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Abstract

This study aims to establish a comprehensive linkage between CO2 emissions and the composition of energy sources, economic growth, and reforestation, thereby shedding light on their intricate connections in Colombia over the period 1970-2018. First, we use different types of energy consumption including non-renewable, renewable, and hydroelectric sources. As expected, our findings reveal a noteworthy effect of non-renewable sources that lead to increased emissions, while renewable sources help mitigate those emissions. Second, the preservation of forested areas plays a crucial role in mitigating CO2 emissions. Third, the agricultural sector significantly contributes to the rise in emissions, encompassing both crops and livestock, a characteristic often observed in emerging economies. Moreover, in the long-run equilibrium, we find real GDP show the characteristic inverted U-shaped pattern commonly linked with the Environmental Kuznets Curve (EKC) hypothesis.

JEL codes: C33, Q53, Q56, E20, Q20

keywords: CO2 emissions, Environmental Kuznets Curve, Renewable energy, Energy consumption, FMOLS

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Conectando los puntos: energía renovable, crecimiento económico, reforestación y emisiones de gases de efecto invernadero en Colombia

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Resumen

Este estudio tiene como objetivo establecer los vínculos y las relaciones de largo plazo entre las emisiones de CO2 y la composición de las fuentes de energía, el crecimiento económico y la reforestación para Colombia durante el período 1970-2018. Primero, usamos diferentes tipos de consumo de energía, incluyendo aquellas fuentes no renovables, renovables e hidroeléctricas. Nuestros hallazgos sugieren, como se esperaba, que hay un efecto significativo de las fuentes no renovables asociado al incremento de las emisiones, mientras que aquellas fuentes renovables ayudan a mitigar dichas emisiones. Segundo, encontramos que la reforestación juega un papel crucial en la mitigación de las emisiones de CO2. Tercero, el sector agrícola contribuye significativamente al aumento de las emisiones (cultivos y ganadería), lo cual es una característica que se observa frecuentemente en las economías emergentes. Adicionalmente, en el equilibrio a largo plazo, encontramos que el PIB real muestra el patrón característico en forma de U invertida comúnmente relacionado con la hipótesis de la curva ambiental de Kuznets (EKC).

Clasificación JEL: C33, Q53, Q56, E20.

Palabras clave: Emisiones de CO2, Hipótesis de la Curva de Kuznets Ambiental, Energía renovable, Consumo de energía, FMOLS

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1. Introduction

Without a doubt, one of the most significant challenges that humanity will face in this century is the fight against climate change in an economic setting in which economic development and environmental preservation must be balanced. Recently, this debate has been in the spotlight due to the worsening environmental quality and the effects of Green House Gas (GHG) emissions on global warming and climate change.According to the Intergovernmental Panel on Climate Change (IPCC (2021)), the global surface temperature was 1.09°C higher in 2011–2020 than 1850–1900,[1] and atmospheric concentrations have increased since 2011 which are reaching annual averages of 410 ppm for carbon dioxide (CO2), 1866 ppb for methane (CH4), and 332 ppb for nitrous oxide (N2O) in 2019.[2] On the report of World Meteorological Organization (WMO), these values constitute, respectively, 149%, 262% and 123% of pre-industrial levels.

Some agreements have already been presented on the political agenda of nations. For instance, the Paris Agreement in 2015 set out an ambitious framework to limit: i) the global temperature increase to 1.5°C and 2°C and ii) greenhouse gas emissions from human activity at net zero[3] between 2050 and 2100. Into this agreement, Colombia committed to reducing its emissions by 20% about those projected by 2030 in the baseline scenario, and up to 30% with appropriate international funding support.[4] Furthermore, the United Nations Framework Convention on Climate Change (UNFCCC) has become a frame of reference for the climate change agenda by completing the Paris Agreement's rulebook bringing together the main actors and coordinating consensus such as the Glasgow climate pact.[5]

Despite the growing recognition of climate change as a critical global issue, recent data suggests that the efforts to address it have been inadequate. Lamb et al. (2021) state that based on current trends, the progress of decarbonization is limited and conclude that the main doubt about that change is related to how rapid technological transitions, demand management, and alternative economic models could be implemented to mitigate the persistent and powerful upward drivers of global emissions. In this line, Höhne et al. (2020) draw attention to the possibility that the Paris targets are in jeopardy and point out that new climate plans have been insufficient in many countries and GHG emissions raised by 14% between 2008 and 2018. The latter implies a more significant adjustment than previously projected in Paris agreement because cumulative emissions determine the long-term temperature increase. Likewise, the authors also mention that the commitments to be acquired could have been underestimated due to a lag in knowledge about climate change and its socio-economic impacts at the beginning of the earliest 2000.

