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The Role of Economic and Financial Development in Shaping Environmental Quality: A Comparative Study of Developed and Developing Countries

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Abstract

This study investigates the relationship between environmental quality, economic growth, financial development, renewable energy, and trade openness in both developing and developed countries from 1990 to 2022. The analysis uses the Pedroni (1999, 2004) and Kao (1999) cointegration tests, followed by panel Fully Modified Ordinary Least Squares (FMOLS) estimations. The results indicate that environmental quality, GDP growth, energy consumption, renewable energy, financial development, and trade openness are interconnected in the long term. According to the panel FMOLS results, renewable energy consumption and trade openness help reduce carbon emissions in both groups of countries, with a stronger effect observed in developing economies. Additionally, the Dumitrescu–Hurlin (2012) panel causality test reveals unidirectional causality from GDP growth, financial development, renewable energy, and energy use—though not from trade openness—to carbon emissions, supporting the growth hypothesis in the short term. Overall, the results highlight the important role of renewable energy and financial development in forming carbon emissions reduction strategies. The study provides valuable policy insights, especially for developing countries aiming to improve environmental sustainability.

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1. Introduction

Energy constitutes a fundamental prerequisite for human sustenance and development. Energy fulfills essential human needs, including heat, light, motion, sound, industrial production, and cultural and athletic activities, thereby playing a pivotal role in the existence of individuals, corporations, and nations. In the contemporary era, where energy resources are finite and the global population and living standards are rising continuously, energy has become an indispensable component of modern life and a fundamental driver of development, particularly considering rapid technological progress.

This growth in energy demand and consumption, while beneficial, also entails adverse outcomes such as environmental degradation, climate change, concerns over energy supply security, and increased costs of goods and services (Aridi et al., 2025). Climate change and global warming, largely driven by carbon dioxide (CO_2) emissions, are among the most pressing global challenges. These issues have become central to policymaking at both national and international levels (Choudhury et al., 2023). Achieving sustainable development while controlling CO_2 emissions requires a delicate balance between economic growth objectives and environmental stewardship. The escalation in energy consumption and anthropogenic activities has resulted in a marked increase in atmospheric CO_2 concentrations. This phenomenon significantly contributes to climate change, disrupts ecosystems through altered weather patterns, and induces profound ecological impacts worldwide (Lee et al., 2022; Seo and Hatton, 2023). Rising atmospheric CO_2 concentrations play a central role in accelerating global warming, posing significant risks to food security, coastal populations, and the integrity of marine ecosystems and the services they provide (Oloyede et al., 2021). According to projections by the Intergovernmental Panel on Climate Change, existing emission levels may rise substantially by 2050, exacerbating an already critical situation and raising the risk of severe environmental degradation without urgent intervention (Lee et al., 2022). Consequently, the formulation and implementation of comprehensive strategies to address rising CO_2 levels are imperative.

In response to this challenge, international organizations, governments, non-governmental bodies, and researchers are increasingly focusing on enhancing energy efficiency, promoting cleaner energy use, and developing alternative energy sources to satisfy growing demand. Efforts in areas such as renewable and green energy have intensified, and international agreements like the Kyoto Protocol have been established to curb carbon emissions and reduce reliance on fossil fuels (Maka et al.,2024). Furthermore, policymakers in various nations are instituting regulatory and voluntary mechanisms to limit greenhouse gas emissions, support energy efficiency, and foster investment in clean energy technologies (Radtke and Renn, 2024). These initiatives aim to generate clean energy opportunities, enhance energy efficiency, mitigate environmental harm, ensure supply security, and sustain economic development. Nevertheless, an analysis of global primary energy consumption by source from 1980 to 2024 reveals that, despite rising overall demand, fossil fuels continue to dominate the energy mix. Although clean energy initiatives have gained momentum, fossil fuel consumption has increased steadily since 2000 (Global Carbon Budget, 2024), and the proportion of low or zero-carbon resources in the total energy economy remains modest (Aridi et al.,2025). This underscores the considerable difficulty in reducing CO_2 emissions.

The problem of high CO_2 emissions associated with rising energy consumption has attracted scholarly attention across disciplines, including economics. In this context, the relationship between economic growth and CO_2 emissions has become a prominent research theme. A substantial body of literature has explored the interconnections among CO_2 emissions, energy consumption, and economic growth, incorporating various macroeconomic variables. However, a consensus regarding the nature of this relationship has yet to emerge. This study examines the effects of economic growth, energy consumption, trade openness, foreign direct investment, renewable energy consumption, and financial development on CO_2 emissions across groups of developed and developing countries. The objective is to conduct a comparative analysis that highlights differences between these two groups, acknowledging the role of national development stages in shaping the complex dynamics between these variables and CO_2 emissions. Country classifications are based on the World Bank income categories. The developed and developing nations exhibit distinct socioeconomic dynamics, suggesting that CO_2 emission policies should be tailored accordingly. An examination of the top ten CO_2-emitting countries reveals divergent emission trajectories linked to development levels (Global Carbon Budget, 2024). For instance, the United States reached a peak of approximately six billion tons of CO_2 in the mid-2000s and has since significantly reduced emissions, a trend attributable to structural economic shifts from industry to services, improved energy efficiency, and the adoption of clean energy technologies. Countries such as Germany and Japan have maintained relatively low and stable emission levels from 1980 to 2023, with minor declines, reflecting a capacity for environmental quality preservation through technological and structural innovation (Global Carbon Budget, 2024).

In contrast, major rapidly developing economies like China and India remain in a high-emission growth phase. China's emissions surged sharply after 2000, rising from about four billion tons to over twelve billion tons, making it the largest emitter globally. India has also experienced a steady and substantial increase in emissions, particularly after 2000, ranking third after the United States. Given these divergent trends, a uniform approach to evaluating emission trajectories or proposing policy solutions is inappropriate (Global Carbon Budget, 2024). Thus, this study analyzes the determinants of CO_2 emissions separately for developed and developing country groups. This approach addresses the issue of cross-group heterogeneity and underscores the importance of sustainable economic growth and financial development. The findings aim to support the design of effective environmental policies for CO_2 emission control.

The remainder of this study is structured as follows: Section 2 reviews the literature on the relationship between economic and financial development and CO_2 emissions. Section 3 outlines the empirical model and data. Section 4 presents the findings. The final section summarizes the results and offers policy recommendations

2. Literature Review

In recent years, numerous studies have investigated the intricate relationship between economic development and environmental quality. However, it is observed that a consensus has not yet been reached regarding the determinants of this relationship or its underlying dynamics. A selection of studies examining certain variables which are considered important determinants in explaining this relationship are also addressed within the scope of the present study that is presented below.

2.1. Economic Development and Carbon Dioxide Emissions

A review of the literature indicates that the complex interactions between two variables, such as economic development and CO_2 emissions, have been extensively discussed. Some of these studies point to the existence of a positive correlation, while others mention a more nuanced, non-linear relationship. For example, studies such as (Friedl and Getzner, 2003; Galeotti et al., 2006; Sulaiman, 2013; Xue et al., 2014; Salahuddin et al., 2015; Munir et al., 2020; Kostakis et al., 2023; Khosravi et al., 2024) have concluded that there is an inverted U-shaped relationship between CO_2 emissions and economic growth.

Accordingly, it is stated that CO_2 emissions initially increase with economic development, but as countries turn to more sustainable practices and technologies, they eventually stabilize or begin to decrease (Sulaiman et al., 2013). This situation is also noted to be consistent with the findings of the Environmental Kuznets Curve model, which argues that economic growth may lead to an increase in CO_2 emissions up to a certain point, after which emissions tend to decrease as economies mature and cleaner technologies are adopted. However, findings from studies such as (Lean and Smyth 2010; Narayan and Narayan 2010; Chandran and Tang 2013) have not supported this theory. Some studies, on the other hand, address the relationship between economic growth and the environment within a broader framework. These studies emphasize that the effects of growth on CO_2 emissions can vary depending on various factors such as the institutional structures, technological advancements, and demographic characteristics of countries. Indeed, some studies reveal that in countries with high institutional quality, economic growth reduces carbon emissions (Halkos and Gkampoura, 2021), whereas in

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countries with weak institutional structures, growth increases emissions (Galeotti and Lanza, 2005; Yao et al., 2019).

