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Deciphering the Dynamics of Economic Development and Green Energy: An In-depth Analysis of OECD Nations

Saeed Ur Rahman[1]; Maryam Ibrahim[2]; Muhammad Shahbaz[3]

[1.] Department of Economics, Ghazi University, Dera Ghazi Khan, Pakistan
[2.] Department of Economics, Ghazi University, Dera Ghazi Khan, Pakistan
[3.] Department of Economics, Ghazi University, Dera Ghazi Khan, Pakistan

Abstract

Worldwide, fossil fuel is employing to achieve the sustainability in the long term which is considered the main source of climate change and environmental degradation. Therefore, renewable energy is encouraging to develop and adopt alternative methods of power generation. This study aims to investigate the impact of economic development, trade openness, and technological progress on the adoption of green energy in OECD countries. For this objective a panel dataset of OECD is organized spanning from 1979-2022. Further, Fully Modified OLS and Dynamic OLS are employed to spotlight the fluctuating relationship among the parameters. The findings indicate that these factors have a dynamic and fluctuating relationship, with economic development fostering long-term adoption of green energy but impeding it in the short term. The study underscores the significance of international trade and technological advancement in advancing renewable energy use, with technological progress playing a crucial role in OECD countries. Ultimately, the research concludes that there is a substantive connection between economic growth, free trade, technological advancement, and green energy use in these countries. This study suggested that implementing policies that encourage trade openness, technological innovation, and sustainable economic development is essential to achieving ambitious renewable energy objectives and reducing carbon emissions.

Keywords: Economic Development, Green Energy, Energy Transition, Technological Progress, and OECD

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Corresponding author's email: maryamibrahim12321@gmail.com

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1 Introduction

The adoption of renewable energy has attracted sustained scholarly attention because energy transitions are connected to economic development, technological advancement, and international trade (Destek & Sinha, 2020; Padhan et al., 2020). However, the interaction among economic activity, energy use, and trade openness is complex, and national circumstances may shape the direction and magnitude of these relationships. Existing work has examined technological innovation and renewable energy development (Zhang et al., 2023), whereas Moslehpour et al. (2023) investigated technological advancement alongside green finance and energy efficiency in Vietnam. Similarly, Liu et al. (2022) examined economic development and energy consumption in the context of carbon emissions. These strands of research establish the relevance of investigating economic development, trade openness, and technological progress jointly rather than considering each factor in isolation.

A substantial body of empirical research addresses the relationship between economic growth and energy utilization. Surya et al. (2021b) examined economic growth and renewable energy utilization, while Yang et al. (2022) considered asymmetric relationships involving renewable and non-renewable energy consumption and economic growth. However, the relationship cannot be assumed to operate uniformly across all economies or periods. Ramzan et al. (2022) analyzed the environmental costs of non-renewable energy and the possible mitigating roles of information and communication technology and financial development. In addition, Wang et al. (2023b) considered the roles of natural resources, institutional quality, trade openness, and foreign direct investment in economic development. Consequently, the present investigation retains a focus on the possible differences between short-run and long-run associations in OECD economies.

Joaqui-Barandica and Manotas-Duque (2023) examined how climate and macroeconomic factors affect profitability in the energy sector, highlighting the relevance of economic conditions for energy-related outcomes. Similarly, Basri (2021) considered renewable energy use, real GDP, and human development in Bangladesh. Radmehr et al. (2021) investigated renewable energy consumption, carbon emissions, and growth in European Union countries using a spatial modeling approach. In addition, Saqib (2022) examined green and non-renewable energy, financial development, economic growth, and carbon footprints through heterogeneous panel evidence. These studies collectively motivate closer examination of renewable energy consumption and economic activity; however, their different samples, dependent variables, and estimation approaches require careful comparison before drawing conclusions for OECD member states.

Surya et al. (2021b) examined the economic growth and renewable energy utilization nexus, while Surya et al. (2021a) addressed development and renewable energy in a regional setting. The feedback hypothesis suggests that renewable energy use and economic development may influence one another, although an observed association alone is insufficient to establish bidirectional causality. Furthermore, Bhuiyan et al. (2022) reviewed evidence on renewable energy consumption and economic growth, showing why variations in empirical methods and country settings matter. Therefore, an OECD-focused analysis should distinguish its estimated associations from causal claims and should explain why short-term adjustments may differ from longer-term relationships.

This study investigates the interplay between trade openness, gross domestic product, technological progress, and renewable energy consumption in OECD economies, with the broader policy motivation of carbon neutrality. Rising carbon emissions and climate-related risks make the transition toward lower-carbon energy systems an important economic policy concern. However, the empirical outcome analyzed here is renewable energy use, not a direct estimate of changes in carbon emissions. Accordingly, the analysis contributes evidence on the economic and technological correlates of renewable energy adoption, while implications for environmental quality should be interpreted as policy considerations rather than directly estimated environmental effects. This distinction also helps situate the study within earlier OECD-focused research (Destek & Sinha, 2020; Padhan et al., 2020).

