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Yasmeen S. A. Abdelmoaty

yasmeen.sameh@guc.edu.eg

German University in Cairo

Dina Yousri

German University in Cairo

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Powering the Transition: What Drives Renewable Energy Consumption Across Developed and Developing Economies?

Yasmeen S. A. Abdelmoaty[1][0009-0001-4849-7939] and Dina Yousri[2][0000-0003-4506-3294]

[1]Department of Economics, The German University in Cairo, Cairo, Egypt
[2]Department of Economics, The German University in Cairo, Cairo, Egypt
yasmeen.sameh@guc.edu.eg
dina.elsayed@guc.edu.eg
Corresponding author: Yasmeen S. A. Abdelmoaty
Email: yasmeen.sameh@guc.edu.eg

Abstract. As the world faces climate change and energy security challenges, the transition to renewable energy has become essential for global sustainability. The factors influencing renewable energy adoption vary between developed and developing countries due to differences in their economic, political, and social contexts. This study investigates the key drivers of renewable energy consumption, focusing on environmental taxes, research and development (R&D) funding, institutional quality, and economic growth. Using panel data from 40 countries, including 20 developed and 20 developing countries, over the period from 1995 to 2021, the study applies fixed effects regression and one year lagged panel regression specifications. The results indicate that, in developing countries, the main determinants are positively associated with renewable energy consumption in the same year fixed effects models and remain positive in the one year lagged specifications. In developed countries, environmental taxes and R&D are positively associated with renewable energy consumption in the same year fixed effects models, whereas in the one year lagged specifications, R&D, institutional quality, and GDP per capita are positively associated with renewable energy consumption, while environmental taxes are negatively associated with it. These findings highlight the complexity of energy transitions and the need for policies tailored to different economic contexts and levels of institutional capacity. The study contributes to the literature by providing a comparative perspective and practical insights for policymakers and investors seeking to support sustainable energy transitions.

Keywords

Renewable Energy Consumption; Environmental Taxation; Research and Development; Institutional Quality; Energy Transition; Developing Economies

1. Introduction

Since the beginning of the third decade of the 21st century, the global energy sector has reached a critical turning point. Growing concerns about climate change, together with the urgent need for sustainable energy sources, have intensified global discussions about the future of energy consumption. The transition to renewable energy changes the way societies interact with the environment and affects economic structures and social priorities by reducing dependence on traditional non renewable energy sources .

In response, governments across the world have implemented a variety of policies to mitigate environmental damage and promote sustainable energy adoption. According to the International Energy Agency, 126 countries have introduced a wide range of strategies, ranging from financial incentives and regulatory tools to energy consumption restrictions, . Among these measures, environmental taxes have emerged as a particularly effective instrument, incentivizing consumers to shift toward cleaner energy alternatives by raising the cost of environmentally harmful products, which supports both ecological and economic benefits, .

In addition to policy measures, the transition toward renewable energy also requires significant investments in research and development (R&D) to drive technological innovation. R&D expenditure is essential for developing cost effective and efficient renewable technologies, yet it remains a challenge, particularly in developing regions. In this context, institutions such as the African Development Bank emphasize R&D's role in advancing green growth and ensuring sustainable use of resources .

Furthermore, institutional quality and government support play a critical role in enabling renewable energy adoption. Effective governance structures are necessary to coordinate large scale investments, implement policies, and encourage public and private collaboration in the energy sector, . Without strong institutional frameworks, even well designed policies may fail to achieve their intended outcomes.

Alongside these factors, economic growth also influences patterns of energy consumption. Although economic growth generally increases energy demand, whether this demand is met by renewable or non renewable energy sources depends on the policy environment and the level of technological development. Countries with greater economic capacity are better able to invest in renewable energy infrastructure, green technologies, and R&D. In turn, these investments can support job creation, improve energy security, and contribute to more sustainable economic development, .

Despite extensive literature on renewable energy determinants, significant gaps remain. Most studies focus on developed countries, often overlooking challenges faced by developing economies. In particular, the combined influence of environmental taxes, R&D investment, institutional quality, and economic growth on renewable energy adoption across diverse economic contexts remains underexplored , . Therefore, understanding these relationships is important for designing policies that can support renewable energy transitions across countries with different levels of development.

In light of these gaps, this study examines how environmental taxes, R&D investment, institutional quality, and economic growth are associated with renewable energy consumption in both developed and developing countries. It further considers the role of policy instruments, innovation,

and governance structures, providing a comparative perspective on the factors that may support or constrain renewable energy adoption.