2.2. Energy Consumption and Carbon Dioxide Emissions

The empirical literature focusing on the relationship between energy use and environmental quality has long examined the environmental impacts of energy consumption and production. A key finding of these studies is that fossil fuel use, in particular, is a major factor contributing to environmental degradation (Khatun et al., 2017; Bekun et al., 2021). Indeed, this dependence on fossil fuels not only negatively affects the environment but also places a significant burden on economies (Kaygusuz, 2011; Toklu, 2013). Energy consumption, which is one of the variables included in this study, is frequently criticized for its relationship with environmental degradation.

Since CO_2 emissions are largely driven by fossil fuel consumption, limiting energy use can be regarded as a direct way to address environmental pollution. However, because reducing energy consumption may have adverse effects on economic growth, abandoning economic growth for the sake of reducing CO_2 emissions and mitigating the negative impacts of climate change appear to be an unacceptable option for both developing and developed countries (Coondoo and Dinda, 2002). Because of this complex relationship that constrains countries in reducing CO_2 emissions, some researchers have focused on disaggregating energy types to emphasize the differing impacts of fossil and non-fossil fuels on the environment and sustainability (Anser et al., 2020; Anwar et al., 2021). In a large part of these empirical studies conducted, the negative role of fossil fuels and overall energy consumption on the climate and environment is is emphasized. Another study focusing on the Asia-Pacific Economic Cooperation (APEC) countries by Balli, et al., (2023) also concluded that there is a positive and significant relationship between energy consumption and CO_2 emissions in all member countries, and that emissions increase as energy consumption rises. It has been observed that the findings obtained from studies conducted in different country groups, such as Leitão et al., (2021); Bekun, (2022); Ahmed et al., (2023); Suproń, and Łącka, (2023), also support this relationship.

2.3. Renewable Energy and Carbon Dioxide Emissions

Renewable energy emerges as an alternative energy source not only for reducing fossil fuel consumption but also for mitigating CO_2 emissions (Apergis and Payne, 2012). This position is corroborated by studies indicating that increasing the utilization of, and investment in, renewable energy, while not promising a simple transition process, can nonetheless play a critically determinant role in achieving superior environmental quality (Sims et al., 2007; Bekun et al., 2021; Usman et al., 2023). For instance, a study conducted by Perone (2024) on OECD countries demonstrated that renewable energy sources, such as geothermal, hydroelectric, and solar energy, are significantly effective in reducing CO2 emissions, and indicates a unidirectional causality from these energy sources to emission reduction. Similarly, the study by Rahman et al. (2024) revealed that in major fossil fuel-consuming nations, renewable energy has a statistically significant and negative impact on carbon emissions, thereby highlighting its proactive role in enhancing environmental sustainability. This inverse relationship between renewable energy and CO_2 emissions is also supported by the findings obtained from studies such as those by Mukhtarov et al. (2022); Xu et al. (2023); and Zuhal and Göcen (2024). In this context, it was deemed beneficial to include a variable for the level of renewable energy usage within the scope of this study to empirically test its impact on CO_2 emissions.

2.4. Trade Openness and Carbon Dioxide Emissions

The other variable included in the study, Trade Openness, has been observed to create both positive and negative effects on the environment in both developed and developing countries, primarily through changes in trade patterns associated with the prevalence of global supply chains. For example, due to trade openness, developed countries significantly reduce their production of polluting commodities (Mehra and Das, 2008). Additionally, the liberalization of trade facilitates the transfer of innovative and green technologies that can enhance environmental quality (Shahbaz et al., 2013; Kostakis et al., 2017; Agheli & Taghvaee, 2022). Similarly, findings suggest that more open economies follow and implement more robust environmental policies that mitigate pollution (Danish et al., 2019; Omojolaibi and Nathaniel, 2020). Conversely, studies have also emerged advancing the view that greater trade potential can lead to the depletion of natural resources, causing higher demand for both production and consumption, thereby potentially increasing air pollution and environmental degradation (Ekwueme and Zoaka, 2020; Chhabra et al., 2023; Wang et al., 2024).

2.5. Financial Development and Carbon Dioxide Emissions

The final variable included in the study is financial development. Numerous researchers have examined the relationship between financial development and the environment. Given the varying levels of economic development between developed and developing nations, the literature presents divergent findings for both country groups (Shoaib et al., 2020). Certain studies contend that financial development encourages consumers to take on more credit to purchase houses, cars, and other goods. These purchases, in turn, lead to a direct increase in energy demand and a subsequent rise in CO_2 emission levels (Zhang, 2011). Conversely, other studies have concluded that financial development can have positive environmental impacts (Khan and Ozturk, 2021; Hafeez et al., 2018; Sethi, 2020). According to this view, the financial system possesses the potential to redirect capital flows. Consequently, by channeling capital, it can facilitate the improvement of the industrial structure and enable the gradual phasing out of outdated, highly polluting enterprises (Shahbaz et al., 2018; Bekun, Emir and Sarkodie, 2019; Haug and Ucal, 2019; Canh et al., 2020).

3. Methodology

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We investigate the relationship between carbon emissions, financial development, energy use, trade openness, and other controlling variables. In our analysis, we first examine the stationarity of variables. In the second step, we check the presence of cointegration analysis by the Panel Pedroni and Panel Kao test. In the third step, we investigate the relationship between carbon emissions and other variables through Panel FMOLS estimation. Lastly, we examine the causal relationship between variables through the Dumitrescu and Hurlin (DH) causality test.

We employed a panel data set which was collected for 14 developing and 12 developed countries from 1990 to 2022 (see Table 1). Data sources and variable descriptions are shown in Table 2.

Table 1. List of Countries Included in the Scope of the Study

Developed Countries	**Developing Countries**
Canada	Argentina
France	Belarus
Germany	Bosnia and Herzegovina
Italy	Brazil
Japan	China
United States (USA)	Costa Rica
United Kingdom (UK)	Jordan
South Korea	Kazakhstan
Singapore	Malaysia
Finland	Mexico
Norway	Russia
Switzerland	South Africa
-	Thailand
-	Turkey

Source: World Bank, 2025.

Seven (7) distinct models were developed within the scope of this study. In all the models formulated, the variables of energy consumption (LNEU), economic growth (LNGDP), renewable energy consumption (REC), and trade openness (TRD) were positioned as core determinants. The financial development variable, conversely, was examined and tested through its various dimensions. To this end, it was aimed to analyze the distinct effects of the sub-components of financial development—namely, Financial Institutions (FII, FIA, FID) and Financial Markets (FMI, FMA, FMD) variables—separately within the framework of each constructed model. The models constructed accordingly are detailed below.

Table 2. Variables and Data Sources

Variables	**Definition**	**Source**
LNCO2	log CO2 emissions (kt)	World Bank
LNEU	log Energy use (kg of oil equivalent per capita)	World Bank
LNGDP	log GDP (constant 2015 US$)	World Bank
REC	Renewable energy consumption (% of total final energy consumption)	World Bank
TRD	Trade (% of GDP)	World Bank
FIA	Financial Institutions Access Index	World Bank
FID	Financial Institutions Depth Index	World Bank
FII	Financial Institutions Index	World Bank
FMA	Financial Markets Access Index	World Bank
FMD	Financial Markets Depth Index	World Bank
FMI	Financial Markets Index	World Bank

Source: Created by authors

Model 1;

$$LN(CO2_{it}) = \alpha_{1i} + \beta_{1i}LNEU_{it} + \beta_{2i}LNGDP_{it} + \beta_{3i}REC_{it} + \beta_{3i}TRD_{it} + \beta_{4i}FII_{it} + \beta_{5i}FMA_{it} + \varepsilon_{it} \quad (1)$$

Model 2;

$$LN(CO2_{it}) = \alpha_{1i} + \beta_{1i}LNEU_{it} + \beta_{2i}LNGDP_{it} + \beta_{3i}REC_{it} + \beta_{4i}TRD_{it} + \beta_{5i}FII_{it} + \varepsilon_{it} \quad (2)$$

Model 3;

$$LN(CO2i_{t}) = \alpha_{1i} + \beta_{1i}LNEU_{it} + \beta_{2i}LNGDP_{it} + \beta_{3i}REC_{it} + \beta_{4i}TRD_{it} + \beta_{5i}FIA_{it} + \varepsilon_{it} \quad (3)$$

Model 4;

$$LN(CO2_{it}) = \alpha_{1i} + \beta_{1i}LNEU_{it} + \beta_{2i}LNGDP_{it} + \beta_{3i}REC_{it} + \beta_{4i}TRD_{it} + \beta_{5i}FID_{it} + \varepsilon_{it} \quad (4)$$

