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The Effects of Economic Cycle Shocks on Polluting Emissions in Developing Countries: Insights from a Panel Vector Autoregression Analysis

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Abstract: This study explores the dynamic relationship between polluting emissions and economic cycle shocks in developing countries using a panel vector autoregressive (PVAR) framework. Recognizing the limitations of prior models that focused primarily on causality between emissions and economic variables without forecasting capabilities, this research incorporates a PVAR methodology aligned with innovative local gray forecast models to generate dynamic forecasts and conduct structural analyses. Employing the PVAR model, impulse–response functions (IRFs) were analyzed to assess the impacts of economic shocks on pollution levels and the challenges these pose to both renewable and non-renewable energy sources. The analysis further involved the decomposition of variance among the variables. Key findings reveal that economic growth in these countries often correlates with increased use of carbon dioxide-emitting energies. However, the substitution of these energies with renewable sources is not only feasible but also pivotal for promoting environmental purification and sanitation through enhanced investments in renewable energies. Despite the theoretical potential for growth in the renewable sector, its actual development in these countries remains inadequate, and its contribution to fostering an ecological environment that supports economic growth is minimal. The study underscores the necessity of robust policies to facilitate ecological growth and the imperative of a shared commitment among nations to ensure the effectiveness of these policies.

Keywords: CO_2 emissions; Economic cycle; Fossil and renewable energies; Panel vector autoregression

1. Introduction

During the last three decades, an increasing amount of research on environmental quality and related concepts has been published across various bases of scientific literature. As a way of illustration, when the term “pollution” is entered into the Google Scholar search engine, it yields nearly 3,750,000 results, whereas searches associated with the term “carbon dioxide (CO_2)” yield 4,070,000 results, and those appended to the concept of “sustainable development” yield 2,790,000 results. This illustrates the central importance of ecological issues and the increased awareness on the part of governments and international institutions regarding the environmental dangers to humanity.

Over the last decade, a recurring debate, which has yet to yield universal agreement or unanimity within the scientific community, has focused on the following question: What is the nature of the relationships that can exist and be established between the economic cycle and ecological balance? Furthermore, although this question has not led to definitive answers in both “developed and developing countries,” a certain consensus has been reached on the importance and centrality of convergence and/or ecological transition, without any deadlines being announced.

This debate has been relatively old, beginning in the 1970s, when the environmental dimension started emerging as a favored field among scientists and researchers. Among the most notable works in this regard is that of

Grossman and Krueger (1991), who affirmed that economic growth remains necessary for a successful ecological transition, regardless of the source and quality of the wealth created (polluting or non-polluting or both). Thus, countries could reduce environmental damage in the long term through the channel of economic growth, as and when this growth would lead to an increase in average per capita income.

Conversely, Shafik & Bandyopadhyay (1992) critically examine the assertion of Grossman and Krueger by invalidating its linearity while considering that the beneficial impact of economic growth on ecology is not mechanical but dependent on a set of complex variables. Therefore, the question arises as to at what stage of economic development growth begins to pay attention to ecology while trying to transition to growth models that do not emit pollutants. The authors were required to answer two other important questions to answer this central question. First, whether the history of the economic growth process is based exclusively on an absolute form of intensive and extensive accumulation of physical capital or rather on the exploitation and use of natural resources. Second, if the accumulation of physical and human capital can occur only to the detriment of natural capital or whether the latter could grow and develop in the presence of the first two. These critical questions have paved the way for an abundance of literature that has focused on interdependence, which could exist between economic cycles on the one hand and the ecological dimension on the other. Literature supports the idea that any improvement in the ecological dimension passes through a path of economic growth. Indeed, with higher income, a higher demand is created for environmental quality, which pushes governments to adopt relatively more stringent measures to protect the environment. Other economists such as Selden & Song (1994) confirmed that the relationship established between growth and the quality of the ecological and environmental dimension is dynamic, which can, at a stage of "economic and social development," be both negative and positive. Thus, the relationship can be initially positive when growth comes from polluting energies. However, when the growth model is reconsidered, we can proceed to green growth scenarios with ecological and environmental implications. From there emerges a central idea that the starting point must begin with questioning the nature of the growth we aim to achieve (polluting versus ecological growth).

A consensus is growing among economists, environmentalists, and other scientific researchers that "environmental degradation" currently poses the most threatening danger to human health and life. According to Zhang & Wang (2017), ecological degradation is multidimensional. As an illustration, we can cite the pollution of the air and various water sources, deforestation and the massive exploitation of natural resources, and astronomical emissions of greenhouse gases (GHGs), contributing to critical situations previously unknown to humanity. This idea is well explained by Apergis et al. (2018) and Wang et al. (2018), who concluded that continued emissions of GHGs can only accelerate global warming, which in turn constitutes an ecological threat and a danger to well-being (public health).

In this line of thought, several other studies on the effects of humans on ecological quality have converged towards alarming results. For example, the World Wildlife Fund 2016 Report (World Wildlife Fund 2016) has demonstrated that we are depleting and overexploiting natural resources. Statistical data indicate that the current consumption of natural resources represents 160% of the resources that our planet can sustainably provide us with. Consequently, humanity consumes not only what is rightfully ours but also encroaching upon resources meant for future generations.

This idea was timid when revealed by Nicholas Georgescu-Roegen in the early 70s. However, it is gaining increasing support from activists, advocating for a healthy environment and responsible exploitation of natural resources. The scientific community also affirms a worrisome imbalance between natural resources and Earth's capacity for their regeneration (Daly, 2013; Jackson, 2009; Rockström et al., 2009).

The standard neoclassical growth model was the first to be accused because it supports a growth model, which, in its essence, is polluting. At this level, urgent solutions need to be applied, despite the multitude of constraints in their applications. The announced objective was to slowdown the acceleration of average temperature increases to stabilize, when necessary, at the level of 2°C. This objective is neither simple nor straightforward to internalize on an international scale because it is strongly linked to the interests of various countries. The Intergovernmental Panel on Climate Change (IPCC 2014) Report has long alerted the world by affirming that the sustainability and intensity of carbon emissions (generating GHGs) are the most impactful factors in continual and lasting increases in temperature, leading to climate change. Therefore, the IPCC announced a strategy to reduce global GHG emissions by 2050 by an interval ranging from 40 to 70% compared with the levels recorded in 2010. The approach and thesis presented by the IPCC are supported by numerous theoretical and empirical studies that suggest that global warming is primarily dependent on pollution and carbon emissions, such as those of CO_2 and methane (Bélaïd & Youssef, 2017; Özokcu & Özdemir, 2017).

