



Assessing the Interaction among Energy Transition, CO₂ Emissions and Green Growth in 63 Economies

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ABSTRACT

This paper analyzes the interactions among energy transition, CO₂ emissions, and green growth in a sample of 63 countries. Cointegration, causality, and panel data models are estimated. The cointegration test shows a stable long-term relationship among the three variables under study. Furthermore, CO₂ emissions and the energy transition cause green growth in the Granger sense, at least in the short term, with lags of 1 and 2 years. Similarly, dynamic panel data models show that the energy transition has a significant impact on reducing CO₂ emissions and drives green growth, while CO₂ emissions have negative effects on green growth in the whole sample. The results provide decision-makers with a solid foundation for designing and implementing public policies that promote the energy transition and reduce CO₂ emissions, thereby driving green growth through the rapid implementation of this transition for a better environment and sustainable development.

Keywords: Energy Transition, CO₂ Emissions, Green Growth, Cointegration, Granger Causality, Panel Data

JEL Classifications: C51, Q40, Q50

1. INTRODUCTION

The environmental crisis of recent decades in many countries, linked to environmental degradation, demands an immediate energy transition. Furthermore, global warming caused by greenhouse gas emissions from industry to drive economic growth has led to the definition of green growth, a new path toward low-carbon economic growth through the intensive use of renewable energy and the sustainable use of natural resources, minimizing the impact on future generations (Khalid and Abdul, 2025; Hwang and Sánchez, 2024; Tinoco-Zermeño, 2022; Valencia-Herrera et al., 2020).

Currently, there is a significant interest in studies on green growth and its determinants: Low-carbon energy transition, greenhouse gases, renewable energy, natural resources, efficient allocation, and social inclusion, among other factors. In short, green growth seeks to decouple GDP growth from environmental degradation,

with the goal of creating a future where economic prosperity and environmental sustainability are coordinated (Ekins, 2002). The hypothesis of this research is that reducing CO₂ emissions and accelerating the energy transition will positively enhance green growth, which will significantly contribute to improving global sustainability.

Extensive literature exists on the relationship between CO₂ emissions and economic growth; however, no assessment has been conducted on the interaction between the energy transition, CO₂ emissions, and green growth. Such an assessment is necessary to provide decision-makers with a solid foundation for designing and implementing public policies that create a future where economic prosperity and environmental sustainability are aligned (Barua, 2022).

One of the main challenges facing the public and private sectors today is the energy transition: The shift from energy production

and consumption systems based on fossil fuels to renewable energy. This transition process must occur at all levels: Global, regional, national, and local. Therefore, strategies, instruments, and incentives are needed to accelerate this process in order to mitigate environmental degradation and, ultimately, achieve better living conditions on our planet.

This paper is distinguished from the current state of the subject in the following aspects: (1) it focuses on a sample of 63 economies, (2) there is greater availability of data with respect to the past, (3) it estimates cointegration and Granger causality to detect relationships among variables in the short, medium and long term, (4) it estimates static and dynamic panel data models, which allows the use of a larger number of countries, variables and periods; (5) it corrects multicollinearity and autocorrelation problems, and, finally, (6) it provides recommendations for the design and implementation of public policies that promote green growth through the energy transition and the reduction of CO₂ emissions.

The remainder of the paper is organized as follows: section 2 presents a literature review; section 3 discusses the nature of the data and carries out the statistical description of the variables; section 4 presents the main empirical results from cointegration, Granger causality, and panel data models; and, finally, section 5 provides conclusions, recommendations and limitations.

2. LITERATURE REVIEW

The role of the energy transition, CO₂ emissions and green growth are addressed in many theoretical and empirical studies, for instance, Ekins (2002) studies the relationship between economic growth and environmental sustainability, providing a measure of green growth. This author is one of the pioneers in defining the conditions of compatibility between economic growth and environmental sustainability, providing measures and criteria by which environmental degradation and economic growth can be related. The author argues that green growth is not only theoretically possible but also economically achievable, and recommends several environmental and economic policies necessary to achieve it. Similarly, Lindmark et al. (2011) analyze the relationship among CO₂ emissions, energy transition and production growth in the Swedish pulp and paper industry over the period 1973-2006, finding that energy substitution and efficiency improvements contributed to the 80% reduction in CO₂ emissions achieved by this industry, and showing that the energy transition coincided with an ongoing structural change in the industry during the 1970s and 1980s, as well as a strong period of environmental adaptation.

Furthermore, Apergis and Payne (2014) study the determinants of renewable energy consumption per capita in a panel of 7 Central American countries over the period 1980-2010, finding that there is a long-term cointegrated relationship among renewable energy consumption per capita, CO₂ emissions per capita, real coal prices, and real oil prices in the 7 countries. Likewise, Dreyfus and Allemand (2018) examine the French Energy Transition for Green Growth Act (FETFGGA), which contains ambitious qualitative and quantitative targets to be implemented by 2030. These

authors find the role of local governments to be very important for the success of energy and climate policies. Three years after the adoption of the FETFGGA, the authors also examine the new energy governance framework in France, and the contribution and challenges of local governments to the national energy transition.

