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International Environmental Agreements and CO_2 Emissions: Fresh Evidence from 11 Polluting Countries

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Abstract: This study attempts to evaluate the energy and carbon footprint within the framework of international environmental treaties and the efforts made by 11 large polluting countries to mitigate climate change. The econometric methodology accounts for the presence of cross-sectional dependence while it employs second-generation panel unit root tests and cointegrated relationships. To secure the robustness of our findings, we conduct an ARDL approach employing dynamic panel data techniques. Dynamic OLS is also applied to verify the validity of the empirical results. The empirical analysis supports that the reduction in CO_2 emissions can be achieved without a slowdown in economic activity for the sample countries. The findings suggest insightful policy implications for policymakers and government officials.

Keywords: energy use; climate change; carbon dioxide emissions; dynamic GMM models; international agreements

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1. Introduction

Energy use is the engine for economic prosperity. However, the increasing energy demand for fossil fuels induced various pollutant gases like carbon dioxide emissions. The need to tackle climate change and mitigate the consequences of global warming resulted in the implementation of various environment-related policies as well as the redesign of energy markets (electricity and gas markets). The decisive step was the remarkable Montreal Protocol, the first multilateral environmental treaty, followed by the two Rio Conventions and the United Nations Framework Convention on Climate Change (UNFCC) back in 1994 (UNFCC 2021a).

The ratification of the Kyoto Protocol by more than 190 countries from all over the world, poses explicit limits to greenhouse gasses (GHG). The Kyoto Protocol, which was adopted back in December 1997, set legally binding targets to mitigate GHG emissions for the period 2008–2012. To achieve these objectives, three flexible mechanisms were created, namely, emissions trading, joint implementation, and clean development mechanism, allowing ratified countries to effectively use the market-based mechanism. Subsequent efforts, starting in Copenh and Cancun (2010), Durban and Doha (2011), Warsaw (2013), Paris agreement (2015), Katowice summit (2018), and the final Bonn Conference (2019) highlight the necessity to mitigate CO emissions and combat climate change. The Paris Agreement on climate change mitigation aims to strengthen the ability of countries to deal with the impacts of climate change by keeping a global temperature rise well below two degrees Celsius above pre-industrial levels.

Since the ratification of the Kyoto Protocol and its entrance into force to the Paris Agreement, a series of environmental measures have been developed. For instance, in the

EU context, the EU ETS, the newly established European Target Model, and the development of the Green Deal bring to the fore both the renewables' penetration into the energy mix and the reduction of carbon footprint. Though, the implementation of environmental treaties remains obscure. Many countries do not adhere to specific goals derived from environmental agreements, especially those in the development path. The growing environmental concerns, the importance of carbon markets, and the increase in renewable energy consumption renovate the scientific interest around the energy and economic growth nexus, also offering a breeding ground for policy recommendations.

Lessening emissions and RES contribution into the energy mix grow momentum under the spectrum of the international agreements and environmental policies. Therefore, this study seeks to examine the impact of RES penetration on output growth and CO_2 abatement in 11 large economies in different development stages. Taking into account both the environmental policies and the United Nations Sustainable Development Goals (SDGs) as described in Adebayo et al. 2021 in the case of South Korea. To the best of our knowledge, the studies focusing on the biggest economies are limited (Behera and Mishra 2019; Shaari et al. 2020). In addition, the study strives to explore the potential relationship of GDP, energy use, and renewable energy consumption from the perspective of CO_2 emissions. Our attempt contributes/our contribution is to fill this gap in the current bibliography. At the core of the empirical analysis are the United States, Russian Federation, Brazil, European Union, Canada, United Kingdom, China, Saudi Arabia, Australia, Japan, and the United Arab Emirates. The period under examination is from 1996 to 2019, considering as a reference point the adoption of the Kyoto Protocol in 1997.

The main novelty of this study is the analysis of the regime of carbon dioxide emissions, energy use, economic growth, and renewable energy consumption within the framework of international environmental treaties and the efforts to mitigate climate change, using the Panel ARDL approach proposed by Perasan et al. (Pesaran et al. 1999). Hence, the ARDL includes the Pooled Mean Group (PMG), the Mean Group (MG), and the Dynamic Fixed Effect estimators to capture the long-run and the short-run equilibria among the variables.

The rest of this paper is organized as follows. Section 2 discusses the empirical literature. Section 3 describes the data and the methodology. Section 4 provides an extensive analysis of the empirical results, while Section 5 concludes the paper by offering some useful policy implications.