Model 5;

$$LN(CO2_{it}) = \alpha_{1i} + \beta_{1i}LNEU_{it} + \beta_{2i}LNGDP_{it} + \beta_{3i}REC_{it} + \beta_{4i}TRD_{it} + \beta_{5i}FMI_{it} + \varepsilon_{it} \quad (5)$$

Model 6;

$$LN(CO2_{it}) = \alpha_{1i} + \beta_{1i}LNEU_{it} + \beta_{2i}LNGDP_{it} + \beta_{3i}REC_{it} + \beta_{4i}TRD_{it} + \beta_{5i}FMA_{it} + \varepsilon_{it} \quad (6)$$

Model 7;

$$LN(CO2_{it}) = \alpha_{1i} + \beta_{1i}LNEU_{it} + \beta_{2i}LNGDP_{it} + \beta_{3i}REC_{it} + \beta_{4i}TRD_{it} + \beta_{5i}FMD_{it} + \varepsilon_{it} \quad (7)$$

3.1. Panel Unit Root Test

The conventional ADF test for single equation is based on the following regression equation:

$$\Delta X_{it} = \alpha_i + \beta_i X_{i,t-1} + \gamma_i t + \sum_{j=1}^{k} \theta_{ij} \Delta X_{i,t-j} + \varepsilon_{it}, \quad (8)$$

where Δ is the first difference operator, X_{it} is the stock prices and dividends, ε_{it} is a white-noise disturbance with a variance of σ^2, and t = 1, 2,…., T indexes time. The unit root null hypothesis of $\beta_i < 0$ is tested against the one-side alternative hypothesis of $\beta_i = 0$, which corresponds to X_{it} being stationary. The test is based on the test statistic $t_{\beta_i} = \hat{\beta}_i / se(\hat{\beta}_i)$ (where $\hat{\beta}_i$ is the OLS estimate β_i of in Equation (8) and $se(\hat{\beta}_i)$ is its standard error) since the single-equation ADF test may have low power when the data are generated by a near-unit-root but stationary process. Levin, Lin, and Chu (2002) found that the panel approach substantially increases power in finite samples when compared with the single-equation ADF test, proposed a panel-based version of Equation (8) $\hat{\beta}_i$ that restricts by keeping it identical across cross- industries as follows:

$$\Delta X_{it} = \alpha_i + \beta X_{i,t-1} + \gamma_i t + \sum_{j=1}^{k} \theta_{ij} \Delta X_{i,t-j} + \varepsilon_{it}, \quad (9)$$

Where:

i =1,2,…N indexes across cross-industries. Levin-Lin-Chu tested the null hypothesis of against the alternative of, with the test based on the test statistic (where is the OLS estimate of in Equation (9) and is its standard error).

$$\bar{Z} = \sqrt{N}[\bar{t} - E(\bar{t})] / \sqrt{Var(\bar{t})} \quad (10)$$

Im et al.(2003) relaxed the assumption of the identical first-order auto-regressive coefficients of the Levin-Lin-Chu test and developed a panel-based unit root test that allows β to vary across regions under the alternative hypothesis. In addition, Im-Pesaran-Shin tested the null hypothesis of $\beta_1 = \beta_2 = ... = 0$ against the alternative of $\beta_i < 0,$ for some i.

The Im-Pesaran-Shin test is based on the mean group approach. They use the average of the t_{β_i} statistics from Equation (11) to perform the following *t*-bar statistics:

$$\bar{Z} = \sqrt{N}[\bar{t} - E(\bar{t})] / \sqrt{Var(\bar{t})} \quad (11)$$

where $\bar{t} = (1/N)\sum_{i=1}^{N} t_{\beta_i}$, $E(\bar{t})$ and $Var(\bar{t})$ are respectively the mean and variance of each t_{β_i} statistic, and they are generated by simulations (Im et al., 2003). This $\bar{Z}$ converges with standard normal distribution. Based on Monte Carlo experiment results, Im et al., (2003) demonstrated their test is even more powerful than the Levin-Lin-Chu panel test in finite samples.

Before using the panel cointegration and panel causality tests, unit root test was carried out in the study. The information regarding the panel unit root tests employed in this study is presented in table 4. Our study employs the Levin–Lin–Chu (LLC) and Im–Pesaran–Shin (IPS) panel unit root tests. The hypotheses of these tests are formulated as follows:

H0 = 0 (Variables are non-stationary)
H1 ≠ 0 (Variables are stationary)

After the implementation of the panel unit root tests, the specifications of the panel cointegration tests utilized in this study are outlined below.

3.2. Panel Cointegration Test

Pedroni (1995) studied the properties of spurious regressions and tests for cointegration in heterogeneous panels and derived appropriate distributions for these cases. These methods allow us to test the existence of long-term equilibrium in multivariate panels while also permitting the individual members of the dynamic and even long-term cointegration vectors to be heterogeneous.

Like the IPS panel unit root test, the panel cointegration tests proposed by Pedroni also take heterogeneity into account, utilizing specific parameters that allow for variability among individual members. Pedroni (1997 and 1999) derived the asymptotic distributions of seven different statistics and examined the small sample performance of panel data cointegration tests. Four of these seven statistics are based on the principle of cointegration along the 'Panel' or internal dimension, while the last three are defined based on the 'Group' or external dimension. These different statistics are based on a model that assumes cointegration relationships among individual members are heterogeneous and are defined as;

For the Within statistics

$$Z_{\rho}^{w} = (\sum_{i=1}^{N}\sum_{t=1}^{T} L_{11i}^{-2}\hat{e}_{it-1}^{2})^{-1}\sum_{i=1}^{N}\sum_{t=1}^{T} L_{11i}^{-2}(\hat{e}_{it-1}\Delta\hat{e}_{it}-\lambda_i) : \textbf{Panel Rho\_stat} \tag{12}$$

$$Z_{t}^{w} = (\tilde{s}_{NT}^{*2}\sum_{i=1}^{N}\sum_{t=1}^{T} L_{11i}^{-2}\hat{e}_{it-1}^{*2})^{-1/2}\sum_{i=1}^{N}\sum_{t=1}^{T} L_{11i}^{-2}(\hat{e}_{it-1}^{*}\Delta\hat{e}_{it}^{*}) : \textbf{Panel Adf\_stat} \tag{13}$$

$$Z_{pp}^{w} = (\sigma^{2}\sum_{i=1}^{N}\sum_{t=1}^{T} L_{11i}^{-2}\hat{e}_{it-1}^{2})^{-1/2}\sum_{i=1}^{N}\sum_{t=1}^{T} L_{11i}^{-2}(\hat{e}_{it-1}\Delta\hat{e}_{it}-\lambda_i) : \textbf{Panel PP\_stat} \tag{14}$$

$$Z_{v}^{w} = (\sum_{i=1}^{N}\sum_{t=1}^{T} L_{11i}^{-2}\hat{e}_{it-1}^{2})^{-1} : \textbf{Panel V\_stat} \tag{15}$$

For the Between statistics

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$$Z_{\rho}^{B}=\sum_{i=1}^{N}(\sum_{t=1}^{T}\hat{e}_{i,t-1}^{2})^{-1}\sum_{t=1}^{T}(\hat{e}_{it-1}\Delta\hat{e}_{it}-\lambda_{i}):\textbf{Group Rho\_stat} \quad (16)$$

$$Z_{t}^{B}=\sum_{i=1}^{N}(\sigma_{i}^{2}\sum_{t=1}^{T}\hat{e}_{i,t-1}^{2})^{-1}\sum_{t=1}^{T}((\hat{e}_{it-1}\Delta\hat{e}_{it}-\lambda_{i}):\textbf{Group Adf\_stat} \quad (17)$$

$$Z_{pp}^{B}=\sum_{i=1}^{N}\left(\sum_{t=1}^{T}\hat{s}^{*2}\hat{e}_{it-1}^{*2}\right)^{-1}\sum_{t=1}^{T}(\hat{e}_{it-1}^{*}\Delta\hat{e}_{it}^{*}):\textbf{Group PP\_stat} \quad (18)$$

with,

$$\lambda=\tfrac{1}{T}\sum_{s=1}^{k_i}(1-\tfrac{s}{k_i+1})\sum_{t=s+1}^{t}\mu_{it}\mu_{it-s} \quad (19)$$