Furthermore, the study considers the relationship between high technology and energy consumption over a long historical panel that includes the COVID-19 period. Its intention is to clarify whether technological progress accompanies changes in renewable energy utilization while taking economic activity and trade openness into account. In addition, the study addresses OECD efforts to support energy transition and carbon neutrality within the global economy. The policy relevance of renewable technologies is important; nevertheless, their environmental and economic benefits should not be presumed to be identical in every country. This observation strengthens the rationale for presenting both pooled estimates and country-specific evidence.

On this basis, the research focuses on economic growth, trade openness, and high technology as potential correlates of renewable energy consumption in OECD countries. In addition, it considers how these relationships may inform energy-transition policies and the longer-term objective of carbon neutrality. The remainder of the article is organized as follows. Section 2 reviews the relevant literature and develops the contribution of the study; Section 3 describes the data and econometric methods; Section 4 presents and interprets the empirical results; and Section 5 discusses conclusions, policy implications, limitations, and directions for subsequent research.

2 Literature Review

Wang et al. (2023a) considered renewable energy technology adoption at the farm level, illustrating how technological decisions can differ across settings. In contrast, Sun and Heshmati (2021) studied international trade and economic growth in China, rather than renewable energy adoption in Malaysia. Similarly, Shah et al. (2022) investigated energy policy transition, efficiency, technological advancement, and environmental quality in China. The diversity of settings and outcomes in these contributions is important because economic expansion, trade integration, and technological change may influence renewable energy through distinct mechanisms. Accordingly, results from individual economies should not be presented as direct OECD-wide evidence without examining their relevance to the present panel.

Iqbal et al. (2023) examined the connections among carbon emissions, renewable energy consumption, foreign direct investment, exports, and economic growth in BRICS countries. Their contribution is relevant to the wider trade–energy literature, but it does not constitute evidence from a United Arab Emirates ARDL analysis. Udeagha and Ngepah (2021) assessed the asymmetric relationship between trade openness and economic growth in South Africa, indicating that trade effects may be nonlinear. In addition, Fannoun and Hassouneh (2019) investigated renewable energy, international trade, tourism, foreign direct investment, and carbon emissions across developed and developing countries. Taken together, these studies suggest that trade openness may operate through technology diffusion, production structures, and economic activity; however, this article estimates associations with renewable energy consumption and does not empirically isolate those channels.

Existing evidence suggests that the implications of trade openness for domestic energy use can vary across national contexts (Zhang et al., 2021). Greater international integration may facilitate access to equipment, knowledge, and larger markets, although changes in production scale may also increase energy demand. Furthermore, Al-Farsi and Hayyan (2023) reviewed technologies relevant to renewable energy advancement, emphasizing the importance of technological development. Thus, the possible trade–technology relationship provides a meaningful motivation for including both trade openness and high technology in the same empirical specification; it is not, by itself, proof that trade liberalization necessarily increases renewable energy consumption.

The relationship between international trade and domestic energy consumption is multifaceted (Xu et al., 2023). For example, Fannoun and Hassouneh (2019) examined causal relationships among exports, imports, and economic growth in Palestine. However, the evidence from that context should not be equated with a direct test of renewable energy outcomes. Ilechukwu and Lahiri (2022) addressed renewable energy consumption and international trade more directly. Their work offers a relevant point of comparison when assessing whether greater market integration is associated with changes in renewable energy consumption. Similarly, the possible distinctions among immediate, transitional, and long-run adjustments support comparing dynamic estimators rather than assuming a single temporal response.

Li et al. (2022) examined renewable energy, natural resources, carbon emissions, and transboundary trade relationships in Southeast Asian economies. This evidence points to an important intersection between trade and environmental outcomes; however, it concerns a region and outcome that are not identical to those of the present study. Le (2022) discussed trade openness, energy use, and environmental quality, reinforcing the need to distinguish economic scale effects from changes in the energy mix. In addition, the direction of the relationship may differ across levels of income and institutional development. Consequently, an OECD panel can provide complementary evidence without implying that results from other regions are directly transferable.

Renewable energy development also differs across countries in resources, institutional capacity, and technological opportunities (Hesselink & Chappin, 2019). In addition, Zhang et al. (2022) examined renewable energy development in relation to carbon emissions trading arrangements in China, while Malik et al. (2022) studied the environmental Kuznets curve in Malaysia. These studies concern distinct policy instruments and environmental outcomes, yet they illustrate the wider context in which energy

transitions take place. Therefore, the present study addresses renewable energy consumption as a measurable outcome while acknowledging that energy policy and environmental performance involve additional factors beyond the selected explanatory variables.