2. Literature Review

The current literature encompasses a plethora of studies that assess the potential linkages among the economic growth, renewable energy consumption, and carbon dioxide emissions mainly searching for causal effects among the variables of interest (see among others, Lin and Moubarak 2014; Shahbaz et al. 2019; Paramati et al. 2017; Koçak and Şarkgüneşi 2017; Fawcett et al. 2015; Liu et al. 2020; Parker and Bhatti 2020; Zhang et al. 2021a, 2021b). Whereas another group of studies explores the energy-growth nexus under the prism of Environmental Kuznets Curves (Bakirtas et al. 2014; Pata 2018; Sinha and Shahbaz 2018).

Many studies underline the relationship between economic growth and energy use concerning causality; among them, some emphasize linkages to carbon dioxide emissions (see Table 1). Apergis et al. (2010) investigating the issue of causality among GDP, renewables, and CO_2 emissions for 19 developed and developing countries, find reverse causality (Azam et al. 2021a). Bidirectional causality is ascertained in the case of 15 European countries in the short run concerning CO_2 emissions and renewable energy (Dogan and Seker 2016). Moreover, in a recent study focusing on the 10 largest economies—United States (USA), Canada, India, Iran, Japan, Russia, United Kingdom, South Korea, Germany, and China—considered as the heavy energy-consuming, and thus, the countries emitting the largest proportion/the most of CO_2 emissions, the authors employing the cointegration method in their study, deduce that the increase in renewable energy consumption positively influence economic growth and lessening in CO_2 emissions (Azam et al. 2021b).

Their findings are in favor of the conservation hypothesis underpinning a unidirectional causality from GDP to renewables in the shorth-run. The use of renewable and nuclear energy. Furthermore, Zeb investigates the causal effects among CO_2 emissions, economic growth, and nuclear energy in 25 countries and finds a short-run causality between the CO_2 and economic growth (Zeb et al. 2014). Similarly, Shaari, Abidin, and Karim support that in the short run higher economic growth results in higher CO_2 emissions in the case of 20 selected countries (Shaari et al. 2020). The authors use the ARDL-PMG approach, while they divide their sample into four distinct sub-groups based on income characteristics (high-income, upper-middle-income, lower-middle-income, and lower-income countries). Furthermore, Ben Jebli and Ozturk confirm a bidirectional causality among the CO_2 emissions, GDP, and RES energy consumption to non-RES energy consumption for 25 OECD countries (Ben Jebli et al. 2016). In a recent study named "*Causality links among renewable energy consumption, CO_2 emissions, and economic growth in Africa: evidence from a panel ARDL-PMG approach*", the findings are in favor of feedback hypothesis in the long run, while in the short run a unidirectional causality derives from CO_2 emissions to economic growth (Attiaoui et al. 2017).

Table 1. List of Empirical Studies Using ARDL and GMM models for the study of CO_2 emissions.

Study	Method	Variables	Major Findings
Azam et al. (2021a)	Panel cointegration, FMOLS, Causality test	GDP (GDP), Fossil fuels (FF), Greenhouse gases (GHG), Carbon dioxide emissions (CO_2), Intergovernmental Panel on Climate Change (IPCC), Nuclear energy consumption (NE), Renewable energy consumption (RE)	- Renewable energy consumption and nuclear energy consumption lessen CO_2 emissions; - Unidirectional causality from GDP to Renewable energy; - Bi-directional causality between nuclear energy and CO_2; - Unidirectional causality from Renewable energy to CO_2.
Adebayo et al. (2021)	ARDL, DOLS, FMOLS, ARDL Bounds test	CO_2 emissions (CO_2), Economic growth (GDP), Gross capital formation (GCF), Energy use (EC), Urbanization (URB)	- Negative relationship between GDP and CO_2 in the short run; - Positive linkage among URB, EC and GDP the in short run; - Positive relationship between GDP and CO_2 in the long run; - Positive linkage between URB and GDP in the long run.
Zakarya et al. (2015)	Cointegration analysis, FMOLS, DOLS	Per capita carbon dioxide emissions (CO_2), Gross Domestic Product (GDP), Foreign Direct Investment (FDI), Total Primary Energy Consumption (EC)	- Long-run relation between CO_2 and the explanatory variables; - Unidirectional causal relationship among CO_2, GDP, FDI, EC.
Arouri et al. (2012)	Cointegration analysis, CCE & CCE-MG procedures, PECM (Panel Error Correction Model) through the application of PMG estimation.	CO_2 emission (C), Energy consumption (E), Per capita real GDP (Y)	- Long-run equilibrium deviations impact the CO_2 emissions; - Positive relationship between CO_2 emissions and energy consumption; - Causal relation from EC to CO_2 emissions in the short run.
Syzdykova et al. (2020)	GMM & Arellano Bond approach	Economic growth (GDP), Renewable energy consumption (REC), Fossil fuels energy consumption (FEC), CO_2 emission (COE)	- REC, CO_2, and FEC have a positive impact on economic growth.
Tiwari (2011)	Structural VAR, IRFs	Renewable energy (HEC), Gross Domestic Product (GDP), Carbon dioxide emissions (CO_2)	- Positive shock on renewable energy consumption; - Positive shock on GDP and CO_2 emissions.

