# Can Finance Drive the Green Energy Transition? A System-GMM Analysis of OECD Countries

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**ABSTRACT**

This study investigates how financial development (FD), foreign direct investment (FDI), and per capita carbon emissions ($CO_2$) influence renewable energy consumption (REC) in 23 OECD countries from 2000 to 2021. Using a dynamic panel data model, it examines the role of financial systems and cross-border capital flows in supporting the shift toward cleaner energy. To handle potential endogeneity and dynamic structure, the two-step system generalized method of moments (System-GMM) estimator is applied, along with robustness checks using Difference-GMM and fixed-effects models. The results reveal three key insights. First, renewable energy consumption shows strong persistence, indicating that energy transitions evolve gradually. Second, financial development has a positive but modest impact on REC, implying that strong institutions and effective regulation are crucial for finance to promote green investment. Third, higher per capita $CO_2$ emissions are associated with lower REC, suggesting that fossil fuel–dependent economies face greater challenges in transitioning to renewables. Overall, both financial systems and FDI can act as catalysts for renewable energy adoption, yet their effectiveness depends on institutional quality and policy coherence. Strengthening green finance, carbon pricing mechanisms, and cross-border investment frameworks may accelerate the green transition in OECD countries.

**Keywords:** Financial Development, Renewable Energy Consumption, Foreign Direct Investment, Carbon Emissions, Dynamic Panel Data Analysis
**JEL Classifications:** C23, F21, G20, Q43, Q54

## 1. INTRODUCTION

Energy consumption stands as a key pillar of economic growth and, at the same time, a crucial factor in ensuring environmental sustainability (Shobande and Ogbeifun, 2022). In recent decades, rising environmental concerns, growing uncertainty about energy security, and the steady depletion of fossil fuel reserves have pushed many countries to seek cleaner and more sustainable energy pathways (Baloch et al., 2019). As this global transition unfolds, scholars have explored its environmental, economic, and social dimensions from multiple perspectives, reflecting an ongoing shift toward renewable energy use (Sun et al., 2023). Yet, the success of energy policies depends on more than just balancing supply and demand. It also rests on the resilience of financial systems, the quality of investment environments, and the strength of environmental governance (Alshagri et al., 2024).

Flows of international investment, the depth of financial markets, and the level of carbon emissions all shape renewable energy consumption, whether directly or indirectly. Doytch and Narayan (2016) emphasize that foreign direct investment can foster the spread of cleaner technologies, while Tamazian and Rao (2010) point out that financial development plays an essential role in improving environmental quality. With growing populations, rapid industrialization, and ongoing technological progress, the pressure on existing energy resources has become more intense—making the shift toward renewable and alternative sources not only necessary but increasingly urgent (Li and Shao, 2023).

Renewable energy has increasingly become a key focus area—not only for environmental sustainability but also within the broader field of financial and economic analysis (Croutzet and Dabbous, 2021). Economic and social activities inevitably shape environmental conditions, while environmental changes, in return, can slow down or negatively affect economic growth. The extensive use of fossil fuels, in particular, has deepened environmental degradation by driving up emissions of greenhouse gases such as carbon dioxide ($CO_2$). Consequently, it has become crucial to examine the factors influencing both carbon emissions and renewable energy consumption from a multidimensional perspective.

Addressing these environmental challenges effectively requires a clear understanding of what drives energy consumption. Factors such as political stability, governance quality, the rule of law, economic growth, financial development, investment levels, energy demand, renewable energy potential, and $CO_2$ emission intensity all play a role in shaping energy patterns (Zeren and Karaca, 2021).

A country's level of financial development is typically reflected in its ability to attract foreign direct investment, the depth of its banking sector, and the sophistication of its capital markets. To measure this more comprehensively, the international monetary fund (IMF) developed the Financial Development Index, which assesses the depth, access, and efficiency of both financial institutions and markets. This index has been published annually for 183 countries since 1980 and is standardized on a scale ranging from 0 to 1 (Şenol, 2019; Sahay et al., 2015).

Financial development often stimulates energy demand in two main ways: By giving individuals easier access to durable goods and by allowing firms to expand production through better financing opportunities. While this process supports economic growth, it can also intensify environmental stress through higher energy use. Likewise, a more active stock market tends to boost investor confidence, spurring greater investment activity and, in turn, driving up energy demand (Sadorsky, 2011).

Foreign direct investment (FDI) represents another important force shaping renewable energy outcomes. Traditionally seen as a channel for transferring knowledge, technology, and management practices from multinational corporations to host economies, FDI can contribute not only to economic expansion but also to structural changes in energy infrastructure—particularly in emerging markets. Although the "Pollution Haven Hypothesis" suggests that some types of FDI may worsen environmental conditions, other evidence highlights that technology spillovers from foreign investors can accelerate the adoption of cleaner and renewable energy systems (Kutan et al., 2017; Aliyu, 2005).

The close link between energy, finance, and the environment remains central to modern economic debates and policy design. The transition toward renewable energy is of strategic importance because it addresses climate change, energy security, and sustainable development at the same time. On the financial side, this transformation relies on stable long-term financing, effective risk-sharing arrangements, well-designed incentive mechanisms,

and robust institutional frameworks (Paramati et al., 2017; Shahbaz et al., 2022).