Other studies have highlighted the ineffectiveness of international cooperation for environmental protection, noting that the laws and agreements adopted by the United Nations and the compromises promised at various Earth summits have not been implemented, thus falling short of achieving a true ecological transition. Many researchers have called for individual solutions with two-pronged national vocation owing to international inefficiencies. A political–economic component, including economic regulation of pollution, pollution tax, and disincentive to polluting investments and technologies, and a cultural component that protects and preserves ecology need to be considered as common values to be defended collectively (Cardenas et al., 2016; Moutinho et al., 2017).

However, another approach argues that although good environmental quality is a global demand, it often comes at a significant cost. This argument is based on the works of Apergis & Tang (2013) and Destek & Aslan (2017), which suggests a trade-off between ecological and economic dimensions. Therefore, any active policy aimed at improving the environment generates major challenges for governments, at least in the short and medium terms, particularly in achieving normal and sustained economic growth rates. To eliminate this trade-off and to reconcile the economy with the environment, many countries are designing ecological transitions towards a green economy, which aims to reduce carbon emissions up to the "zero net carbon emissions" threshold. Various solutions are possible to achieve this transition, including investments in renewable energies, ecological innovation, and the progressive growth limitation (a degrowth policy).

Therefore, environmental issues are particularly significant and have attracted increasing interest. Nevertheless, we noticed that most studies examined the relationship between carbon emissions as an explained variable and the vector of explanatory variables (economic growth, consumption of fossil fuels, and renewable energies) using univariate models.

Furthermore, few studies using the multivariate panel approach have demonstrated a trade-off between the effects of the economic cycle, consumption of renewable energies and fossil fuels, and their effects on "CO_2 emissions." Unlike previous studies that used traditional econometric models, herein, we used a recent econometric tool called panel vector autoregression (PVAR). Through this study, we tried to design solutions to make economic growth a cause rather than an effect of polluting emissions. In this context, we have developed this research work, which, in our view, constitutes a real contribution to the theoretical and empirical literature regarding the effects of economic growth, consumption of fossil fuels, and renewable energies on CO_2 emissions in developing countries. The choice of developed countries as the focus of our research is not arbitrary but is based on logical reasons. Most importantly, these countries are large energy consumers and their ecological transitions are difficult, allowing us to elucidate the nature of the trade-off they have established between polluting and renewable energies.

At this stage of the analysis, it is necessary to emphasize the novelty of our study, considering that it adds value to the existing literature in more than one way. First, this study attempts to address energy transition and its effects on economic growth while examining the trade-offs between the "consumption of polluting energies" and other non- or relatively less-polluting sources. Second, our research does not aim at a simple contemplation or description of the causality established between the different variables retained by the model. Instead, it moves past this static vision to a dynamicity based on strategic forecasts of the effects of production and consumption of renewable and non-renewable energies on growth while using the most appropriate model for these purposes.

Therefore, to present our work, we have subdivided it into six distinct sections. In the second section, we present a literature review on the relational interdependence between the three main variables relating to our research, i.e., economic growth, energy consumption (EC), and CO_2 emissions. The third section discusses the data and econometric methods used in this research to achieve our objective. In the fourth section, we discuss and analyze the empirical results derived from our model. The fifth section discusses the main implications of economic policies in the context of the obtained results. The sixth and final section concludes the work presented in this paper by providing new perspectives for future work.

2. Literature Review

It is necessary to divide the literature review into two separate subsections to be exhaustive and to situate our study relatively well. First, we present the primary research on the relationship between EC and economic growth. The second section focuses on the relationship between economic growth and CO_2 emissions.

2.1 Relationship Between EC and Growth

The following literature review focuses on a few relatively more significant and recent studies in this area (spanning the period from 2001 to 2022) to contextualize our study among previous works addressing similar and related research, elucidating the main themes of concern presented in these studies.

Aqeel & Butt (2001) attempted to resolve the problem of the trade-off between the economic and ecological perspective in Pakistan by examining the relational nature between economic growth and EC to determine the extent to which this relationship will affect employment. Using conventional econometric techniques, the authors showed the importance of the consumption of polluting energies as an economic engine and generator of expansion and development. This polluting economic model would persist unless an ecological strategy, backed by "political" will, could be designed for a successful ecological transition. In the same line of idea, Hondroyiannis et al. (2002) tried to address a problem similar to that investigated by AlKhars et al. (2020), involving testing, in the case of Greece, the nature of the relationship between the economic cycle and the consumption of polluting energies from 1960–1996. The results reported by the authors are consistent with those of Aqeel & Butt (2001) to the extent that the variables retained in the model are cointegrated, confirming the existence of a long-term relationship between the triad components (economic cycle, price index, and EC). The authors highlighted their results by considering them as guidelines for political decision-makers who, based on effective structural regulations, can encourage energy savings without limiting growth.

Subscribing to the same dominant logic and submitting to the same theoretical paradigm, Wesseh Jr & Zoumara (2012) tested and analyzed whether a certain causal relationship exists between EC and economic growth in the case of Liberia. The results estimated from the "bootstrap methodology" confirm a bidirectional causal relationship (using Granger causality analysis) between the variables considered. This reflects a low-income country that will remain dependent on polluting energies for a long time, and the neoclassical growth model will continue for a long time. The work of Tang et al. (2016) used Solow's neoclassical growth model to analyze the relationship between the economic cycle and consumption of polluting energies in Vietnam during the period ranging from 1971–2011. They used cointegration techniques and Granger causality analysis to determine the relational nature between the abovementioned variables. The authors reached the following two important conclusions: first, that there is a long-term equilibrium between the variables (cointegration), and second, deduced from the Granger causality test, that EC causes, in a way, univocal economic growth.

Following the same line of conduct as previous authors, Shahbaz et al. (2017) tested the effects of the consumption of polluting energies on the economic cycle in the case of India during the period extending from the first quarter of 1960 until the fourth quarter of 2015. The authors concluded that their results converged toward the findings commonly accepted and acquired by the scientific community. First, there is a long-term balance between the variables, which implies that the Indian development model based on the use of pollutants persists over time. Second, only negative shocks on EC and on financial development could affect economic growth.

Wang et al. (2019) were interested in determining the primary determinants of the consumption of polluting energies, which, according to the authors, are three in number (economic growth, prices, and urbanization). For empirical validation, the authors used a long-term time series (ranging from 1980 to 2015, covering 186 countries at different levels of development) on the abovementioned variables and classic econometric techniques, such as Granger causality tests and impulse–response functions (IRFs). As confirmed by the majority of the literature, the authors prove the existence of a long-term cointegration relationship between these determinants. Through Granger causality tests, it was shown that a direct causal link exists between the variables urbanization and consumption of polluting energies, specifically in non-rich countries, including "high and low middle-income countries." This finding can be attributed to the fact that where development is yet embryonic, these countries remain dependent on the standard neoclassical growth model based on the intensive exploitation of natural resources, which is inherently polluting. In countries where per capita income is high, this causality ceases to exist, which implies that the link between ecological pollution and growth starts to break down, suggesting that without much risk, the economic growth of a country allows it to transition smoothly to green growth. In addition, unanimously, the authors noted that a bidirectional causal relationship exists between the wealth created and EC at the level of all countries included in the sample. The IRF graphs show that urbanization does not necessarily accelerate EC.

