



A causal link between renewable energy, energy efficiency, property rights, and CO2 emissions in developed countries: A road map for environmental sustainability

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Abstract

CO2 emissions are the leading causes of deterioration in air quality and global warming. Likewise, it has been shown that clean energy reduces air pollution, so this would be a way out of environmental pollution. Some previous studies have focused on knowing the determinants of environmental pollution; however, they have omitted the State's role. Thus, this study explores the long-term nexus between CO2 emissions and renewable energy, energy efficiency, fossil fuels, GDP, property rights from 1995 to 2019 in nine developed countries. The results reveal a long-term equilibrium relationship in developed European countries, but not in developed non-European countries. The main results show that renewable energy and energy efficiency are negatively correlated with CO2 emissions. In developed European countries, a 1% increase in renewable energy consumption represents a 0.03% decrease in CO2 emissions. Finally, some policy measures are suggested to achieve environmental sustainability.

Keywords Renewable energy · Carbon dioxide · Property rights · FMOLS

Introduction

The industrial development registered in the last century, like the irresponsible behavior of the human being, is associated with the increase in carbon dioxide (CO2) emissions that have increased notably around the world and have been the cause of environmental degradation, such as decreased air quality, global temperature rise and climate change (Ali 2018; Pata 2018). According to the United Nations (2020), since 1990, CO2 emissions have increased (almost 50%) and global

warming. This problem goes beyond the sustainability of the earth and the availability of natural resources for economic activity since it threatens the survival of humanity due to the lack of water, air pollution, the reduction of the layer ozone, etc. (Adedoyin et al. 2020; Kallel et al. 2020). Therefore, the term “Sustainable Development” must be understood in the same dimension by households, companies, and government, to achieve environmental sustainability (Hopwood et al. 2005; Ponce et al. 2020).

According to statistics published by the BP (2020), the Asia Pacific region (50.5%) are responsible for the highest amount of CO2 emissions worldwide, followed by North America (17.5%) and Europe (12%). Additionally, during the last decade, CO2 emissions registered a growth of 2.7% in Asia Pacific countries, 2.6% in Middle East countries, and 2% in African countries, and in Europe and North America, CO2 emissions decreased by 1.5% and 0.8%, respectively. The decrease in CO2 emissions in Europe and North America countries is due to the good environmental practices that have occurred in these countries, such as investment in clean energy and promote green energy consumption (Saidi and Omri 2020; Sulaiman et al. 2020; Bekun et al. 2019).

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This scenario has not been unnoticed by world leaders and organizations; since 1990, some events have been carried out to mitigate environmental pollution, such as the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, the Kyoto Protocol in 1997, and the Paris Agreement in 2015 (Ozcan and Gultekin 2016). In the Sustainable Development Goals (SDGs), the proposed goals on climate change clearly show the arduous effort that must be made to achieve this goal (Le Blanc 2015). This aims to reduce CO₂ emissions and preserve the global temperature rise below 2 degrees Celsius concerning pre-industrial pollution levels (Liu et al. 2020; Salvia et al. 2021; Vrontisi et al. 2020). Figure 1 highlights the relationship between CO₂ emissions and renewable energy consumption, which shows an inverse relationship.

Some of the main recommendations have been to prioritize renewable energy consumption sources in the industrial sector to mitigate pollution and climate change (Saidi and Omri 2020; Solarin et al. 2018). However, companies' pro-environmental practices depend on aspects such as their size or geographical location, among others (González-Benito and González-Benito 2006). Based on the total global renewable energy consumption in 2019, the regions with the highest consumption of renewable energy are the Asia Pacific region (37.3%), Europe (28.2%), and North America (23.1%); however, it is the region with the highest pollution (BP 2020). This particularity may be associated with two key factors. The first is that Asia Pacific registers the highest amount of fossil fuel consumption (225.08 exajoules) worldwide, representing 2.3 times more than North America and 3.6 times more than Europe (BP 2020). According to Hanif et al. (2019), in their research carried out for 15 Asian countries, environmental deterioration and CO₂ emissions are directly related to fossil fuel consumption. The second key factor is energy efficiency

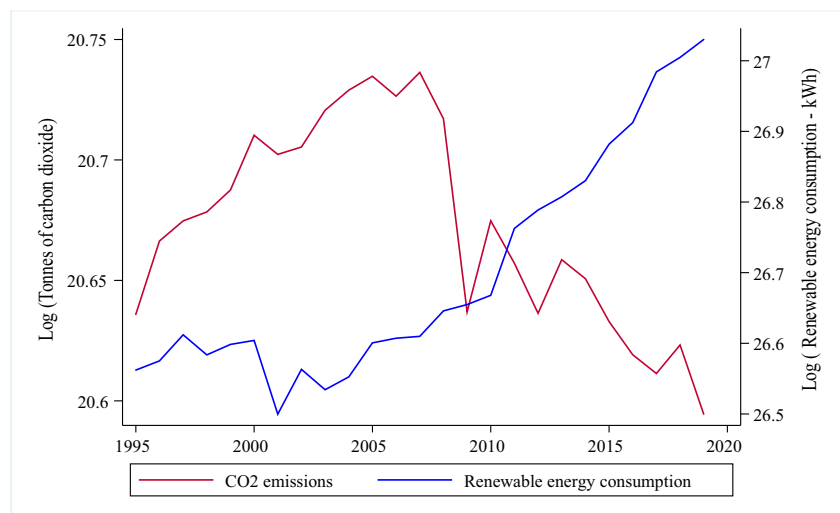
and environmental strategy used by most companies seeking to achieve environmental sustainability (Albino et al. 2009; Dyllick and Hockerts 2002). Europe allocates USD 1845 million for RD&D spending on energy efficiency, North America USD 1594 million, and Asia Pacific USD 982 million (International Energy Agency, IEA, 2020). Thus, Wang et al. (2020c) establish that energy efficiency is negatively related to CO₂ emissions. Energy efficiency means saving energy, for example, energy-saving bulbs or lamps are frequently used due to their low energy consumption (Guo and Pachauri 2017).