OECD countries provide a natural testing ground for the energy transition, given their advanced financial systems and strong institutional frameworks. Yet, the literature indicates that this process does not unfold uniformly across nations. Structural factors such as market depth, environmental regulation, investment climate, and the composition of the energy mix all play decisive roles (Aliyu, 2005; Omri and Kahouli, 2014; Tan and Uprasen, 2022). In some cases, foreign direct investment (FDI) facilitates the transition by transferring clean technologies, whereas in others, the so-called "pollution haven" effect may still prevail.

This study examines how financial development (FD), foreign direct investment (FDI), and per capita carbon emissions ($CO_2$) influence renewable energy consumption (REC) across 23 OECD countries during 2000-2021, using a dynamic panel framework estimated through the System-GMM method. By incorporating FD, FDI, and $CO_2$ into a single model, the analysis captures multiple transmission channels simultaneously and enhances robustness through alternative estimations with Difference-GMM and fixed-effects models.

The central objective is to explore the joint effects of financial development, foreign direct investment, and carbon emissions on renewable energy consumption. Unlike many prior studies, this research focuses exclusively on renewable energy rather than total energy use, linking structural financial and environmental factors within a unified empirical framework. It further extends the green finance literature by investigating how finance and FDI influence renewable energy not only via investment flows but also through the carbon intensity of economic activity.

The empirical analysis employs the system generalized method of moments (System-GMM) developed by Arellano and Bover (1995) and Blundell and Bond (1998). This estimator enables a more accurate assessment of dynamic relationships by simultaneously accounting for time variation and cross-country heterogeneity.

The rest of this paper is organized as follows: Section 2 reviews the relevant literature; Section 3 presents the model and dataset; Section 4 explains the methodology; Section 5 discusses the empirical findings; and Section 6 concludes with key results and policy implications.

## 2. LITERATURE REVIEW

A review of the existing literature reveals that although many studies have explored the link between renewable energy consumption and economic growth, relatively few have examined—within a single analytical framework—the combined relationships among renewable energy consumption, financial development, foreign direct investment (FDI), and carbon emissions (Tichá et al., 2024; Kutan et al., 2017).

Sadorsky (2009), in an analysis of 18 developing economies, found no short-term connection between renewable energy use

and economic growth but identified a bidirectional relationship in the long run. Similarly, Menegaki (2011), studying 27 European countries, reported no statistically significant link between these two variables. Sbia et al. (2014), using data from the United Arab Emirates, examined the interactions among FDI, clean energy, trade openness, $CO_2$ emissions, and economic growth. Their findings showed that while FDI, trade openness, and $CO_2$ emissions tend to reduce energy demand, both economic growth and clean-energy use have a positive effect on it.

Omri and Kahouli (2014) investigated 65 countries with differing income levels and observed that in high-income nations, there is bidirectional causality among energy consumption, FDI, and economic growth. For middle-income countries, they found bidirectional causality between economic growth, energy consumption, and FDI, alongside a unidirectional effect from FDI to energy consumption. In contrast, in low-income countries, their analysis revealed bidirectional causality between growth and FDI and one-way causality from growth to energy consumption and from energy consumption to FDI.

Paramati et al. (2017) concluded that financial development positively influences renewable energy consumption, whereas Al-Mulali et al. (2015) detected no significant relationship between the two. Focusing on Turkey, Pata (2018) argued that the country's renewable energy consumption remains insufficient to meaningfully curb $CO_2$ emissions.

Similarly, Khandker et al. (2018) identified a long-run bidirectional causal link between FDI and renewable energy consumption in Bangladesh, while no significant short-term relationship was observed. Kılıçarslan (2019) found a long-term association between FDI and renewable energy generation across the BRICS countries and Turkey. Charfeddine and Kahia (2019) reported that renewable energy consumption helps reduce $CO_2$ emissions in MENA economies; however, financial development showed no meaningful influence on environmental degradation.

Yılancı et al. (2019) examined the relationships among FDI, trade openness, and renewable energy use in BRICS nations. Their analysis revealed that FDI positively affects renewable energy consumption in Russia, whereas the relationship was statistically insignificant in China and South Africa. Erdinç and Aydınbaş (2020) analyzed the effects of GDP, public spending, $CO_2$ emissions, the rule of law, FDI, and the labor force on renewable energy consumption. They observed negative links with $CO_2$ emissions and positive relationships with the remaining variables, though the impact of FDI on renewable energy use was not statistically significant.

Arı (2021) found no long-term causal relationship between FDI and renewable energy consumption in Turkey. Tan and Uprasen (2022) assessed the environmental implications of FDI in BRICS countries, offering additional evidence on the complex interplay between investment flows and sustainability outcomes.

## 2.1. Financial Development → Renewable Energy
Financial development can encourage renewable energy investments through various channels such as capital allocation,

innovation financing, the reduction of risk premiums, and increased market depth (Sadorsky, 2011; Paramati et al., 2017). In recent years, the expansion of green bond and loan markets, the rise of sustainable index funds, and the inclusion of climate risk in financial pricing mechanisms have further strengthened this relationship (Zhang et al., 2023; Shahbaz et al., 2022). However, some studies also warn that financial expansion may raise energy demand and $CO_2$ emissions in the short term (Tamazian and Rao, 2010).