For their part, Flores-Chamba et al. (2019) investigated how the behavior of the consumption of polluting energies is explained within the European Union (EU) framework. To answer this question, the authors designed a model whose explained variable was EC. For the explanatory variables, the authors chose a vector composed of three distinct variables, i.e., human capital, oil price, and Kyoto Protocol policy. The data extend over 17 years (2000–2016) and cover 34 countries (26 of which belong to the EU). The authors conducted panel data econometrics and performed a spatial econometric analysis using the "spatial Durbin model" to achieve this. The authors concluded that the law of demand is confirmed, stating that EC is inversely proportional to energy prices. Likewise, the accumulation of human capital adversely affects the demand for polluting energies, suggesting that the accumulation of human capital on a macro-social scale makes it possible to exert increased pressure on governments to encourage them to make a real ecological transition. This finding is consolidated by the other conclusion made by the authors, following the estimation of the spatial model, affirming that a negative relationship exists between the political variable and EC within EU countries. This result is extremely significant because it shows that ecological transition has become, in recent years, a political issue that politicians have tried to make a reality, specifically as there is a common trend at the EU level to make it a reality.

AlKhars et al. (2020) examined and analyzed past studies, which looked at the nature of the relationship that can be established between the economic cycles and consumption of polluting energies in the case of Gulf countries, i.e., Saudi Arabia, United Arab Emirates, Bahrain, Qatar, Oman, and Kuwait. The authors concluded that 13% of studies confirmed the neutrality of the effects of EC on growth, whereas 26% concluded the proportionality between EC and economic growth. Moreover, only 18% of the studies supported the growth hypothesis, whereas 43% supported the growth feedback hypothesis. The authors found strong evidence in favor of the growth model, which, in the Gulf Cooperation Council countries, has focused on ensuring a constant supply of energy to support the expansion and growth of their industrial and development activities.

Wang et al. (2022) studied the economic cycle behavior (during 1997–2015) of the Organization for Economic Cooperation and Development (OECD) countries where the growth model is based on renewable energies while assuming different possible risks, i.e., political, financial, economic, and composite. Based on the estimation of a "panel threshold model," the authors concluded that the most determining risk in economic growth is certainly the economic risk. Thus, renewable energies can positively affect economic development only when economic risk ceases to exist. This result confirms the logic inherent in the "Kuznets curve". Alshami (2023) attempted to verify the extent to which the consumption of polluting energies could affect the economic cycle in the case of the United Arab Emirates. Using a time series from 1996 to 2020, the author confirmed a positive relationship between two types of energy (renewable and non-renewable) and the economic cycle. This allows us to conclude that in the case of this country, there is a real transition from a polluting model to an economic model of an ecological nature.

2.2 Theoretical Relationship Between CO_2 Emissions, EC, and Growth

In Turkey, Ozturk & Acaravci (2010) aimed to determine whether there is long-term causality between economic growth, carbon emissions, EC, and the employment rate. The authors used the autoregressive cointegration method of distributed shift limits to resolve this problem, which allowed them to identify three essential results from a time series spreading over 38 years from 1968 to 2005. First, a long-term relationship exists between different variables at the 5% significance level. Second, carbon emissions positively affect per capita income, expressed by an income elasticity of CO_2 emissions per person of 0.606. Third, the consumption of pollutants is at the origin of an economic growth effect, expressed by an income elasticity of EC per person of 1,375.

Fei et al. (2011) studied the relationship between EC, carbon emissions, and economic growth in the case of China. The study covered a spatial horizon of 30 provinces in mainland China and a temporal horizon of 23 years (ranging from 1985 to 2007). The results from the econometric modeling implemented by the authors, i.e., the unit root panel method, heterogeneous panel cointegration, and dynamic OLS based on a panel, confirmed the existence of a long-term positive effect exerted by the economic cycle and EC. The coefficients estimated by the authors claim that a 1% increase in real gross domestic product (GDP) per capita (GDPpc) increases EC by 0.48 to 0.50%, which, in turn, will generate an increase in CO_2 emissions ranging from 0.41 to 0.43%.

Alkhathlan & Javid (2013) attempted to perform a similar work consisting of testing, in the Saudi case, whether there is an interdependent relationship between economic growth, carbon emissions, and EC. The results confirmed the results of previous studies, revealing that carbon emissions generate income increases. However, when the development model is based on gas consumption, both long- and short-term income elasticities of carbon emissions are negative. This allows us to conclude that when the Saudi economy moves from oil to gas consumption, the accompanying economic growth would allow for a reduction in carbon emissions.

Heidari et al. (2015) tested a similar causal relationship for five countries of the Association of Southeast Asian Nations (ASEAN-5), i.e., Indonesia, Malaysia, the Philippines, Singapore, and Thailand. The objective was to determine how the variables economic growth, CO_2 emissions, and EC behave in terms of causality both in the short and long term. The authors used the "panel smooth transition regression" model to achieve this. Anticipating two possible regimes, the authors concluded that, in the first regime, characterized by GDPpc levels below US dollars (USD) 4,686, environmental quality deteriorates further with economic growth. However, the situation reversed in the second regime (GDPpc greater than 4,686 USD). In addition, the authors concluded that EC, in both the first and second regimes, always generates an increase in CO_2 emissions, confirming the validity of the environmental Kuznets curve hypothesis in this group of countries.

Ozcan et al. (2019) investigated whether there were causal links between EC, economic growth, and environmental degradation in OECD countries during the period 2000 to 2013. Two main results were obtained in the study. First, in most countries (33) the Kuznets curve is verified, which implies that these countries had followed the same growth path and were subject to the same social logic of arbitration between the ecological and the economic perspectives. Second, in most countries in the sample, the covariates confirmed bidirectional causal relationships.

Munir et al. (2020) addressed the same questions as those put forth by Ozcan et al. (2019) and applied them to the case of ASEAN-5 countries using data for the period extending from 1980 to 2016. Correcting the problems associated with conventional tests by applying new "non-Granger causality" panel tests that address the dependence and heterogeneity of cross-sectional data, the authors reached different results. A unidirectional relationship between GDP and CO_2 emissions was noted for four of the five countries. In addition, the authors noticed the existence of a unidirectional relationship between GDP and EC in three of these countries. In Singapore, unidirectional causality was recorded from EC to GDP. In the Philippines, a bidirectional causality was observed between GDP and EC.