Evidence suggesting that renewable energy use results in economic growth is detected by Azam et al. (2021a) who studies a panel of 25 developing economies, indicating a bidirectional causality both in the short run and the long run. While a negative relationship both between renewables and carbon intensity as well as between energy intensity and renewables consumption has been denoted in the case of the five largest African economies (Olanrewaju et al. 2019). In another study, a negative relationship between renewable energy consumption and economic growth for MENA states is supported (Aimer 2020). Moreover, findings differ concerning the European Union member-states in which there is no evidence of causality between renewable consumption and GDP (Menegaki 2011). Therefore, the empirical attempts depend on various determinants of economic growth. The macroeconomic aggregates of the countries under investigation, i.e., employment rate, foreign direct investment, domestic credit, res contribution into the energy mix, and the CO_2 abatement, are of great importance. Furthermore, many researchers seeking to deal with the issues of heterogeneity across different countries examine/set sub-groups concerning income, regional, and/or demographic characteristics for instance low/high income or oil importing/oil-exporting economies (Musah et al. 2020; Aimer 2020).

3. Data and Methodology

This section discusses the estimation strategy and the methodology applied to empirically estimate the relationship between globalization and environmental degradation. Specifically, we first perform the necessary unit root testing to check for the order of integration of our sample variables, and then we proceed with the panel cointegration testing to uncover possible structural relationships and secure the validity of our findings.

3.1. Data and Variables

The study examines the relationship among carbon dioxide emissions, GDP growth, renewable energy consumption, and total energy use, via a panel data analysis for 11 developed and developing countries including large economies such as the US, UK, EU, Brazil, China, Japan, Saudi Arabia, the United Arab Emirates, Australia, Canada, and Russian Federation. The sample countries are heavily energy-dependent, and contribute to the increase of the global CO_2 emissions and thus to climate change.

We use annual observations obtained from the World Bank Development Indicators for carbon dioxide emissions, energy use, GDP, and renewable energy over the period from 1996 to 2019, within 23 years. All the variables are transformed into natural logarithms (see Table 2). The dependent variable LnCO2 is expressed in kg per PPP $ of GDP, considering the inflation rate. The lnENUSE is in terms of kg of oil equivalent per $1000 GDP, deflated (constant 2017 PPP). The explanatory variable LnGDP is used as a proxy for economic growth and is expressed in Purchasing Power Parity, accounting again for inflation. The LnRES depicts renewable energy consumption as a percentage (%) of total final energy consumption.

Table 2. Description of variables.

Variable Name	Macroeconomic Aggregate	Unit	Indicator-Source
LnCO2	Carbon Dioxide Emissions	kg per PPP $ of GDP	WDI 2021
LnENUSE	Total Final Energy Consumption	Kg of oil equivalent per $1000 GDP (constant 2017 PPP)	WDI 2021
LnGDP	Economic Growth	PPP (current international $)	WDI 2021
LnRES	Renewable Energy Consumption	% Of total final consumption	WDI 2021