## 2.2. Foreign Direct Investment (FDI) → Renewable Energy
Foreign direct investment (FDI) is generally discussed in the literature under two main hypotheses. The Technology Transfer Hypothesis suggests that FDI contributes to the spread of environmentally friendly technologies in host countries by promoting efficiency gains and knowledge spillovers (Khandker et al., 2018). Conversely, the Pollution Haven Hypothesis argues that polluting industries tend to relocate to countries with weaker environmental regulations (Aliyu, 2005). When cross-country differences are considered, income levels and regulatory capacities emerge as decisive factors (Omri and Kahouli, 2014; Tan and Uprasen, 2022). In the case of Turkey, the relationship between FDI and renewable energy consumption has generally been found to be weak or statistically insignificant (Türköz, 2023).

## 2.3. $CO_2$ ↔ Renewable Energy (REC)
Most empirical studies identify a negative relationship between $CO_2$ emissions and renewable energy consumption. Economies characterized by carbon-intensive production structures tend to limit the share of renewables in their total energy mix (Charfeddine and Kahia, 2019). However, in the long term, mechanisms such as carbon pricing, stricter environmental regulations, and green innovation policies can reshape this dynamic by promoting a gradual shift toward cleaner energy sources (Chiu and Zhang, 2023; Pata, 2018).

While the connection between renewable energy consumption and economic growth has been extensively studied, relatively few analyses have incorporated structural and environmental variables—such as financial development, foreign direct investment (FDI), and carbon emissions—into a single integrated framework. Much of the existing research either focuses on single-country case studies or examines only bilateral relationships between variables. Within this context, the present study contributes to the literature by jointly analyzing the effects of financial development, FDI, and carbon emissions on per capita renewable energy consumption across 23 OECD countries from 2000 to 2021. Given the scarcity of studies that dynamically investigate the FD–FDI–$CO_2$ nexus, this paper aims to fill that gap by employing the System-GMM approach, which enhances robustness by accounting for dynamic interactions and potential endogeneity.

## 3. MODEL AND DATA SET

This section investigates how financial development, foreign direct investment (FDI), and carbon emissions influence renewable energy consumption (REC) across 23 OECD countries between

2000 and 2021, using a panel data framework. In the empirical model, renewable energy consumption (REC) serves as the dependent variable, while the financial development index (FD), foreign direct investment (FDI), and per capita carbon emissions ($CO_2$) are included as independent variables.

Renewable energy consumption (REC) represents the percentage share of renewable sources in total final energy use. The financial development index (FD), developed by the ınternational monetary fund (IMF), is a composite indicator that captures the depth, accessibility, and efficiency of financial institutions and markets. Foreign direct investment (FDI) refers to long-term investment activities by foreign individuals or corporations in a host country. The carbon emissions variable ($CO_2$) indicates annual per capita carbon emissions, measured in metric tons.

The sample of 23 OECD countries was selected based on data availability, the continuity of the variables, and the statistical requirements of panel data analysis. The list of countries included in the study, together with descriptive statistics and data sources for each variable, is presented in Table 1.

Annual data for financial development, renewable energy consumption, Foreign direct investment (FDI), and carbon emissions were employed in the analysis. The variables used in the econometric model are summarized in Table 2.

The variables used in this study are summarized in Table 2 above. The panel dataset, covering the period from 2000 to 2021, incorporates both environmental and financial indicators, including renewable energy consumption, the financial development index, foreign direct investment (FDI), and per capita carbon dioxide

### Table 1: List of OECD countries included in the econometric model

| Turkey | United states | Germany | Australia | Austria |
|--------|---------------|---------|-----------|---------|
| Belgium | Canada | Denmark | Finland | France |
| Italy | United Kingdom | Japan | Ireland | Switzerland |
| Sweden | Spain | Portugal | Luxembourg | Netherlands |
| Norway | New Zealand | Greece | | |

### Table 2: Variables used in the analysis and their data sources (2000-2021)

| Abbreviation | Variable | Data source | Period |
|--------------|----------|-------------|--------|
| REC | Renewable Energy Consumption (as a percentage of total energy use) | World Development Indicators | 2000-2021 |
| FD | Financial Development Index | International Monetary Fund (IMF) | 2000-2021 |
| FDI | Foreign Direct Investment | United Nations Conference on Trade and Development (UNCTAD) | 2000-2021 |
| $CO_2$ | Per Capita Carbon Dioxide Emissions | World Development Indicators | 2000-2021 |

($CO_2$) emissions. Renewable energy data—measured as its share in total final energy consumption—were obtained from the World Bank's World Development Indicators database. Data on financial development (FD) were sourced from the IMF's Financial Development Index dataset, FDI figures were drawn from the UNCTAD database, and per capita $CO_2$ emission data were obtained from the World Bank. The selection of countries and time period was based on data availability and consistency, while the choice of variables follows established approaches in the existing literature.