Ozcan et al. (2020) elucidated the nature of the interdependence established between the variables, i.e., EC, economic growth, and environmental degradation, to design the most effective public policies in ecological and environmental matters in the case of 35 OECD countries. To conduct this study, we spread the data over a time horizon ranging from 2000 to 2014. Two major results were obtained in this study. First, once sustained, sustainable economic growth makes it possible to rethink the ecological perspective, which is gradually beginning to take precedence over the economic dimension and changing EC patterns. Second, progressive convergence towards a true ecological transition is observed in this group of countries.

Chikezie Ekwueme et al. (2022) conducted similar research using new variables not considered in previous research. They investigated, in the case of eight Asian countries, whether a causal relationship exists between a set of variables, including economic growth, the importation of tourism, industrialization, renewable and non-renewable energies, trade openness and environmental sustainability, represented by carbon emissions. On the technical side, to test causal relationships, the authors used several techniques, including the Pooled Mean Group Autoregressive Distributive Lag model and the Granger causality analysis developed by Dumitrescu & Hurlin (2012). Among the results obtained is that in the long term, carbon emissions will be reduced following a set of variables, including the use of new clean sources of energy, economic growth, and trade openness. However, pollution is positively affected by the intensified consumption of polluting and non-reproducible energies.

3. Empirical Methodology

After having seen the different theoretical aspects in the previous sections, we considered it wise in this empirical framework to examine the quantitative interactions likely to occur between the economic growth process and the variables inherent to the consumption of different types of energy. Considering the predictive and dynamic nature of our problem, where we aimed to determine the interdependence of our variables in both static and dynamic contexts, we resorted to PVAR modeling (Öztürk et al., 2023; Wu et al., 2023; Zhang et al., 2023). Thus, this section is dedicated to measuring the effects of the current economic growth model on the ecological and environmental dimensions in a geographical area comprising 35 developing countries.

3.1 Data

Considering that our work had two essential objectives, i.e., to determine the behavior of the economic cycle following polluting CO_2 emissions and to elucidate how the economic cycle reacts to different qualities of energy, the set of variables to be retained in the model included the following: the economic cycle measured in terms of GDPpc, polluting emissions measured in quantity of CO_2, consumption of polluting energies measured in terms of per capita fossil fuel/ energy use (FEUpc), and per capita renewable energy use (REUpc). Although no previous study has used all four variables simultaneously, we were inspired by studies with approaches similar to those used in this study. As an illustration, we can cite Yi et al. (2023) (who retained economic growth, financial globalization, urbanization, consumption of fossil fuels, use of renewable energies, and their combined impact on the factor carrying capacity in Mexico); Omri & Saadaoui (2023) (who developed a model bringing together nuclear energy, economic growth, trade openness, fossil fuels, and carbon emissions); and Lotfalipour et al. (2010) (who explored economic growth, CO_2 emissions, and fossil fuel consumption in Iran).

Our study covered a sample of 35 developing countries, cited as follows: Albania, Algeria, Angola, Armenia, Bolivia, Cameroon, Congo, Ivory Coast, Egypt, Ecuador, Ethiopia, Georgia, Ghana, India, Indonesia, Iran, Iraq, Jamaica, Jordan, Morocco, Nicaragua, Nigeria, Pakistan, Philippines, Saudi Arabia, Senegal, Tajikistan, Tanzania, Togo, Tunisia, Ukraine, Yemen, Zambia, and Zimbabwe. The study period was 1990–2020. The variables were chosen from the official websites of the World Bank and the International Energy Agency to establish our database.

3.1.1 Statistical description of variables

As shown in Table 1, the average CO_2 emissions during 1990–2020 were 1,487.625 kg, with a minimum of 16.313 kg and a maximum of 1,3270.4 kg. The average GDPpc was 2,133.06 USD (constant 2015). Regarding FEU, the average value was 510.44 kg of oil equivalent per capita. The average value of REU is 224.5358 kg of oil equivalent per capita, which is extremely low.

Table 1. Descriptive statistics of variables

Variable	Observations	Mean	Stand Deviation	Min	Max
CO_2pc	1,085	1,487.625	1,664.631	16.313	13,270.4
GDPpc	1,085	2,133.06	1,382.204	218.102	6,218.24
FEUpc	1,085	5,10.44	652.505	4.918	4,825.07
REUpc	1,085	2,24.5358	169.8025	.83	776.343

Abbreviations: CO_2pc, per capita carbon dioxide emissions; GDPpc, per capita gross domestic product; FEUpc, per capita fossil fuel/ energy use; REUpc, per capita renewable energy use.

3.1.2 Correlation matrix

We first ensured the absence of possible multicollinearity between the explanatory variables to estimate the model accurately. As we were working on the economic growth and environmental quality variables in developing countries, it was necessary to carry out certain tests to arrive at credible estimates. The results of the variable correlation matrix are shown in Table 2.

Table 2. Correlation matrix between variables from developed countries

Variables	CO_2pc	GDPpc	REUpc	FEUpc
CO_2pc	1.0000			
GDPpc	0.6357	1.0000		
REUpc	−0.5204	−0.4835	1.0000	
FEUpc	0.6806	0.5697	−0.5127	1.0000

Abbreviations: CO_2pc, per capita carbon dioxide emissions; GDPpc, per capita gross domestic product; FEUpc, per capita fossil fuel/ energy use; REUpc, per capita renewable energy use.

As shown in Table 2, the levels of correlation between the different variables in our study were extremely low, being less than 0.7 (limit drawn by Kervin (1992). This result allowed us to conclude that, on average, we did not have a multicollinearity problem.

3.2 PVAR Specification

This section describes the use of the PVAR method, initially conceived by Love & Zicchino (2006), to detect and compute the possible effects of economic cycles and energy use on the ecological dimension. Formally, the method enabled us to model the endogenous relationship assumed between the variables "growth in annual GDP, CO_2 emissions, and energy use." We formalized the PVAR model using the following specification:

$$Z_{it} = \alpha_{it} + \Gamma(L)Z_{it} + \mu_i + d_{cit} + \varepsilon_{it} \tag{1}$$

where, Z_{it} is the column vector of the four stationary variables. It should be noted that the source variables chosen for this econometric study are growth in real GDPpc, use of fossil fuels (FEUpc), use of renewable energies (REUpc), and CO_2 emissions (CO_2pc).

μ_i is a vector of individual-specific effects (of countries) introduced to capture country heterogeneity, d_{cit} is a country-specific temporal dummy variable intended to measure shocks that affect all countries uniformly in a given year, and ε_{it} is an idiosyncratic error vector.