The Economist Intelligence Unit (EIU) estimates the costs related to global warming at US$ 7.9 trillion if mitigation policies are not implemented, which implies the world Gross Domestic Product (GDP) economy will be 3% smaller in 2050.[6] According to the EIU's framework, Africa and Latin America are the least resilient region to the impact of climate change by losing 4.7% and 3.8% of their GDP. On the contrary, North America (1.1%) and Western Europe (1.7%) would present the smallest losses. Although the income level mainly explains those results, EIU stands out in the relevance of institutional quality as a key factor in minimizing the impacts of climate change. Dellink et al. (2019) project GDP losses between 1.0% to 3.3% by 2060 in scenarios where impacts on labor productivity and agriculture are projected to have the largest negative economic consequences. In addition, the authors find that countries in higher latitudes could benefit from activities such as tourism, energy, and health as a consequence of balance damages in other regions; overall, damages in those sectors are small from a global perspective. Similarly, Kompas et al. (2018) estimate that the world economy would experience losses of US$9593.71 billion (3% of 2100 GDP).

Given the above, the increasing concern about reducing GHG emissions and its relationship with climate change is unquestionable, thus in the last decade, a plethora of literature seeks to improve knowledge, quantify and have a better understanding of climate changes physical damages as well as the economic impacts of global warming. In this line, Mardani et al. (2019) review 175 studies that deal with CO2 and economic growth during the recent two decades and analyze the methodologies and results of each article by using qualitative systematic and meta analysis methods (PRISMA). As a result, the authors conclude that the nexus between CO2 emissions and economic growth provides relevant reasons for implementing policy strategies that aim to reduce emissions by forcing limits on some economic production as well as by boosting the use of clean technologies.

Based on the survey conducted by Mardani et al. (2019), we can divide the literature about GHG emissions and its determinants into four groups: i) those who study the impact of economic growth on C02 emissions (Bengochea-Morancho et al. (2001), Narayan & Narayan (2010), Apergis (2016)), ii) those who explore the relationship between CO2 emissions, energy and economic growth (Ang (2007), Apergis & Payne (2009), Pao & Tsai (2010), Doğan & Değer (2018), Salari et al. (2021)), iii) studies evaluating the role of renewable energies (Bengochea &

[1]The period 1850–1900 is used as an approximation for pre-industrial conditions by the Intergovernmental Panel on Climate Change.

[2]ppm = the number of molecules of the gas per million (10^6) molecules of dry air, ppb = the number of molecules of the gas per billion (10^9) molecules of dry air

[3]The same levels that trees, soil and oceans can absorb naturally.

[4]However, in 2020, the Colombian government submitted its National Determined Contribution (NDC) in which increased its previous commitment to 51% in 2030 as well as to reduce black carbon by 40% compared to 2014.

[5]In the Glasgow climate pact, nations reaffirmed their duty to fulfill the pledge of providing 100 billion dollars annually from developed to developing countries.

[6]EIU developed a new Climate Change Resilience Index and has submitted some reports about climate change and its economic impacts. See, https://www.eiu.com/public/topical_report.aspx?campaignid=climatechange2019

Faet (2012), Raza & Shah (2018), Saidi & Omri (2020), Jebli & Kahia (2020)) and iv) studies that include the previous one and assess other variables as determinants or drivers of GHG emissions such as international trade (Akin (2014), Essandoh et al. (2020)), financial development (Gök (2020), Lv & Li (2021)), urbanization (Poumanyvong & Kaneko (2010), Martínez-Zarzoso & Maruotti (2011), Shafiei & Salim (2014)) and globalization (You & Lv (2018), Pata (2021)).

