-shaped relationship between economic growth and CO_2 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_2 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_2 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_2 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_2 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_2 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_2 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_2 emissions was proposed. Second, a nonlinear inverted U-shaped relationship between economic growth and CO_2 emissions was proposed. Third, a positive relationship of urban density and trade openness with CO_2 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_2 emissions in both the short and long term. Specifically, it was estimated that a 1% increase in renewable energy consumption reduces CO_2 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_2 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_2 emissions.

It was also found that trade liberalization increases CO_2 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_2 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_2 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_2 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_2 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.

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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_2 emissions