On the other hand, Osobajo et al. (2020) explore the effect of both energy consumption and economic growth on CO₂ emissions by using Ordinary Least Squares (OLS) regressions, Fixed Effects (FE) models, Granger causality and Cointegration with panel data. These authors study 70 countries between 1994 and 2013. The Granger causality tests reveal that the study variables (population, capital stock and economic growth) have a bidirectional causal relationship with CO₂ emissions, while energy consumption has a unidirectional relationship towards CO₂ emissions. Likewise, they find with the cointegration tests, that there is a long-term relationship between both energy consumption and economic growth with CO₂ emissions. In the same way, the authors show, through OLS and FE, that both energy consumption and economic growth have a significant positive impact on CO₂ emissions. Finally, the authors suggest the global transition to clean energy to reduce CO₂ emissions through climate financing.

Likewise, Murshed et al. (2021) examine Bangladesh's aim to achieve carbon neutrality in a global agenda following the ratification of the Paris Agreement (PA) and the declarations of the United Nations Sustainable Development Goals (UNSDG). The authors assess the environmental impacts associated with energy consumption and other macroeconomic variables of Bangladesh over the period 1975–2016. Through a causality analysis, they find that aggregate energy consumption, fossil fuel consumption, and natural gas consumption increase the carbon footprint figures in Bangladesh, also find that non-fossil fuel consumption and hydropower consumption reduce the carbon footprint levels, and note evidence that economic growth and international trade further increase carbon footprints. Finally, the authors suggest a clean energy transition in Bangladesh to address the persistent environmental challenges in the country.

Likewise, Barua (2022) assesses the sustainable energy transition and green growth in 10 emerging economies, using data from the World Bank and the Global Green Growth Institute. The assessment concludes that, in contrast to an encouraging energy transition, these economies show an increasing dependence on fossil fuels and a declining trend in renewable energy supply. Furthermore, the author highlights that energy inefficiency and support for fossil fuels are steadily increasing in these economies. The author also describes several challenges that prevent emerging economies from moving toward green growth driven by sustainable energy, including a lack of financial and economic capacity, market imperfections and failures, a fragile economic system with weak governance, a lack of investment priority in research and innovation, and insufficient regulatory and policy frameworks. As emerging economies are expected to experience the strongest growth in the coming decades and lead the global economy, it is critical to ensure they do so sustainably. The author concludes that green growth, supported by sustainable energy, is no longer an option, but a necessity.

Moreover, Meng and Asuka (2022) study the role of the energy system transition for greenhouse gas mitigation in Japan. They find that electricity can contribute 50% to the reduction of existing CO₂ emissions. They also indicate that the development of technologies and continuous efforts in energy saving can provide a substantial contribution to the issue. The authors highlight Japan's efforts to reduce emissions through an energy transition in the electricity sector and that Japan can meet the expectation of achieving the objectives of the Paris Agreement. Likewise, Razzaq et al. (2023) study energy transition, environmental governance, and green growth in 37 economies from 2010 to 2020. These authors apply Dynamic Panel Threshold Model (DPTM) to integrate the threshold and endogenous effects of energy transition and environmental governance on green growth. They find that environmental regulation shows a significant and positive influence on green growth. Their results suggest that an inclusive and long-term policy for energy transition and governance is imperative to achieve the green growth agenda.

Furthermore, Di Febo et al. (2023) analyze the relationship among renewable energies, CO₂ emissions and economic growth in the European Union (EU) over the period 1995-2020. Finally, the authors indicate that the long-term relationship among Gross Domestic Product (GDP), renewable energy consumption and CO₂ emissions is evident, pointing out that economic growth can increase environmental pollution in Europe, while an increase in the use of renewable energy can reduce CO₂ emissions, which is a trade-off between economic development and CO₂ emissions.

More recently, Handaja et al. (2024) examine the links between energy and CO₂ emissions in Indonesia. The authors find that on the one hand, the Indonesian government is trying to reduce emissions towards net zero emissions by 2060, in line with the ratification of the Paris Agreement, while on the other hand, the government continues to increase oil and gas production, which are sources of CO₂ emissions. The Indonesian government's strategy to meet the challenge of CO₂ reduction is for the domestic oil and gas industry to undertake carbon capture, storage and utilization, and increasing oil production, while achieving the goal of energy transition. Hence, the authors suggest the prompt implementation of innovative practices for the energy transition to favor the reduction of CO₂ emissions and drive green growth in favor of a better environment and sustainable development that benefits the world's population. Likewise, Hwang and Sánchez-Díez (2024) examine the impact of the renewable energy transition on green growth through an econometric analysis of panel data from 14 Latin American countries between 2003 and 2020. They find that the renewable energy transition significantly boosts green economic growth; however, its effect differs significantly depending on the country's geographic location, dependence on fossil fuels, and dependence on mineral resources. The authors identify five mediating variables between the renewable energy transition and green growth: capital investment, dependence on hydropower for electricity generation, residential electricity consumption per capita, human capital, and formal job creation.