The study is guided by four research questions:

1. How are environmental taxes associated with renewable energy consumption across developed and developing economies?
2. How is R&D expenditure associated with renewable energy consumption in developed and developing countries?
3. How is institutional quality associated with renewable energy consumption in developed and developing countries?
4. How is economic growth associated with renewable energy consumption across developed and developing economies?

To address these research questions, the study tests the following hypotheses. The hypotheses are formulated for the overall sample and further examined separately for developed and developing countries to capture potential differences across levels of economic development.

H1: Environmental taxation is positively associated with renewable energy consumption.

H1a: Environmental taxation is positively associated with renewable energy consumption in developed countries.

H1b: Environmental taxation is positively associated with renewable energy consumption in developing countries.

H2: R&D expenditure is positively associated with renewable energy consumption.

H2a: R&D expenditure is positively associated with renewable energy consumption in developed countries.

H2b: R&D expenditure is positively associated with renewable energy consumption in developing countries.

H3: Institutional quality is positively associated with renewable energy consumption.

H3a: Institutional quality is positively associated with renewable energy consumption in developed countries.

H3b: Institutional quality is positively associated with renewable energy consumption in developing countries.

H4: GDP per capita is positively associated with renewable energy consumption.

H4a: GDP per capita is positively associated with renewable energy consumption in developed countries.

H4b: GDP per capita is positively associated with renewable energy consumption in developing countries

Testing these hypotheses provides a comparative understanding of the factors associated with renewable energy consumption and highlights whether their relationships differ between developed and developing economies, thereby offering policy relevant insights for renewable energy transitions across different stages of development.

The rest of the paper is structured as follows. Section 2 reviews the relevant literature and theoretical foundations. Section 3 describes the methodology, including the study sample, variable descriptions, and the models employed. Section 4 presents the empirical results, including the PCA

results, fixed effects regression results, and one year lagged regression results for both developed and developing countries. Section 5 discusses the main findings. Finally, Section 6 concludes the study by presenting its limitations, directions for future research, and policy, managerial, and theoretical implications.

2. Literature Review

2.1. Renewable Energy Overview

Renewable energy, or clean energy, refers to sources that produce minimal or no CO_2 emissions and are not depleted by consumption. These include sunlight, wind, flowing water, geothermal heat, and biomass. Such energy can be used directly, stored in batteries, or converted into electricity, heat, or transportation fuels. Renewable energy is central to advancing sustainability and energy security, offering a cleaner alternative to finite, polluting fossil fuels. As a result, it has become a central focus of national and international policy efforts aimed at transforming power generation, heating, and biofuels toward a sustainable future , , , .

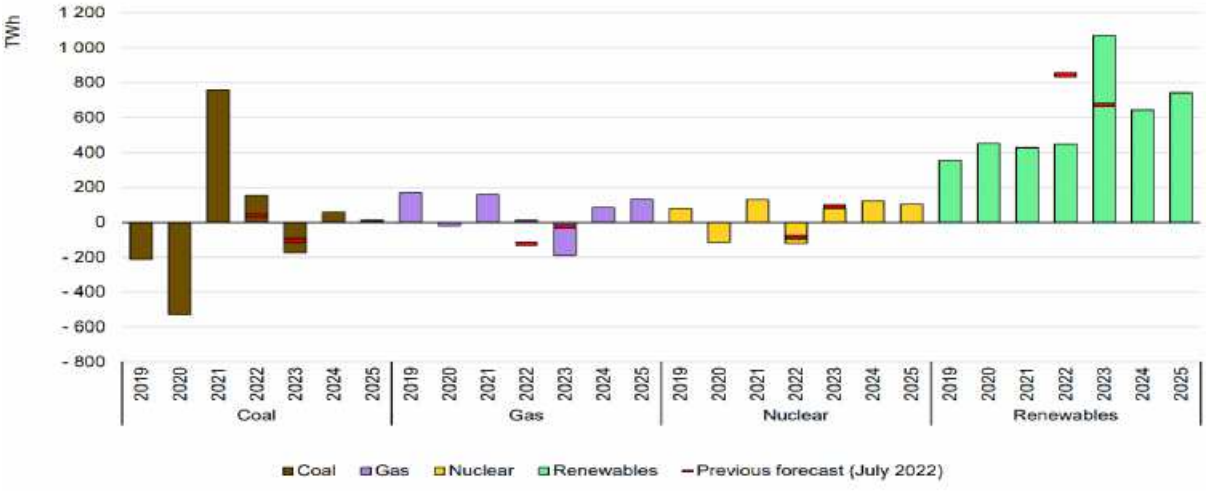

Fig. 1 *Year-on-Year Global Change in Electricity Generation by Source (2019-2025).*

Source: World Economic Forum: IEA 2023; Electricity Market Report 2023.