Therefore, the research's objective is to examine the long-run equilibrium relationship between renewable energy consumption, energy efficiency, fossil fuel consumption, gross domestic product (GDP), property rights, and CO₂ emissions. Annualized data is used for nine developed countries selected during 1995–2019, from various official sources. Subsequently, second generation econometric cointegration techniques are used to test the relationship between the model variables.

The study then defines five hypotheses related to CO₂ emissions that are described in section two. This study selects these countries because they have made great efforts in the technological innovation of energy consumption. For this reason, the study's contribution is novel. Unlike studies such as that of Bekun et al. (2019) and Sulaiman et al. (2020), the research's contribution is novel since it considers the role of property rights and energy efficiency. The latter is very important due to the savings in energy consumption it represents, whether in renewable or nonrenewable energy.

The rest of the paper is organized as follows: Section 2 contains the previous literature and the research hypotheses. Section 3 describes data sources and econometrics approaches. Section 4 discusses the empirical results. Finally,

Fig. 1 Co₂ emissions and renewable energy consumption relationship



concluding remarks and policy implications are provided in Section 5.

Literature review and hypotheses development

This section describes the relationship between each explanatory variable and CO₂ emissions.

CO₂ emissions and renewable energy consumption

One of the most recent studies carried out by Bekun et al. (2019), for 16 countries of the European Union (EU) using the panel pooled mean group-autoregressive distributive lag model (PMG-ARDL) identify that renewable energy consumption is negatively correlated with air pollution. Like Sulaiman et al. (2020), who find similar results in the EU. Also, the Saidi and Omri study (2020) for 15 OECD countries using fully modified ordinary least squares (FMOLS) and Vector Error Correction (VEC) model reveal that renewable energy consumption, such as nuclear reduces CO₂ emissions. Dong et al. (2017), using the AMG approach for BRICS countries, determine that an increase of 1% in clear energy reduces air pollution by 0.26%. Results that coincide with the findings of Vo et al. (2020), Wang et al. (2020c), Sharif et al. (2020), and Inglesi-Lotz and Dogan (2018). Likewise, in selected countries from South Asian, the findings of Ikram et al. (2020) indicate that clean energy is key to reducing air pollution, however, indicate that the improvement of the quality environment is also due to the adoption of ISO 14001 certification. In contrast, Charfeddine and Kahia (2019), employing a panel vector autoregressive (PVAR) for 24 countries in Africa, indicate that green energy consumption in improving the environment quality is low can be improved with efficient environmental policies.

- **Hypothesis 1:** Increases in renewable energy consumption is negatively associated with CO₂ emissions.

CO₂ emissions and energy efficiency

Energy efficiency allows energy savings in the production processes of goods and services (He et al. 2021; Zheng et al. 2021), and, like renewable energy, it is decisive to reduce carbon dioxide emissions (Qin et al. 2020; Masoud 2020). In the primary economic sector, Imran et al. (2020) study, cotton growers' energy efficiency in South Punjab, Pakistan. Their results found that 23% of energy consumption could be conserved, and carbon emissions significantly reduced. In the

secondary economic sector Xia et al. (2020), in Xinjiang, China, they find that the energy efficiency potential of 7 key industries from the sector would reduce energy consumption between 70% and 50%, respectively, and subsequently, CO₂ emissions. Similarly, the works of Du et al. (2021) and Zhang et al. (2021) show this relationship in the Chinese cement and metallurgical industry. Also, in Switzerland's secondary metallurgical sector, Bhadbhade et al. (2019) define that energy efficiency could reduce CO₂ emissions by 6%. In the same sector, in the construction, Pylsy et al. (2020) and Kamal et al. (2019) mention that buildings with high energy efficiency and adequate management of the heating system, cooling system, and connection to the power grid, helps to reduce polluting gases. In the services, the economic sector, Wang et al. (2020b) indicate that China's CO₂ emissions are closely related to regional economic development and production technology. CO₂ emissions are high in provinces with high economic development and low energy efficiency levels, while in provinces with advanced energy efficiency and underdeveloped economies, CO₂ emissions are relatively low. Energy efficiency also reduces CO₂ emissions in port services and freight transport by road (Martínez-Moya et al. 2019; González Palencia et al. 2017).

- **Hypothesis 2:** Increases in energy efficiency is negatively associated with CO₂ emissions.

CO₂ emissions and fossil fuel consumption

Fossil fuel consumption is highly polluting due to the high carbon concentration they have, which later becomes CO₂ emissions in the combustion process (Khattak et al. 2020). Even in the Intergovernmental Panel on Climate Change (IPCC') Fifth Report, they indicate that fossil fuel consumption is the main factor for environmental degradation (Chen et al. 2019). For example, Hanif et al. (2019), using an ARDL approach for 15 Asian developing countries, determine that fossil fuel consumption and economic growth increase CO₂ emissions. Indeed, Rasoulinezhad and Saboori (2018) use FMOLS and DOLS to study the determinants of long-term CO₂ emissions in 12 CIS state members. Their findings show that fossil fuel consumption is the primary driver in increasing CO₂ emissions in the long-term. Likewise, Naseem et al. (2020), using the ARDL approach, indicate that fossil fuel consumption degrades environmental quality. By the same econometric approach, Abokyi et al. (2019) attempt the drivers of greenhouse gases in long-term Ghana conclude that fossil fuels combustion is the leading cause of greenhouse gases. Thus, several measures to replace the use of fossil fuels

are carried out, for example in Turkey waste cooking oil is used to substitute polluting fuels (Arslan and Ulusoy 2017).

- **Hypothesis 3:** Increases in fossil fuel consumption is positively associated with CO₂ emissions.