Likewise, Hoffert et al. (2002) analyze carbon-free energy sources, such as onshore solar and wind power, solar-powered satellites,

biomass, nuclear fission, nuclear fusion, and fission-fusion hybrids, and their role in improving the environment. They find that non-primary energy technologies that could contribute to climate stabilization include efficiency improvements, hydrogen production, storage and transport, superconducting global power grids, and geo-engineering. The authors indicate that these approaches have serious shortcomings that limit their ability to stabilize the global climate and conclude that a wide range of intensive research and development is urgently needed to generate technological options that enable both climate stabilization and economic development. On the other hand, Gustavsson and Sathre (2006) study the effects of energy on CO₂ emissions in the construction industry, as previous studies have shown that the use of wood for construction generally results in lower energy consumption and CO₂ emissions than the use of concrete. The authors find that the wood-framed building materials had lower energy and CO₂ balances than the concrete-framed building, and conclude that using wood as a building material instead of concrete, along with greater integration of wood byproducts into energy systems, would be an effective means of reducing fossil fuel use and net CO₂ emissions to the atmosphere.

Furthermore, Kern and Smith (2008) examine the energy transition in the Netherlands. The authors conclude that despite considerable achievements, their approach risks being absorbed into the existing energy regime, thereby undermining the original policy ambitions of structural innovation of the energy system. Likewise, Solomon and Krishna (2011) analyze the adoption of sustainable energy systems, historical energy transitions and how to accelerate the current transition. The authors review three case studies: Brazil, moving from an oil-based transport system to one based on sugarcane ethanol (a success story); France, moving from oil-based electricity to nuclear energy (another success story); and the United States, which attempted to shift from foreign oil to a mix of domestic energy resources (failure case). The authors also examine attempts to manage energy transitions in different countries, identifying several policy instruments to accelerate a transition. They conclude that the global energy supply transition will be very slow, and suggest simultaneously implementing programs in countries with different economic policies, a greater focus on energy efficiency, promotion of smart grids, and possibly a new treaty to accelerate the current energy transition.

It is also important to point out Kivyiro and Arminen's (2014) work that examine the links among CO₂ emissions, energy consumption, economic development and foreign direct investment in 6 sub-Saharan African countries using autoregressive models and cointegration analysis. They find that foreign direct investment increases CO₂ emissions in some of the countries, while in other countries foreign direct investment reduces CO₂ emissions. The most common unidirectional Granger causality relationships run from the other variables toward CO₂ emissions, and from Gross Domestic Product toward foreign direct investment. They also conclude that causality relationships vary greatly across countries, making it impossible to give universal policy recommendations. Similarly, Heidari et al. (2015) examine the relationship between economic growth, CO₂ emissions and energy consumption in 5 countries using panel data models. They find that with levels

of GDP per capita below 4,686 US dollars, environmental degradation increases with economic growth, while it is the opposite with levels of GDP per capita above 4,686 US dollars. Finally, they find that energy consumption leads to an increase in CO₂ emissions in the countries analyzed.

On the other hand, Zaman and Moemen (2017) examine the interrelationship between energy consumption, economic growth and CO₂ emissions in the context of low- and middle- and high-income countries, and in an aggregated panel, over the period 1975–2015. They find in a large group of economies the need for a development policy agenda for sustainable growth. On the other hand, Sattler et al. (2018) examine possible energy futures for Illinois after the Future Energy Jobs Act was passed in late 2016; technologies that could replace coal plants in the state, and the costs and benefits of replacing these plants. The authors conclude that Illinois can retire and replace coal plants with local clean energy alternatives, saving consumers money and improving the health of its residents.

Similarly, Bekun et al. (2019) explore the links between energy use and economic growth during 1960–2016 in South Africa, taking into account capital, labor, and CO₂ emissions, and using cointegration analysis. The authors find a long-run equilibrium relationship between the variables studied. Granger causality tests indicate unidirectional causality from energy use toward economic growth, supporting the energy-led growth hypothesis. Additionally, they find an inverted U-shaped pattern between energy use and economic growth in the long term, and reveal that at a higher level of economic development there is less intensification of energy consumption, which means a decrease in energy intensity while validating energy efficiency in South Africa.

Likewise, Bouyghrissi et al. (2021) explore the relationships between renewable energy consumption and CO₂ emissions, controlling for economic growth, financial development, and foreign direct investment inflows, in Morocco during the period 1980–2017. The authors find that renewable energy consumption reduces CO₂ emissions in both the short and long term. Also, financial development and foreign direct investment increase CO₂ emissions, and indicate that renewable energy consumption interacts with financial development and foreign direct investment to jointly decrease CO₂ emissions in Morocco in the long term. The authors recommend that the Moroccan government adopt relevant policies for the energy transition, at the same time, it is also necessary for Morocco to achieve environmentally sustainable economic growth by greening its financial sector and reviewing its financial globalization policies.

Moreover, Hao et al. (2021) study green growth on CO₂ emissions for G7 countries from 1991 to 2017. Using panel data, they find that green growth reduces CO₂ emissions. Furthermore, they find that environmental taxes, human capital, and the use of renewable energy reduce CO₂ emissions. The impact of GDP growth on both the short and long term is environmental depletion; their results support the theoretical notion that green growth sustains environmental quality.