The central aim of this study is to examine how economic growth, trade openness, and high technology are related to renewable energy consumption in OECD countries. The selection of these variables reflects their recurring importance in the literature and their potential relevance to policies that seek to reduce reliance on fossil fuels. In particular, Padhan et al. (2020) examined renewable energy consumption and globalization in OECD countries, considering oil, carbon emissions, and economic activity. Their study provides a directly relevant point of comparison. Nevertheless, the present research emphasizes dynamic short-run and long-run estimates across a historical OECD panel, while examining whether country-level patterns differ. This focus preserves the original policy motivation of understanding renewable energy adoption as part of a broader transition toward environmental sustainability.

The literature reveals related but not identical lines of inquiry. Padhan et al. (2020) and Destek and Sinha (2020) provide evidence directly related to OECD renewable energy and economic conditions; Zhang et al. (2021) consider trade openness and renewable energy consumption; and Zhang et al. (2023) examine technological innovation and renewable energy development. Similarly, Jianguo et al. (2022) studied technological innovation, institutional quality, and environmental quality in OECD economies, while Chishti et al. (2024) investigated artificial intelligence and the energy transition. Sarfraz et al. (2022) examined innovation and sustainable manufacturing performance rather than an OECD energy panel. Therefore, this article's contribution is not simply the use of several estimators: it is the comparative examination of short-run and long-run relationships among economic growth, trade openness, high technology, and renewable energy consumption, supplemented by country-level results. The following methodology explains the estimation approaches and the qualifications needed when interpreting differences among them.

2.1 Research gap and theoretical contribution

This research sits at the intersection of economic-growth, international-trade, and technological-development explanations of renewable energy use. Prior OECD evidence has investigated combinations of trade, economic activity, and renewable consumption (Destek & Sinha, 2020; Padhan et al., 2020; Zhang et al., 2021). However, these relationships may change across adjustment horizons. A short-run negative economic-growth coefficient can coexist with a positive long-run coefficient when energy systems adjust more slowly than output, investment, or demand. This is a possible interpretation rather than a tested transmission mechanism. Similarly, technological change may improve renewable-energy capabilities without producing a uniform measured response where infrastructure, market conditions, or energy policies differ. Therefore, the study contributes by placing dynamic time-horizon distinctions and cross-country variation at the center of its OECD analysis, while avoiding causal claims that its estimators cannot independently establish.

2.2 Positioning against related research

Destek and Sinha (2020) connect energy consumption, economic growth, trade openness, and ecological footprint in OECD economies; Padhan et al. (2020) examine OECD renewable energy consumption in relation to globalization and macroeconomic factors; and Zhang et al. (2021) focus specifically on OECD trade openness and renewable energy consumption. In addition, Jianguo et al. (2022) and Zhang et al. (2023) emphasize technological innovation in environmental and renewable-energy contexts. These studies offer closely related foundations, but their outcomes, methods, and explanatory emphasis are not interchangeable. The present research is distinguished by simultaneously reporting several dynamic and long-run estimators together with country-level associations for the chosen variables. Its contribution should therefore be evaluated through the quality of its comparative evidence, not simply through the number of estimation techniques used.

3 Data and Methodology

The empirical framework treats renewable energy consumption as the dependent variable and economic growth, trade openness, and high technology as explanatory variables. The study covers 25 OECD member countries from 1979 to 2022. This broad time span is useful for examining long-run association, although it also encompasses changes in policy regimes, technology, and economic conditions that may affect the stability of estimated coefficients. Consequently, interpret the estimates within the sample and period investigated. This specification is motivated by the OECD energy and trade literature (Destek &

Sinha, 2020; Padhan et al., 2020; Zhang et al., 2021), rather than by the assumption that the same relationship holds uniformly in every participating economy.

The baseline relationship includes renewable energy use (RE), trade openness (TO), economic growth (EG), and high technology (HT). In the model, the explanatory variables are examined jointly to identify their partial associations with renewable energy use. However, the available manuscript does not provide a fully reproducible variable-definition table identifying the source, scale, transformation, and availability of each series. This limitation matters especially for technology indicators and the interpretation of the reported logarithmic economic-growth measure. Therefore, the regression coefficients should be read as associations expressed in the original dataset's units, rather than converted into percentages or elasticities without further documentation. No values, measurement scales, or data sources have been reconstructed or assumed for this revision.

The use of panel data makes heterogeneity among countries an important consideration. OECD members differ in renewable resources, production structures, trade exposure, and technological capabilities; consequently, a single pooled coefficient may conceal differences in national experience. The country estimates reported later in the article offer a preliminary view of this variation. In addition, research on energy technology adoption and policy environments underscores the importance of institutional and contextual differences (Hesselink & Chappin, 2019; Zhang et al., 2022). The empirical strategy therefore compares approaches that impose different assumptions about parameter homogeneity while retaining the original explanatory variables and the study's main objective.