The global shift toward renewable energy can be seen in the changing energy mix. As shown in Figure 1, electricity generation is gradually moving away from fossil fuels and toward renewable energy sources between 2019 and 2025. Coal increased slightly in 2021 but then began to decline, while electricity generated from gas shows some fluctuations before also decreasing. Nuclear energy remains relatively stable over the period. In contrast, renewable energy continues to grow, especially between 2023 and 2025. This increase reflects the growing use of cleaner energy sources worldwide. The forecasts from July 2022, shown by the red lines, indicate some small changes in the expected values but still show the same general pattern of declining fossil fuel use and increasing renewable energy generation.

2.2. Factors Affecting Renewable Energy Consumption

Several factors influence renewable energy consumption, including economic policies, institutional quality, R&D investment, and economic growth. Understanding these determinants matters for designing effective policies to accelerate the global transition toward sustainable energy.

2.2.1. Environmental Taxes

Economic policies such as environmental taxes and subsidies incentivize the transition from fossil fuels to cleaner energy sources by imposing costs on environmentally harmful activities and generating revenues that can support environmental objectives. Environmental taxes such as energy, transport, pollution, and resource taxes are designed to promote more efficient resource use and contribute to sustainable development.

The relationship between environmental taxation and renewable energy consumption can be theoretically explained through Pigouvian Taxation Theory and Double Dividend Theory. Pigouvian Taxation Theory suggests that environmental taxes internalize the social costs associated with environmentally harmful activities, which alters relative prices and creates economic incentives for substituting fossil fuels with cleaner energy alternatives , Complementing this perspective, Double Dividend Theory emphasizes that environmental taxation may generate both environmental improvements and economic benefits when tax revenues are used efficiently, including through reductions in other distortionary taxes . Together, these theoretical perspectives suggest a positive relationship between environmental taxation and renewable energy consumption; however, the magnitude and nature of this relationship may vary between developed and developing economies due to differences in fiscal capacity, institutional conditions, and stages of energy transition.

This variation across economic contexts shows up in the data as well: empirical evidence on the relationship between environmental taxation and renewable energy is mixed. In G7 countries, environmental taxes are positively associated with renewable energy adoption , while and report similar long term positive effects in Asia and OECD nations, respectively. Similarly, highlights their role in promoting clean energy in green economies. Conversely, and report negative relationships in certain contexts, suggesting that the effectiveness of environmental taxation in supporting renewable energy may vary across countries and economic conditions.

2.2.2. Research and Development (R&D)

Research and development (R&D) refers to systematic activities undertaken by firms, institutions, and other organizations to generate new knowledge, develop innovative technologies, and improve existing products and processes. In the renewable energy sector, R&D investment is a key driver of technological innovation, reducing production, and improving the efficiency and performance of renewable energy technologies, which enhances their competitiveness relative to traditional energy sources ,.

The relationship between R&D and renewable energy consumption can be theoretically explained through Endogenous Growth Theory, which emphasizes the role of knowledge accumulation and technological innovation in promoting sustained economic and technological development. From

this perspective, investment in R&D drives technological progress by supporting the development and diffusion of new technologies, improving production efficiency, and enabling more efficient use of natural resources and energy ,. In the renewable energy context, Endogenous Growth Theory suggests that greater R&D expenditure promotes technological advancement, improving the efficiency and competitiveness of renewable energy technologies, although its influence may vary across developed and developing economies.

Empirical studies show mixed outcomes: found short run negative but long run positive effects in EU countries, while reported an overall positive relationship in OECD countries despite temporary declines. Similarly, identified positive effects in China and Japan but insignificant effects in India, whereas documented positive relationships in some European countries alongside negative or insignificant results in others. This variation in empirical findings further suggests that the relationship between R&D and renewable energy consumption may depend on countries' technological and economic conditions.

2.2.3. Institutional Quality

Institutional quality reflects the effectiveness, stability, and governance capacity of a country's institutions, influencing social and economic coordination. Strong institutions reduce transaction costs, enhance policy implementation, and create favorable conditions for renewable energy adoption .

The relationship between institutional quality and renewable energy consumption can be theoretically explained through Institutional Theory, which emphasizes the role of institutional structures, regulations, policies, and norms in shaping economic and social decisions. In the renewable energy context, effective institutional frameworks can help align technological innovation with energy policies and support the transition toward renewable energy sources ,. Accordingly, stronger institutional quality is expected to be positively associated with renewable energy consumption, although this relationship may vary across institutional and development contexts.