CO₂ emissions and GDP

Most economic activities demand any energy to produce goods and services; therefore, GDP is a critical driver of CO₂ emissions and environmental pollution (Gong et al. 2020; Murshed 2020). The conceptual framework for the study of GDP and environmental pollution is defined under the Environmental Kuznets Curve (EKC) hypothesis based on the Kuznets curve developed by Simon Kuznets (1955). The EKC states that increases in GDP cause more CO₂ emissions up to a certain level. After this critical point, increases in GDP lead to environmental improvements. Consequently, several studies have focused on examining the EKC hypothesis. Thus, Du et al. (2019), using the threshold model, carry out a study for 71 countries between 1996 and 2012, in which they confirm the EKC hypothesis.

Similarly, Kacprzyk and Kuchta (2020) evaluate the EKC for 161 countries; their findings also evidence the EKC hypothesis. However, studies such as that of Munir et al. (2020), carried out for five Asian countries using FMOLS and DOLS, check the breach of the EKC hypothesis. Complementarily, in a study developed in the BRICS countries, Cheng et al. (2019) conclude that the increase in GDP has a linear behavior with CO₂ emissions; as economic activity grows, so does the CO₂ emissions. These results are similar to those found in studies performed in the G7 group, in which they show that increases in GDP increase CO₂ emissions, although they are characterized as developed countries (Liu et al. 2020; Awaworyi et al. 2019; Zafar et al. 2019).

- **Hypothesis 4:** Increases in GDP are positively correlated with CO₂ emissions.

CO₂ emissions and property rights

Panayotou (1997) mentioned that pollution is the environmental price of a country's economic growth, due to market failures, such as ill-defined property rights related to institutions' quality, government effectiveness, etc. (Delmas and Toffel 2004). Furthermore, Carlsson and Lundström (2000) affirm that property rights generate long-term investments. For example, farmers with more secure property rights could make investments in sustainable cultivation techniques. A study by

Andersson (2018) addresses a series of institutional and legal reforms that have taken place in China since the 1990s, developing greater protection of property rights and an economy based on free-market institutions. As a result, it considers that property rights are associated with an increase of between 1% and 2% in CO₂ emissions. This scenario is since property rights are associated directly with trade and indirectly with CO₂ emissions (Costinot 2009; Ma et al. 2010). Otherwise, On the other hand, Bhattacharya et al. (2017) performed research for 85 countries with different levels of development and conclude that institutional quality is a driver to reduce CO₂ emissions. Likewise, the research carried out by Abid (2016), for 25 Sub-Saharan Africa economies (SSA), examines the effect of institutional indicators on CO₂ emissions. Their conclusions indicate that institutional variables maintain an inverse relationship with air pollution. Complementarily, Bernauer and Koubi (2008) examine the effect of institutional indicators in 107 cities in 42 countries. Their results affirm that democracy reduces air pollution between 1.6% and 0.05%.

- **Hypothesis 5:** Increases in property rights are negatively associated with CO₂ emissions.

Econometric strategy and data source

Data

The research uses annualized data for nine European and non-European developed countries according to available information in various databases, including Germany, Norway, Sweden, Switzerland, Australia, Canada, Japan, New Zealand, and the United States, from 1995 to 2019. CO₂ emissions are used as a dependent variable. Explanatory variables, such as renewable energy (Bekun et al. 2019; Ikram et al. 2020; Inglesi-Lotz and Dogan 2018; Vo et al. 2020), energy efficiency (Ruizhi Wang et al. 2020; Xia et al. 2020a, b), fossil fuels (Adjei et al. 2019; Cho and Sohn, 2018; Hanif et al. 2019), GDP (Kacprzyk and Kuchta 2020; Liu et al. 2020; Munir et al. 2020, 2020) and property rights (Andersson 2018) are frequently used to examine drivers of environmental degradation. Table 1 provides information about the model variables.

Table 2 indicates the main descriptive statistics of model variables. The panel has 225 observations from nine developed countries and covering 25 years.

Likewise, Table 3 indicates the strength of the correlation between the variables examined, which preliminarily indicate the explanatory variables' direction with respect to the

Table 1 Definition of variables

Variable	Symbols	Description	Source data
Carbon dioxide emissions	CO2	Log Tonnes of carbon dioxide per capita	Statistical Review of World Energy (2020)
Renewable energy consumption	REC	Log Renewable energy consumption per capita (kWh), from renewable resource sources (water, wind, solar, geothermal, biomass).	Statistical Review of World Energy (2020)
Energy Efficiency	EE	Total RD&D spending in Energy efficiency per capita (USD 2019 prices and PPP)	World Bank (2020)
Fossil fuel	FF	Log Oil consumption tonnes per capita	Statistical Review of World Energy (2020)
Gross domestic product	GDP	Log Gross domestic product per capita (constant 2010 US\$)	World Bank (2020)
Property rights	PR	It measures the accumulation of private property that the State legally recognizes. 0 means that private property is prohibited, and 100 is private property guaranteed by the government.	Heritage Foundation (2020)

dependent one. At 5% significance (*) REC, EE, and FF are positively associated with CO₂, while GDP has a negative relationship with CO₂.

In this way, Fig. 2 displays the evolution of the variables during the period examined, both for the developed European

(EU) and developed non-European (NUE) countries. Compared to NUE, the EU decreases carbon dioxide emissions and renewable energy consumption and fossil fuel consumption. However, the EU shows an increasing trend in GDP and energy efficiency. On the other hand, after 2015,