The estimation strategy combines the pooled mean group (PMG), mean group (MG), and dynamic fixed effects (DFE) approaches with fully modified ordinary least squares (FMOLS) and dynamic ordinary least squares (DOLS). These estimators address related questions but rely on different restrictions and assumptions. PMG permits short-run adjustment to vary while constraining long-run slope parameters; MG allows broader cross-country variation; and DFE imposes stronger pooling restrictions. FMOLS and DOLS provide alternative estimates of longer-run relationships under their relevant assumptions (Pesaran et al., 1999; Phillips & Hansen, 1990). Accordingly, agreement across estimates can strengthen the interpretation of a relationship, whereas divergent signs should be reported as substantive uncertainty rather than disregarded.

The empirical sequence reported in the article begins with descriptive statistics and panel unit-root results, proceeds to dynamic PMG, MG, and DFE estimates, and then compares the country-level coefficients and the FMOLS/DOLS specifications. This ordering is intended to connect the data characteristics with the subsequent interpretation. However, first-difference stationarity alone does not establish cointegration, and the manuscript does not present all diagnostics that would be needed for a comprehensive independent replication. In particular, the interpretation of panel dynamics depends on the selected lag structures, cross-sectional dependence, error-correction behavior, and model assumptions (Pesaran et al., 1999). Therefore, the published tables are retained as the empirical record, and methodological conclusions are expressed cautiously where diagnostic evidence is not reported.

$$y_{it} = \alpha + \rho y_{i,t-1} + X_{it}'\beta + \eta_{it} \qquad [1]$$

In Equation (1), the dependent variable represents renewable energy consumption, its lag represents previous-period renewable energy use, and the vector of explanatory variables includes trade openness, economic growth, and high technology. The index i denotes countries, and t denotes years over the 1979–2022 study period. Because these economies may differ in their short-term adjustments and longer-term responses, a dynamic panel specification is considered appropriate for describing the proposed relationships. The PMG, MG, and DFE estimators are compared using the general heterogeneous-panel approach described by Pesaran et al. (1999). However, the empirical estimates do not, on their own, establish a causal effect of each explanatory variable. Differences in model restrictions must therefore be recognized throughout the interpretation.

$$\Delta(Zi)\,t = \sum_{h=1}^{n-1} \rho^{i}{}_{h}\Delta(Zi)_{t-h} + \sum_{h=0}^{m-1} \gamma^{i}{}_{h}\Delta(Y_i)_{t-h} + \lambda^{i}[(Zi)_{t-1} - \{\delta^{i}{}_{0} + \delta^{i}{}_{1}(Yi)t - 1\}]\eta_{it} \qquad [2]$$

Equation (2) expresses the proposed dynamic relationship in an error-correction form. The formulation is intended to distinguish immediate changes in renewable energy consumption from the adjustment toward a longer-run relationship involving trade openness, economic growth, and high technology. In this interpretation, an appropriately signed and estimated error-correction coefficient provides evidence about the direction and speed of adjustment, subject to the specification assumptions. Consequently, the short-run coefficients should not be interpreted as interchangeable with long-run coefficients. This

distinction is central to the study's policy question because a factor that accompanies renewable energy use over a long horizon may have a different estimated association during shorter periods of adjustment (Pesaran et al., 1999).

The PMG estimator allows the short-run coefficients, intercepts, adjustment speeds, and residual variances to differ between countries, while requiring homogeneous long-run slopes across the panel (Pesaran et al., 1999). This restriction can improve efficiency when it is appropriate; however, it should be examined rather than assumed. A negative error-correction coefficient is consistent with movement toward long-run equilibrium, but neither an arbitrary minimum absolute value nor the coefficient's sign alone establishes validity. In addition, residual dependence, specification choices, and the accuracy of standard errors remain relevant. The results reported below are therefore discussed with attention to these assumptions and to possible disagreements with the more flexible MG estimates.

The MG approach estimates a separate dynamic relationship for each country and then averages the resulting coefficients. Its principal advantage is that it permits short-run and long-run parameters to vary across the panel, rather than imposing the common long-run slopes used by PMG (Pesaran et al., 1999). However, the flexibility of MG can come at the cost of reduced precision when individual country series do not contain sufficient information. The presence of 25 countries is a feature of this study's sample and should not be presented as satisfying or violating a universal numerical threshold for validity. Consequently, MG provides a useful comparison against the restrictions underlying the PMG estimates.

The DFE model imposes common slope and adjustment parameters while permitting country-specific intercepts, making it more restrictive than MG and, in important respects, PMG. This specification may be informative when countries share similar adjustment processes; however, the assumption should not be taken for granted in a heterogeneous OECD sample. The potential relationship between lagged dependent variables and disturbances also requires appropriate econometric care. Similarly, a Hausman comparison can be used to assess the consistency of competing estimators under the stated null hypothesis, but it is not a general test that removes endogeneity. The analysis therefore uses DFE as an additional comparison rather than as definitive evidence of a single homogeneous process (Pesaran et al., 1999).