3.2. Methodology and Research Design

Numerous research studies employ the Dynamic Conditional Correlation (DCC) and copula models to measure both the unidirectional and bi-directional spillover effects of interconnectedness. The DCC representation was originally introduced by Engle (2002) to capture the empirically observed dynamic contemporaneous correlations of asset returns. The DCC approach allows for a time-varying correlation and can be used to identify the interdependence and volatility transmission across equity markets (see also Do et al. 2020). Rahahleh et al. (2017) and Rahahleh and Bhatti (2017), use this approach to explain the nexus between the information flow of international equity. The relevant studies employ various versions of the DCC models to explore the stochastic forward vs. backward dynamics of financial markets along the lines of Nguyen and Bhatti (2012). Despite its merits, the DCC approach has significant limitations compared to the ARDL and GMM modeling. Specifically, DCC has no obvious or desirable mathematical or statistical properties. In addition, the relevant approach captures the dynamic conditional covariances of the standardized residuals and hence does not yield dynamic conditional correlations (see Caporin and McAleer 2013). Moreover, the DCC analysis does not have testable regularity conditions, while it yields inconsistent two-step estimators, with no asymptotic properties. All in all, DCC may be a useful filter or a diagnostic check that can capture the dynamics in what is purported to be conditional 'correlations', even if they arise through possible model misspecification.

In this study, we employ one of the most prevalent specifications in the related literature, which is the Distributed Lag model (DL). The latter can be augmented using lags of the dependent variable. This yields the Autoregressive Distributed Lag (ARDL) model and when estimated using a panel of countries, takes the following form:

$$LnCO2_{it} = a_i + \sum_{l=0}^{L} b_l Ln(ENUSE_{i,t-l}) + \sum_{l=0}^{L} c_l Ln(GDP_{i,t-l}) + \sum_{l=0}^{L} d_l Ln(RES_{i,t-l}) + \sum_{l=0}^{L} \psi_l Ln(CO2_{i,t-l}) + \varepsilon_{it}, \quad (1)$$

where $LnCO2_{it}$ is the dependent variable first step in our analysis indicating the carbon dioxide emissions, $LnENUSE_{it}$ denotes the total final energy consumption, $LnGDP_{it}$ represents the economic growth, and $LnRES_{it}$ is renewable energy consumption. a_j is a set of country dummy variables. L is the number of lags in the upstream and downstream prices and ε_{it} represents the error term, while b_l, c_l, d_l, ψ_l are the coefficients of the explanatory variables.

Our primary concern is to determine the variables' stationarity via performing the necessary unit roots tests for panel data analysis. Given that most of the macroeconomic variables suffer from unit-roots. We use the second-generation panel unit roots tests (Im-Pesaran-Shin) as well as the Perasan's CADF of cross-section dependence (Pesaran 2007). After defining the order of integration of each variable, i.e., I(d), we proceed to cointegration analysis searching for a potential long-run equilibrium among the variables under investigation.

Afterwards, an ARDL model is applied based on the Akaike criterion (AIC) for the appropriate selection of lags. The ARDL approach is preferred given that permits the existence of long-run and short-run relationships among variables with different order of integration, I(d), and is considered "*more reliable for small samples*" (Menegaki 2019). To verify the validity of results, Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares are also applied as in previous studies (Adebayo et al. 2021; Azam et al. 2021b; Zakarya et al. 2015). Moreover, to assess both the long-run and the short-run dynamics of our ARDL model, we proceed to PMG, MG, and DFE estimations and the appropriate Hausman tests, dealing with issues of heterogeneity across the group of countries, as proposed by Pesaran, Shin, and Smith (Pesaran and Smith 1995; Pesaran et al. 1999). The PMG method permits the existence of "*short run relationships containing the coefficients, the speed of adjustment and the error variances to be heterogenous, while PMG assumes that the long-run coefficients are the same*, i.e., *identical and homogenous for all the countries in the panel*" (Shaari et al. 2020). Under the MG technique, heterogeneity is assumed both in the short and long run, while the results are consistent even if the regressors are I(1) (Pesaran et al. 1999). The Dynamic Fixed Effect (DFE) technique is similar to the PMG estimator providing consistency to lo run estimations. Furthermore, it restricts the adjustment coefficient giving reliable results in the short run.

Depending on various macroeconomic factors such as environmental policies or economic development, we can select the most appropriate model accounting for long-term homogeneity or heterogeneity among the examined countries.