We used *i* as the country index and *t* as the time index, whereas $\Gamma(L)$ is a lag operator in the polynomial matrix form with the following functional form:

$$\Gamma(L) = \Gamma_1 L^1 + \Gamma_2 L^2 + \cdots + \Gamma_p L^p \tag{2}$$

Therefore, our methodology consisted of first studying the stationarity of the three variables. It is appropriate for the stationarity test to use two generations of unit root tests on panel data, where the first generation assumes of independence between individuals and the second generation integrates various possible forms of inter-individual dependencies. These two generations of tests were used in this study. Based on the work of Love & Zicchino (2006), the second step involved transforming the initial model, and this was performed using "direct mean differentiation" or the "Helmert's procedure." In the context of panel data, it is necessary to emphasize that the application of the vector autoregression (VAR) model requires and imposes restrictions to ensure the homogeneity of the model structure for all individuals at any time.

It is plausible to introduce fixed effects into the model to address heterogeneity issues that may arise. According to Antonakakis et al. (2016), resorting to the conventional "mean difference" procedure to counteract and eliminate fixed effects is not invariably without risk because it can generate biased coefficients as long as said fixed effects are dependent on the regressors, and this is because of the shifts in the dependent variables. Helmert's procedure (Arellano & Bover, 1995) allowed us to avoid this problem. We used a procedure of differentiation based on Helmert's future observations to verify the specific individual and temporal effects and remedy the problem of the endogeneity of variables. It consisted of using the unobservable, specific effects of each individual and instrumenting the delayed exogenous variables.

The PVAR model offers several advantages. Among them, there are two main advantages. The first advantage involves considering the common temporal effects introduced into the model to capture the aggregated macroeconomic shocks specific to a country, but which, in turn, could influence the other individual countries retained in the model indifferently. Following Charfeddine & Kahia (2019), to treat the temporal effects, we distinguished all the variables before their introduction into the model, and these variables corresponded to the implementation of dummy variables in the system. Another advantage of the PVAR approach, as confirmed by Antonakakis et al. (2016), is its power and relative sensitivity to measure and highlight the effects of any shock exerted by one variable on another while subjecting to the "*ceteris paribus*" condition, i.e., without touching the other variables. This step was performed using IRFs, which allow us to visualize the binary effects that can take place between two variables without affecting the others. The results describe the reaction/ response of a variable to an action (shock) due to another variable in the system while maintaining the other variables unchanged.

The decomposition of the variance over a given period allowed us to determine the portion (part) of the variation of a variable of the system explained by another variable. We used the Cholesky variance decomposition method, which allowed us to isolate part of the variance of a certain variable of the system, explained by another variable, all other parameters being equal. We report the cumulative effect over 10 years; however, longer horizons (20 years) provide equivalent results (Love & Zicchino, 2006).

3.3 Unit Root Tests

Before estimating the model, it was necessary to begin with the stationarity variables. This process passes through unit root tests covering two generations. The first-generation tests, including those proposed by Levin & Lin (1992), Levin & Lin (1993), Levin et al. (2002), Im et al. (1997), Maddala & Wu (1999), and Hadri (2000) are characterized by independence in cross-section. Thus, independence exists among the individuals. The tests of this generation formulate the hypothesis that individuals inside the panels are distributed independently. The second-generation tests, including those proposed by Pesaran (2007), Moon & Perron (2004), Bai & Ng (2002), Bai & Ng (2004), Chang (2002), and Carrion-i-Silvestre et al. (2005), recognize the presence of cross-sectional addiction. Thus, there is dependence between individuals, where the tests of this generation formulate the hypothesis that individuals inside the panels are distributed in a dependent manner (Barbieri, 2009).

Therefore, among the different unit root tests presented here, we used those formulated by Levin et al. (2002), the Augmented Dickey–Fuller (ADF) tests (Dickey & Fuller, 1979) and the Philips–Perron–Fisher (Phillips & Perron, 1988) (Fisher–PP) tests. Table 3 summarizes the results of the stationarity tests.

Table 3. Stationarity tests of panel data from developed countries

Variables	LLC-Test		Fisher-ADF Test		Fisher-PP Test	
	Statistics	Prob	Statistics	Prob	Statistics	Prob
Stationarity in Level						
lnCO_2pc	−4.4122	0.0000	96.5481	0.0195	82.9234	0.1385
lnGDPpc	−2.0232	0.0215	48.8245	0.9746	34.3355	0.9999
lnFEUpc	2.4808	0.0066	83.2652	0.1329	53.6343	0.9266
lnREUpc	2.0701	0.9808	40.7902	0.9980	39.4163	0.9988
Stationarity in the First Difference						
lnCO_2pc	−4.4122	0.0000	406.7603	0.0000	702.1050	0.000
lnGDPpc	−2.0232	0.0215	352.7494	0.0000	427.9856	0.000
lnFEUpc	2.4808	0.0066	440.9373	0.0000	861.0303	0.0000
lnREUpc	2.0701	0.9808	347.8307	0.0000	844.7767	0.0000

Source: Authors' calculations based on the appropriate test. Abbreviations: LLC-test, Levin–Lin–Chu test; ADF, Augmented Dickey–Fuller; Fisher-PP, Philips–Perron–Fisher; CO_2pc, per capita carbon dioxide emissions; GDPpc, per capita gross domestic product; FEUpc, per capita fossil fuel/ energy use; REUpc, per capita renewable energy use. ln denotes the natural logarithm.

The stationarity tests that we developed before starting the estimation of our model allowed us to affirm that the variables lnCO_2pc, lnREUpc, and lnFEUpc exhibited p-values greater than 5% for the Levin–Lin–Chu (LLC) tests (Levin et al., 2002) and the ADF and Fisher–PP tests. The lnGDPpc variable had p-values below 5% for the LLC tests (2002) and ADF tests. The LLC tests (2002) and ADF and Fisher–PP tests of these variables in the first difference had p-values of less than 5%. This allowed us to state that all the variables are stationary in the first difference.

3.4 Cointegration Test

The panel cointegration tests of Pedroni (2004) were performed for panel data of developing countries to highlight the cointegration relationship and refer to the results of the panel unit root test, and the results are presented in Table 4.

The test results presented in Table 4 led to acceptance of the null hypothesis, stipulating the absence of a cointegration relationship between the model variables at the 5% significance level. Therefore, we conclude that the model variables did not maintain long-term relationships.

Table 4. Pedroni's cointegration test

Statistics and Probability of the Test	MPP-stat	PP-stat	ADF-stat
Statistics	1.3520	−1.3209	−1.0323
Probability	0.0882	0.0933	0.1510

Abbreviations: MPP-stat, Modified Phillips–Perron test; PP-stat, Phillips–Perron test; ADF-stat: Augmented Dickey–Fuller test.