Taking into account this review, the present study tries to shed light on the main drivers of GHG emissions for the Colombian economy between 1970 and 2018 by using the Fully Modified Least Squares methodology (FM-OLS) that was originally proposed by Phillips & Hansen (1990). Our research seeks answers to the following questions for the Colombian case: i) Which are the local main drivers of environmental degradation?, ii) Do some international variables affect Colombian GHG emission patterns? and iii) What variables could help mitigate the dynamics of GHG emissions?. To do that, we assess the role of agriculture production given its large participation in Colombian GDP as well as the energy production divided by source. Furthermore, we evaluate if renewable energy and reforestation contribute to environmental quality. Finally, we include a proxy variable of globalization which enables us to determine how the interaction with the global economy has affected GHG emission patterns.

This article is organized as follows. In the next section, we cover a literature review that helps to understand the nexus between GHG emissions and forest area, energy consumption, agriculture production, GDP, and globalization. In section 3, we introduce the data and methodology and present the main results and findings about the relationship between GHG emissions and some drivers of their dynamic. Our conclusions and some policy implications are drawn in the final section.

2. Literature review

Given the scientific consensus that an increase in GHG emissions causes environmental concerns and, in turn, exacerbates climate change which has deteriorated several socioeconomic aspects, it is relevant to determine which drivers explain the GHG emission patterns. Below is a summary of the main findings in the literature on this subject, emphasizing the variables we use in the empirical exercise proposed for Colombia.

The first strand of the literature on determinants of GHG emissions can be characterized by the relationship between economic growth and pollution. In the environmental economics literature, the seminal work of Grossman & Krueger (1991) introduced the Environmental Kuznets Curve (EKC) hypothesis, which explains the dynamics associated with income and environmental quality. The EKC asserts that there is an inverted U-shaped relationship between emissions and per capita income. Thus, economic growth makes environmental quality worse while countries are developing. Still, after a threshold, when nations reach a higher degree of development, it enables improving environmental conditions by using better technologies or more friendly environmental production schemes, which implies that in the latter phases of development, degradation begins to fall. In other words, EKC suggests that pollution first rises and then falls according to the pace of economic development. Empirical research yields mixed results regarding the EKC hypothesis, and the results seem to support the invalidity of its existence (Kijima et al. (2010), Shahbaz & Sinha, Anwar et al. (2022)). Different elements in the literature might explain the divergence and heterogeneity in the findings: the countries (developed and developing), the sample period, the environmental indicator, the use of additional explanatory variables, and the econometric method to estimate that relationship. In particular, while some studies confirm the hypothesis such as Jaunky (2011), Pablo-Romero et al. (2017), Olale et al. (2018), Destek et al. (2018) and Adzawla et al. (2019), other studies find evidence against its (Caviglia-Harris et al. (2009), Ajmi et al. (2015), Wang et al. (2016), Lawson et al. (2020), Frodyma et al. (2022)).

On the other hand, depending on the characteristics of the country and its economy, some sectors have a more critical explanation than others in the conduct of GHG emissions. As it is mentioned by Lamb et al. (2021), on a global scale, the most significant proportion of emissions in 2018 was originated in the energy sector (34%), followed by industry (24%), agriculture, forestry, and other land use (21%), transport (14%) and buildings (6%). These trends are opposite in the case of Latin America and Africa, where agriculture, forestry, and other land use gain an important share of the economy. According to FAO (2021), although the contribution of agriculture to emissions is decreasing over time, in 2019, it was 57 and 72 percent in Africa and Latin America, respectively.

Regarding the agricultural sector, Zhang et al. (2019) find a bidirectional causality between the farm sector and carbon emissions in both the short-run and the long run in China, where an increase in agricultural production causes GHG emissions and pollutes the land's productivity. Lin & Xu (2018) state that the modernization of the agricultural sector in China has led to significant energy consumption and CO2 emissions. Still, it has been heterogeneous among provinces which depends on the degree of industrialization, fixed-asset investment, financial capability, and urbanization. Furthermore, Appiah et al. (2018) disaggregated agriculture production into crop and livestock production indexes. They showed evidence that a 1% increment in those variables causes an increase in CO2 emissions by 27.6% and 28.2% on average for selected emerging countries.