On the other hand, Apostu et al. (2022) study the actions of the public and private sectors to promote the energy transition, decarbonisation and green transition for a more sustainable economy. The authors identify several factors that influence per capita CO₂ emissions in European countries: Level of economic development, level of globalization, trade openness and intensity of the energy transition measured by the share of renewable energy in total energy consumption. They also study 42 European countries in the period 1990–2018, finding a greater share of green energy in energy consumption, with relatively high differences between the countries analyzed, and the funds to finance the development of renewable energies are influencing the dynamics of the energy transition, with implications for size and destination.

On the other hand, Belucio et al. (2022) analyze the effects of natural gas on CO₂ emissions for 16 European countries over the period 1993–2018. An unrestricted error correction model is used to identify short-term impacts, long-term elasticities, and speed of model fit. The authors find that, in the short term, natural gas has a negligible impact on CO₂ emissions (6.7 times less than oil), while renewable energy consumption reduces CO₂ emissions in both the short and long term. They also recommend that governments use natural gas instead of oil, and suggest turning to renewable energy and hydroelectric consumption to reduce CO₂ emissions as well as accelerate the energy transition. Recently, Trimech (2024) studies the energy transition towards low-carbon economies and the need for innovative sector-specific policies that promote sustainable energy practices and reduce air pollution. The author explores the relationship between CO₂ emissions and renewable energy consumption, with aggregated and sector-specific information, in USA, in the period 1989–2022. The author highlights the need to adapt energy strategies to sectoral dynamics, that despite the growing adoption of renewable energies in the industrial and transportation sectors, their impact on reducing CO₂ emissions remains limited, however, the electric power sector shows promising potential to reduce emissions through greater integration of renewable energies.

Moreover, Liu et al. (2024) study the role of technological progress in sustainable development in China. They find that: (1) In the early stages of economic growth, the green transition is in a stable state; when economic growth reaches a certain level, the level of green technology is endogenous to economic growth and continues to improve, which promotes the green transition and carbon emission reduction. (2) Due to the scale effect, carbon emissions increase with economic growth. However, when economic growth reaches a certain level, carbon emissions first increase with the growth of the economy and then decline, showing an inverted “U” trend, which is attributed to the emissions reduction and green transition effects of green technology. (3) As can be seen from the prediction results, after carbon peaks, advances in green technology play a dominant role in carbon emissions, contributing to a rapid reduction in carbon emissions.

Likewise, Khalid and Abdul (2025) investigate the effects of green growth, foreign direct investment, human capital, and financial expansion on carbon emissions in Bangladesh over the period 1980–2022, studying both short- and long-term dynamics. The

authors find that green growth significantly promotes ecological sustainability by spurring green methods and financing incremental innovations specifically aimed at reducing carbon emissions.

In the context of this literature review, the lack of an assessment of the interaction between the energy transition, CO₂ emissions, and green growth is noteworthy. Such an assessment would provide decision-makers with a solid foundation for designing and implementing public policies that promote both the energy transition and the reduction of CO₂ emissions, thereby driving green growth through the rapid implementation of this transition to achieve a more sustainable environment.

In summary, one of the most pressing challenges facing the public and private sectors today is the energy transition. Decision-makers at the global, regional, national, and local levels must employ strategies, instruments, and incentives to accelerate the current energy transition in order to reduce CO₂ and greenhouse gas emissions, mitigate climate change and environmental degradation, and ultimately achieve better living conditions on our planet.

3. NATURE OF DATA, DESCRIPTIVE STATISTICS AND GRAPHICAL ANALYSIS

The statistical information used in this study is available from the World Bank and Global Green Growth Institute. The energy transition is measured as the shift from fossil-based systems of energy production and consumption to renewable energy. The statistical information on energy is obtained from the World Bank. The data on CO₂ emissions are given in millions of tonnes of CO₂ equivalent (MtCO₂e) and are obtained from World Bank statistics. The data of Green Growth Index is obtained from Global Green Growth Institute. All variables correspond to the period 2010–2021. In this research, a balanced panel data is available. The period is restricted to data availability. The sample includes 63 economies: Argentina, Austria, Belgium, Burkina Faso, Bangladesh, Bolivia, Brazil, Bhutan, Canada, Chile, Cameroon, Republic of the Congo, Colombia, Costa Rica, Cuba, Germany, Denmark, Dominican Republic, Algeria, Ecuador, Egypt, Spain, Finland, France, Gabon, United Kingdom, Guatemala, Honduras, Haiti, Indonesia, India, Ireland, Italy, Japan, Kenya, Korea, Lebanon, Luxembourg, Morocco, Madagascar, Mexico, Mali, Malaysia, Namibia, Netherlands, Norway, New Zealand, Pakistan, Peru, Philippines, Portugal, Romania, Rwanda, Senegal, El Salvador, Sweden, Togo, Tunisia, Tanzania, Uganda, Uruguay, United States, South Africa.