3.5 Determination of VAR Order

It is necessary to estimate the multi-VAR processes for lags of order one to four to determine the order of integration leading to the stationary tests of the covariance of the VAR process. In addition, it is recommended to use three information criteria, i.e., the Akaike Information Criterion (AIC), Schwarz Information Criterion (SIC), and Hannan–Quinn Information Criterion, to converge to the optimal autoregression order for each model. We resorted to SIC, which is generally recommended when the sample is relatively large and corresponds exactly to our case, instead of AIC to determine the optimal model. The results are summarized in Table 5.

Table 5. Determination of VAR order

Lag		J	J *p*-value	AIC	Schwarz Information Criterion	Hannan–Quinn Information Criterion
1	0.7166	55.92852	0.2016555	−269.2342	−40.07148	−127.7315
2	0.7349074	28.81769	0.6284058	−187.9575	−35.18231	−93.62229
3	0.7552227	19.62254	0.2377044	−88.76504	−12.37746	−41.59746
4	0.3977221	…..	…	…	…	…

The first-order PVAR had the smallest modeled SIC, modeled AIC (MAIC), and modeled Hannan–Quinn Information Criterion. To avoid over-identification issues associated with using the Hansen test at the 5% threshold, which could bias the specification in the model, we retained only the third order of PVAR, having the lowest J statistic and the lowest MAIC.

4. Results and Discussion

In this section, we present the results obtained for testing the response of environmental quality to an economic growth shock in developing countries and discuss the implications of these results. We evaluated the effects of economic growth on environmental quality by modeling the endogenous behavior between the four variables, i.e., CO_2pc, GDPpc, FEUpc, and REUpc. This required the use of PVAR modeling. The choice of this technique is justified by the fact that PVAR modeling is a simultaneous combination of two distinct approaches. The first is the so-called classic approach of the basic VAR model, which considers each variable as an explained variable, whereas the second uses panel data. Likewise, compared with other panel data processing techniques, the PVAR technique allows for proper management of the unobservable characteristics of different individuals (introducing fixed effects) at the origin of the heterogeneity that affects variable differences. This heterogeneity could have improved the efficiency of the estimates. Our empirical analysis comprised the following three steps:

1. Estimation of the PVAR model.
2. Estimation of IRFs, which allow for the detection of the impact of an economic growth shock on CO_2 emissions and other variables having a direct relationship with economic growth, as well as with the quality of the environment, and are related to fossil energies and renewable energies.
3. Using the variance decomposition method to quantify the contribution of economic growth and fossil and renewable energies in investments and CO_2 emissions.

4.1 Estimation of the Model Using the GMM Method

The estimation of our model allowed us to obtain the results presented in Table 6.

Table 6 presents a critical set of results. First, 13 coefficients were statistically significant at the 1, 5, and 10% thresholds. Second, when the variable D ($\ln CO_2pc_t$) was chosen as the explained variable, the coefficient of D($\ln GDPpc_{t-1}$) was positive and significant at the 1% level, which implies that the increasing model is primarily dependent on past and present carbon emissions. The coefficients of variables D (ln $FEUpc_{t-1}$) and D ($\ln FEUpc_{t-2}$) were positive and statistically significant at the 5 and 10% thresholds, respectively. This seems normal, considering that we continue to produce fossil energy as much as it contributes to strengthening the standard economic model based on environmental pollution. Third, when D (ln $REUpc_t$) was chosen as an independent variable, we noticed that D ($\ln GDPpc_{t-1}$) and D ($inkpo_{t-2}$) were positive and negative, respectively, at a threshold of 10%. This implies that growth lagged by two years adversely affects the use of renewable energies, as indicated by the associated coefficient (−0.7). This finding indicates that the source of growth was polluting energies, with no contribution from renewable energies to economic growth. However, the effects of growth lagged by one year were positive and significant, implying that in the previous year, increases in wealth stimulated significantly increased consumption and use of renewable energy. Therefore, the factor that explains the need to transition to a green economy (with an ecological vocation) is undoubtedly growth or the economic cycle.

Table 6. PVAR model estimation of panel data of developed countries

	Independent Variables			
Response to	**(lnGDPpc $_t$)**	**D (ln CO_2pc $_t$)**	**D (lnFEUpc $_t$)**	**D (ln REUpc $_t$)**
D (lnGDPpc $_{t-1}$)	0.5534281*** (.1260971)	0.3723955*** (0.1262768)	0.1962837* (0.1156935)	0.6969924* (0.3923589)
D (lnGDPpc $_{t-2}$)	0.1567984*** (.0570636)	−0.0729067 (0.1238607)	0.0660672 (0.1021636)	−0.7448858* (0.4226474)
D (lnGDPpc $_{t-3}$)	−0.0061175 (0.0458366)	0.081444 (0.0973684)	0.0667487 (0.1129273)	−0.0094035 (0.1404641)
D (lnCO_2pc $_{t-1}$)	−0.036162 (0.04407)	−0.0868988 (0.1055121)	0.1099082 (0.0789378)	0.0565613 (0.2327144)
D (lnCO_2pc $_{t-2}$)	−0.0378498 (0.0234991)	−.1676221** (0.0740722)	−0.1678035*** (0.0622923)	−0.1258149 (0.2320068)
D (lnCO_2pc $_{t-3}$)	−0.0020148 (0.0152352)	0.0468726 (0.0804334)	0.0711542 (0.0768858)	−0.2847164 (0.1837926)
D (lnFEUpc $_{t-1}$)	0.0624854 (0.0457824)	0.1787929* (0.0964097)	0.0109947 (0.0704307)	−0.1705612* (0.1011141)
D (lnFEUpc $_{t-2}$	0.0041302 (0.0207758)	0.1588047** (0.0655667)	0.1172585* (0.0629156)	0.0192235 (0.039473)
D (lnFEUpc $_{t-3}$)	0.0123056 (0.0162932)	−0.0539107 (0.0874852)	−0.0775412 (0.0815652)	0.0850324* (0.0477592)
D (lnREUpc $_{t-1}$)	−0.0120003 (0.0165554)	−0.0035468 (0.0342569)	−0.0109155 (0.0251564)	0.0571307 (0.0746584)
D (lnREUpc $_{t-2}$)	−0.002597 (0.0153167)	−0.0283251 (0.0307304)	−0.0136317 (0.0210752)	−0.0465255 (0.046606)
D (lnREUpc $_{t-3}$)	0.0116031 (0.0111628)	0.0183219 (0.0235613)	0.025797 (0.024315)	−0.04653 (0.06237)

Note: ***, **, and * indicate significance at 1, 5, and 10%. D (.) denotes the first difference, and ln denotes the natural logarithm.

To assess the interactions between the annual growth of real GDPpc, the growth of FEU, REU, and CO_2 emissions in developing countries, we used the IRF of the PVAR model. This function was used to analyze the dynamic relationships between the four variables in our model. Consequently, it is appropriate to analyze the effects of GDP-based economic growth shocks using the IRF to capture the reactions of the use of fossil fuels, renewables, and CO_2 emissions (Figure 1).