Colombia[7] and other developing countries find agriculture a source of sustainable development. Still, it is essential to note that the agricultural sector must achieve a global conversion by the requirements to adapt its production to the objectives of the worldwide agenda on climate change for the coming decades. For example, Calvin et al. (2016) simulate several scenarios

[7]In Colombia, the contribution of rural activities on emissions is around 60%.

for Latin America CO2 emissions and their relationship with agriculture, forestry, and land uses. They also find a significant uncertainty in the future path of emissions with and without climate policy. The authors point out the relevance of bioenergy and its production process and the availability of afforestation options in climate mitigation policy. In addition, Aydoğan & Vardar (2020) find a negative impact of agriculture on CO2 emissions in E7 countries due to those countries still using a high share of fossil energy for agricultural production. Given the dependence on fossil fuels, a way to mitigate and combat climate change is to transfer clean technologies and subsidize the use of renewable energy in that sector (Ben Jebli & Ben Youssef (2017)).

A second strand of the literature focuses on the role of energy and its composition between renewable and non-renewable energy. The nexus between energy consumption, economic growth, and emissions have been explored in several studies, which could be grouped into four hypotheses about the link between GDP and energy: i) neutrality (Payne (2009)), ii) growth (Ang (2007), Rahman (2017)), iii) conservation (Ang (2008)) and iv) feedback (Apergis & Payne (2009), Farhani et al. (2014)).[8] Although the latter seems to be the most expected result, the overall evidence is still mixed. Apergis & Payne (2009) show evidence of a strong relationship between economic growth, energy consumption, and CO2 emissions in both the short and long term for Central American Countries. They show proof of bidirectional causality between economic growth and energy, which supports that these are complementary. Thus, GDP expansions demand additional energy use, leading to higher emissions. However, these early studies ignored the composition and sources of energy production in the context of CO2 emissions and the relevance of renewable energy as a source of emission mitigation.

Given the relevance of renewable energy, the third strand of the literature explicitly includes renewable energy as an explanatory variable of GHG emissions. Like the relationship between GDP and energy, the results of the impact of renewable energy use on emissions in the long term are ambiguous in the environmental literature. It is difficult to determine the reason for this uncertainty,[9] which can be explained by the definition of the period of analysis, the countries chosen, or the variables used. For example, Sarkodie & Strezov (2019), Sarkodie et al. (2020) and Brini (2021) show a negative elasticity from renewable energy to GHG emissions, which contribute to mitigate climate change. In contrast, Jebli & Youssef (2017) and Nathaniel & Iheonu (2019) find the opposite result for African countries, implying that the adoption of clean energies does not help to reduce emissions. Notwithstanding, Brini (2021), unlike previous studies for African countries, includes both renewable and non-renewable energy separately and other explanatory variables in order to determine the role of renewable energy on GHG emissions. As a result, non-renewable energy and GDP have a positive and on temperature, which deteriorates the climatic conditions; on the contrary, the author suggests that renewable energy consumption can help to mitigate climate change in African countries. In addition, another explanation for that ambiguity might be that some studies include hydroelectric sources as renewable energy, but they also pollute (Fearnside (2016), Samiotis et al. (2018)). Although that hydro-power does not produce fossil fuel burning or smokestacks, the reservoirs where water is stored also produce both carbon dioxide and methane due to the content of high organic matter, high water, and sediment temperature, and an anoxic bottom layer special in tropical and equatorial places (Demarty & Bastien (2011)).

Finally, the four strand of the literature links GHG emissions and other economic variables in which globalization has been proposed as the primary cause of environmental degradation due to the impact of economic activities on the depletion of natural resources. Pata (2021) shows that although globalization is the main contributor to CO2 emissions in BRIC countries, renewable energy generation could alleviate this environmental pressures in special for China. You & Lv (2018) examine the correlation between C02 emissions and economic globalization in a panel of 83 countries. The authors found that globalization has a negative and significant indirect effect on environmental quality which dominates the positive but statistically insignificant direct effect of higher production on pollution. Thus, they found a net negative total effect which suggests that being surrounded by highly globalized countries can enhance environmental quality.