3.1 Comparison of PMG, MG, and Dynamic Fixed Effects

PMG may be more efficient than MG when its restriction of homogeneous long-run slopes is consistent with the data (Pesaran et al., 1999). The Hausman specification test is intended to examine whether differences between relevant estimators are statistically systematic. Under the null hypothesis, the more restrictive estimator is consistent and may be preferred for efficiency; rejection raises concerns about its restrictions. However, the test result should be interpreted using the reported statistic, p-value, and specific pair of models compared. Accordingly, the preference for PMG described in this article is conditional upon the displayed comparisons, and it should not be generalized as evidence that all OECD countries necessarily share the same underlying mechanisms or the same short-term responses.

Phillips and Hansen (1990) developed the fully modified ordinary least squares approach for inference in cointegrating relationships, addressing important complications associated with endogeneity and serial dependence. The present study uses FMOLS as an additional long-run estimator. Furthermore, DOLS introduces leads and lags of changes in explanatory variables under a cointegrating framework. The two methods provide complementary checks on estimated long-run coefficients; however, disagreement between their results requires interpretation rather than selective reliance on the most favorable specification.

$$\mathrm{RE}_{t} = \beta_0 + \beta_1 \mathrm{TO}_{it} + \beta_2 \mathrm{EG}_{it} + \beta_3 \mathrm{HT}_{it} + \eta_{t} \qquad [3]$$

In Equation (3), RE denotes renewable energy, TO denotes trade openness, EG denotes economic growth, and HT denotes high technology. The coefficients describe the conditional associations within the proposed long-run equation, while the disturbance term captures variation not represented by the explanatory variables. The panel covers 25 countries, and the country and time indices retain their meanings from the earlier equations. DOLS is employed as an alternative cointegrating regression approach that can include leads and lags of first differences of the regressors. Nevertheless, the exact lag choices and related diagnostics should be documented when the estimates are replicated, and the present revision does not assume unreported implementation details.

4 Results and Discussion

Table 1 presents the descriptive statistics for the selected variables. Mean renewable energy is reported as 22.87, with a standard deviation of 2.32 and values ranging from 0 to 27.01. Trade openness has a reported mean of 72.31, while the economic-growth and high-technology series have respective means of 10.19 and 8.76. However, the table does not independently establish the physical units or transformations of all measures. Consequently, the statistics are described in the numerical form shown, without attributing unsupported units such as terajoules or annual multiples. In addition, the wide reported maximum for trade openness merits attention when evaluating the distribution and possible influence of unusually open economies.

Table 1: Descriptive Statistics

Variables	Mean	Std. Dev.	Min	Max
Renewable energy	22.87	2.32	0	27.01
Trade openness	72.31	2.14	10.73	333.54
Economic growth	10.19	0.49	7.84	11.39
High technology	8.76	1.91	3.18	13.17

Source: Authors' calculations based on the study data.

Before estimating dynamic relationships, the time-series properties of the panel variables must be examined. Table 2 reports panel unit-root statistics at levels and first differences, using the tests identified in its column headings. The displayed first-difference statistics are more negative than the corresponding level results, which the original analysis interprets as evidence of stationarity after differencing. However, the tests should be assessed against their relevant distributions and reported significance levels, and stationarity in first differences does not by itself demonstrate a valid long-run cointegrating relationship. Therefore, the panel-model interpretation should distinguish unit-root evidence from any additional cointegration evidence required for reliable long-run inference.

Table 2: Results of the Panel Unit-Root

	Level		**First Difference**	
	Im, Pesaran & Shin (2003)	Maddala & Wu (1999)	Im, Pesaran and Shin (2003)	Maddala and Wu (1999)
Renewable Energy	-1.39	1.85	-8.12	-22.93
Trade Openness	-1.95	-0.72	-4.55	-8.65
Economic Growth	-1.94	2.49	-7.48	-21.29
High Technology	-1.31	-0.43	-5.16	-8.07

*Source: Authors' calculations based on the study data. *** shows significance at the 1% level.*

The reported unit-root results are interpreted as indicating that the study variables become stationary after first differencing. This conclusion supports consideration of integrated-series methods, subject to the assumptions of the selected estimator. However, the first-difference results alone are not sufficient to establish cointegration or to select an ARDL specification unequivocally. Additional diagnostic evidence would strengthen the interpretation of the long-run coefficients and the error-correction formulation.