Table 1 shows the variables used in this research, as well as their averages, standard deviations, minimum and maximum levels. For the sample of 63 economies the average energy transition amounts

to 1692.84, with a standard deviation of 29678.77. The minimum is 0.0037945, which corresponds to Algeria in 2010, and the maximum is 716454, which corresponds to Bhutan in 2014. CO₂ emissions have an average of 175.4015 millions of tonnes of CO₂ equivalent (MtCO₂e), a standard deviation of 273.5918 MtCO₂e, with a minimum of emissions of -59.67761 MtCO₂ corresponding to Romania in 2019, while the maximum of CO₂ emissions is 2048.493 MtCO₂e corresponding to Mali 2021.

The Green Growth Index measures countries' performance in achieving sustainability goals, including the Sustainable Development Goals, the Paris Agreement on Climate Change, and the Biodiversity Targets, across four dimensions of green growth: Efficient and sustainable use of resources, protection of natural capital, green economic opportunities, and social inclusion. The average green growth index is 56.58479, the standard deviation is 9.157876, the minimum is 35.13 and corresponds to Pakistan in 2011, and the maximum is 74.88 and corresponds to Denmark in 2021.

Below are the results of the graphical analysis that relates the CO₂ emissions with the energy transition in the 63 countries studied in this research. Figure 1 shows the dynamics between the logarithm of the energy transition and the logarithm of CO₂ emissions for the sample analyzed in this research. A negative relationship is observed between the logarithms of these variables. An increase in the energy transition is related to the reduction of CO₂ emissions and vice versa, a decrease in the energy transition implies higher CO₂ emissions.

On the other hand, the Figure 2 shows a negative relationship between CO₂ emissions and Green Growth, an increase in CO₂ emissions has negative effects on green growth in the countries studied, while the reduction of CO₂ emissions has a passive impact on green growth in the sample countries and in the period 2010–2021.

Moreover, the Figure 3 shows the positive relationship between energy transition and green growth. An increase in the energy transition has positive effects on green growth, while a decrease in the energy transition has a negative impact on green growth in the countries under study over the period 2010–2021.

4. ECONOMETRIC SPECIFICATIONS AND EMPIRICAL RESULTS

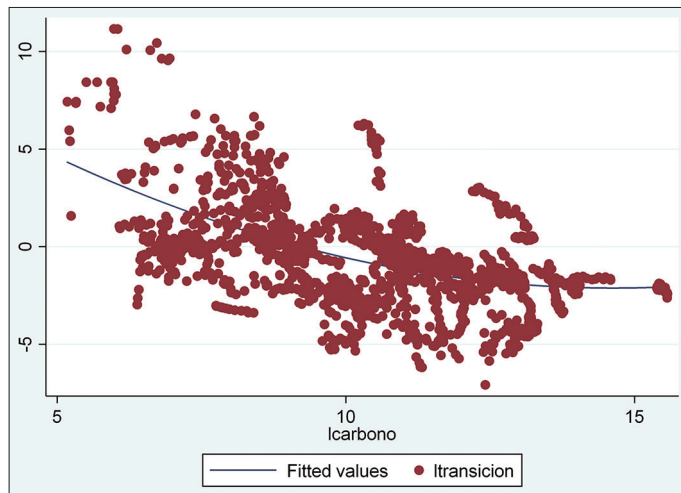
The objective of this section is to analyze the interaction among the energy transition, CO₂ emissions and green growth. To do so, we use cointegration analysis, Granger causality and estimation of panel data models (both static and dynamic) in 63 economies, in the period 2010–2021. The estimates are obtained from the statistical package Stata.

Table 1: Descriptive statistics

Variable	Notation	Average	Deviation	Minimum	Maximum
Energy Transition	Transicion	1692.84	29678.77	0.0037945	716454
CO ₂ emissions	Carbono	175.4015	273.5918	-59.67761	2048.493
Green Growth Index	ggindex	56.58479	9.157876	35.13	74.88

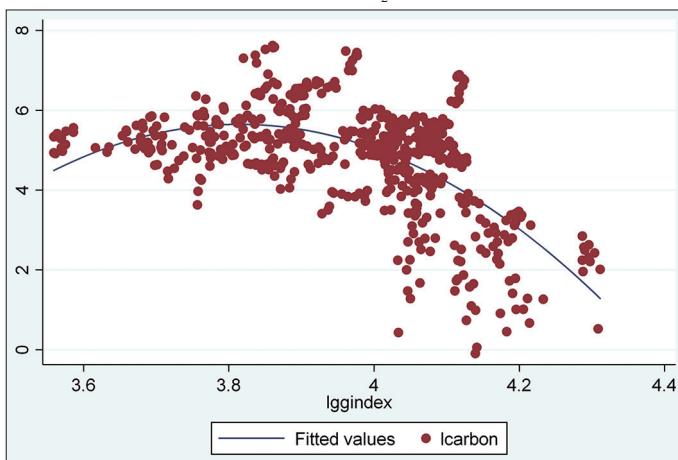
Source: Authors' own elaboration based on data from World Bank and the Global Green Growth Institute, using Stata