3. Data, empirical estimation and results

3.1. Data

In order to analyze the long-run relationship between the green house gases emission (CO2e)[10] and some variables that would help mitigate environmental impacts we include the following set of information: Livestock (LSTOCK), agriculture (CROPS), forest area (FOR), non-renewable energy supply (NON-REN), hydroelectric energy supply (HYD),[11] renewable energy supply (REN) and a globalisation index (KOFGI). Furthermore, we incorporate the gross domestic product (GDP) into our analysis to examine the validity of the environmental Kuznets curve hypothesis. The detail definitions of the series, the measuring units and data sources are presented in Tables A.5 and A.6. We used yearly data from 1970 to 2018 for the Colombian case.

[8]The neutrality hypothesis suggests that there is no causality link between economic growth and energy. The growth hypothesis states that there is a causality relationship between energy and GDP growth. Therefore, energy consumption causes economic growth. The conservation hypothesis affirms that there is unidirectional causality from GDP to energy, then any reduction in energy consumption may not have much effect on economic growth. Finally, the feedback hypothesis shows a bidirectional causality where both variables influence each other.

[9]Overall, despite this ambiguity, the most accepted statement is that renewable energy helps to mitigate emissions.

[10]The Kyoto basket encompasses the following six greenhouse gases: carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), and the so-called F-gases(hydrofluorocarbons and perfluorocarbons) and sulphur hexafluoride (SF6). Each gas is weighted by its global warming potential and aggregated to give total greenhouse gas emissions in CO2 equivalents.

[11]Hydroelectricity is a crucial energy source in Colombia, as it accounts for approximately 58% of the country's energy consumption.

Figure 1 shows the total CO2e emissions and GDP trajectories using a base index of 1970=100. This allows for a comparison of the values on a common scale, despite the distinct units of measurement for each variable. As previously stated, theoretically, the trend of GHG emissions is linked to the changes in the level of economic growth. It is evident from the data that from 1970 to 2018 that the GHG emissions exhibited a similar upward trend to that of GDP, thereby highlighting the strong correlation between economic activity and emissions. During this period, GHG emissions grew by an annual rate of 2.1%, while the rate of economic growth was close to 4.0%.

Figure 1: Evolution: CO2e emissions and GDP

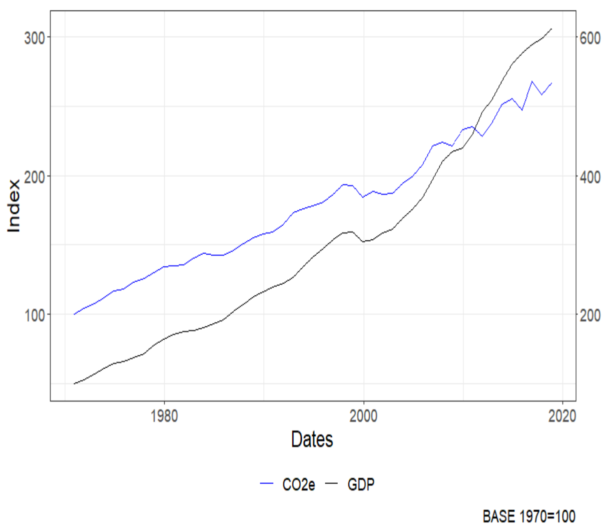

Figure 2 presents the CO2e emissions and the rest of variables. There is a noticeable reduction in the slope of emissions from the agricultural sector in contrast to total emissions, especially after the late nineties. In terms of energy consumption, although hydraulic generation is the main source of energy in Colombia, the participation of renewable energies increased significantly after 2008, thanks to the implementation of several solar and wind energy projects. The usage of non-renewable energy sources demonstrated a slight downward trend.

3.2. Unit root analysis

In the first step of the analysis, we examine the stationarity properties of the variables by using well-known unit root tests such as augmented Dickey & Fuller (1979) (DF), KPSS Kwiatkowski et al. (1992) and ERS Elliott et al. (1996). The Schwarz's Bayesian criterion (BIC) is used to determine the optimum number of lags in the DF and the ERS test. As a result, we find that all variables in the set of information contain a unit root at their level values. Thus, it indicates that once the first differencing is applied, all of our series attain stationarity at a 5% level of significance.