Table 3: The Dynamic Models of PMG, MG, and DEF

	PMG		**MG**		**DFE**	
Renewable Energy Use	**Short**	**Long**	**Short**	**Long**	**Short**	**Long**
Err Corr.	-0.31***		-0.48***		-0.07***	
TO	(-0.05)		(0.05)		(0.01)	
	0.02		0.02		0.06	
EG	(0.01)		(0.01)		(0.02)	
	-0.33*		0.28		0.22	
	(0.18)		(0.33)		(0.66)	
HT	-0.08		-0.08		-0.05	
	(-0.01)		(0.11)		(0.09)	
Hausman Test			4.1(0.13) *			0.93(0.81) *
TO		0.02*		0.03		0.09
		(0.01)		(0.06)		(0.01)

	PMG		MG		DFE	
Renewable Energy Use	**Short**	**Long**	**Short**	**Long**	**Short**	**Long**
EG		0.57***		4.42**		1.99**
		(0.04)		(1.83)		(0.97)
HT		-0.01		-0.29		0.31
		(0.02)		(0.47)		(0.33)
Constant	5.65***		0.97		0.37	
	(1.05)		(3.51)		(0.69)	

*Source: Authors' calculations based on the study data. ***, **, and * indicate the reported significance thresholds of 1%, 5%, and 10%, respectively. Parenthetical entries are reproduced as reported in the original table; their statistical meaning should be checked against the model output.*

Table 3 compares PMG, MG, and DFE estimates together with the Hausman specification results. The reported PMG long-run coefficient for economic growth is positive, whereas its short-run coefficient is negative. This contrast is consistent with the article's central interpretation that economic development may have different associations with renewable energy use across time horizons. However, the results remain conditional on the econometric specification, and the term 'GDP per capita' should be used only insofar as it corresponds to the economic-growth measure in the underlying dataset. Similarly, the coefficients for trade openness and high technology require separate examination rather than being inferred from economic growth outcomes.

The PMG results suggest a positive long-run association between economic growth and renewable energy consumption alongside a negative short-run coefficient. The MG and DFE estimates offer useful comparisons, although differences in statistical precision and parameter restrictions limit direct equivalence. The Hausman statistics reported in Table 3 have been used to favor PMG; however, this interpretation depends on the corresponding test specification and p-values. Trade openness is positively associated with renewable energy consumption in the PMG long-run estimates, while the corresponding short-run association is comparatively limited. Therefore, policy conclusions should distinguish the evidence for long-term relationships from claims about immediate effects or causal necessity.

The PMG estimates do not indicate a clear immediate effect of trade openness on renewable energy consumption, even though the long-run coefficient is positive in the reported model. The technology coefficient is not uniformly positive or statistically persuasive across specifications. Accordingly, the results should not be read as establishing that technological progress invariably increases renewable energy use. Nevertheless, Table 4 suggests country-specific differences: for example, the high-technology entries are positive in the Netherlands and Norway and negative in France and the United States. Such contrasts are consistent with cross-country heterogeneity, although they do not identify the underlying mechanisms. In addition, the distinction between pooled and country-specific evidence motivates further investigation into energy-system structures and technology adoption pathways.

Table 4: 25 Member States from OECD

Countries	Constant	Trade Openness	Economic Growth	High Technology
Netherlands	-0.25***	0.01	-0.77	1.98*
Norway	-0.55***	0.01	-0.82	0.16*
France	-0.67***	0.002	0.36	-1.03**
Iceland	-0.01	0.003	0.404	-0.05*
United States	-0.48***	0.014	-0.92	-0.78**
Australia	-0.52***	0.001	0.29	0.02
Belgium	0.00***	0.004	-0.503	0.19
Finland	-0.32***	0.013***	-0.88	0.09
Greece	-0.14	-0.014	-0.26	0.03
Ireland	0.61	0.302	0.189	0.07
Israel	0.95	0.48	0.82	0.87
Italy	-0.06	-0.002	-1.302***	0.11
Japan	-0.78***	0.004	0.86	0.01
Korea, Rep.	-0.47***	-0.002	-1.048	0.33
Luxembourg	-0.41***	0.005*	-0.42	0.01
Portugal	-0.78***	0.024**	-1.47	0.13
Austria	-0.34***	0.001	-1.107	-0.12

Countries	Constant	Trade Openness	Economic Growth	High Technology
Canada	-0.14***	0.004**	0.109	-0.02
Denmark	0.00***	-0.006	1.47	-0.08
Germany	0.04	0.007	-1.091	-0.09
New Zealand	-0.14***	0.001	0.299	0.1
Spain	-0.37***	0.002	-2.37	-0.001
Sweden	-0.63***	0.006	-0.22	-0.05
Switzerland	-0.73***	0.003	-1.023	-0.13
United Kingdom	0.09**	-0.003	0.77	-0.09

Source: Authors' calculations based on the study data.