The analysis utilizes annual data for 23 OECD countries spanning 2000-2021. Because the variables are continuous and numerical, a natural logarithmic transformation was applied to minimize the impact of outliers and stabilize variance across observations. To explore the dynamic effects of financial development, foreign direct investment, and carbon emissions on renewable energy consumption, the following panel regression model was estimated:

$$\ln REC_{it} = \beta_0 + \beta_1 \ln REC_{it\text{-}1} + \beta_2 \ln FD_{it} + \beta_3 \ln FDI_{it} + \beta_4 \ln CO2_{it} + u_{it} \tag{1}$$

In this model, the subscripts $i$ and $t$ denote country and time period, respectively, while $u_{it}$ represents the error term. The variable $REC_{it}$ refers to renewable energy consumption, and $REC_{it-1}$ denotes its one-period lag. $FD$, $FDI$, and $CO_2$ correspond to financial development, foreign direct investment, and carbon emissions, respectively. The coefficients $\beta_2$, $\beta_3$, and $\beta_4$ represent the elasticities of the related variables with respect to renewable energy consumption. According to the general expectations in the literature, the effect of carbon emissions is expected to be negative ($\beta_4 < 0$), whereas the effects of the other variables are anticipated to be positive ($\beta_2$, $\beta_3 > 0$).

Since the lagged value of the dependent variable ($ln(REC_{(i,t-1)})$) is included in the model, this term is correlated with the individual fixed effects ($\mu_i$). In this case, the classical ordinary least squares (OLS) estimators become biased and inconsistent because $Cov(ln(REC_{(i,t-1)}), \mu_i) \neq 0$. This bias is particularly significant when the time dimension (T) is small and the cross-sectional dimension (N) is large. Nickell (1981) demonstrated this issue, identifying it as a fundamental methodological problem in dynamic panel data models.

Therefore, generalized method of moments (GMM)-based approaches are employed to obtain consistent estimators in such models. In the empirical analysis, the Difference-GMM method developed by Arellano and Bond (1991) was initially applied. This method eliminates fixed effects by taking the first differences of the model and uses lagged values of the dependent variable as instrumental variables. However, the Difference-GMM approach may lead to weak instrument problems, especially when the variables are non-stationary or when the number of instruments becomes excessively large.

To overcome the aforementioned limitation, the System-GMM approach developed by Blundell and Bond (1998) was employed.

The System-GMM framework jointly estimates a two-equation system—one in differences and the other in levels—thereby expanding the set of instruments and incorporating additional information. This improvement enhances both the consistency and efficiency of the estimated parameters.

In this study, the two-step System-GMM estimator was adopted, as it generally provides more reliable empirical results by producing heteroskedasticity-robust standard errors. The validity of the instrument set was assessed using the Hansen over-identification test, while the Arellano–Bond AR(1) and AR(2) tests were applied to detect possible serial correlation. Furthermore, a series of robustness checks were conducted by varying the instrument sets, lag structures, and estimation techniques—including Difference-GMM and fixed-effects models—to confirm the stability of the results.

Before presenting the empirical findings, the basic statistical characteristics of the variables and their correlations were analyzed. The descriptive statistics for all variables included in the model are reported in the Table 3 below.

Table 3 presents the descriptive statistics for the key variables used in this study. The balanced panel includes 506 observations for REC, FD, and $CO_2$, while FDI has 504 observations. The data show a fairly wide range across variables, with some noticeable outliers, especially in the FDI and $CO_2$ series. To reduce skewness and stabilize variance, all variables were transformed into natural logarithms before running the regressions. This transformation also helps smooth out extreme values and ensures that the variables are measured on a more consistent scale.

To check whether the model was correctly specified, a simple correlation analysis was performed among the independent variables. As shown in Table 4, there is a positive and statistically significant correlation of around 57% between financial development (FD) and foreign direct investment (FDI). Likewise, FDI and carbon emissions ($CO_2$) show a negative correlation of about 14%, while the link between FD and $CO_2$ is also negative and significant at roughly 10%.

In general, the relatively low correlation values suggest that multicollinearity is not a serious concern in this study. This supports the idea that the variables can be included together in the same model without creating specification problems. Figure 1 presents the conceptual model of the study.

This model illustrates the interactions among financial development (FD), foreign direct investment (FDI), carbon emissions ($CO_2$), and renewable energy consumption (REC). Financial development enhances the efficiency of capital flows and expands investment capacity, which in turn encourages greater inflows of foreign

direct investment. Through this channel, FDI is expected to move toward renewable energy sectors. Therefore, the FD → FDI → REC pathway reflects how financial depth and market efficiency can support green investments.

Meanwhile, $CO_2$ represents environmental pressure and carbon intensity. The directional link from $CO_2$ to REC suggests that rising carbon emissions may trigger a shift toward renewable energy. However, the strength and even the direction of this relationship can differ across countries, depending on income levels, policy strictness, and institutional capacity.

Overall, the model underlines the hypothesis that financial development and FDI indirectly influence the renewable energy transition. It also integrates the "pollution haven" and "environmental transition" perspectives into a unified conceptual framework, forming the theoretical foundation of this study.

## 4. METHODOLOGY

This study examines how selected economic and environmental factors influence renewable energy consumption, using a panel dataset of 23 OECD countries covering the years 2000-2021. In this dataset, the countries form the cross-sectional dimension, while the years make up the time dimension.

Dynamic panel data models are often estimated using two main econometric approaches: The ordinary least squares (OLS) and the generalized method of moments (GMM). When the model includes a lagged dependent variable, OLS typically leads to biased and inconsistent results because of endogeneity problems (Mátyás and Sevestre, 2008). To overcome this issue, the present study relies on the GMM estimator, which provides a more reliable framework for handling such dynamics.