The long-run equation under the MG framework is as follows:

$$LnCO2_{it} = \alpha_i + \beta_{0i}LnCO2_{i,t-1} + \beta_{1i}LnENUSE_{i,\,t-1} + \beta_{2i}LnGDP_{i,\,t-1} + \beta_{3i}LnRES_{i,\,t-1} + \varepsilon_{it}. \tag{2}$$

In the context of ARDL-PMG and DFE, our reference model, Equation (1), will take the following form in the long run, as in Shaari, Abidin, and Karim (Shaari et al. 2020):

$$LnCO2_{it} = \beta_i + \sum_{j=1}^{p} \lambda_{ij}LnCO2_{I,\,t-j} + \sum_{j=0}^{q} d_{1ij}LnENUSE_{i,\,t-j} + \sum_{j=0}^{r} d_{2ij}LnGDP_{i,\,t-j} + \sum_{j=0}^{s} LnRES_{i,\,t-j} + \varepsilon_{it}, \tag{3}$$

where t represents the period (1996–2019), i denotes the countries in our sample, β_i is the countries specific effect, p, q, r, s represent the optimal lag length, while ε_{it} is the error term.

To capture the short-term dynamics, we proceed to an Error-Correction Model (ECM). Within the framework of the ECM, the Equation (2) becomes:

$$\begin{aligned}\Delta LnCO2_{it} = \alpha_i + \varphi_i(LnCO2_{i,\,t-1} - \lambda_1 LnENUSE_{i,t-1} - \lambda_2 LnGDP_{i,t-1} - \lambda_3 LnRES_{i,t-1}) + \sum_{j=1}^{p} \lambda_{ij}\Delta LnCO2_{i,\,t-j} + \\ \sum_{j=1}^{q} \delta_{1ij}\Delta LnENUSE_{i,\,t-j} + \sum_{j=1}^{r} \delta_{2ij}\Delta LnGDP_{i,\,t-j} + \sum_{j=1}^{s} \delta_{3ij}\,\Delta LnRES_{i,\,t-j} + \varepsilon_{it}.\end{aligned} \tag{4}$$

In the above equation λ_i declares the long-run parameters, φ_i represents the error-correction term measuring the speed of adjustment to the long-run equilibrium.

Dynamic GMM Models

To check for the robustness of our findings, we re-estimate the two price and revenue equations by employing a GMM estimator that controls for the endogeneity (Hansen 1982). The latter can be a problem because, if unobserved, variables jointly affect both the dependent and control variables, then the coefficient estimates for the independent variables may be biased (Abrevaya et al. 2010). For this reason, we utilize a dynamic GMM estimator developed in Arellano and Bond (1991). This estimator considers the unobserved time-invariant bilateral specific effects, while it can deal with the potential endogeneity arising from the inclusion of several control variables. The primary reason for using this estimator is that it increases efficiency in cases where the lagged levels of the regressor are poor instruments for the first-differenced regressors. Moreover, Blundell and Bond (1998, 2000) showed that when the dependent variable is persistent, then the accuracy of the estimates is dramatically improved using the dynamic-GMM.

A Dynamic Panel Analysis on the grounds of Generalized Methods of Moments and Arellano–Bond procedure is employed, as in the recent study of Aziza Syzdykova et al. (2020). Thus, we obtain the following equation:

$$y_{it} = x_{it}\beta + y_{i,\,t-1} + c_i + \mu_{it}. \tag{5}$$

Arellano–Bond approach surpasses the problem of heterogeneity in term c_{it} which is the same for every observation in each group, suggested also for panels with small T and large N. Therefore, the dynamic panel regression within the Arellano–Bond framework will be expressed as follows:

$$LnCO2_{it} = \alpha LnCO2_{i,t-1} + \beta X_{it} + \eta_{it} + \varepsilon_{it}, \tag{6}$$

where $LnCO2_{it}$ represents the carbon dioxide emissions of country I at year T, $LnCO2_{i,t-1}$ indicates the carbon dioxide emissions of country I at year $T-1$, while X_{it} represents the set of variables including arguments. Furthermore, the parameters of the lagged value of the dependent variable are α and β (Syzdykova et al. 2020).

4. Results and Discussion

This section discusses the estimation strategy and the methodology applied to empirically estimate the relationship between energy use and environmental degradation. Specifically, we first perform the necessary unit root testing to check for the order of integration of our sample variables. Then we proceed with the panel cointegration testing to uncover possible structural relationships and secure the validity of our findings.

4.1. Panel Unit Root Tests and Cointegration

Before applying unit root tests, we need to check for the applicability of the first or second-generation unit root tests. Specifically, one of the additional complications that arise when dealing with panel data compared to the pure time-series case is the possibility that the variables or the random disturbances are correlated across the panel dimension. The early literature on unit root and cointegration tests adopted the assumption of cross-sectional independence (Pesaran 2014).