Figure 2: Evolution: CO2e emissions and other variables

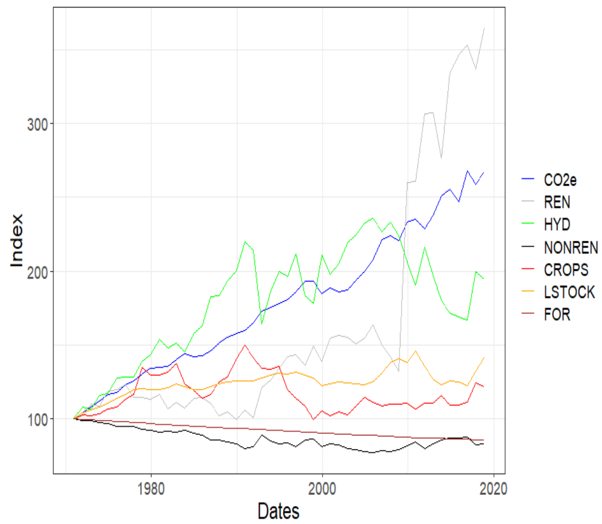

Table 1: Unit root tests for the series in levels†

	DF		KPSS		ERS	
	Stat	CVal	Stat	CVal	Stat	CVal
CO2e	0.397	-2.930	4.766	0.463	0.729	-1.950
CROPS	-2.214	-2.930	0.711	0.463	-2.024	-1.950
FOR	-1.768	-2.930	4.906	0.463	0.201	-1.950
LSTOCK	-2.160	-2.930	2.822	0.463	-0.331	-1.950
REN	0.943	-2.930	3.327	0.463	1.048	-1.950
HYD	-2.083	-2.930	3.144	0.463	-0.558	-1.950
NONREN	-2.086	-2.930	3.317	0.463	-0.478	-1.950
KOFGI	0.282	-2.930	4.646	0.463	1.004	-1.950
GDP	1.678	-2.930	4.562	0.463	0.990	-1.950

† This table presents the statistic values for the DF test (H_0: the series is non-stationary), KPSS test (H_0 : the series is stationary) and ERS test (H_0 : the series is non-stationary). The critical values of the statistics (CVal) are presented at 0.05 significance level.

Table 2: Unit root tests for the series in first differences†

	DF		KPSS		ERS	
	Stat	CVal	Stat	CVal	Stat	CVal
CO2e	-5.774	-2.930	0.131	0.463	-1.902	-1.950
CROPS	-3.972	-2.930	0.145	0.463	-2.678	-1.950
FOR	-2.368	-2.930	2.044	0.463	-2.390	-1.950
LSTOCK	-3.836	-2.930	0.168	0.463	-2.124	-1.950
REN	-4.643	-2.930	0.169	0.463	-2.779	-1.950
HYD	-5.694	-2.930	0.242	0.463	-1.881	-1.950
NONREN	-6.188	-2.930	0.130	0.463	-2.670	-1.950
KOFGI	-4.807	-2.930	0.042	0.463	-4.626	-1.950
GDP	-3.769	-2.930	0.081	0.463	-2.513	-1.950

† This table presents the statistic values for the DF test (H_0: the series is non-stationary), KPSS test (H_0 : the series is stationary) and ERS test (H_0 : the series is non-stationary). The critical values of the statistics (CVal) are presented at 0.05 significance level.

3.3. Cointegration test

According to the result of unit root tests, we examine the cointegration relationship between those variables in the next step by testing it in four sets of variables included to estimate the following models (Mod1, Mod2, Mod3 and Mod4): The first model focused on the relevance of the agriculture, land, and livestock variables. In the second one, we include the renewable energy and non-renewable energy.[12] The third model adds a globalization index and finally, the four model includes GDP and squared GDP to evaluate the environmental Kuznets curve hypothesis.

We used the cointegration test proposed by Shin (Shin, 1994), which is based on the KPSS test for the residuals from the cointegrating regressions estimated by the method suggested by Stock and Watson Stock & Watson (1993).[13] The results of the Shin test are presented in Table 3 which imply that the four set of variables are cointegrated at 0.05 significance level.

Table 3: Cointegration tests†

Model	Statistics	Critical values 0.1	0.05	0.01
Mod1	0.078	0.121	0.159	0.271
Mod2	0.073	0.075	0.097	0.158
Mod3	0.074	0.075	0.097	0.158
Mod4	0.074	0.075	0.097	0.158

† This table presents the statistic values for the Shin cointegration test Shin (1994), where the null hypothesis indicates that the variables are cointegrated.