4.1.1 Effects of GDPpc growth shocks on CO_2 emissions

An immediate observation is that there is an instantaneous positive response in CO_2 emissions, following a shock generated by the growth in real GDPpc during the first and second years (Ahmad et al., 2021; Zhu et al., 2021). This response diminished slightly after the second year and slowly faded by the end of the seventh year. In the long term, there is a trend toward a decrease in polluting emissions, which confirms that the studied group of countries is in the last phase of the Kuznets curve, implying a real ecological transition and perhaps a certain mutation to the degrowth model.

4.1.2 Effects of GDPpc growth shocks on FEU

Notably, a positive shock to per capita growth will have a positive and significant effect on FEU. Thus, to grow, the countries included in our sample need to extract relatively more energy and consequently pollute more. This confirms that developing countries are far from transitioning toward an ecological and continuous growth model along the neoclassical growth path. However, this preliminary response started diminishing subsequently and was neutralized after 6 years. To situate this result in relation to those reported in previous studies, we can deduce without much risk that our results do not generate unanimity.

4.1.3 Effects of FEU shocks on REU

The results indicate that during a shock from renewable energies, the growth in fossil EC reacts negatively, implying that as long as non-polluting energy substitutes are exploited for intermediate or final consumption, the use of polluting energy decreases. However, the effects of such a shock, reaching their maximum in the first year with a value equal to −0.18, began to decrease subsequently, becoming slightly neutralized. Consequently, the neutrality of such shocks can be analyzed in the medium and long term by considering that the most fragmented reality is that the growth model based on polluting energies will persist in the long term. This may encourage us to ask ourselves certain questions, the most important of which is, “Can we consider all calls for a world with zero carbon emissions to be only a myth?”

4.1.4 Effects of REU shocks on CO_2 emissions

As economic theory confirms, we noted that following a positive shock to renewable energies, there was an instantaneous negative response in CO_2 emissions during the first and second years. This response had a value of −0.025, which decreased slightly and was slowly neutralized at the end of the third year. From then on, any investment in renewable energies can only reduce carbon emissions and promote ecology. Nevertheless, the problem raised is that this orientation is only ephemeral and ceases to continue. This can be attributed to the complexity and relative cost of the energy transition, particularly in developing countries, which prevent them from focusing on ecological growth in the short and medium terms.

Figure 1 traces the IRF. The extreme curves of all these graphs in (red color) represent the confidence intervals at the 95% level.

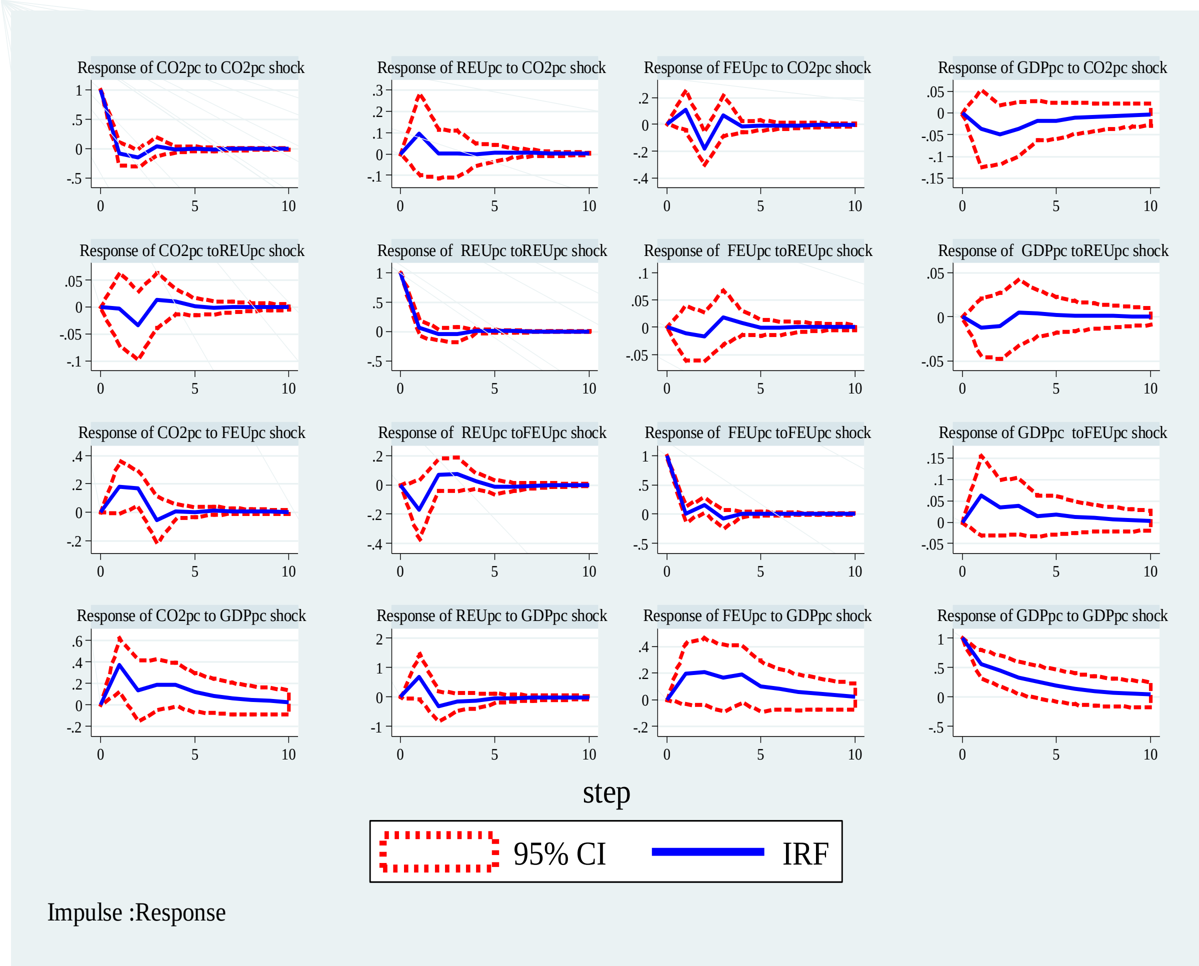

Figure 1. Graphs of IRFs

4.2 Variance Decomposition Analysis

Table 7. Variance decomposition of the PVAR model (%)

Response Variables	Impulse Variables			
	D(ln$GDPpc_t$)	D(ln$FEUpc_t$)	D(ln$REUpc_t$)	D(lnCO_2pc_t)
D(ln$GDPpc_t$)	98,730	0,444	0,099	0,727
D(ln$FEUpc_t$)	5,702	92,340	0,096	1,862
D(ln$REUpc_t$)	6,996	1,942	90,833	0,229
D(lnCO_2pc_t)	10,007	48,783	1,643	39,567

Notes: Results are based on orthogonalized impulse responses. The variation in the column variable, 10 periods ahead, can be explained based on the row variable. D(.) denotes the initial difference.