Table 3 shows that the variables are not stationary at level, while examining their first difference they become stationary, thus integrated of order one I(1), except for the Fisher unit root test for LnCO2, LnGDP, and LnRES in which we reject the null hypothesis (Ho) that "*all the panels contain unit roots*" (see Table 4).

Table 3. Results of the first generation panel unit root tests.

Variables	Levels				First Differences			
	Harris–Tzavalis Rho Statistic	Breitung Lambda	IPS Z-t-Tilde-Bar	LLC Adjusted t	Harris-Tzavalis Rho Statistic	Breitung Lambda	IPS Z-t-Tilde-Bar	LLC Adjusted t
LnCO2	0.8820	−0.5626	2.5490	−1.6952 **	−0.0342 *	−3.4255 *	−8.4071 *	−5.4308 *
LnENUSE	1.0055	0.4131	5.3941	−0.8329	−0.0544 *	−2.9704 *	−4.3692 *	−4.3348 *
* LnGDP	0.9716	1.3345	1.7090	−3.2460 *	0.2601 *	−2.0617 **	−6.0792 *	−4.4124 *
LnRES	0.8486	−0.3774	1.3915	0.7428	−0.2779 *	−4.2287 *	−7.9931	−6.2858 *

Note: * denotes statistical significance at 1%, ** denotes statistical significance at 5%.

Table 4. Second-generation Fisher-type unit-root test.

Variables	Levels				First Differences			
	P Stat.	Z Stat.	L Stat.	Pm Stat.	P Stat.	Z Stat.	L Stat	Pm Stat
LnCO2	42.4766 *	−2.7372 *	−2.7664 *	3.0870 *	158.8423 *	−10.5017 *	−13.3151 *	20.6297 *
LnENUSE	29.9308	0.0874	0.2325	1.1956	85.1932 *	−6.5331 *	−7.0323 *	9.5267 *
LnGDP	44.4052 *	−3.6365 *	−3.4314 *	3.3777 *	104.0324 *	−7.7872 *	−8.6958 *	12.3668 *
LnRES	50.4069 *	−3.5916 *	−3.7486 *	4.2825 *	191.8582 *	−11.6248 *	−16.0841 *	25.6071 *

Note: The Fisher unit root test includes drift. * Denotes statistical significance at 1%.

After examining the issue of stationarity, we proceed to the necessary cointegration tests. We employ Kao, Pedroni, and Westerlund cointegration tests. Based on the five tests under the Kao cointegration test, we conclude that the variables are cointegrated, and the Ho of "No cointegration" is rejected (see Table 5). Westerlund's test shows that the variables are cointegrated. However, at the 10% significance level. Likewise, we examine cointegration with the Pedroni test—assuming that AR is the same for all the panels including and excluding trend—and we find that the existence of cointegration among the variables. Our results for the existence of a long-run relationship among the variables under investigation are consistent with previous empirical findings (Azam et al. 2021a; Adebayo et al. 2021; Zakarya et al. 2015; Arouri et al. 2012).

Table 5. Cointegration testing.

Test					
Kao	Modified Dickey–Fuller t −3.2098 *	Dickey–Fuller t −1.5122 ***	Augmented Dickey–Fuller t −1.7528 *	Unadjusted modified Dickey–Fuller t −3.5204 *	Unadjusted Dickey–Fuller t −1.6316 **
Westerlund		Variance ratio −1.5951 ***			
Pedroni	Modified variance ratio 1.4941 **	Modified Phillips-Perron t −1.5084 ***	Phillips–Perron t −3.8687 *	Augmented Dickey–Fuller t −4.3251 *	
Pedroni including trend	Modified variance ratio −0.0672	Modified Phillips–Perron t −0.2661	Phillips–Perron t −4.5015 *	Augmented Dickey–Fuller t −5.0281 *	

Note: In Pedroni's test, the AR parameter is considered the same for all panel data. * Denotes statistical significance at 1%, ** denotes statistical significance at 5%, *** denotes statistical significance at 10%.