Figure 1: Relationship between energy transition and carbon dioxide emissions



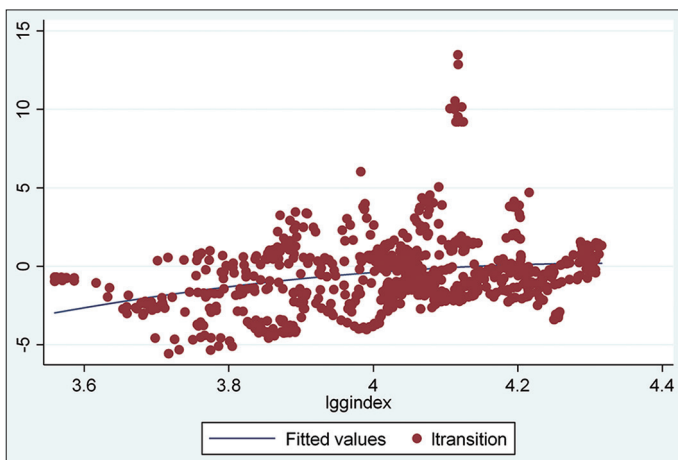
Source: Authors' own elaboration based on data from World Bank and the Global Green Growth Institute, using Stata

Figure 2: Relationship between CO₂ emissions and green growth



Source: Authors' own elaboration based on data from World Bank and the Global Green Growth Institute, using Stata

Figure 3: Relationship between energy transition and green growth



Source: Authors' own elaboration based on data from World Bank and the Global Green Growth Institute, using Stata

4.1. Cointegration Analysis

Cointegration means that even though the series are not stationary at an individual level, a linear combination of two or more time series can be stationary. This phenomenon can be conceived as the stationary difference between a pair of series. The series are cointegrated if they move together in the long term, and the differences between them are stationary or stable; cointegration reflects equilibrium over time. Moreover, if two series are cointegrated, at least one of them must cause the other. Cointegration from an economic perspective indicates that certain variables should not move too far from others in the long term. Such variables may move away in the short term, but there are market mechanisms and economic policies that tend to unite them over time.

Table 2 shows the results of cointegration between the logarithm of the energy transition and the logarithm of CO₂ emissions, for the 63 countries in the sample, in the period 2010-2021. The table indicates the relevant results of the cointegration tests. The null hypothesis consists of the non-existence of cointegration between the logarithm series of the energy transition (ltransition) and the logarithm of CO₂ emissions (lcarbono).

The augmented Dickey-Fuller statistic is associated with a P-value of 0.0053, which is <0.05, indicating that the null hypothesis of no cointegration between the series is rejected and, therefore, the logarithm of the energy transition and the logarithm of CO₂ emissions are cointegrated. The cointegration between the variables indicates the existence of long-term stability between the energy transition and CO₂ emissions, and the cointegration reveals that at least one of the variables causes the other. The cointegration results reinforce the hypothesis of our work, of the existence of causality between the energy transition and CO₂ emissions. Likewise, the logarithm of CO₂ emissions and the logarithm of the green growth index are cointegrated. In addition, the logarithm of energy transition and the logarithm of the green growth index are cointegrated. In summary, the cointegration tests show the existence of both long-term stability and causality among the energy transition, CO₂ emissions and green growth, evidence that supports the hypothesis of this research.

4.2. Causality Test and Empirical Results

Granger's (1969) causality test is a fundamental analysis to detect if past values of one variable are correlated with current values of another variable. The rejection criterion is based on detecting the statistical value of *F* and its level of significance. In this way, the null hypothesis of no causality between variables is rejected if the associated P-value is less than 0.05. On the other hand, Dumitrescu and Hurlin (2012) propose the methodology to estimate Granger causality for panel data. The authors propose a Granger (1969) non-causality test for panel data models, they use individual Wald statistics of Granger non-causality averaged across cross-sectional units, and they show that the statistic converges sequentially to a standard normal distribution. They also propose a standardized statistic based on an approximation of the moments of the Wald statistics. Below are the causality tests among the logarithms of the energy transition, CO₂ emissions and the green growth index.

Table 3 shows the causality tests between all variables of interest with one and two lags. We find important empirical results. First, the P-value associated with the null hypothesis that CO₂ emissions do not Granger-cause green growth with one lag is <0.05, indicating that the null hypothesis is rejected; therefore, CO₂ emissions Granger-cause green growth, similarly the energy transition Granger-causes green growth. Moreover, for the second lag, the null hypothesis that CO₂ emissions do not Granger-cause green growth is rejected, indicating that CO₂ emissions Granger-cause green growth. On the other hand, the energy transition Granger-causes green growth. In summary, the energy transition and the CO₂ emissions Granger-cause green growth with one and 2-year lags.

Granger causality analysis indicates that CO₂ emissions and the energy transition Granger-cause green growth, at least in the short term, with a 1-year and 2-year lag. This reinforces the research hypothesis that CO₂ emissions and the energy transition are relevant to global green growth.