Table 2 Descriptive statistics

Variable	Carbon dioxide emissions	Renewable energy consumption	Energy Efficiency	Fossil fuel consumption	Gross domestic product	Property rights
Sample countries						
Mean	2.34	9.23	4.72	0.69	10.56	87.74
Median	2.10	9.45	3.08	0.53	10.69	90
Std. Dev.	0.76	1.58	6.27	0.75	0.73	5.86
Min.	1.47	6.64	0.11	-0.49	8.23	70
Max.	4.38	11.95	40.34	2.70	11.43	96.1
Obs.	225	225	225	225	225	225
Developed European countries						
Mean	1.94	9.61	5.09	0.50	10.98	8.75
Median	1.93	9.71	3.41	0.50	10.99	90
Std. Dev.	0.25	1.27	6.41	0.18	0.30	5.64
Min.	1.47	6.65	0.18	0.15	10.45	70
Max.	2.41	11.38	40.34	0.80	11.43	95
Obs.	100	100	100	100	100	100
Developed non-European countries						
Mean	2.66	8.92	4.43	0.84	10.22	87.58
Median	2.26	8.27	2.35	0.58	10.59	90
Std. Dev.	0.87	1.74	6.17	0.97	0.80	6.05
Min.	1.65	6.64	0.11	0.08	8.23	70
Max.	4.38	11.95	36.37	2.70	10.92	96.1
Obs.	125	125	125	125	125	125

Table 3 Correlation matrix

	CO2	REC	EE	FF	GDP	PR
CO2	1.0000					
REC	0.4033*	1.0000				
EE	0.4234*	0.5294*	1.0000			
FF	0.9155*	0.6756*	0.5359*	1.0000		
GDP	-0.8504*	-0.3331*	-0.3098*	-0.7328*	1.0000	
PR	0.0535	0.1794	-0.0027	0.0455	-0.1053	1.0000

property rights become decreasing for both groups of countries.

Model and methodology

This research study the long-term equilibrium of renewable energy consumption, energy efficiency, fossil fuel consumption, GDP, and property rights on carbon emissions from 1995 to 2019 for nine developed countries worldwide. Based on the study of Bekun et al. (2019), the following econometric equation is estimated:

$$CO2_{it} = \alpha_1 + \alpha_2 REC_{it} + \alpha_3 EE_{it} + \alpha_4 FF_{it} + \alpha_5 GDP_{it} + \alpha_6 PR_{it} + \varepsilon_{it} \tag{1}$$

Where *CO2* represents carbon dioxide emissions, *REC* is renewable energy consumption, *EE* is energy efficiency, *FF* is fossil fuel consumption, *GDP* is a gross domestic product, and *PR* is property rights. α_1 representa la constante y ε el término de error. The sub-indices *i* and *t* are the countries, $i = 1, 2, 3, \dots, N$ and the temporal period $t = 1995, 1996, \dots, T$, respectively.

The interdependence between countries due to globalization, trade, economic cooperation, political and social relations, etc., leads to countries depending on each other (Zafar et al. 2020; Wang et al. 2020b). For this reason, it is important to control possible interdependence in the dataset panel due to the interaction between the analyzed countries (Breusch and Pagan 1980). Thus, the cross-sectional dependence (CD) is of utmost importance to avoid possible bias in the estimated results (Aydin 2019). Following Altıntaş and Kassouri (2020), Chen et al. (2020), Ike et al. (2020), the Pesaran (2015) test is employed to examine the cross-sectional dependence in the model variables. The null hypothesis assumes that cross-sections units are independent, in contrast to the

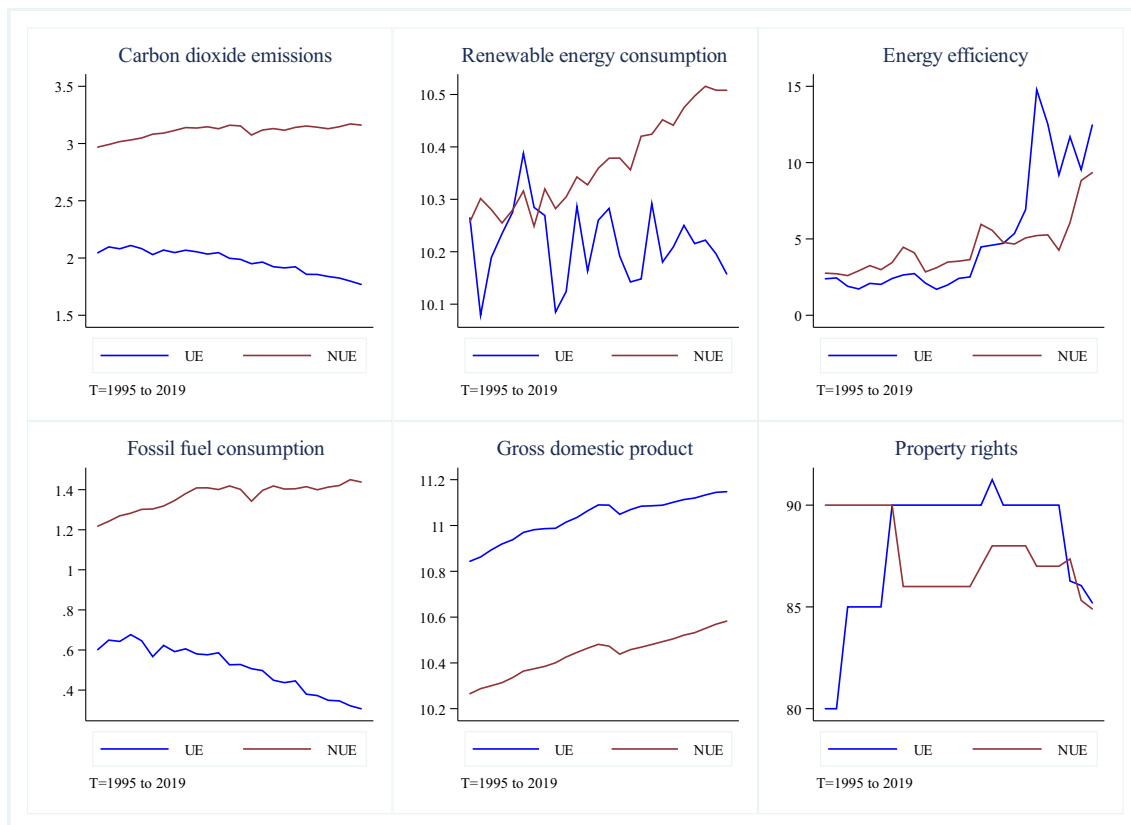


Fig. 2 Evolution of model variables

alternative hypothesis of cross-section units' dependence. The CD test equation is this as follow:

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

N is the total number of cross-section units, T is the number of years of the research, and $\hat{\rho}_{ij}$ represents the heterogeneous correlation of stochastic variations. After, according to Wang et al. (2020a) and Mensah et al. (2019), the slope homogeneity test ($\bar{\Delta}_{adj}$) was developed by Pesaran and Yamagata (2008) is applied to consider the heterogeneous characteristics of each country. Based on the model of Swamy (1970), Pesaran and Yamagata (2008) define a standardized dispersion test statistic for panel data considering cross-section dimensions (N) and time-series dimension (T) (Altıntaş and Kassouri 2020). The null hypothesis assumes the slope homogeneity, in contrast to the alternative hypothesis of non-homogeneity. The test equation can be formalized as follows:

$$\bar{\Delta}_{adj} = \sqrt{N} \left(\frac{N^{-1} \bar{S} - E(\bar{Z}_{iT})}{\sqrt{var(\bar{Z}_{iT})}} \right) \tag{3}$$

Where $E(\bar{Z}_{iT}) = k$ and $var(\bar{Z}_{iT}) = 2k(T-k-1)/(T+1)$. Subsequently, with cross-sectional dependence and slope heterogeneity in the panel data, second generation unit root and cointegration tests should be used. Unit root tests that consider heterogeneity and cross-sectional dependence in the procedure should be applied (Iglesias-Lotz & Dogan, 2018). Thus, this applies the cross-section augmented Im-Pesaran-Shin (CIPS), and cross-section augmented Dickey-Fuller tests (CADF) developed by Pesaran (2007) to determine the stationarity of the series. The null hypothesis indicates that non-stationarity. The alternative hypothesis indicates otherwise. Both unit root tests can be written as:

$$\Delta X_{it} = \omega_{it} + \varphi_i X_{it-1} + \rho_i T + \sum_{j=0}^n \vartheta_{ij} \Delta X_{i,t-j} + \varepsilon_{it} \tag{4}$$

Where X_{it} represents the analyzed variable, i explicates the number of cross-section units, t denotes the temporal period, ε_{it} determine the error model. According to the second generation cointegration test, the Westerlund (2007) test is employed to examine the long-term equilibrium relationship. The test provides four statistical (G_b, G_a, P_b, P_a), which are based on the following equation:

$$\Delta y_{it} = \delta'_i f_t + \varphi_i \left(y_{it-1} - \omega'_i x_{it-1} \right) + \sum_{j=1}^{K_i} \theta_{ij} \Delta y_{it-j} + \sum_{j=q_i}^{K_i} \Delta x_{it-j} + \varepsilon_{it} \tag{5}$$

Where f_t is the deterministic component. The null hypothesis is $H_0 : \tau = 0$, and the alternative hypothesis is $H_1 : \tau < 0$. Rejection of the null hypothesis implies a long-term relationship for the general panel. The test can also be estimated considering three situations, the non-existence of deterministic components, the presence of a constant factor, and the existence of a constant and a tendency.

Hence, FMOLS are employed to estimate the long-run coefficients. The FMOLS coefficient is calculated with the following equation:

$$\hat{\alpha}_{XFMOLS} = N^{-1} \sum_{n=1}^N \hat{\alpha}_{FMOLS,n} \tag{6}$$

Where, $\hat{\alpha}_{XFMOLS,n}$ represents the FMOLS estimator for each explanatory variable applied to country n . Likewise, the t-statistic is found with the next equation:

$$t_{\hat{\alpha}_{XFMOLS}} = N^{-1/2} \sum_{n=1}^N t_{FMOLS,n} \tag{7}$$

Like Uddin (2020), the Dumitrescu and Hurlin (2012) causality test is conducted to determine the directionality among the model variables. The test formalizes in the following equation:

$$y_{i,t} = \alpha_i + \sum_{i=1}^K \gamma_i^{(k)} y_{i,t-k} + \sum_{i=1}^K \delta_i^{(k)} x_{i,t-k} + \varepsilon_{i,t} \tag{8}$$

Where $\alpha_i, \gamma_i^{(k)}$, and $\delta_i^{(k)}$ denote the constant term, lag parameter, and the slope coefficient. The null hypothesis tests the no causal relationship for any of the cross-section units, against the alternative hypothesis that a causal relation occurs for at least one subgroup of the panel. Finally, similar to Charfeddine and Kahia (2019), the impulsive-response and variance decomposition graphs are developed to show the examined variables' behavior.

Results and discussion

Before the cointegration analysis, Table 4 presents the cross-sectional dependence results sand the slope homogeneity tests. The p value of the CD test by Pesaran (2015) rejects the null hypothesis of cross-sectional independence among the study variables. In other words, the interdependence between the study variables is very high. Furthermore, the p value of the Pesaran and Yamagata (2008) test is less than 0.01%, which suggests rejecting the null hypothesis of slope

Table 4 Cross-sectional dependence and slope homogeneity tests

CD test						
Variables	CO2	REC	EE	FF	GDP	PR
test statistic	7.83***	3.15***	10.66***	2.51*	28.29***	3.30***
<i>p</i> value	0.000	0.000	0.000	0.012	0.000	0.000
Slope Homogeneity Tests						
	Δ				Δ _{adj}	
test statistic	9.797***				11.460***	
<i>p</i> -value	0.000				0.000	

Notes: ***, ** and * indicates significance at 0.1, 1% and 5% levels

homogeneity. Consequently, given the cross-section dependence of the variables and heterogeneity of the slope of the examined countries, cointegration techniques with second-generation tests should be used in subsequent analyzes.

Thus, Table 5 presents Pesaran's (2007) CIPS and CADF unit root test results that consider the cross-sectional dependency and slope homogeneity issues. Besides, the test proposed by Breitung and Das (2005) is carried out to validate the robustness of the unit root test. At 1%, the null hypothesis of non-stationary of the study variables is rejected. The variables have cointegration order I (1) with their first difference, implying that the possible existence of long-term cointegration can be evaluated.