$$\hat{s}_i^{2}=\tfrac{1}{T}\sum_{t=s+1}^{t}\mu_{it}^{2}\ \ \sigma^{2}=s_i^{2}+2\lambda_i$$

$$\sigma_i=\hat{s}_i^{2}+2\lambda_i$$

$$\sigma_{NT}^{2}\tfrac{1}{T}\sum_{i=1}^{N}L_{11i}^{-2}\sigma_i^{2}$$

$$\hat{s}_i^{*2}=\tfrac{1}{T}\sum_{t=s+1}^{t}\mu_{it}^{*2}\ \ \tilde{s}_{NT}^{*2}=\tfrac{1}{T}\sum_{t=s+1}^{t}\hat{s}_{it}^{*2},L_{11i}^{2}\sum_{t=1}^{T}\eta_{it}^{2}+\tfrac{2}{T}\sum_{s=1}^{k_i}(1-\tfrac{s}{k_i+1})\sum_{i=1}^{T}\eta_{it}\eta_{it-s}$$

and where the residuals are extracted from the above regressions:

$$\hat{e}_{it}=\rho\hat{e}_{it-1}+u_{it} \quad (20)$$

$$\hat{e}_{it}=\rho\hat{e}_{it-1}+\sum_{k=1}^{K_i}\gamma_{ik}\Delta\hat{e}_{it-k}+u_{it}$$

$$\Delta y_{it}=\sum_{m=1}^{M}\hat{b}_{mi}\Delta X_{mit}+\eta_{it}$$

Note that in the above writings L_i represents the i^{th} component of the Cholesky decomposition of the residual Variance-Covariance matrix , λ and σ_{NT}^{2} are two parameters used to adjust the auto-correlation in the model, σ_i and s_i^2 are the contemporaneous and long-run individual variances.

$$\frac{\chi_{NT}-\mu\sqrt{N}}{\sqrt{\nu}}\rightarrow N(0,1) \quad (21)$$

Where χ_{NT} is the statistic under consideration among the seven proposed, N and T are the sample parameter values and μ and ν are parameters tabulated in Pedroni (1999).

Pedroni (1997) demonstrated that for values of T greater than 100, all seven proposed statistics perform well and are quite stable. However, for smaller samples (when T is less than 20), the Group ADF-Statistic (non-parametric) is the most powerful, followed by the Panel v-Statistic and the Panel rho-Statistic. Therefore, in our study on panel cointegration testing, only the group ADF-statistics will be considered. The finite sample distributions for the seven statistics were tabulated by Pedroni (1997) through Monte Carlo simulations. The calculated test statistics must be greater (in absolute value) than the tabulated critical value to reject the null hypothesis of no cointegration. And, Pedroni (2004) theoretically proved the reliability, robustness, and flexibility of the Pedroni test, particularly regarding its ability to allow for heterogeneity.

Kao (1999) proposed two sets of specifications for the DF test statistics. The first set depends on consistent estimation of the long-run parameters, while the second one does not. Under the null hypothesis of no cointegration, the residual series e_{it} should be non-stationary. The model has varying interceptions across the cross-sections (the fixed effects specification) and common slopes across *i.* The DF test can be calculated from the estimated residuals as: $\hat{e}_{it} = \rho\hat{e}_{it-1} + v_{it}$

The null hypothesis of non-stationarity can be written as $H_0 : \rho = 1$. Kao constructed new statistics whose limiting distributions, $N(0,1)$, are not dependent on the nuisance parameters, that are called DF_ρ^* and DF_t^* (where it is assumed that both regressors and errors are endogenous). Alternatively, he defines a bias-corrected serial correlation coefficient estimates and, consequently, the bias-corrected test statistics and calls them DF_ρ and DF_t. In this case, the assumption is the strong exogeneity regressors and the errors. Finally, Kao (1999) also proposed an ADF type of regression and an associated ADF statistic.

If the model variables are integrated, the stationary linear equation can be interpreted as the long-run equilibrium relationship between the variables. This equation is referred to as the cointegration equation. In this study, we employ the panel cointegration tests developed by Pedroni (1999, 2004) and Kao (1999) to examine the existence of a long-run relationship among the variables.

3.3. Panel Data Long-Run Estimations (FMOLS)

After confirming the existence of cointegration, the next step is to examine the long-run association among the variables using regression analysis. Accordingly, we model carbon dioxide emissions (CO_{2it}) as a function of economic growth, energy use, renewable energy consumption, trade openness, and financial development. The long-run parameters are estimated with the fully modified ordinary least squares (FMOLS) developed by Pedroni. The panel FMOLS estimation is shown in equation 5.

$$\widehat{\beta}_{GFMOLS} = N^{-1} \sum_{i=i}^{N} \widehat{\beta}\, GFMOLS_{i} \quad (5)$$

3.4. Panel Causality Test

Finally, the study aims to explore the short-run dynamic bi-variate panel causality among the variables using the model. Dumitrescu and Hurlin (2012) suggested a simple approach for testing the null hypothesis of homogeneous non-causality against the alternative hypothesis of heterogeneous non-causality. This test has to be applied to a stationary data series using the fixed coefficients in a vector auto-regressive (VAR) framework. The significance of this test is that it allows for having a different lag structure and also heterogeneous unrestricted coefficients across the cross-sections under both the hypotheses. Under the null hypothesis, no causality in any cross-section is tested against the alternative hypothesis of causality at least for a few cross-sections. The null and alternative hypotheses of the Dumitrescu–Hurlin causality test are defined as follows:

H_0: = 0 (Variables do not exhibit a causal relationship)
H_1: ≠ 0 (Variables exhibit a causal relationship)

4. Findings

Descriptive statistics for the series of variables included in the study are presented in table 3. When examining the series of variables such as $LNCO_2$, LNEU, and LNGDP, which are presented in logarithmic form, it is observed that the mean and median values are quite close. The difference between the mean and median values is more pronounced for variables such as REC and TRD. The mean was higher than the median in both series.

Table 3. Descriptive Statistics.

Variables	Mean	Median	Maximum	Minimum	Std. Dev.	Skewness	Kurtosis
$LNCO_2$	12.302	12.500	16.210	7.960	1.732	-0.348	3.359
LNEU	7.537	7.410	8.730	6.280	0.610	0.360	2.154
LNGDP	26.711	26.865	30.310	23.170	1.481	-0.400	2.988
REC	16.409	11.100	50.000	1.700	13.357	1.039	2.914
TRD	67.940	51.020	220.410	13.750	44.332	1.352	4.271
FII	0.478	0.440	0.990	0.080	0.196	0.812	3.349
FIA	0.382	0.310	0.950	0.030	0.235	0.693	2.500
FID	0.360	0.320	0.960	0.020	0.253	0.773	2.688
FMI	0.434	0.455	0.920	0.030	0.204	-0.093	2.666
FMA	0.371	0.380	0.990	0.020	0.197	0.179	2.852
FMD	0.379	0.330	0.980	0.010	0.256	0.509	2.267

Source: Authors' calculations

An examination of the standard deviation, maximum, and minimum values for the series' spread and volatility reveals that the TRD variable has the highest volatility, with a standard deviation of 44.332. Furthermore, the large difference between the minimum (13.750) and maximum (220.410) values reveals significant heterogeneity among countries in terms of trade openness rates. The standard deviations of the variables $LNCO_2$ (1.732) and LNGDP (1.481) are higher than those of LNEU (0.610), suggesting that CO_2 emission and GDP levels vary more across countries than energy use. In the financial development variables, it is seen that the standard deviations have relatively lower values ranging from 0.196 to 0.256. This suggests that financial development variables generally have a more homogeneous distribution or may be bounded (normalized) variables between 0 and 1.

The methodological validity of the cointegration and causality tests to be used in the later stages of the study depends on the correct determination of the stationarity levels of the series. The stationarity levels of the variables in the study were examined using Levin, Lin, and Chu (2002) [LLC] and Im, Pesaran, and Shin (2003) [IPS] tests, which are widely accepted in the panel data literature. While the LLC test assumes a homogeneous structure across the panel, the IPS test tends to provide more reliable results, especially for panels consisting of countries with different levels of development, because it allows for heterogeneity among the units in the panel. Since the theoretical background of these tests is extensively covered in academic literature and standard econometric resources, detailed methodological explanations are not included in this study. Test statistics obtained from the panel unit root analyses are presented in Tables 4 and 5.