4.3. Panel Data Specifications

Panel data models are becoming relevant for applied research. Panel data are a sample of characteristics that individuals (countries) have over time, that is, it is a simultaneous combination of time series and cross-sectional data. One of the models to be estimated in the present research is the Fixed Effects (FE) model:

$$y_{it} = \alpha + \beta X_{it} + u_{it} \tag{1}$$

Where y_{it} is the dependent variable, namely, green growth, which change depends on $i = 1, \dots, n$ ($n = 63$ the number of countries) and

Table 2: Cointegration test

Kao test for cointegration Series: ltransition lcarbono			
H ₀ : No cointegration	Augmented	P-value	Result
H ₁ : All panels are cointegrated	Dickey-Fuller		
		0.0053	H ₀ is rejected
Kao test for cointegration Series: lggindex lcarbono			
H ₀ : No cointegration	Augmented	0.0007	H ₀ is rejected
H ₁ : All panels are cointegrated	Dickey-Fuller		
Kao test for cointegration Series: lggindex ltransition			
H ₀ : No cointegration	Augmented	0.0126	H ₀ is rejected
H ₁ : All panels are cointegrated	Dickey-Fuller		

Source: Authors' own elaboration based on data from World Bank and the Global Green Growth Institute, using Stata

Table 3: Causality test results

Lag	Hypothesis	P-value	Observations
Lag order: 1	Carbon does not Granger-cause gindex	0.0000	H ₀ is Rejected
	Transition does not Granger-cause gindex	0.0000	H ₀ is Rejected
	Carbon does not Granger-cause gindex	0.0065	H ₀ is Rejected
Lag order: 2	Transition does not Granger-cause gindex	0.0040	H ₀ is Rejected

Source: Authors' own elaboration based on data from World Bank and the Global Green Growth Institute, using Stata.

$t = 1, \dots, T$ ($T = 12$ the number of years), X_{it} are the explanatory variables: energy transition and CO₂ emissions. The u_{it} are, as usual, random disturbances. In this case, Ordinary Least Squares (OLS) estimates will be biased, even for samples with large values of N when T is small (Nickell, 1981; Arellano and Bover, 1991). To avoid biases from estimation by OLS, the random disturbance u_{it} is divided into two parts, $u_{it} = v_i + \varepsilon_{it}$, one of which is associated to each country, v_i and the other part, ε_{it} , is a random perturbation meeting the requirements of OLS. Then, the Random Effects (RE) model has the following specification:

$$y_{it} = \alpha + \beta X_{it} + v_i + \varepsilon_{it} \tag{2}$$

On the other hand, the dynamic model that corrects autocorrelation problems in FE and RE models is given by:

$$y_{it} = \alpha y_{it-1} + \beta X_{it} + u_{it} \tag{3}$$

For the estimation of the dynamic panel data model, the Generalized Method of Moments (GMM) is used in differences in one and two stages, as well as the system GMM model in one and two stages. These methods were developed by Arellano and Bover (1995), and later included improvements made by Blundell and Bond (1998), which are used in the present research. In this case, the estimators present advantages over FE and RE, since they estimate unbiased parameters in small samples or in the presence of endogeneity. The optimal GMM estimator has the following form:

$$\hat{\theta}_{GMM} = \begin{pmatrix} \hat{\alpha}_{GMM} \\ \hat{\beta}_{GMM} \end{pmatrix} = \left[\begin{pmatrix} y_{-1}^* & x^* \end{pmatrix}' z^* V_N^{-1} z^{*'} \begin{pmatrix} y_{-1}^* \\ x^* \end{pmatrix} \right]^{-1} \begin{pmatrix} y_{-1}^* & x^* \end{pmatrix}' z^* V_N^{-1} z^{*'} y^* \tag{4}$$

Equation (4) is a system consisting of a regression that jointly contains information in levels and in differences in terms of moment conditions. For a more detailed analysis of the methodology see Arellano and Bover (1995). Additionally, for having a more robust analysis, it is important to perform the first and second order autocorrelation tests, the Sargan test of overidentification and the validity of the instruments to ensure the proper functioning of the GMM proposed by Arellano and Bond (1995) and Blundell and Bond (1998).

Table 4: Static panel data models

Dependent variable:	RE	FE
ltransition	0.0010394 (0.594)	-0.0003808 (0.845)
lcarbono	0.0097606 (0.005)	0.0168736 (0.000)
Constant	3.939356 (0.000)	3.891107 (0.000)
R ²	0.2351	0.2466
Hausman	Prob >Chi-square=0.0000	
Number of countries		63
Number of observations		596

Source: Authors' own elaboration based on data from World Bank and the Global Green Growth Institute, using Stata. Standard error in parentheses

Table 5: Dynamic panel data models

Dependent var: Lggindex	GMM Difference		GMM System	
	1 Step	2 Steps	1 Step	2 Steps
lggindex.L1	0.8540489 (0.000)	0.8576673 (0.000)	0.9038886 (0.000)	0.9076872 (0.000)
ltransition	0.0002719 (0.860)	0.0001762 (0.530)	-0.0015596 (0.199)	0.0015613 (0.000)
lcarbon	0.0011535 (0.728)	0.0009749 (0.059)	-0.0030612 (0.187)	-0.0031649 (0.000)
Constant	0.576503 (0.003)	0.5636827 (0.000)	0.3983133 (0.000)	0.3844009 (0.000)
AR (1)	--	Prob>Z = 0.0015	--	Prob>Z = 0.3639
AR (2)	--	Prob>Z = 0.3828	--	Prob>Z = 0.9244
Sargan	--	Prob>Chi-square=0.644	--	Prob>Chi-square=0.924
Number of countries			63	
Number of observations			544	

Source: Authors' own elaboration based on data from World Bank and the Global Green Growth Institute, using Stata. Standard error in parentheses.