The GMM technique is a semi-parametric and efficient estimation method that has become popular in empirical
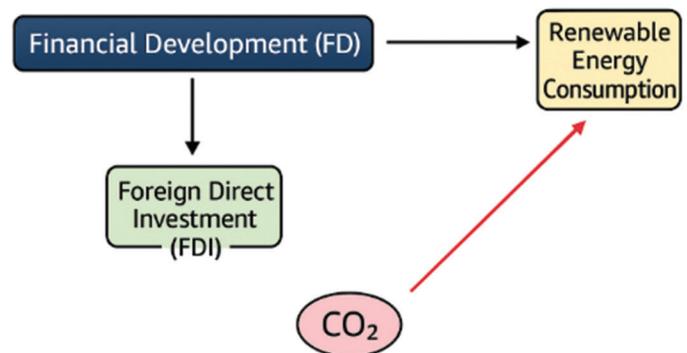
**Figure 1:** Conceptual model



**Table 3: Descriptive statistics**

| Variable | Observations | Mean | Standard deviation | Minimum | Maximum |
|----------|-------------|------|--------------------|---------|---------|
| REC | 506 | 1.818.696 | 1.443.214 | 0.8 | 61.4 |
| FD | 506 | 0.736917 | 0.132101 | 0.33 | 1 |
| FDI | 504 | 2.882.324 | 5.124.151 | −22309 | 32476 |
| $CO_2$ | 506 | 49900000 | 32300000 | 512848 | 100000000 |

**Table 4: Correlation matrix among independent variables**

|  | LnFD | lnFDI | LnCO$_2$ |
|---|---|---|---|
| LnFD | 1.000 |  |  |
| LnFDI | 0.5769 | 1.000 |  |
| LnCO$_2$ | −0.1090* | −0.1376*** | 1.000 |

research involving endogenous variables. Its key strengths include:

- The ability to control both time-specific and country-specific (cross-sectional) fixed effects.
- The use of lagged values of potentially endogenous variables as instruments to reduce bias.

Because of these advantages, GMM has been widely applied in recent studies focusing on financial development, investment dynamics, and environmental interactions.

In dynamic panel analyses, two main types of GMM estimators are commonly employed: The Difference-GMM and the System-GMM approaches. The first estimator, developed by Arellano and Bond (1991), eliminates cross-sectional (country- or individual-specific) effects by estimating the first-differenced form of each equation. In this method, the lagged levels of the explanatory variables are used as instruments. However, when the error term ($u_{it}$) is correlated with the explanatory variables—that is, when endogeneity exists—the ordinary least squares (OLS) estimator and other estimators derived from it become inconsistent and biased (Baltagi et al., 2008: 140).

Although the Difference-GMM estimator has been widely used, it suffers from certain limitations. When the explanatory variables display a high degree of persistence over time, their lagged levels become weak instruments for the first-differenced regression equation. This weakness leads to biased and inefficient coefficient estimates. To overcome this problem, Arellano and Bover (1995) and Blundell and Bond (1998) proposed the System-GMM estimator, which improves upon the Difference-GMM by combining equations in both first differences and levels.

Due to its lower bias and higher efficiency, the System-GMM estimator is generally considered superior to the Difference-GMM approach. Empirical evidence also suggests that the System-GMM method performs better in capturing dynamic relationships, particularly when dealing with panels characterized by a relatively small time dimension and a larger cross-sectional dimension.

Within the framework of our model analyzing the effects of financial development, foreign direct investment, and carbon emissions on renewable energy consumption, the following dynamic panel regression equation proposed by Arellano and Bond (1991) is considered:

$$REC_{it} = \alpha REC_{i,-1} + \beta'X_{it} + \mu_i + u_{it} \quad i=1,\ldots\ldots,N \; t=1,\ldots Ti \qquad (2)$$

In this model, $REC_{it}$ represents the renewable energy consumption of country $i$ at time $t$, while $REC_{i,t-1}$ denotes its one-period lagged value. $X_{it}$ is a set of explanatory variables that includes financial

development and other factors that may influence renewable energy consumption. $u_{it}$ denotes the error term.

A distinctive feature of the dynamic regression model is the inclusion of the lagged dependent variable on the right-hand side of the equation. The parameters $\alpha$ and $\beta$ represent, respectively, the coefficient of the lagged dependent variable and the vector of coefficients associated with the independent variables.

Looking at the consistency of the GMM estimator, it can be seen that it depends on the assumption that the error terms do not carry serial correlation (autocorrelation) and that the validity assumption of the instrument variables is realized. To make appropriate estimates with the GMM estimator, these two assumptions must be tested. The first should be tested using the Arellano Bond AR(1) and AR(2) tests, and the second should be tested using the Sargan test, which exhibits an asymptotic $\chi2$ distribution.

## 5. EMPIRICAL FINDINGS

In this study, the dynamic panel data model is estimated using the Difference-GMM method proposed by Arellano and Bond (1991) and the System-GMM estimator developed by Blundell and Bond (1998). Both techniques are designed to address the inconsistency of the ordinary least squares (OLS) estimator, which arises due to endogeneity and country-specific fixed effects ($\mu_i$) when a lagged dependent variable is included in the model.

This section compares the results from the System-GMM, Difference-GMM, and fixed effects (FE) estimators. It also reports subgroup, interaction, and robustness tests to check the reliability of the empirical findings.