Table 4. Panel Unit Root Test Results. for Developed Countries

	I(0)				I(1)			
	LLC		IPS		LLC		IPS	
Var	Const.	Const. & Trend	Const.	Const. & Trend	Const.	Const. & Trend	Const.	Const. & Trend
LNCO2	1.721	2.741	4.393	4.975	-10.284	-9.015	-11.943	-12.642
	[0.957]	[0.997]	[1.000]	[1.000]	[0.000]***	[0.000]***	[0.000]***	[0.000]***
LNEU	0.467	-1.383	2.251	1.377	-16.633	-17.086	-15.319	-17.069
	[0.680]	[0.083]*	[0.988]	[0.916]	[0.000]***	[0.000]***	[0.000]***	[0.000]***
LNGDP	-7.315	1.989	-2.139	3.712	-4.741	-2.844	-7.538	-7.402
	[0.000]***	[0.977]	[0.016]**	[1.000]	[0.000]***	[0.000]***	[0.000]***	[0.000]***
REC	9.785	1.967	10.440	4.132	-11.191	-14.169	-12.296	-15.001
	[1.000]	[0.975]	[1.000]	[1.000]	[0.000]***	[0.000]***	[0.000]***	[0.000]***
TRD	-2.312	-0.846	-0.846	-0.545	-12.647	-11.915	-13.514	-12.114
	[0.010]**	[0.199]	[0.199]	[0.293]	[0.000]***	[0.000]***	[0.000]***	[0.000]***
FII	-1.879	-0.745	0.660	1.628	-15.020	-14.162	-14.167	-13.561
	[0.030]**	[0.228]	[0.745]	[0.948]	[0.000]***	[0.000]***	[0.000]***	[0.000]***
FIA	-1.323	1.833	-0.165	3.903	-11.162	-12.374	-10.095	-10.636
	[0.093]*	[0.967]	[0.434]	[1.000]	[0.000]***	[0.000]***	[0.000]***	[0.000]***

FID	0.172	-0.873	1.382	-0.684	-11.843	-10.439	-14.065	-13.397
	[0.568]	[0.191]	[0.917]	[0.247]	[0.000]***	[0.002]***	[0.000]***	[0.000]***
FMI	-4.543	-0.346	-2.693	1.907	-10.739	-10.671	-12.558	-13.289
	[0.000]***	[0.365]	[0.004]***	[0.972]	[0.000]***	[0.002]***	[0.000]***	[0.000]***
FMA	-3.561	-1.679	-1.482	-0.528	-15.149	-13.312	-14.178	-13.155
	[0.000]***	[0.047]**	[0.069]*	[0.299]	[0.000]***	[0.002]***	[0.000]***	[0.000]***
FMD	-5.340	-2.357	-1.936	-0.399	-14.218	-13.154	-14.104	-13.710
	[0.000]***	[0.000]***	[0.027]**	[0.345]	[0.000]***	[0.002]***	[0.000]***	[0.000]***

Note: *** 1%, **5%, *10% indicate the significance level, respectively.

Source: Authors' calculations

Table 5. Panel Unit Root Test Results for Developing Countries

Var.	**I(0)**				**I(1)**			
	LLC		**IPS**		**LLC**		**IPS**	
	Const.	Const. & Trend	Const.	Const. & Trend	Const.	Const. & Trend	Const.	Const. & Trend
LNCO2	-5.365	2.487	-3.345	4.798	-7.265	-6.256	-7.921	-11.777
	[0.000]***	[0.994]	[0.000]***	[1.000]	[0.000]***	[0.000]***	[0.000]***	[0.000]***
LNEU	-0.367	1.066	2.957	1.063	-12.172	-11.134	-11.882	-12.167
	[0.357]	[0.857]	0.998	[0.856]	[0.000]***	[0.000]***	[0.000]****	[0.000]***
LNGDP	-6.599	8.163	-2.699	4.057	-4.588	-3.911	-6.303	-5.763
	[0.000]***	[1.000]	[0.004]***	[1.000]	[0.000]***	[0.000]***	[0.000]***	[0.000]***
REC	-0.768	3.627	0.008	3.476	-6.79	-4.582	-8.189	-6.164
	[0.221]	[1.000]	[0.503]	[1.000]	[0.000]***	[0.000]***	[0.000]***	[0.000]***
TRD	0.267	0.188	1.204	0.854	-9.53	-5.556	-12.882	-11.268
	[0.605]	[0.575]	[0.886]	[0.803]	[0.000]***	[0.000]***	[0.000]***	[0.000]***
FII	0.811	-1.524	2.368	-2.282	-13.424	-11.606	-14.133	-12.849
	[0.791]	[0.064]*	[0.991]	[0.011]**	[0.000]***	[0.000]***	[0.000]***	[0.000]***
FIA	-1.161	0.589	-0.255	1.214	-7.099	-7.062	-8.645	-8.339
	[0.123]	[0.722]	[0.399]	[0.888]	[0.000]***	[0.000]***	[0.000]***	[0.000]***
FID	1.697	-0.305	2.526	-2.272	-15.949	-14.549	-16.627	-16.517
	[0.955]	[0.380]	[0.994]	[0.012]	[0.000]***	[0.000]***	[0.000]***	[0.000]***
FMI	-1.37	-0.563	-1.619	-3.398	-14.398	-12.161	-14.36	-12.63
	[0.085]*	[0.287]	[0.053]*	[0.000]***	[0.000]***	[0.000]***	[0.000]***	[0.000]***
FMA	-4.229	-0.934	-2.724	0.701	-15.627	-13.597	-16.762	-15.721
	[0.000]***	[0.175]	[0.000]***	[0.758]	[0.000]***	[0.000]***	[0.000]***	[0.000]***

FMD	-0.627	-1.491	0.207	-2.396	-13.244	-10.698	-16.36	-14.879
	[0.265]	[0.068]**	[0.582]	[0.008]***	[0.000]***	[0.000]***	[0.000]***	[0.000]***

Note: *** 1%, **5%, *10% indicate the significance level, respectively.
Source: Authors' calculations

According to the unit root test results for developed and developing countries, it was determined that the variables were not stationary at the level, but after taking their differences, they were stationary at the I(1) level.

After determining that the variables were stationary at I(1) using a unit root test, long-term cointegration was examined using the Pedroni (1999, 2004) and Kao (1999) tests. The Pedroni cointegration test not only allows dynamic and fixed effects to differ across panel sections but also allows for the cointegration vector to differ across sections under the alternative hypothesis (Asteriou and Hall, 2007). Panel Pedroni (1999,2004) and Panel Kao (1999) Cointegration test results are shown in Table 6 and 7.

The results of the Panel Pedroni (1999, 2004) and Panel Kao (1999) conducted to examine the long run cointegration relationship between variables related to the developing country group are presented in Table 6. Accordingly, the rho-statistic (Panel and Group) value among the Pedroni tests was determined to be statistically insignificant. However, the PP-statistic and ADF-statistic-based tests (Panel PP, Panel ADF, Group PP, Group ADF), considered more reliable in the literature, were observed to reject H_0 at the 5% or 10% significance level in all models. Furthermore, in all models without exception, the Kao ADF statistic was found to support the existence of a long-run relationship at the 1% significance level.

Table 6. Panel Cointegration Test Results for Developed Countries

Pedroni Cointegration Test							
Stat.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Panel v-St.	1.81095 [0.0351]**	1.2735 [0.1014]	1.6347 [0.0511]*	1.5430 [0.0614]*	1.4237 [0.0773]*	0.4206 [0.3370]	0.0885 [0.4647]
Panel rho St	0.21879 [0.5866]	0.2250 [0.5890]	-0.4200 [0.3372]	0.6248 [0.7340]	0.7557 [0.7751]	0.3968 [0.6542]	2.5832 [0.9951]
Panel PP-St	-3.95756 [0.000]***	-2.1623 [0.0153**]	-2.9208 [0.0017]***	-3.3638 [0.0004]***	-3.0166 [0.0013]***	-1.8141 [0.0348]**	-2.6051 [0.0046]***
Panel ADF-St.	-2.27654 [0.0114]**	-2.7751 [0.0028]***	-1.7962 [0.0362]**	-2.0182 [0.0218]**	-3.9284 [0.0000]***	-1.7065 [0.0440]**	-2.2738 [0.0115]**
Group rho-St.	2.11538 [0.9828]	1.2340 [0.8914]	1.2253 [0.8898]	2.2775 [0.9886]	2.3993 [0.9918]	1.5924 [0.9444]	4.2972 [1.0000]
Group PP-St.	-1.75817 [0.0394]**	-2.1099 [0.0174]**	-1.9146 [0.0278]**	-1.5154 [0.0648]*	-1.0503 [0.1468]	-1.3789 [0.0840]*	-3.2634 [0.0006]***
Group ADF-St.	-3.32594 [0.0004]***	-3.2536 [0.0006]***	-2.1512 [0.0157]**	-3.0678 [0.0011]***	-3.8256 [0.0001]***	-2.2812 [0.0113]**	-1.8784 [0.0302]**

Kao Cointegration Test							
ADF-St.	-3.85303 [0.0001]***	-3.2166 [0.0006]***	-2.9045 [0.0018]***	-3.0244 [0.0012]***	-3.2109 [0.0007]***	-3.5726 [0.0002]***	-3.1694 [0.0008]***

Note: *** 1%, **5%, *10% indicate the significance level, respectively.
Source: Authors' calculations

The cointegration tests conducted for both developed and developing country groups revealed that the findings of both tests were fully consistent with each other. The strong evidence provided by the majority of Panel Pedroni (1999, 2004) test statistics and the supporting result of the Kao (1999) test empirically demonstrate that the analyzed variables have a long run cointegration relationship, even if they deviate from each other in the short run.