Empirical evidence generally supports the importance of institutional quality, although the relationship varies across regions and time horizons. Found positive long run effects across 38 countries, while short run effects were often insignificant. Similarly, reported differences across colonial legacies in Sub Saharan Africa, while identified negative short run but positive long run effects in developing countries. Confirmed a significant positive long run relationship, whereas studies focusing on Bangladesh and Tunisia reported mixed or context specific findings, .

2.2.4. Economic Growth

Economic growth reflects the long-term expansion of a country's productive and economic capacity and is influenced by factors such as human capital, knowledge accumulation, education, and innovation . GDP per capita growth and per capita energy consumption have also demonstrated a strong positive correlation over time, highlighting economic growth as an important driver of increased energy demand and consumption. As a result, economic growth may support a shift from traditional fossil fuels toward higher quality electricity sources .

The relationship between economic growth and renewable energy consumption can be theoretically explained through the Environmental Kuznets Curve (EKC) and Green Growth Theory. The EKC suggests that environmental quality may initially deteriorate as economic growth increases; however, as economies mature, greater demand for environmental protection and technological advancement can contribute to improved environmental outcomes and the adoption of cleaner energy sources,,. Complementing this perspective, Green Growth Theory proposes that economic growth can coexist with environmental sustainability through more efficient resource use and reduced environmental pressures. Together, these theoretical perspectives provide a foundation for expecting economic development to support the transition toward renewable energy consumption as economies advance.

Empirical evidence on the relationship between economic growth and renewable energy consumption varies across income levels and regions. Studies and found positive long run effects in developing and Sub Saharan countries, respectively. Similarly, observed that economic growth promotes renewable energy in middle and high income countries but reduces it in low income countries. Evidence from OECD countries and China indicates positive long run effects, while short run effects are often limited or negative , . Similarly, studies focusing on South Asia and other developing regions confirmed a positive long term influence with limited short term effects , .

Research Gap and Contribution

Although a growing body of literature has examined the determinants of renewable energy consumption, important gaps remain regarding how fiscal, technological, institutional, and economic drivers operate jointly across different stages of development. Existing studies have often focused on individual determinants, specific regions, or relatively homogeneous country groups, while the combined relationships of environmental taxes, research and development (R&D), institutional quality, and economic growth across developed and developing economies remain comparatively underexplored. This limitation is particularly important because countries differ substantially in fiscal capacity, technological capability, institutional effectiveness, infrastructure, and their ability to finance and implement renewable energy transitions. This study addresses this gap by examining these determinants within a unified comparative framework using a balanced panel of 40 countries—20 developed and 20 developing economies—over the period 1995–2021. Its main contribution lies in demonstrating that the drivers of renewable energy consumption are not uniform across stages of development or over different time horizons. By comparing the associations of environmental taxation, R&D, institutional quality, and economic growth across the two country groups, the study provides evidence of development in the renewable energy transition. It therefore advances the literature beyond the question of whether these factors are associated with renewable energy consumption toward a deeper understanding of how, when, and under what development conditions they matter, providing a stronger empirical, theoretical, and managerial basis for designing differentiated and context-specific renewable energy strategies and policies rather than applying uniform prescriptions across economies.

3. Methods

3.1. Sample

This study examines the associations of environmental taxation, research and development (R&D), institutional quality, and economic growth with renewable energy consumption. It employs a balanced panel dataset comprising 40 developed and developing countries over the period 1995–2021, selected based on data availability to ensure consistency and reliability.

The classification of countries into developed and developing groups follows the International Monetary Fund (IMF) classification for 2024. Specifically, countries classified by the IMF as advanced economies are categorized as developed countries in this study, while those classified as emerging market and developing economies are categorized as developing countries.

The developed economies include France, Germany, Italy, Latvia, Greece, Switzerland, the United Kingdom, Slovenia, Sweden, Portugal, the Slovak Republic, the Netherlands, Norway, Iceland, Finland, the Czech Republic, Austria, Japan, South Korea, and Australia. The developing economies consist of Bulgaria, Georgia, Romania, Hungary, Poland, Turkey, China, Kazakhstan, Malaysia, Brazil, Guatemala, Costa Rica, Mexico, Panama, Argentina, Colombia, Uruguay, Egypt, Tunisia, and South Africa.

This country selection captures a wide range of economic, institutional, and geographical contexts, allowing for comparative analysis across different stages of development. By incorporating diverse economies, the study provides insights into how the associations between environmental policies, innovation capacity, institutional quality, and renewable energy consumption vary across developed and developing economies.