Traditional fixed effects (FE) or OLS estimators tend to produce biased estimates because $Cov(y_{i,t-1}, \mu_i) \neq 0$ (Nickell, 1981). To deal with this issue, Arellano and Bond (1991) introduced the Difference-GMM estimator, which uses deeper lags of the dependent variable as instruments in the first-differenced equation. However, when variables are highly persistent, the Difference-GMM method can face weak instrument problems. To overcome this limitation, Blundell and Bond (1998) developed the System-GMM estimator, which combines the level and difference equations into a single system. This approach expands the available moment conditions, allowing for more efficient and reliable parameter estimation.

The econometric model is finally estimated using the two-step System-GMM approach, which provides heteroskedasticity-robust standard errors. The empirical results obtained from these estimations are summarized in Table 5 below.

Two-Step System-GMM estimation results are presented in Table 5. The coefficient of the lagged dependent variable is 0.970 and statistically significant at the 1% level ($P < 0.01$). This indicates that renewable energy consumption (REC), the dependent variable, is strongly dependent on its previous value, confirming that REC exhibits a high degree of persistence and that the energy transition progresses slowly in the short run.

## Table 5: Two-step system GMM panel estimation results

| Arellano and bover/blundell and bond two-step system generalized method of moments (GMM) | | | | |
|---|---|---|---|---|
| Dependent variable: REC | | | | |
| Variables | Coefficient | Standard error | z-statistic | Probability |
| $LnREC_{t-1}$ | 0.970469 | 0.0150634 | 64.43 | 0.00 |
| LnFD | 0.155047 | 0.102899 | 1.51 | 0.132 |
| LnFDI | 0.002066 | 0.0037773 | 0.55 | 0.584 |
| $LnCO_2$ | −0.01244 | 0.0089708 | −1.39 | 0.166 |
| Model information | | | | |
| Number of Instruments | 12 | | | |
| Number of Instruments | 23 | | | |

| Test | Statistic | Probability |
|---|---|---|
| Arellano-Bond AR (1) Tests | −3.36 | 0.001 |
| Arellano-Bond AR (2) Tests | −1.56 | 0.119 |
| Hansen test | 8.67 | 0.277 |
| Difference hansen tests Equation | | |
| Hansen Testi | 3.25 | 0.776 |
| Fark Hansen Testi | 5.42 | 0.02 |
| Instrument equation | | |
| Hansen Testi | 3.95 | 0.412 |
| Fark Hansen Testi | 4.72 | 0.193 |

The coefficient of financial development (FD) is 0.155, positive but only marginally significant (P ≈ 0.13). This finding suggests that financial depth supports renewable energy investments, though the effect remains weak due to country-level heterogeneity.

The impact of foreign direct investment (FDI) is small (0.002) and statistically insignificant (P > 0.10), implying that FDI may flow toward environmentally friendly sectors in some OECD countries but remain concentrated in traditional industries in others.

The coefficient for per capita carbon emissions ($CO_2$) is negative (–0.012), indicating that economies with higher carbon intensity tend to have a smaller share of renewables in their energy mix. The Arellano–Bond AR(1) test is significant, while the AR(2) test is not, confirming the absence of second-order serial correlation (AR(1) = –3.36, P = 0.001; AR(2) = –1.56, P = 0.119). The Hansen test yields a high P-value (P = 0.277), indicating that the overidentifying restrictions are valid and that the instruments used are appropriate. Overall, these results confirm that the model is econometrically consistent, and the System-GMM estimates provide statistically reliable and robust inferences.

In this study, three statistical thresholds were considered when assessing the significance of coefficients, as required by the nature of dynamic panel data models: Significance levels of 1%, 5%, and 10%. However, due to the limited number of observations in system-GMM estimators, the large number of instrumental variables, and the heterogeneity of countries in the sample, the statistical power of some coefficients may be weakened. As frequently emphasized in the literature (Roodman, 2009; Blundell and Bond, 1998), this situation requires the 10% significance level to be accepted as the marginal significance threshold. Therefore, results obtained with P < 0.10 were considered "marginally significant"; although these coefficients are statistically weak, they were interpreted as economically meaningful relationships. This approach is a widely adopted practice in dynamic panel models and parallels studies in the energy-finance interaction literature (Paramati et al., 2017; Zhang et al., 2023).

### 5.1. Comparison with Alternative Estimators

To assess the reliability of the model, several robustness tests were conducted using alternative estimators. In particular, the robustness of the model was examined by comparing the results obtained from the Difference-GMM and fixed effects (FE) estimators. These comparisons allow for an evaluation of the consistency of the coefficient signs and magnitudes across different estimation techniques. The summary of the results is presented in Table 6 below.

The findings of this study show that the System-GMM estimator performs better both methodologically and statistically than the Difference-GMM and Fixed Effects models. The two-step System-GMM approach enriches the instrument set by combining the difference and level equations, which significantly reduces the weak instrument problem. This feature ensures that the estimated coefficients remain both unbiased and consistent, especially in dynamic panel settings that include a lagged dependent variable.

When the results are compared, the direction and magnitude of the coefficients in the System-GMM model are broadly consistent with those from the Difference-GMM and Fixed Effects estimations. However, System-GMM delivers smaller standard errors and higher statistical significance, indicating stronger explanatory power and better reliability. By keeping the number of instruments within a reasonable range, this method also avoids instrument proliferation and upholds the validity of the Hansen test results.