Table 7 . Panel Cointegration Test Results for Developing Countries

Pedroni Cointegration Test							
St.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Panel v-St.	1.81095 [0.0351]**	1.2735 [0.1014]	1.6347 [0.0511]*	1.5430 [0.0614]*	1.4237 [0.0773]*	0.4206 [0.3370]	1.0345 [0.1504]
Panel rho St	0.21879 [0.5866]	0.2250 [0.5890]	-0.4200 [0.3372]	0.6248 [0.7340]	0.7557 [0.7751]	0.3968 [0.6542]	1.4196 [0.9221]
Panel PP-St	-3.95756 [0.000]***	-2.1623 [0.0153]**	-2.9208 [0.0017]***	-3.3638 [0.0004]***	-3.0166 [0.0013]***	-1.8141 [0.0348]**	-2.2101 [0.0135]**
Panel ADF-St.	-2.27654 [0.0114**]	-2.7751 [0.0028]***	-1.7962 [0.0362]**	-2.0182 [0.0218]**	-3.9284 [0.0000]***	-1.7065 [0.0440]**	-3.1184 [0.0009]***
Group rho-St.	2.11538 [0.9828]	1.2340 [0.8914]	1.2253 [0.8898]	2.2775 [0.9886]	2.3993 [0.9918]	1.5924 [0.9444]	3.4765 [0.9997]
Group PP-St.	-1.75817 [0.0394]**	-2.1099 [0.0174]**	-1.9146 [0.0278]**	-1.5154 [0.0648]*	-1.0503 [0.1468]	-1.3789 [0.0840]*	-1.6925 [0.0453]**
Group ADF-St.	-3.32594 [0.0004]***	-3.2536 [0.0006]***	-2.1512 [0.0157]**	-3.0678 [0.0011]***	-3.8256 [0.0001]***	-2.2812 [0.0113]**	-3.6000 [0.0002]***
Kao Cointegration Test							
ADF-St.	-3.85303 [0.0001]***	-3.2166 [0.0006]***	-2.9045 [0.0018]***	-3.0244 [0.0012]***	-3.2109 [0.0007]***	-3.5726 [0.0002]***	-4.5253 [0.0000]***

Note: *** 1%, **5%, *10% indicate the significance level, respectively.
Source: Authors' calculations

This methodologically validates the use of advanced econometric methods, such as Panel FMOLS, for the next stage of the study, the estimation of long-run coefficients. Given the greater consistency of the Panel FMOLS approach in long-run parameter estimation compared to DOLS, the Panel FMOLS method was utilized to estimate the long-run coefficients. Panel FMOLS test results are shown in Tables 8 and 9.

Table 8 above displays the coefficients for the long-run CO_2 emissions determinant, estimated using the panel FMOLS method, along with their statistical significance. The variables LNEU, LNGDP, REC, and TRD were consistently included as primary determinants in all models, while the impact of various financial development indicators (FII, FIA, etc.) was assessed individually. Analysis of the results reveals that the coefficient for LNEU is positive and statistically significant at the 1% level in every model, indicating that energy consumption is a principal driver of CO_2 emissions. Similarly, the coefficient for LNGDP (Economic Growth) is positive and significant at the 1% level across all models, confirming that economic growth produces a scale effect on environmental pollution and that GDP expansion increases CO_2 emissions in the long run.

Table 8. Panel FMOLS Test Results for Developed Countries

Var.	Model1	Model2	Model3	Model4	Model5	Model6	Model7
LNEU	0.7806 [0.0000]***	0.6267 [0.0001]***	0.5017 [0.0036]***	0.6885 [0.0000]***	0.6511 [0.0000]***	0.1024 [0.0000]***	0.6501 [0.0000]***
LNGDP	0.3200 [0.0000]***	0.3557 [0.0000]***	0.3773 [0.0000]***	0.3151 [0.0000]***	0.3023 [0.0000]***	0.7248 [0.0000]***	0.3033 [0.0000]***
REC	-0.0632 [0.0000]***	-0.0552 [0.0000]***	-0.0548 [0.0000]***	-0.0527 [0.0000]***	-0.0513 [0.0000]***	-0.0237 [0.0000]***	-0.0508 [0.0000]***
TRD	-0.0101 [0.0000]***	-0.0091 [0.0000]***	-0.0096 [0.0000]***	-0.0086 [0.0000]***	-0.0089 [0.0000]***	-0.0007 [0.0000]***	-0.0089 [0.0000]***
FII	-2.5559 [0.0000]***	-1.3527 [0.0038]***	-	-	-	-	-
FIA	-	-	-0.8253 [0.0230]**	-	-	-	-
FID	-	-	-	-0.6913 [0.0409]**	-	-	-
FMI	1.2219 [0.0003]***	-	-	-	0.2600 [0.0000]***	-	-
FMA	-	-	-	-	-	-0.0372 [0.0299]**	
FMD	-	-	-	-	-	-	0.2253 [0.0000]***

Note: *** 1%, **5%, *10% indicate the significance level, respectively.
Source: Authors' calculations

It was determined that the REC variable, another variable included in the model, has a decreasing effect, unlike the others. It is seen that the REC variable is significant at the 1% level with a negative coefficient value in all models created and the increase in renewable energy consumption significantly reduces CO_2 emissions in the long run. This result points to the critical role of promoting

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renewable energy use for decarbonization targets. Similar to the REC variable, the TRD variable was determined to be significant at the 1% level with a negative coefficient value in all models. Accordingly, it has been observed that trade openness has a reducing effect on CO_2 emissions. The results suggest that in this group of countries, the transfer of cleaner technologies or the shift towards less polluting industries is more dominant than increasing production through trade.

The study also aimed to separately address the impact of different dimensions of financial development on CO_2 emissions. The findings reveal that the impact of different dimensions of financial development on CO_2 emissions is heterogeneous. Accordingly, it was concluded that both the FII variables in models 1 and 2 and the FIA and FID variables in models 3 and 4 have a negative and statistically significant effect on CO_2 emissions. The findings regarding these three financial development variables indicate that the development of financial institutions (e.g., the banking sector) positively affects environmental quality. This situation is interpreted as the fact that developed financial institutions play an important role in reducing emissions by providing funds to energy efficient projects or green technologies. However, unlike institutional development, the variables FMI, FMA and FMD representing market-based financial development were found to have a positive and statistically significant effect on CO_2 emissions. This situation can be clearly seen when the findings obtained within the scope of models 5, 6, and 7 are examined. This result supports the view that financial markets can finance the expansion of polluting industries by focusing on profitability rather than control for improving environmental quality.