The main purpose of this section is to build both static and dynamic panel data models that allow examining the relationship among energy transition, CO₂ emissions and green growth in 63 economies: The variables are expressed in logarithms: Lggindex is the logarithm of the green growth index, ltransition is the logarithm of the energy transition, and lcarbono is the logarithm of CO₂ emissions. The period analyzed is 2010–2021. A balanced panel is estimated using the Stata package.

Table 4 shows the results of static panel data estimates, the first column indicates that the dependent variable is the logarithm of green growth index. The explanatory variables are logarithm of CO₂ emissions and logarithm of energy transition. It also shows the constant, the coefficient of determination R², the Hausman test, the number of countries and number of observations. The best-fitting static model is the FE Model. The second column of Table 4 shows the RE model estimation which indicates a positive expected coefficient of the logarithm of the energy transition, but is not significant. Likewise, second column shows an unexpected and significant positive sign of the logarithm of CO₂ emissions. The constant is positive and significant. Finally, note that R² = 0.2351 is very low. The third column of Table 4 shows the results of the FE model estimates, in which the logarithm of energy transition has an unexpected and negative sign, but is not significant. The logarithm of CO₂ emissions has an unexpected positive sign that is significant. The constant is positive and significant, the R² is very low, 0.2466, but better than FE model. Finally, the Hausman test yields prob > Chi-square = 0.0000, indicating that the FE estimation is preferable to the RE estimation.

On the other hand, the Durbin-Watson test indicates the presence of autocorrelation in both models RE and FE. The autocorrelation problems present in static panel data models can be corrected with dynamic panel data models. Table 5 presents the main results of the estimated dynamic models. The first column shows the dependent variable, the logarithm of the green growth index, as a function of the lagged logarithm of green growth index, the logarithm of the energy transition, the logarithm of CO₂ emissions, the constant, the first and second order serial autocorrelation tests, the Sargan test, the number of countries and the number of observations. Estimates using dynamic models help mitigate the autocorrelation problems present in static models. The second column of the table shows the results of the estimation by GMM in differences in one stage, the third column presents the estimates by GMM in differences in two stages, the fourth column shows the results of the estimation

by systematic GMM in one stage, and the fifth column presents the estimates by systematic GMM in two stages.

The best fitting model in Table 5 is the model estimated by systematic GMM in two stages and it shows coefficients with the expected signs and they are significant. The first and second order autocorrelation tests reject the presence of autocorrelation problems. The Sargan test rejects the null hypothesis of over-identification, therefore the general validity of the instruments and the specification of the model are admitted. Likewise, the model estimated by system GMM in two stages shows that the lagged logarithm of the green growth index, the logarithm of the energy transition and the constant have the expected positive signs, while the logarithm of CO₂ emissions has the expected negative sign, all coefficients are significant. The estimates of dynamic panel data models indicate that the best-fitting model is the model estimated with system GMM in two-stage, indicating that a 1% increase in the energy transition implies a 0.15613%, it also indicates that a 1% increase in the energy transition implies a 0.15613% increase in green growth, while a 1% increase in CO₂ emissions implies a reduction in green growth by 0.0031649%, in the 63 countries. In summary, Empirical evidence shows that the energy transition has positive effects on green growth, while CO₂ emissions have negative effects.

5. CONCLUSION

Empirical evidence presented in this research reveal that: (1) the energy transition has a significant impact on the reduction of CO₂ emissions, (2) the energy transition has a positive impact on green growth, and (3) CO₂ emissions have negative effects on green growth in the 63 economies in the period 2010–2021.

This research initially demonstrates, through a literature review, the relevant relationship between the energy transition, CO₂ emissions, and green growth. Subsequently, graphical analysis reveals that the energy transition is negatively associated with CO₂ emissions, while the latter have negative effects on green growth, and the energy transition is positively associated with it. Furthermore, the results of the cointegration analysis among the energy transition, CO₂ emissions, and green growth reveal a stable long-term relationship between these variables.

Subsequently, dynamic panel data models estimated using the two-stage GMM system indicate that the energy transition has

a significant impact on reducing CO₂ emissions and, likewise, drives green growth, while CO₂ emissions have negative effects on green growth in the 63 countries. In summary, the interrelationship between the energy transition, CO₂ emissions, and green growth is analyzed in 63 economies between 2010 and 2021.

Based on the results of this research, it is suggested that decision-makers implement strategies and instruments to promote the energy transition, contributing to the reduction of CO₂ emissions and the increase in green growth, as well as to climate change mitigation and the promotion of sustainable development. The energy transition, the structural shift from fossil fuel-based energy systems to clean, renewable sources, is essential to green growth, as it allows for the decoupling of economic development from environmental degradation and greenhouse gas emissions. Furthermore, renewable energy enables countries to reduce their dependence on fossil fuel imports, thereby mitigating their exposure to the volatility of international prices.

One of the limitations of this research is that the time period is restricted by data availability. Future research will broaden the analytical scope with additional variables and instruments, as well as, increase the sample size.

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