4.2. Empirical Findings

Using four different methods to estimate the long-run relationships, we find that energy use has a positive impact on carbon dioxide emissions. All the estimates prove that LnENUSE results in higher carbon emissions (LnCO2) at the 1% level of significance (see Table 6). A 1% increase in energy use increases CO_2 emissions by 1.73% according to PMG estimations, while an increase by 1.52% is deducted by the MG estimator. The DFE estimator also suggests an increase of approximately 1.22%. As far as the economic growth things differ. The PMG and DOLS estimates suggest that LnGDP and LnCO2 have a negative relationship; a 1% increase in GDP would reduce carbon emissions by 0.14% and 0.31%, respectively. Our findings are in alignment with the study of Dagoumas et al. (2020), where they observe a negative relationship between an increase in CO_2 and economic growth. Similarly, the coefficient of DFE proves evidence of a negative relationship, but at the 10% significance level. Our results concerning the effects of renewable energy consumption on carbon dioxide emissions are not statistically significant indicating that LnRES does not influence LnCO2, unlike Azam et al. (2021b) who suggest that renewable energy lessens CO_2 emissions.

The error-correction term (ECT) has a negative sign and is strongly statistically significant, satisfying the conditions of negative value and statistical significance in every estimation method. The ECT in PMG depicts that the variables interact with a speed of adjustment of −0.45 in the short term to restore the long-run equilibrium, similarly, the speed of adjustment in MG is −0.76, while the ECT of −0.39 in the Dynamic fixed effects technique implies that LnCO2 moves towards the long-run equilibrium by approximately 39% during the first year.

Table 6. Long run estimations.

		Variable	
Method	**LnENUSE**	**LnGDP**	**LnRES**
ARDL: PMG	1.73041 *	−0.1494257 *	−0.0229969
ARDL: MG	1.522632 *	−0.1595731	0.4281658
ARDL: Dynamic FE	1.22245 *	−0.1939003 ***	−0.021652
DOLS	1.064211 *	−0.313543 *	−0.016413

Note: * denotes statistical significance at 1%, *** denotes statistical significance at 10%.

In the short run, a 1% increase in lnENUSE results in a moderate reduction in LnCO2 according to both the MG and FE results (see Table 7). Furthermore, the PMG denotes a negative relation, but at the 10% level of significance which is contrary to previous studies such as Arouri et al., Mohamed El Hedi et al. that find a positive causal linkage between CO_2 and energy consumption (Zakarya et al. 2015). Concerning the LnGDP, we find evidence of a negative linkage between carbon dioxide emissions and GDP only within the MG framework; a 1% increase in LnGDP lessens carbon dioxide emissions by 0.34%. Our results are similar to Adebayo et al. (2021) where a negative short-run relation between GDP and CO_2 is reported. However, our findings differ from Attiaoui et al. where authors find a positive linkage between CO_2 emissions and GDP in both the long and the short run (Attiaoui et al. 2017). Regarding renewable energy consumption, the estimates do not provide evidence of a potential linkage that differs from previous empirical attempts (Azam et al. 2021a; González-Sánchez and Martín-Ortega 2020). The Hausman tests for PMG, MG, and DFE estimations prove that PGM is superior to MG estimation and Dynamic FE estimates are also preferred to PMG.

Table 7. Short-run estimations.

		Variable			
Method	**Error-Correction Term**	**LnENUSE**	**LnGDP**	**LnRES**	**Constant**
ARDL: PMG	−0.453 *	−0.485 **	−0.035	0.054	−2.270 *
MG	−0.767 *	−0.737 *	−0.336 **	−0.018	0.3006
Dynamic FE	−0.398 *	−0.476 *	−0.095	0.0246	−0.568

Note: * denotes statistical significance at 1%, ** denotes statistical significance at 5%.

4.3. Robustness Checks

This section presents the robustness checks by incorporating the dynamic GMM analysis, which accounts for the possible endogeneity and reverses the causality of our models.

Our Dynamic Panel Analysis using the GMM and Arellano Bond method deducts that the lagged value of the dependent variable and the renewable energy consumption is significant at the 1% significance level (see Table 8). The coefficient of renewable energy use shows that a 1% increase in the level of renewable consumption increases by 0.09% of the CO_2 emissions. Likewise, the lagged value of carbon dioxide emissions has a positive effect on present carbon dioxide emissions, namely, an increase of 1% leads to an increase of 0.79 points.

Table 8. Dynamic GMM estimations.

Variables	**Coefficients**
LnCO2	0.7979 * (0.000)
LnEnuse	0.0383 (0.351)
LnGDP	−0.092 (0.545)
LnRes	0.096 * (0.001)
Tests	
Sargan test	9.478 (0.9849)
AR(1)	−2.488 (0.0128) **
AR(2)	−0.0664 (0.5066)

Note: * denotes statistical significance at 1%, ** denotes statistical significance at 5%. *p*-values are in parentheses.