Subsequently, Table 6 presents the results of Westerlund's (2007) long-term cointegration test, which controls the cross-sectional dependency in the estimated model. At 0.1%, the null hypothesis of the model's non-cointegration for developed countries and the EU is rejected. Therefore, a long-term equilibrium relationship is evidenced by renewable energy consumption, energy efficiency, fossil fuel consumption, gross domestic product (GDP), property rights, and CO2 emissions. However, the NUE results do not allow rejecting the null hypothesis of non-cointegration. Esta diferencia,

podría asociarse a que los países europeos han definido varios programas en conjunto para disminuir los niveles de contaminación hasta el año 2050. For example, the “green deal” that seeks to mitigate CO2 emissions in European countries by substituting polluting energies for renewable energies and by increasing energy efficiency (Montanarella and Panagos 2021).

Later, Table 7 presents FMOLS coefficients. The findings show that renewable energy consumption has a negative and statistically significant relationship with CO2 emissions. This determines that energy consumption from pro-environmental and unlimited resource sources reduces environmental pollution in the EU. These findings are similar to those found by Bekun et al. (2019), Sulaiman et al. (2020), and Saidi and Omri (2020), who establish that clean energy guarantees to counteract the levels of pollution in the environment.

Similarly, the coefficient of energy efficiency is negative and significant, which means that the mechanisms, technologies, or instruments implemented in the process of any activity are reflected in the reduction of CO2 emissions. The results confirm previous findings in studies by Qin et al. (2020), Imran et al. (2020), and Xia et al. (2020). These studies affirm that green energy is a determining factor in reducing CO2 emissions, and energy efficiency reduce the energy intensity in the production process, reducing CO2 emissions. Indeed, companies that seek to achieve environmental sustainability have energy efficiency as the primary sustainable strategy (Albino et al. 2009; Dyllick and Hockerts 2002).

Then, fossil fuel consumption is positively and significantly associated with pollution, since in its combustion process, it generates carbon dioxide and, also, it comes from energy sources with scarce resources. The findings are in line with the study by Chen et al. (2019), Hanif et al. (2019), and Rasoulinezhad and Saboori (2018), who identify fossil fuels as the main driver for pollution since their consumption is high in most countries. Similarly, GDP is directly related to CO2

Table 5 Panel unit root test

Group/Test		First difference					
		CO2	REC	EE	GDP	PR	FF
Developed countries	CIPS	-5.539***	-5.353***	-4.291***	-3.237***	-4.128***	-5.419***
	CADF	-3.611***	-3.333***	-3.198***	-2.998***	-3.301***	-3.107***
	Breitung and Das	-3.9549***	-3.3197***	-6.1466***	-5.1041***	-8.8608***	-4.1547***
Developed European countries	CIPS	-5.029***	-5.592***	-4.354***	-3.168***	-5.128***	-6.050***
	CADF	-4.200***	-3.470***	-2.989**	-3.214***	-4.274***	-3.049***
	Breitung and Das	-2.6796**	-3.2797***	-5.2513***	-3.7935***	-7.1025***	-3.3375***
Developed non-European countries	CIPS	-5.511***	-5.138***	-4.476***	-4.173***	-3.882***	-5.103***
	CADF	-3.307***	-3.435***	-2.487**	-3.664***	-2.752**	-3.204***
	Breitung and Das	-6.3667***	-7.6329***	-4.2974***	-4.5242***	-5.6573***	-5.9202***

Notes: ***, ** and * indicates significance at 1%, 5% and 10% levels

Table 6 Panel cointegration test Westerlund 2007

Statistic	Developed European countries	Developed non-European countries
Gt	-3.028	-2.370
Ga	-7.124	-3.901
Pt	-8.436 ^{***}	-4.513
Pa	-14.266	-3.100

Notes: ^{***}, ^{**} and ^{*} indicates significance at 0.1%, 1% and 5% levels

emissions, given that the dynamization of economic activity generates an increase in the exchange of products and demand for greater consumption of energy and some services, such as transport (González Palencia et al. 2017). Although the countries are developed, the increase in economic activity causes more pollution, which is also discovered in previous studies (Liu et al. 2020; Awaworyi Churchill et al. 2019; Zafar et al. 2019).

The study by Bekun et al. (2019) and Sulaiman et al. (2020) have previously examined the role of renewable energy consumption in reducing pollution in European Union countries. However, the great help generated by energy efficiency in caring for the environment has not been considered, since it allows saving energy consumption, together with the consumption of renewable energy, they become key instruments to achieve sustainable development (Dong et al. 2018; Zhu et al. 2020).

Next, Table 8 summarizes the causality relationship between the model variables employing the Dumitrescu and Hurlin (2012) test. First, there is a unidirectional relationship that goes from GDP to CO₂ emissions in the panel. Second, there is a unidirectional causal relationship between property rights to CO₂ emissions at 5% significance in the EU. These results provide valid arguments for the definition of public policies, which must consider government effectiveness to guarantee individuals' property rights and economic growth.

Finally, property rights are positively related to CO₂ emissions. In other words, when the State gives greater security on the right to private property, individuals take a behavior that generates more contamination. The results agree with Anderson (2018), who indicates that property rights stimulate trade and worsen air quality. However, they are contrary to

Abid's (2016) findings, who affirm that government effectiveness leads to lower CO₂ emissions. The literature review's defined hypotheses have been confirmed according to the results obtained, except for H5, in which PR shows a direct relationship with CO₂ emissions.

Finally, the impulse response variance decomposition graph is a way to forecast the variables' behavior in the future. At 5% significance, renewable energy, energy efficiency, fossil fuels, GDP, and property rights predict the behavior of CO₂ emissions in the coming years (see Figs. 3 and 4).