Table 4 indicates substantial variation in the reported country-specific high-technology coefficients. Positive entries appear for the Netherlands and Norway, whereas negative entries appear for France, Iceland, and the United States. Several other country estimates are small in magnitude, and many have no displayed significance marker. However, a coefficient's sign does not by itself demonstrate that recent technological advancement caused an increase or decrease in renewable energy consumption. Similarly, differences among countries may reflect economic structure, policy settings, measurement, or other unobserved factors. Therefore, the country-level evidence is best presented as an illustration of heterogeneous associations within the OECD sample, not as a direct causal ranking of national technology policies.

The study supplements the dynamic PMG, MG, and DFE comparisons with FMOLS and DOLS estimates, which are reported in Table 5 rather than Table 3. Both approaches are designed for specific forms of long-run regression and involve assumptions about integration, cointegration, and the relation between regressors and disturbances. However, they differ in how corrections for endogeneity and serial dependence are implemented. Their estimates can therefore be compared as a robustness exercise, while discrepancies should remain visible. In particular, different coefficient signs must not be treated as equivalent empirical support for the same policy conclusion (Phillips & Hansen, 1990).

As shown in Table 5, the FMOLS and DOLS estimates differ in meaningful ways. Economic growth has positive coefficients under both methods, whereas trade openness is positive under FMOLS and negative under DOLS. Similarly, the high-technology coefficient is positive in FMOLS but negative in DOLS. This divergence is relevant to the interpretation of technology and trade effects and should not be obscured by describing the methods as fully confirming one another. The original PMG long-run results in Table 3 also provide an additional comparison. Consequently, the strongest recurring pattern across these reported long-run estimators concerns economic growth, while the direction of the trade and technology associations is more sensitive to model selection.

Table 5: FMOLS and DOLS Results

Renew Energy	FMOLS		DOLS	
	Coefficient	**Std. Err**	**Coefficient**	**Std. Err**
Trad Openness	0.79	0.002	-0.35	0.09
Economic Growth	2.35	0.008	1.31	0.17
High Technology	0.47	0.003	-0.113	0.17
	R Square	0.86	R Square 0.81	

Source: Authors' calculations based on the study data.

4.1 Interpretation of conflicting estimates and research implications

Three distinctions are important when reading Tables 3–5. First, the short-run and long-run PMG coefficients describe different temporal relationships, so the negative short-run economic-growth estimate does not negate the positive reported long-run association. Second, the high-technology signs differ across PMG, FMOLS, and DOLS, and the trade-openness signs also differ across FMOLS and DOLS. These results make a uniformly beneficial trade or technology effect difficult to defend from the current specifications alone. Third, Table 4 identifies potentially useful country differences, although its coefficients should not be interpreted as causal national impacts. Further empirical work could test alternative lag structures, cross-sectional dependence, cointegration, and heterogeneous long-run parameters. Such procedures are recommendations for subsequent verification, not additional tests performed in the present study.

4.2 Policy differentiation across OECD economies

The findings imply that policy discussion should separate time horizon, trade exposure, and technological capacity. When short-run economic adjustment matters, renewable energy financing and implementation continuity may help prevent transitional delays. Where trade openness facilitates access to equipment and specialist knowledge, policies can address practical barriers to deployment, while also monitoring changes in fossil-energy demand. Similarly, countries with different technological coefficients may benefit from evaluating the fit between research investment, grid readiness, and local energy systems before assuming identical outcomes. These recommendations are informed by the study's reported associations and by related renewable-energy research (Hesselink & Chappin, 2019; Ilechukwu & Lahiri, 2022; Zhang et al., 2023); they are not direct evaluations of specific policy interventions.

Adj R^2 0.83

Adj R^2 0.86

FMOLS modifies ordinary least squares estimation in a cointegrating regression to address specified forms of endogeneity and serial dependence (Phillips & Hansen, 1990). In the present study, the FMOLS results in Table 5 show a positive coefficient for economic growth in the 25-country OECD panel. The DOLS coefficient for economic growth is also positive, providing more consistent directional support across the two specifications. However, the reported table does not provide the complete set of inferential statistics needed to verify every claim about statistical significance. Moreover, these results do not estimate any non-OECD comparison. Therefore, policy contrasts between OECD and non-OECD countries should be treated as context for future investigation rather than an empirical finding established by the reported sample.

4.3 Limitations and Directions for Future Research

Several limitations should guide the interpretation and subsequent use of these results. The sample covers 25 OECD countries through 2022,limitings direct generalization to other economies or more recent developments. The report does not fully identify all original data series, units, and transformations, and it does not supply a complete set of diagnostic and lag-selection details. Moreover, the disagreement between several long-run estimators means that trade and technology associations are specification-sensitive. The outcome is renewable energy consumption rather than a direct measure of greenhouse gas emissions, so environmental effects remain outside the model's estimated scope. Future research could provide a replicable variable dictionary, test cross-sectional dependence and cointegration explicitly, assess nonlinear growth or trade responses, and examine institutional quality, green finance, carbon pricing, and energy-system characteristics as additional explanatory factors. Subgroup estimates may also clarify differences between OECD economies with contrasting energy mixes and innovation capacities. Such extensions would preserve the original research theme while improving comparability, reproducibility, and usefulness for subsequent research.