3.4. Model estimation (FM-OLS)

Given that the analyzed series are cointegrated, we estimate the long-run relationships among the variables using Fully Modified Least Squares (FM-OLS) methodology (Phillips & Hansen, 1990). The objective of FM-OLS is to provide optimal estimates of the long-run coefficients in a cointegration framework. This method modify the traditional least squares methodology to account for the endogeneity in the regressors that result from the existence of a cointegration relationship Phillips (1995). The results obtained are shown in the Table 4 for each of the four estimated models.

The expected signs of the elasticities of GHG emissions in relation to GDP, agriculture and livestock, globalization and non-renewable energy consumption are positive. The EKC suggests that, despite the positive elasticity of GDP, it should marginally decrease as technological advancements in environmental production improve. Thus, while the GDP coefficient is positive, the coefficient of squared GDP is negative. On the contrary, the expected sign of renewable energy consumption and afforestation is negative, consistent with the hypothesis that increased consumption of renewable energy will lead to a reduction in emissions in the long term. In the case of reforestation, it is known that the production of oxygen by trees purifies the air and forms fertile soils that, in turn, prevent erosion and other environmental problems. As we progress from the initial model (Mod1) to more comprehensive models (from Mod2 to Mod4), we observe that the expected signs of coefficients remain and the values appear to be robust to the specification. These results are consistent with the international evidence mentioned in the previous section.

Table 4: Long run elasticity estimates of green house gases emissions for Colombia†

	Mod1	Mod2	Mod3	Mod4
Intercept	106.965	111.929	103.735	56.848
	(0.000)	(0.000)	(0.000)	(0.0000)
CROPS	0.122	0.126	0.129	0.106
	(0.000)	(0.000)	(0.000)	(0.000)
FOR	-5.587	-6.260	-5.838	-3.671
	(0.000)	(0.000)	(0.000)	(0.000)
LSTOCK	0.190	0.256	0.226	0.222
	(0.001)	(0.000)	(0.000)	(0.000)
REN		-0.025	-0.0271	-0.0123
		(0.001)	(0.000)	(0.443)
HYD		0.227	0.2818	-0.0841
		(0.000)	(0.000)	(0.596)
NONREN		1.206	1.308	0.503
		(0.000)	(0.000)	(0.000)
KOFGI			0.115	0.132
			(0.000)	(0.054)
GDP				1.959
				(0.002)
GDP2				-0.069
				(0.005)

† The values in parentheses represent the p-values of the coefficients

Among the results, it is highlighted that the effect of non-renewable energy consumption on emissions is more than proportional, meaning its elasticity is greater than one (Mod 2 and Mod3). Likewise, it is greater in magnitude than those observed for agricultural and livestock activities, as well as for globalization. The positive effects of renewable energy are not enough to offset the negative impact of those variables on the environment.

An interesting and controversial result is related to the generation of hydroelectric energy, which in some cases is considered as renewable energy, but it is also a source of environmental pollution (Demarty & Bastien (2011), Fearnside (2016) and Samiotis et al. (2018)), so it is not completely clean. The evidence found in this study suggests a similar magnitude of elasticity for hydroelectric energy and livestock for models two and three, but it is not statistically significant for the full model (Mod4).

Despite the upward trend in deforestation caused by illegal mining, extensive cattle ranching, and the lack of access to rural areas due to the ongoing armed conflict spanning over four decades in the national territory, we found statistical evidence that the preservation of forested areas stands as a primary driver to mitigate emissions in Colombia. Our findings underscores the relevance of public policies aimed not only at safeguarding the Amazon rainforest but also at fostering reforestation and afforestation initiatives. It is worth noting the coefficient associated with afforestation has a significantly high magnitude (from -3.671 to -6.260) which indicate a relevant and more than proportional impact on decreasing atmospheric pollution. This

[12]We separate the hydroelectric energy from the other renewable energy because the first one generates significant CO2 emissions.

[13]This method consists in estimating a long-term dynamic regression showing the leads and lags of the first differences explanatory variables and provides a robust correction for its possible presence of the endogeneity between these variables as well as the serial correlation of estimated errors.

could even generate global benefits on a larger scale.