Conclusions and policy implication

Unlike previous research (Bekun et al. 2019; Sulaiman et al. 2020), this study considers the role of property rights and energy efficiency in the CO₂ emissions of nine developed countries selected from 1995 to 2019. Additionally, other variables were considered, such as renewable energy consumption, GDP, and fossil fuel consumption. Using the Pesaran (2015) and Pesaran and Yamagata (2008) tests, the existence of cross-section dependence of the variables and heterogeneity of the countries' slope is verified. Consequently, second-generation tests were used to avoid bias in the estimates. The results of Westerlund (2007) establish a long-term equilibrium relationship between the study variables in developed European countries, but not in non-European countries. Moreover, the FMOLS coefficients confirm a positive relationship between fossil fuel consumption, GDP, property rights, and CO₂ emissions. In contrast, renewable energy consumption and energy efficiency are negatively related to CO₂ emissions.

Table 7 Long-run coefficients – FMOLS

Explanatory variables	Developed countries		Developed European countries	
	Coefficient	t-statistic	Coefficient	t-statistic
Renewable energy consumption	-0.05 ^{***}	-6.98	-0.03 ^{***}	-3.18
Energy Efficiency	-0.02 ^{***}	-3.16	-0.01 ^{***}	-3.67
Fossil fuel consumption	0.60 ^{***}	43.78	0.70 ^{***}	47.89
GDP	0.41 ^{***}	10.01	0.34 ^{***}	6.74
Property rights	0.01 ^{***}	4.41	0.01 ^{***}	5.53

Notes: ^{***}, ^{**} and ^{*} indicates significance at 0.1%, 1% and 5% levels

Table 8 Dumitrescu-Hurlin panel causality tests

Direction of causality	Developed countries		Developed European countries	
	Z-bar	p value	Z-bar	p value
REC → CO2	-0.2566	0.7975	-0.8899	0.3735
CO2 → REC	0.5256	0.5991	-0.3128	0.7544
EE → CO2	0.1027	0.9182	1.5183	0.1289
CO2 → EE	-0.8013	0.4230	-0.2098	0.8338
GDP → CO2	1.9828	0.0497*	-1.0465	0.2953
CO2 → GFP	-0.3997	0.6894	-0.4780	0.6326
PR → CO2	1.7488	0.0803	2.4947	0.0126*
CO2 → PR	0.4248	0.6710	0.3893	0.6971
FF → CO2	1.1191	0.2631	-0.4908	0.6236
CO2 → FF	0.5051	0.6135	-1.5678	0.1169

Notes: ***, ** and * indicates significance at 0.1%, 1% and 5% levels

Based on empirical results, the research recommends the following policy implications to EU governments. First, to promote renewable energy consumption by taking advantage of the availability of resources in these countries, especially

wind and solar, to replace nonrenewable energy consumption in the long term. Design a tax incentive plan for companies that succeed in substituting renewable energy consumption for clean energy in a sustainable approach. Second, to encourage