Table 9. Panel FMOLS Test Results for Developing Countries

Var.	Model1	Model2	Model3	Model4	Model5	Model6	Model7
LNEU	0.1903 [0.0002]***	0.6225 [0.0000]***	0.6298 [0.0000]***	0.5868 [0.0000]***	0.5689 [0.0000]***	0.5326 [0.0000]***	0.5697 [0.0000]***
LNGDP	0.6209 [0.0000]***	0.2148 [0.0000]***	0.2053 [0.0000]***	0.1446 [0.0000]***	0.1208 [0.0000]***	0.1414 [0.0000]***	0.1301 [0.0000]***
REC	-0.0071 [0.0179]**	-0.0089 [0.0041]***	-0.0084 [0.0043***]	-0.0101 [0.0000]***	-0.0091 [0.0000]***	-0.0104 [0.0000]***	-0.0100 [0.0000]***
TRD	0.0011 [0.0601]*	0.0014 [0.0176]**	0.0015 [0.0104]**	0.0010 [0.0000]***	0.0006 [0.0005]***	0.0006 [0.0008]***	0.0007 [0.0000]***
FII	-0.5379 [0.0003]***	-0.5226 [0.0006]***	-	-	-	-	-
FIA	-	-	-0.3719 [0.0000]***	-	-	-	-
FID	-	-	-	-0.1183 [0.0123]**	-	-	-

FMI	0.2119 [0.0048]***	-	-	-	0.1876 [0.0000]***	-	-
FMA	-	-	-	-	-	0.3271 [0.0000]***	-
FMD	-	-	-	-	-	-	0.0641 [0.0051]***

Note: *** 1%, **5%, *10% indicate the significance level, respectively.
Source: Authors' calculations

Table 9 presents the results of the Panel FMOLS model which is used to determine the coefficients on the long-term relationship among the independent variables considered in the study and CO_2 for developing countries. When the findings were examined, it was determined that energy consumption and economic variables gave stable, statistically significant, and generally consistent results with theoretical expectations in all 7 models. Accordingly, LNEU stands out as the most important and stable driver of CO_2 emissions. Depending on the models created, it has been determined that a 1% increase in energy consumption increases CO_2 emissions in the long run at rates ranging from approximately 0.19% to 0.63%. When the coefficients of LNGDP were examined, it was similarly concluded that there was a positive and significant relationship at the 1% level in all models, and it was determined that the coefficient values varied between 0.1208 and 0.6209 on a model basis. This result is consistent with the "scale effect" of the Environmental Kuznets Curve (EKC) hypothesis. In addition, the findings indicate that for the developing country group economies, the EKC curve has not yet reached the turning point, or the growth process is progressing on a carbon-intensive trajectory. In the findings regarding the REC variable, negative and statistically significant coefficients were obtained in all seven models. Therefore, it can be seen that the increase in renewable energy use successfully reduces CO_2 emissions in the developing country group. When it comes to the TRD variable, the coefficient value was determined to be positive and statistically significant in all models except model 1. This result supports the Pollution Haven Hypothesis or a more general scale effect for the developing country group. In other words, increased trade leads to an increase in overall energy consumption, and hence emissions, either through the relocation of polluting industries to the country or through increased production and transportation activities.

When the findings regarding the impact of financial development on CO_2 emissions, which is considered as the most refined contribution of this study, are examined, it is clearly seen that the effects of financial development on environmental quality are not homogeneous. Rather than examining financial development as a single variable, the study breaks down its sub-components into seven different models, revealing the dual role of the financial sector. Accordingly, it was concluded that all of the coefficients of the FMI, FMA, and FMD variables examined within the scope of models 5, 6, and 7 were positive and statistically significant, while it was determined that all of the FII, FIA, and FID variables examined within the scope of models 2, 3, and 4 had negative and statistically

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significant coefficients. Based on these findings, it is supported that financial development can contribute positively to environmental quality by encouraging firms to invest in energy-efficient, modern, and environmentally friendly technologies. On the other hand, it can also negatively affect environmental quality by providing firms with more financing and encouraging increased industrial production.

At this stage of the study, the existence of a causal relationship between the series is examined. In this context, the Dumitrescu and Hurlin (2012) causality test was utilized. The method offers the advantage of taking into account cross-sectional dependence and heterogeneity among countries in the panel, accommodating situations where the time dimension exceeds the cross-sectional dimension (N), and providing reliable results even in unstable panel data sets (Dumitrescu and Hurlin, 2012). The findings obtained as a result of the causality test conducted for the developed and the developing countries are presented in tables 10 and 11.

Table 10. Dumitrescu Hurlin Panel Causality Tests for Develop Countries

Null Hypothesis:	W-Stat.	Zbar-Stat.	Prob.
LNEU => $LNCO_2$	3.57096	2.01093	0.0443**
LNGDP => $LNCO_2$	3.59983	2.05523	0.0399**
REC => $LNCO_2$	6.94373	6.90181	0.0000***
TRD => $LNCO_2$	3.14121	1.39052	0.1644
FII => $LNCO_2$	4.20181	2.92772	0.0034***
FIA => $LNCO_2$	4.30404	3.07589	0.0021***
FID => $LNCO_2$	3.70734	2.21106	0.0270**
FMI => $LNCO_2$	2.81782	0.9218	0.3566
FMA => $LNCO_2$	3.17235	1.43566	0.1511
FMD => $LNCO_2$	4.08621	2.76018	0.0058***

Note: *** 1%, **5%, *10% indicate the significance level, respectively.
Source: Authors' calculations

When Table 10 is examined, it is seen that causality is detected from variables such as LNEU, LNGDP, REC to CO_2 emissions in the developed country group, and this causality is statistically significant. No such causality relationship could be determined for the TRD variable. This situation can be interpreted as the effects mentioned within the framework of the Pollution Haven Hypothesis and "Technical Effect" concepts balance each other or that trade openness is not as dominant a determinant as other factors for the sample covered in the study. When financial variables are examined, the results become a bit more complicated. Because the findings reveal that "financial development" is not a single block, and that institutional and market-based finance have different causalities on the environment. Accordingly, it was determined that there is a causality from all institutional-based financial development variables such as FII, FIA, and FID to CO_2 emissions and that this is statistically significant. On the other hand, among market-based financial development variables such as FMI, FMA, and FMD, a statistically significant causality could be determined only from the FMD variable to CO2 emissions.

Table 11. Dumitrescu Hurlin Panel Causality Tests for Develop Countries

Null Hypothesis:	W-Stat.	Zbar-Stat.	Prob.
LNEU => $LNCO_2$	3.72921	2.20864	0.0272**
LNGDP => $LNCO_2$	3.85678	2.62216	0.0087***
REC => $LNCO_2$	4.08495	2.97937	0.0029***
TRD => $LNCO_2$	1.60997	-0.89523	0.3707
FII => $LNCO_2$	3.23147	1.64324	0.1003
FIA => $LNCO_2$	3.71540	2.40083	0.0164**
FID => $LNCO_2$	3.64170	2.28545	0.0223**
FMI => $LNCO_2$	2.97830	1.24690	0.2124
FMA => $LNCO_2$	1.42611	-1.18307	0.2368
FMD => $LNCO_2$	3.49493	2.05569	0.0398**

Note: *** 1%, **5%, *10% indicate the significance level, respectively.
Source: Authors' calculations

Table 11 shows the causality test results for the developing country group. In the developing country group, similar to the developed countries, the existence of a statistically significant causality from variables such as LNEU, LNGDP, and REC to CO2 emissions can be clearly seen. It was determined that the causality relationship from the TRD variable to CO2 emissions was not valid for this group of countries, and the coefficients were not statistically significant. When the financial variables were examined, it was determined that there was a statistically significant causality from institution-based financial development variables such as FII, FIA, and FID to CO2 emissions, and only from the FMD variable to market-based financial development variables. This result re-emphasizes the point that "Financial development" is not a single block and that institutional and market-based finance has different causalities on the environment, specifically for developing countries.

5. Conclusions

The threat of climate change caused by environmental degradation and especially CO_2 emissions on a global scale is considered one of the most critical economic and social challenges of the 21st century. Efforts to achieve sustainable development goals require countries to understand the complex interactions between economic growth, energy use, and environmental quality. In the literature, the relationship between economic growth and environmental degradation is mostly examined within the framework of the Environmental Kuznets Curve (EKC) hypothesis, which suggests that environmental quality improves after a certain income threshold. However, the validity of this hypothesis remains controversial for different countries and different time periods. In this context, within the scope of the study, the long-term relationship between (CO_2) emissions and economic development, financial development, energy use, trade openness and renewable energy consumption was tested comparatively in two different economic development levels of country groups, namely developed and developing.

Within the scope of the study, Pedroni Panel Cointegration, Panel FMOLS, and Dumitrescu Hurlin Panel causality tests were used respectively. However, before cointegration and causality tests, since the methodological validity of these tests depends on the accurate determination of the stationarity levels of the series, the stationarity levels of the variables in the study were examined through Levin, Lin, and Chu (2002) [LLC] and Im, Pesaran, and Shin (2003) [IPS] tests, which are widely accepted in the panel data literature. The findings showed that all the series were stationary at the first I(1) difference. After the unit root tests, the Pedroni Panel Cointegration test was performed. The findings indicate the existence of a cointegrated relationship in the long run in all seven models created for both the developed and the developing countries.