The results of the Sargan test indicates that the model is specified well, likewise examining for serial correlation, the Arellano–Bond test provides evidence of first-degree autocorrelation, AR(1) is negative and statistically significant at the 1% level, while the null hypothesis of no autocorrelation of order 2 cannot be rejected. Thus, the estimates satisfy the Arellano–Bond assumptions.

5. Conclusions and Policy Implications

This study seeks to investigate the level of compliance of 11 robust economies within the framework of international environmental treaties and the effort to mitigate climate change. For this reason, the selected countries are large economies under different phases of their economic cycle. Considering that these countries rely heavily on energy use we expect a higher level of GHG emissions. Therefore, our attempt seeks to explore the potential linkages of economic growth and energy use on carbon dioxide emissions alongside the contribution of RES into the energy mix. The reference period spans from 1996 to 2019 as the efforts to combat the negative implications of climate change become more intensive. This paper aims to investigate if the large economies comply with the international environmental agreements, and thus, contribute to carbon emissions abatement.

It is critical to mention that the negative relationship derived from GDP and carbon dioxide emissions supports the assumption that economic prosperity can be achieved without harming the environment, even in heavily energy-consuming economies. Furthermore, an increase in GDP leads to a slight reduction in carbon emissions. These findings suggest that the sample economies show signs of compliance. However, policymakers must speed up the efforts to differentiate their energy mix and pose further restrictions to conventional energy sources such as fossil fuels.

On the contrary, in the long run, energy use increases carbon dioxide emissions. The relevant findings coincide with previous studies that find a positive relationship between carbon dioxide emissions and energy consumption (see among others Syzdykova et al. 2020; Zakarya et al. 2015; Adebayo et al. 2021). However, our short-run estimates differentiate from earlier studies (Arouri et al. 2012). In this study, the energy use does not affect carbon emissions, given that a negative relation between emissions and energy use is detected. Nonetheless, the long-run coefficients sustain that the 11 polluting countries preserve a low rate of change concerning energy use and carbon emissions. Therefore, the energy use amplifies the CO_2 emissions suggesting that the sample countries rely heavily on traditional energy sources.

Moreover, the absence of statistical significance regarding the energy use in some of the estimated models exemplifies that renewable energy consumption does not contribute to carbon dioxide emissions. This means that maximizing renewable energy consumption safeguards both economic development and environmental treaties. However, unlike González-Sánchez and Martín-Ortega (2020), the GMM estimators show that energy use exhibits a positive effect on carbon dioxide emissions leading to a slight increase in the overall environmental degradation.

Based on the above, our empirical attempt supports that economic growth can be achieved without a significant increase in carbon emissions. This finding is of paramount importance, especially for "*weak*" and emerging economies where economic and technological constraints prevent energy differentiation and clean energy use. Thus, the optimum solution for these countries is to invest in clean energy infrastructures and encourage RES investments. Our findings also indicate that the sample polluting countries must accelerate their efforts to mitigate climate change.

Hence, the applied international treaties will have a positive impact and do not harm economic growth even in large polluting economies. This deduction is crucial for international and government agencies to shape and implement the right energy-related policies. A clear message to policymakers and government officials is to intensify the penetration of renewable energy sources into the energy mix, and strengthen the regime of carbon markets through limitations in emission allowances. In parallel, governments must provide more incentives to large firms and domestic consumers to use clean energy sources.

This study can be extended in several ways. First, future research may explore similar research questions in other countries or spatial units (i.e, regions, municipalities, provinces). This would greatly enhance the reliability and the robustness of the empirical results. Second, to study in-depth possible nonlinear effects, one can use non-parametric or semi-parametric techniques to precisely estimate the shape and the possible "*turning*" point(s) of the CO_2 emissions function. In this way, certain environmental policies might be applied to better supplement the international climate agreements. Third, an alley for future research may be to include spatial or trade aspects such as the geographical proximity and trade flows to uncover possible spillover effects and identify the underlying sources of these different patterns among the sample units. Fourth, this study focuses on one global pollutant (CO_2 emissions), which is related to global warming and the international climate agreements (Paris Agreement). Consequently, future research could focus on the assessment of all greenhouse gases to further check and validate the results of this analysis.

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