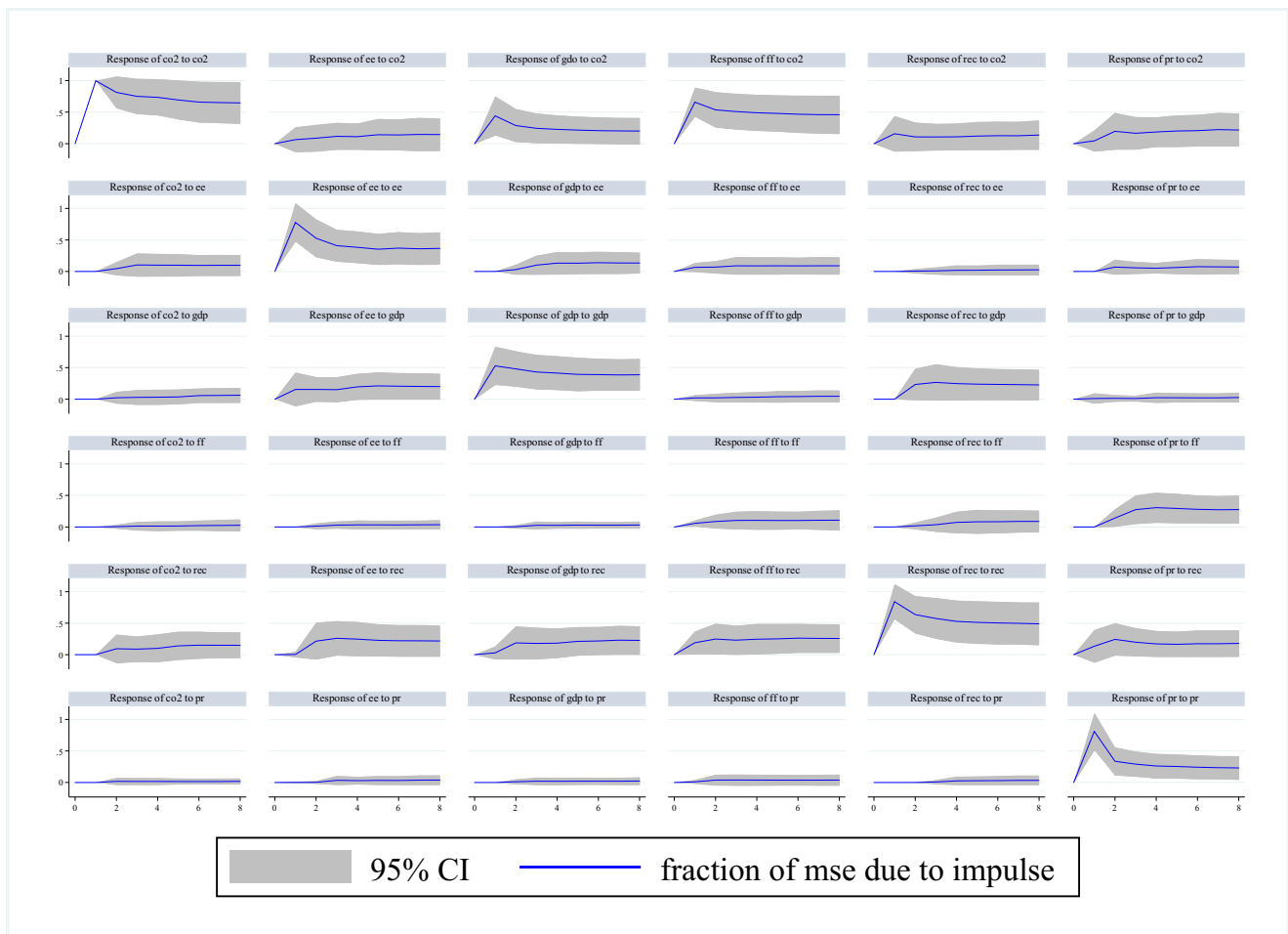


Fig. 3 Variance decomposition graph – Developed countries

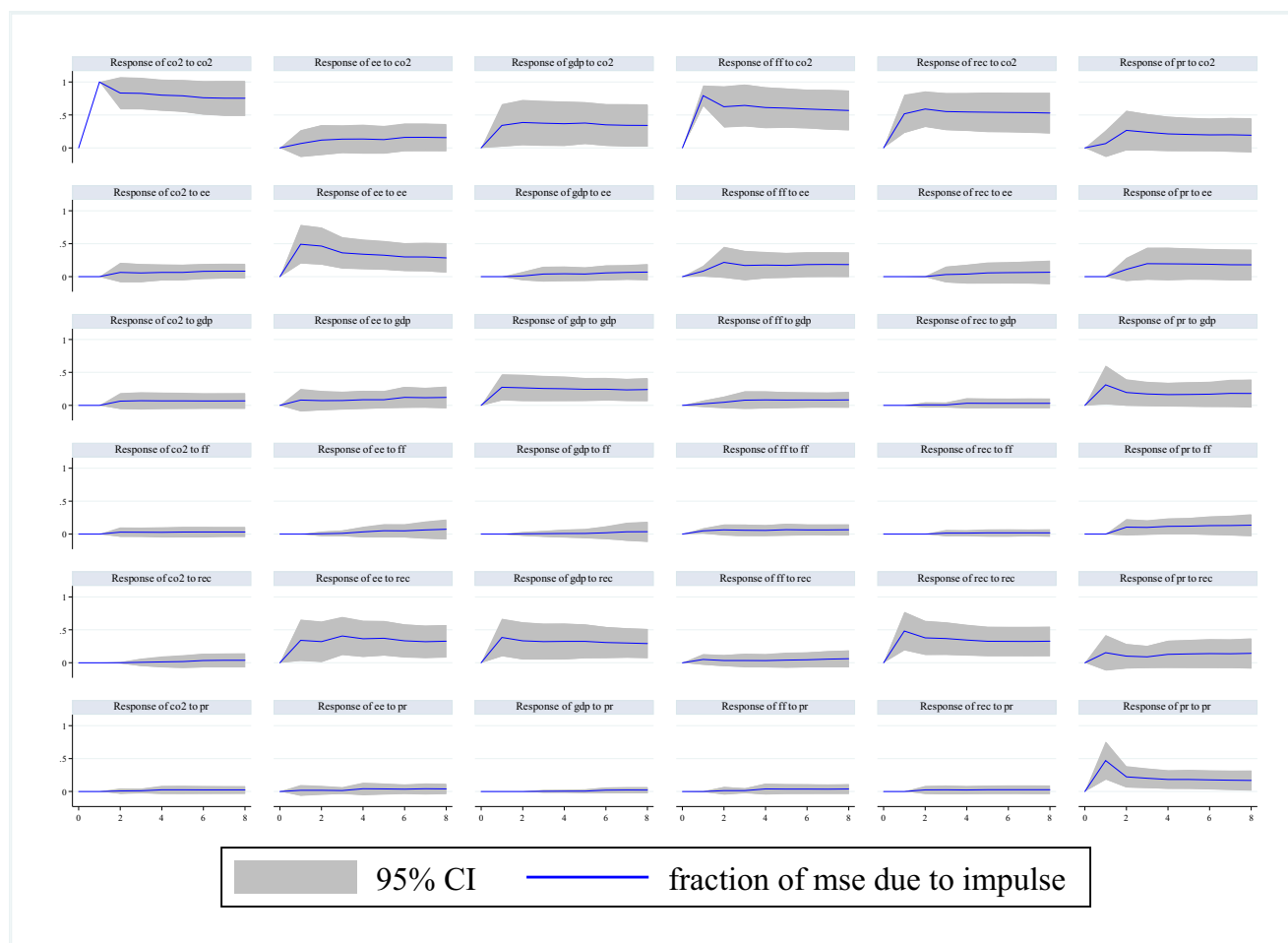


Fig. 4 Variance decomposition graph – Developed European countries

companies to use technologies that contribute to saving energy in their production chain through loans with low-interest rates. In a complementary way, promote the strengthening of companies dedicated to the manufacture of energy-saving devices.

Third, create public programs to encourage the purchase or construction of energy-efficient homes. Also, implement ordinances so that buildings' construction or remodeling have energy-saving technology in the heating, cooling systems, etc. For its part, lower taxes for the purchase of electric vehicles and appliances with low energy consumption. Fourth, environmental regulations for private property rights must be improved through laws that oblige users to follow pro-environmental practices. Fifth, companies create laws to invest in clean technology to replace fossil fuel consumption, especially in Germany and Switzerland, which have oil as their main source of primary energy. Also, taxes should be tightened on those companies that demand large amounts of fossil fuels, which could be used as a cross-subsidy to promote renewable energy consumption and accelerate the process of substitution of polluting energies. One of the limitations of the

research is the availability of data, which is why the number of countries examined is small. One of the possible extensions of the research is to examine the role of energy efficiency by industrial sector.

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Data availability The datasets used and/or analyzed during the current study are available on reasonable request.

Compliance with ethical standards

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

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