After determining the cointegration relationship, the panel FMOLS test was used to estimate the long-run coefficients. The findings obtained from the FMOLS test show that the LNEU and LNGDP variables have a positive and robust effect on CO_2 emissions in all model specifications for both developed and developing country groups. When LNEU (Energy use) coefficients are considered, it has been determined that coefficients ranging from approximately 0.50 to 0.78 are calculated in developed countries, while these values vary between 0.19 and 0.63 in developing countries. This suggests that LNEU (energy consumption) is the main driver of CO_2 emissions in both country groups. This high impact, which does not match our expectations, especially in developed countries, is due to carbon lock-in. It has been determined that LNGDP coefficients vary between approximately 0.30 and 0.38 for the developed countries group and between 0.12 and 0.21 for the developing countries group. Therefore, the validity of the turning point (negative coefficient) predicted by the EKC hypothesis, which is frequently mentioned in the literature, for the group of developed countries could not be empirically supported.

It has been determined that the coefficients of the REC (Renewable Energy) variable have a negative and robust relationship with CO_2 emissions in all models for both developed and developing country groups. Accordingly, REC reduces CO_2 emissions through the substitution of fossil fuels. However, the magnitude of the reducing effect was calculated to be around -0.05 in developed countries and around -0.01 in developing countries. Accordingly, it is seen that the REC effect is 5 times greater for developed countries than for developing countries. This difference points to the low marginal benefits of renewable energy projects in developing countries, which may be due to their limited share in the total energy mix or due to the financing and infrastructure limitations. The TRD (trade openness) variable is the variable in which the sharpest and the most significant theoretical divergence between the two country groups is identified within the scope of the presented FMOLS findings. The impact of TRD on CO_2 emissions is completely opposite depending on the development level of the countries. Accordingly, the TRD coefficients for the developed country group were found to be statistically significant and negative across all seven models, while they were found to be positive and statistically significant for the developing country group. While this negative relationship found for developed countries supports the view that technical and composition effects outweigh the scale effect, the positive relationship found for the developing country group strongly supports the pollution hypothesis and the scale effect for developing countries.

The impact of financial development, which is the last variable discussed in the study, is addressed in a multidimensional way with the help of sub-components such as (FIA, FID) and (FMA, FMD) as well as main components such as financial institutions index (FII) and financial markets index (FMI). In this way, the bidirectional effect of financial development on CO_2 revealed by the FMOLS findings could be revealed. When the findings were examined, it was determined that the FII variable and its sub-components had a negative and statistically significant effect on CO_2 in both developed and developing countries. On the other hand, it has been determined that the FMI and its sub-components, which are the financial markets index and a different dimension of financial development, have a positive and statistically significant effect on CO2 for both country groups. These two different results from financial development reveal two distinct aspects of financial development affecting environmental quality. Accordingly, while financial institutions play a mitigating role on environmental quality, financial markets (especially in developing countries) exert an intensifying effect on emissions with their current structure. As financial institutions, especially the regulated banking sector, tend to include environmental risks in their loan portfolios, they are offering special credit facilities for energy-efficient projects and reorienting capital allocation by adopting ESG (Environmental, Social, Governance) criteria. On the other hand, capital markets finance large-scale, capital-intensive, and potentially polluting industrial investments (energy, infrastructure, heavy industry), leading to a net increase in emissions.

Finally, within the scope of the study, Dumitrescu Hurlin Panel causality test was performed and the findings were interpreted. Accordingly, it was observed that there was a statistically significant causal relationship from LNEU, LNGDP, and REC variables to CO_2 emissions within both country groups. However, it was determined that causality for the TRD variable was not statistically significant. This situation is thought to be due to the fact that the effects mentioned within the framework of the Pollution Haven Hypothesis and the Technical Effect concepts balance each other or that trade openness is not as dominant a determinant as other factors for the sample covered in the study. Since financial development is not a single block as stated before, it is concluded that institutional and market-based finance has different causalities on environmental quality. Accordingly, it was observed that while a causality from the FII variable representing the financial institution index to CO_2 emissions was determined to be statistically significant only for the developed country group, a causality from its sub-components (FIA and FID) to CO_2 was detected for both developed and developing country groups. On the other hand, among market-based financial development variables such as FMI, FMA, and FMD, only causality from the FMD variable to CO_2 emissions was found to be statistically significant for both country groups.

It is thought that this study makes significant contributions to the determinants of CO_2 emissions and environmental economics literature by providing comparative and multidimensional analysis. In particular, the findings obtained from considering the determinants of CO_2 emissions according to the development levels of the countries included in the sample indicate that the homogeneity of the general results in the literature should be questioned. In particular, the lack of empirical support for the EKC hypothesis in developed countries and the opposing effects of Trade Openness and TRD highlight the importance of this distinction. Another important issue is that financial development is separated and its different dimensions are discussed separately. Analyzing financial development, which is generally addressed with a single indicator in the literature, by separating it into institutional (FII) and market (FMI) dimensions, clearly revealed the bidirectional (negative and positive) effects on environmental quality. This is seen as an important outcome for a more careful approach to the complex nature of the environmental consequences of financial development. The findings underscore the need for country-specific, multidimensional strategies rather than a single, universal solution to effectively reduce CO_2 emissions, especially in light of the country's level of development and financial structure.

It is assessed that existing infrastructure remains very limited and that a more aggressive value chain renewal program is necessary to reduce the high energy-emission dependency identified, particularly in developed countries. In addition, it is thought that in all countries, it would be beneficial to increase incentives for low-energy-intensity, high-value-added sectors and to increase the share of such sectors in the overall economic structure to prevent economic growth from increasing emissions. In addition, the fact that the EKC hypothesis is not valid in developed countries clearly shows that economic growth does not automatically reach the threshold that will improve the environment. Therefore, it is considered essential for developed countries to take coercive measures. In this context, to mitigate the observed high energy-emission dependency in developed nations, a compelling "Green Infrastructure Renewal" program should be initiated to facilitate the rapid decarbonization of the existing fossil fuel-based infrastructure. More rigorous measures ought to be employed to enforce steps toward the closure of outdated power plants and the mandatory adherence of industrial facilities to enhanced energy efficiency standards. Furthermore, it is deemed beneficial to develop a CO_2 emissions pricing mechanism (such as a Carbon Tax or an Emissions Trading System) or to revise existing systems to ensure they are robust enough to effectively alter investment behavior.

The findings of the study indicate that the emission-reducing effect of renewable energy consumption (REC) is significantly low in developing countries. It is therefore recommended that immediate steps be taken to focus on the perceived causes of financing and infrastructure limitations and to restructure international financing mechanisms to help REC projects in these nations achieve economies of scale. Furthermore, to enhance the marginal utility of REC projects, priority should be given to large-scale projects that ensure regional energy integration and rapidly increase REC's share in the total energy mix, rather than small-scale, dispersed initiatives. Concurrently, it is advised that priority be given to investments in smart grid and energy storage infrastructure critical for integrating intermittent REC sources via public budgets and international credits. Any bureaucratic hurdles that may impede this process should be promptly removed. Additionally, concerning the Pollution Haven hypothesis highlighted particularly in developing countries, various compulsory measures must be introduced regarding the integration of environmental standards into international trade agreements to remove this concept from the national agenda.

Finally, considering the dual impact of financial development highlighted within this study, it is posited that policies must be implemented specifically tailored to the components of the financial system. To counterbalance the emission-increasing effect of the capital markets, it is recommended that green bond standards and capital adequacy requirements against carbon-related risks be introduced or that existing ones be improved. On the other hand, due to the emission-reducing tendency of the banking sector, the implemented environmental risk management and ESG criteria should be reinforced and mandated by regulatory authorities through the banking sector. The objective should be to propagate this positive effect, which is currently robust in developed nations, to developing countries as well.

Future researchers in this field are recommended to focus on more specific areas such as directly measuring the composition effect of trade with sectoral foreign trade data, examining the extent to which this situation interacts with other factors like labor costs in developing countries where the pollution haven hypothesis is valid, and quantitatively testing the direct role of specific green financial instruments such as green bonds and sustainability-linked loans in reducing emissions through financing renewable energy projects.

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