Overall, the System-GMM estimator offers higher efficiency than the Difference-GMM and greater consistency than the Fixed Effects model. For these reasons, the interpretation of the empirical results and the formulation of policy recommendations in this paper are based primarily on the System-GMM estimates. This approach is viewed as the most suitable both theoretically— because it accounts for dynamic effects and endogeneity—and empirically, thanks to its robustness and stability.

The empirical findings indicate that financial development has a positive effect on renewable energy investments; however, this effect is conditional on factors such as income level, institutional capacity, and the stringency of environmental regulations (Adedoyin et al., 2022). These results suggest that the green transition depends not only on market mechanisms but also on the strengthening of appropriate political, financial, and institutional frameworks (Saqib et al., 2022).

To enable renewable energy investments to achieve economies of scale, long-term and low-cost financing mechanisms are

**Table 6: Robustness test — comparison across alternative estimators**

| Variable | System-GMM | Difference-GMM | Fixed effects (FE) | Comment |
|---|---|---|---|---|
| Ln (REC$_{t-1}$) | 0.970*** | 0.890*** | 0.760*** | Dynamic effects are underestimated in the FE model |
| ln (FD) | 0.155 | 0.100 | 0.090 | Coefficient signs are consistent; financial development remains positive |
| ln (FDI) | 0.002 | 0.001 | 0.0008 | The impact of FDI is weak; System-GMM performs more efficiently |
| ln (CO$_2$) | −0.012 | −0.010 | −0.009 | High sign consistency across estimators |

essential. In this regard, expanding the use of green bonds and other sustainable finance instruments can enhance investor confidence and mobilize private sector capital toward green projects (Zhang et al., 2023). The effective utilization of green bonds helps channel private investment into renewable energy projects, thereby improving energy efficiency and contributing to carbon reduction targets.

Publicly supported green finance funds, risk-sharing mechanisms, and ESG (Environmental, Social, and Governance) rating systems can further encourage private sector participation (Paramati et al., 2017). In OECD countries, capital market regulators should adopt a unified framework similar to the EU Green Bond Standard (GBS) and the Taxonomy Regulation to harmonize classification, verification, and reporting standards for green finance activities.

The empirical results show that the direction and magnitude of FDI effects are heterogeneous across countries. This finding is consistent with the Pollution Haven Hypothesis (Aliyu, 2005; Omri and Kahouli, 2014). Investment incentives should therefore be tied to environmental performance requirements. International firms investing in green technologies should be granted tax reductions, while those engaged in polluting activities should face additional financial costs through carbon pricing mechanisms.

Green investment screening criteria should be integrated into FDI approval processes, aligning with the European Union's carbon border adjustment mechanism (CBAM) framework. Lower-income OECD members, in particular, should develop joint venture models that strengthen FDI's contribution to knowledge transfer and innovation capacity through technology transfer agreements (Tan and Uprasen, 2022). FDI policies should focus on quality rather than quantity—prioritizing investments in green technologies—and environmental regulations and investment incentives should be made conditional upon sustainability criteria.

The findings also indicate a negative relationship between carbon emissions and renewable energy consumption, underscoring the importance of market-based instruments aimed at reducing carbon-intensive production structures. According to OECD (2023b) data, existing carbon taxes cover only about 30% of total emissions, with even lower coverage in energy-intensive sectors. This highlights the need to broaden the scope and effectiveness of carbon pricing frameworks to accelerate the clean energy transition.

Carbon pricing and emissions trading systems (ETS) stand out as key fiscal tools that can accelerate the shift toward renewable energy. Reforms in energy taxation should go hand in hand with the gradual phase-out of fossil fuel subsidies and the adoption of tax neutrality principles (OECD, 2023a). Introducing a common carbon price floor across OECD countries—say, around €60 per

ton—could help limit market distortions and make investments in green technologies more appealing from a financial perspective.

The weak statistical significance of the financial development variable may reflect deeper institutional issues. Limited sustainable finance infrastructure and the lack of comprehensive environmental data make it difficult for market participants to assess and price long-term risks properly. A taxonomy-aligned data system would therefore help quantify and evaluate the real impact of green investments.

Climate-related financial disclosures, such as those proposed by the Task Force on climate-related financial disclosures (TCFD) and the ınternational sustainability standards board (ISSB), should become mandatory. Banks and investment funds need to account for carbon-related risks directly on their balance sheets. At the same time, public agencies can play a leading role by issuing sustainability reporting guidelines to improve investor awareness and transparency. In parallel, OECD members should strengthen the role of financial supervisors by requiring green taxonomy alignment, climate-risk disclosure, and environmental stress testing within their regulatory frameworks.

In emerging OECD economies such as Turkey, Poland, and Mexico, the ability of financial markets to support the green transition remains relatively limited. Governments in these countries could consider setting up publicly backed green project finance facilities (Green Public Funds) and work jointly with international climate funds—such as the green climate fund (GCF) and the Climate Investment Funds (CIF)—to develop blended or co-financing models.

Central banks can play an important role in supporting the green transition by improving the liquidity of sustainable financial products—particularly through collateral programs that accept green securities. For developing OECD economies, building hybrid policy frameworks that blend fiscal, monetary, and investment policies will be essential. Such frameworks can foster green growth while keeping macro-financial stability intact.