4. Final remarks

In the current century, global warming and climate change have become a major focus of concern in the political agenda of national governments. In line with global agreements and ongoing research, one way to address this problem is to adopt low-carbon production methods that can help to reduce greenhouse gas emissions. Additionally, society should prioritize research that enhances our understanding of the relationship between greenhouse gas emissions and economic growth. This will support the formulation of climate and energy policies and facilitate the development of sustainable energy production methods.

In this study, we found statistical evidence that suggests the existence of the EKC. Since Colombia is a developing economy, economic growth has a negative impact on environmental conditions, but this impact becomes gradually smaller as new technologies are incorporated and adopted in the production processes. While globalization can indirectly benefit the reduction of CO2 emissions through the transfer of clean production technologies and green investments, its direct impact suggests a negative effect on environmental quality (measured by the KOF globalization index). One possible explanation for this is that the process has stimulated an increase in national production driven by international trade, and it should also be noted that one of the main export products is oil and other minerals.

According to international evidence, the generation of non-renewable energy has a negative impact on environmental quality while renewable energy sources help mitigate environmental damage. Increased consumption of non-renewable energy leads to an increase in emissions, especially in industries like transportation, agriculture, electricity generation, and manufacturing. This reality poses a significant obstacle to achieving the medium-term goal of shifting the Colombia's energy matrix towards a sustainable development path with lower carbon intensity. Conversely, transitioning towards renewable energy sources would decrease the impact of fuel price volatility on domestic prices.

From the policy perspective, it is crucial to develop strategies that incentivize the adoption of renewable energy, such as pricing policies, regulations that promote greater efficiency, private sector participation, and technological innovation incentives. This must be done within a general framework that establishes sectoral decarbonization targets and allows for sectors to achieve them at the lowest possible cost. Additionally, it can contribute to accelerating the spread of technological advancements and establishing suitable pricing. Despite the above, it should be noted that Colombia has made great efforts in this matter in the last decade and in fact, according to the Latin American Energy Organization (OLADE), Colombia is the third country in Latin America that has made the most progress in this transition, achieving a 65.9% installed capacity for the production of renewable energy.

Finally, it is important to note that a significant impact of reforestation was found on the reduction of CO2 emissions. In the Colombian case, this result leads to an interesting and potentially valuable public policy related to the care of our Amazon rainforest and the protection of forests in the national territory. This will be boosted by the current peace process in which it is expected to grant greater access to rural areas by government entities. Furthermore, the conservation of the Amazonian region by Colombia and other Latin American nations could result in global benefits and positive spillover effects. To achieve this goal, it is not sufficient for Latin American governments to be committed, but also for the promotion of aid and cooperation from advanced countries to be emphasized on the international agenda.

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Appendix A. Data description

Table A.5: Description of the variables

Variable	Description
CO2e	Green house gases emissions produced by energy, industrial, agriculture and waste sectors.
CROPS	Harvested areas of cereals (wheat, barley, corn, oatmeal, sorghum and rice), coffee, and oil palm.
FOR	Land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ. Excludes land that is predominantly under agricultural or urban land use. Note that Forest land is determined both by the presence of trees and by the absence of other predominant land uses.
LSTOCK	Sum of ruminant heads (cows, buffalo, sheep, and goats) and pig heads.
REN	Share of primary energy supply by renewable energy excluding hydroelectric energy, includes solar energy, wind energy, and geothermal energy.
HYD	Share of hydroelectric energy.
NONREN	Share of primary energy supply by fossil fuels (oil, gas, and coal).
GDP	Gross domestic product.
KOFGI	A composite index that measures globalisation along the economic, social and political dimension.

Table A.6: Measuring units and source of the variables

Variable	Measuring Unit	Data Source
CO2e	Kilotones (Kt) of CO2 equivalent	Potsdam Institute for Climate Impact Research (PIK)
CROPS	Hectares	Food and Agriculture Organization (FAO)
FOR	Hectares	Food and Agriculture Organization (FAO)
LSTOCK	Animal heads	Food and Agriculture Organization (FAO)
REN	% of primary energy supply	Our world in Data
HYD	% of primary energy supply	Our world in Data
NONREN	% of primary energy supply	Our world in Data
GDP	Billions of pesos (COP)	National Department of Statistics of Colombia (DANE)
KOFGI	Scale of 1(least) to 100 (most globalised)	ETH- Zurich Institute