Trade openness may affect renewable energy use through access to technologies, exposure to international competition, and changes in production and energy demand (Ilechukwu & Lahiri, 2022; Zhang et al., 2021). The results in Table 5, however, are not uniform: FMOLS reports a positive trade-openness coefficient, whereas DOLS reports a negative one. Similarly, FMOLS indicates a positive high-technology coefficient, while DOLS indicates a negative coefficient. These differences do not justify claiming that technical progress consistently increases renewable energy use. Instead, they suggest sensitivity to estimation assumptions and possible cross-country heterogeneity. In addition, the country-level patterns in Table 4 support a cautious interpretation of technological associations rather than a single universal mechanism. Subsequent work could evaluate these differences using additional diagnostics, specifications, and country groupings.

5 Conclusions and Policy Implementation

The study contributes to the literature on renewable energy consumption in OECD economies by examining economic growth, trade openness, and high technology through complementary panel estimators. Its principal empirical contribution is the distinction between short-run and long-run relationships, together with evidence of variation across national estimates. The results suggest that economic growth is negatively associated with renewable energy use in the short run under the PMG specification but positively associated in the long run. However, the findings for trade openness and technological progress are less consistent across methods. Therefore, claims of a universal or causal effect

go beyond the reported evidence, and the contribution is better framed as a comparative analysis of dynamic associations.

The results offer a basis for subsequent research on economic activity, international trade, and renewable energy consumption in both OECD and other national settings. Destek and Sinha (2020) and Padhan et al. (2020) provide directly relevant OECD comparisons, while Zhang et al. (2021) examine trade openness and renewable energy use in OECD economies. In addition, Ilechukwu and Lahiri (2022) consider renewable energy and international trade, and Fannoun and Hassouneh (2019) examine relationships involving trade, renewable energy, and emissions across developed and developing countries. These studies address related but not identical outcomes. Accordingly, the positive PMG long-run trade coefficient can be situated within this literature, but the opposing FMOLS and DOLS trade signs require acknowledgement before drawing general policy conclusions.

The technological-progress results require a differentiated interpretation. The PMG long-run high-technology coefficient in Table 3 is slightly negative, while the FMOLS and DOLS coefficients in Table 5 have opposite signs. Furthermore, the country estimates in Table 4 vary appreciably. Consequently, the evidence does not establish a uniform positive technology effect for the OECD sample. Nevertheless, technological capabilities remain relevant to energy-transition research because adoption conditions, innovation systems, and policy environments may differ across countries (Jianguo et al., 2022; Zhang et al., 2023). This qualified conclusion is more consistent with the reported estimates than a claim that all technological advancement has already increased renewable energy dependence.

Promoting renewable energy commonly involves technological investment, infrastructure, policy incentives, and effective implementation. OECD countries may have advantages in income and technological capability, but their energy systems and resource endowments remain diverse. Therefore, support for renewable energy should be designed with national circumstances in mind, rather than assuming identical responses across the panel. In addition, research on technology adoption indicates that resources, incentives, and other barriers can affect uptake (Hesselink & Chappin, 2019). Although technological development may support the transition, the present estimates do not measure particular policies or quantify the environmental consequences of individual renewable technologies. Such distinctions should inform the interpretation of policy recommendations.

The reported relationships among economic growth, trade openness, high technology, and renewable energy consumption are relevant to designing long-term energy strategies in OECD countries. However, the evidence indicates that temporal dynamics and model choice matter. Policies supporting renewable energy can therefore combine stable investment conditions with measures to address short-run adjustment difficulties. Similarly, trade policy may facilitate the diffusion of equipment and knowledge, but its net association with renewable energy should be evaluated against the contrasting long-run estimates. In addition, support for technological innovation should be coordinated with country-specific implementation capacity. These implications align with the study's broader environmental motivation, although the reported renewable-energy regressions did not directly estimate reductions in carbon emissions.

Policies that encourage renewable energy production and use may also support broader economic development objectives. Investing in technological capabilities is a plausible way to support renewable energy adoption, particularly where infrastructure and financing barriers limit implementation. Likewise, well-designed carbon-pricing measures can be part of a broader climate policy package, although the present analysis does not estimate their separate effects. Therefore, recommendations on carbon pricing, trade liberalization, and innovation should be considered policy directions to evaluate rather than direct causal conclusions from the model. Future research can extend the framework to measure emissions, institutional quality, and additional transition mechanisms while preserving the central interest in renewable energy and economic development.

Ethical Statement: Not applicable

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