Taken together, the policy insights suggest that the pace of the green transition depends largely on three pillars: Financial depth, robust environmental regulation, and international cooperation. Financial development on its own is not enough; yet, when paired with a sound regulatory environment, it can make the shift to renewable energy both more stable and more effective.

These conclusions align well with the broader literature. The depth of the financial system acts as a catalyst for channeling funds into green investments (Paramati et al., 2017). The strictness of environmental regulations influences not only the scale but also

the quality of FDI inflows (Omri and Kahouli, 2014; Tan and Uprasen, 2022). And carbon pricing continues to stand out as one of the most efficient fiscal tools for changing both energy demand patterns and investment portfolios (Chiu and Zhang, 2023).

In short, stronger coordination among green financial integration, high-quality FDI, and well-designed carbon policies—aligned with sustainable development goals—can help OECD countries move faster toward their net-zero emission targets.

# 6. CONCLUSION AND POLICY IMPLICATIONS

This study examined the effects of financial development (FD), foreign direct investment (FDI), and carbon emissions ($CO_2$) on renewable energy consumption (REC) in 23 OECD countries using panel data covering the period 2000-2021. To account for the dynamic structure of the model, the two-step system generalized method of moments (System-GMM) approach was employed. For robustness purposes, comparative estimations were conducted using the Difference-GMM and fixed effects (FE) models.

The empirical findings reveal that renewable energy consumption exhibits a high degree of persistence. This suggests that the energy transition process involves short-term inertia and that the effects of policy interventions tend to materialize gradually over time. The positive coefficient of financial development highlights the importance of financial depth in financing green investments. However, the limited statistical significance of this effect indicates that the impact of financial development on renewable energy is conditional on factors such as institutional capacity, market transparency, and the quality of financial regulation (Paramati et al., 2017; Zhang et al., 2023).

The impact of foreign direct investment (FDI) was found to be weak and statistically insignificant. This result implies that the direction and effectiveness of FDI vary depending on country-specific factors such as investment climate, regulatory stringency, and technological advancement. In some economies, FDI supports renewable energy development through the transfer of environmentally friendly technologies, while in others, it may create a "pollution haven effect", negatively influencing environmental sustainability (Omri and Kahouli, 2014; Tan and Uprasen, 2022).

Finally, a negative relationship was identified between carbon emissions ($CO_2$) and renewable energy consumption. This finding suggests that economies characterized by carbon-intensive production structures tend to experience a slower transition toward renewable energy sources (Chiu and Zhang, 2023).

This study offers three main contributions to the existing literature. First, it brings together financial development, FDI, and $CO_2$ variables within a single dynamic panel framework, allowing for a more integrated view of financial and environmental linkages. Second, it tests the methodological robustness of the results through a multidimensional comparison across System-GMM, Difference-GMM, and Fixed Effects estimators. Third, the paper provides a detailed treatment of heterogeneity and endogeneity issues—areas that earlier studies addressed only partially (Sadorsky, 2011; Pata, 2018).

The results indicate that financial systems can act as catalysts in supporting the shift toward renewable energy. Yet, the extent of this influence depends largely on institutional quality and the strength of the regulatory environment. Within this context, three major policy directions stand out.

First, strengthening financial depth by expanding green bond markets, introducing sustainable lending programs, and boosting ESG-oriented investment funds can amplify the role of finance in renewable energy development (OECD, 2023a). Second, improving the environmental quality of FDI requires aligning investment incentives with environmental performance criteria, raising tax burdens on polluting sectors, and encouraging bilateral agreements that facilitate green technology transfers (Tan and Uprasen, 2022). Finally, greater coordination in carbon pricing—through harmonized carbon taxes and emissions trading systems across OECD countries—can speed up the shift toward renewables, especially in carbon-intensive sectors (Chiu and Zhang, 2023; OECD, 2023b).

These policy recommendations are consistent with the European Green Deal and the OECD's green finance and investment framework strategies. The central conclusion of this research is that financial development, on its own, is not a sufficient engine for the green transition. Its effectiveness increases substantially when supported by sound regulation, strong institutional infrastructure, and coherent long-term policy coordination.

In this context, OECD countries with deeper and more mature financial systems tend to advance faster in sustainable energy investments. By contrast, lower-income members often experience slower progress, largely due to weaker institutional capacity and limited policy alignment. The findings of this study are consistent with recent evidence in the literature: The indirect effect of financial development on renewable energy (Paramati et al., 2017), the dependence of FDI's environmental impact on institutional quality (Omri and Kahouli, 2014; Tan and Uprasen, 2022), and the effectiveness of carbon pricing as a regulatory mechanism (Chiu and Zhang, 2023) are all reaffirmed here.

Future research could extend this analysis in several directions. The components of financial development—such as banking, capital markets, and fintech—can be analyzed separately to reveal their individual effects on renewable energy. Using firm-level microdata would allow for a better understanding of how financing channels work in practice. Within the framework of carbon-neutrality targets, future studies could integrate new indicators such as a Green Innovation Index or financial technology variables. Comparative analyses with non-OECD developing countries would also shed light on the transferability and effectiveness of green policy models. Together, these extensions could deepen our understanding of the financial dynamics shaping the global energy transition and provide valuable guidance for policymakers.

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