It needs to be noted that the "decomposition of the forecast error variance" allows us to take advantage of the possibility of determining how much each shock contributes to the percentage error variance. We used the

Cholesky variance decomposition method, the results of which are presented in Table 7, to describe the breakdown of the accumulated variance over a 10-year horizon. The variance in the row variables can be partly explained based on the column variables. This method allowed us to isolate part of the variance of a certain variable of the system explained by another variable, all other parameters being equal.

In this study, we use this decomposition method to measure the relative magnitude of the shock to the annual growth rate of real GDPpc in developing countries on CO_2 emissions, fossil fuel consumption, and the use of renewable energies. As shown in Table 7, the levels of CO_2 emissions are slightly impacted by variations in economic growth. The shock on this variable contributes up to 10.007% toward the variance in the growth in CO_2 emissions over the following 10-year period. This result indicates the importance of economic growth in the variation in CO_2 emissions in developing countries. The variance decomposition shows that GDP growth contributes to approximately 5.702% of the variation in the consumption of fossil fuels, which is the origin of the emissions of CO_2. Based on this variance decomposition, GDP growth contributes to approximately 6.996% of the variations in the consumption of renewable energy. We also noted that in developing countries, the shock to the consumption of fossil fuels contributes up to 48.783% of the variance in the growth of CO_2 emissions over a 10-year horizon. Concerning the consumption of renewable energies, we noted that it contributes to approximately 0.099% of the variations in economic growth and 1.643% in CO_2 emissions. This clearly shows that renewable energies remain far from being the real source that could establish a new growth model as an alternative to the standard one. Once again, developing countries are far from the target and lack the financial means to ensure an energy transition. Thus, these countries are in the first phase of the Kuznets curve.

5. Conclusion

In conclusion, the present study has allowed us to converge to one whole reality, i.e., it is the actual time for the sample of countries chosen in our study to move toward a new ecological model. Based on this major observation, four other results emerged. The first result is the unanimous confirmation of the positive relationship between the GDPpc growth variable and the CO_2 emissions and the use of fossil fuels. The use and recourse to renewable energies have adversely affected CO_2 emissions, which can be considered a reasonable indicator of the possibility to improve the quality of environments in the studied countries through investments in green technologies to promote the “renewable energy” sector. This result is intended to be reinforced by the negative and significant impact that renewable energies have had on fossil fuels, implying that an increase in the consumption of “renewable energies” reduces the consumption of fossil fuels.

Using the IRF, we can readily see that, following economic growth shocks, CO_2 emissions suffered an instantly positive effect during the first and second years. This effect gradually diminished after the second year and was subsequently neutralized at the end of the seventh year. Similarly, a positive shock to real GDPpc growth generates a slightly instantaneous positive response to FEU. This response decreased slightly and faded by the end of the fourth year. These reactions show that the growth model in these countries continues to be dominated by polluting emissions and that the transition to cleaner models remains far away. Concerning the use of renewable energy, the results show that a shock exerted on them generates an instantaneous negative response in CO_2 emissions. This response diminished slightly and slowly faded by the end of the third year. Finally, an analysis of the decomposition of variance accumulated over a 10-year horizon highlights the following key points presented below.

The growth of GDPpc contributes 10.007% to the variance in the growth of CO_2 emissions over a 10-year horizon. This result indicates the importance of “economic growth” in the variation of CO_2 emissions in developing countries.

In addition, the growth of “GDPpc” contributes to approximately 5.702% of the variations in the use of fossil fuels, which can be considered a crucial source of “CO_2 emissions.” Finally, the variations in the use of renewable energies contribute to a small proportion of the variations in “economic growth,” i.e., 0.099%, and only 1.643% of the variations in “CO_2 emissions.” This leads us to deduce that the contribution of the “renewable energy” sector to the process of “economic growth” remains, until now, insignificant and extremely timid. Consequently, as long as there is no desire to move toward ecological growth in a pure and simple sense, the current dominant logic is far from giving way to environmentally friendly substitutes. These findings are reinforced and consolidated when we note that, in the case of our sample, the shock on the consumption of fossil fuels contributes 48.783% to the variance in the growth of CO_2 emissions over 10 years.

5.1 Political Implications

Based on the diverse results obtained, we noticed that the transition to ecological models remains variable from one country to another, despite the growing collective awareness of its importance. However, although public will is growing, reality is often different and does not reflect the dominant international discourse. Thus, it becomes relatively more important to follow the logic of degrowth based on distribution rather than production. This perspective has been acknowledged since 1986 by Amartya Sen, who affirmed that the Indian famine of the 1960s could not be attributed to a shortage of foodstuffs but rather to inadequate distribution. Therefore, investments in renewable energy following the principle of comparative advantages are crucial to succeeding in the energy transition. Likewise, international cooperation is required to help low-income countries succeed in their transition.

5.2 Limitations and Future Recommendations

Despite the advantages of this study and its effectiveness in enriching the literature focusing on similar issues, certain limitations exist. The first is the relative weakness of the retained variables, which could have been broadened by introducing certain control variables that could have further explained the questions raised. The second limitation is the heterogeneity of the sample, which can neutralize certain effects, even though they are real and influential. Relying on the various results obtained in this study, we recommend, in subsequent research, that researchers place much more emphasis on the question of degrowth, which represents a thorough and advanced stage of energy transition and carbon neutrality.

Improving the quality of the environment without reducing economic growth is an elusive goal for all countries. It is clear that behind this economic growth, there is a deterioration in the quality of the environment and environmental and social injustice. Certainly, the GDP indicator ceases to be synonymous with well-being, and other relatively more representative indicators are needed. Reduction in growth and CO_2 emissions only in developed countries, as claimed by the proponents of degrowth, will not be able to solve the problem as more than two-thirds of GHG emissions are caused by developing countries. The problem of environmental deterioration is global and cannot be solved by one country or a group of countries but through the combined efforts of the entire international community, which must slow down or perish.

Author Contributions

Zaher Abdulrahim Meshari: Writing – original draft, Formal analysis, Data curation, Conceptualization. Issaoui Fakhri: Formal analysis, Data curation. Majed Bin Othayman: Methodology, Formal analysis. Guesmi Mourad: Writing – original draft, Formal analysis, Data curation. Akram Jamee: Writing – review & editing, Data curation.

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Data availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflict of interest

The authors declare that they have no conflicts of interest.

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