3.2. Variable Description

This study employs panel data comprising both developed and developing countries from 1995 to 2021. The dependent variable, Renewable Energy Consumption, measures the proportion of total final energy use derived from renewable sources across end-use sectors (residential, industrial, transport, commercial, and agriculture), reflecting the extent to which economies rely on clean energy.

The independent variables include Environmentally Related Tax Revenue, measured in US$ millions and comprising revenues from taxes related to environmentally relevant tax bases, including energy, transport, pollution, and resource use; Research and Development Expenditure, measured as a percentage of GDP and representing national expenditure on research and development activities; GDP per capita, measured in current US dollars and reflecting the level of economic prosperity; and the Institutional Quality Index, constructed by the author using Principal Component Analysis (PCA) based on six World Governance Indicators—Control of Corruption, Government Effectiveness, Political Stability and Absence of Violence/Terrorism, Regulatory Quality, Rule of Law, and Voice and Accountability each measured on a percentile rank from 0 to 100.

The control variables include CO_2 emissions, which represent carbon dioxide emissions resulting from fossil fuel combustion and industrial processes, and urban population, defined as the proportion of the population residing in areas classified as urban by national statistical offices.

This set of variables captures the economic, institutional, technological, and demographic determinants of renewable energy consumption across diverse national contexts.

Table 1 Variables' Definitions and Sources

Variable Type	Variable Name	Measure / Unit	Symbol	Source
Dependent Variable	Renewable Energy Consumption	% of total final energy consumption	REC	World Bank (2024), World Development Indicators (WDI)
Independent Variables	Environmentally Related Tax Revenue	US$ (millions)	ERT	OECD (2024); IMF (2024)
	Research and Development Expenditure	% of GDP	R&D	World Bank (2024), World Development Indicators (WDI)
	GDP per Capita	Current US$	GDP-PC	World Bank (2024), World Development Indicators (WDI)
	Institutional Quality Index	Percentile rank (0–100)	IQ	World Bank (2024), Worldwide Governance Indicators (WGI)
Control Variables	CO_2 Emissions	Metric tons per capita	CO_2	World Bank (2024), World Development Indicators (WDI)
	Urban Population	% of total population	URPOP	World Bank (2024), World Development Indicators (WDI)

Source: Constructed by author

3.3. Statistical methods

An Institutional Quality Index (IQI) was constructed using Principal Component Analysis (PCA), based on six World Governance Indicators: Control of Corruption, Government Effectiveness, Political Stability and Absence of Violence/Terrorism, Regulatory Quality, Rule of Law, and Voice and Accountability, following , , . Descriptive statistics and correlation analyses were initially conducted to summarize the dataset and assess inter-variable relationships.

To capture variations across countries and over time while addressing unobserved heterogeneity, a panel data regression model was estimated ,. The Fixed Effects (FE) estimator was selected based on the Hausman test results, which indicated correlation between individual specific effects and regressors, which favors FE over the Random Effects (RE) model , ,.

To examine delayed relationships, one year lagged panel regression specifications were estimated, with the optimal lag selected according to the Vector Autoregression (VAR) lag length criteria . These specifications use lagged levels of the explanatory variables to examine delayed associations. Diagnostic tests including the Variance Inflation Factor (VIF) for multicollinearity, the Modified Wald test for groupwise heteroskedasticity, and the Wooldridge test for first order serial correlation were conducted to assess the validity of the model assumptions. Given the evidence of heteroskedasticity and serial correlation, fixed effects models were estimated using Huber White cluster robust standard errors at the country level to obtain inference robust to heteroskedasticity and within country correlation of the disturbances .

All variables were transformed into natural logarithmic form to stabilize variance, reduce heteroscedasticity, and facilitate elasticity-based interpretation. The stationarity properties of the transformed variables were subsequently examined using the Levin Lin Chu (LLC) panel unit-root test.

In all equations (1–4), i denotes the country and t denotes the year. In Equations (3) and (4), the explanatory variables are lagged by one year (t−1), based on the VAR lag selection criteria.

Equation 1:

$$LNREC_{it} = \beta_0 + \beta_1 LNERT_{it} + \beta_2 LNR\&D_{it} + \beta_3 LNIQ_{it} + \beta_4 LNCO2_{it} + \beta_5 LNURPOP_{it} + \epsilon_{it}$$

Equation 2:

$$LNREC_{it} = \beta_0 + \beta_1 LNERT_{it} + \beta_2 LNR\&D_{it} + \beta_3 LNGDP\text{-}PC_{it} + \beta_4 LNCO2_{it} + \beta_5 LNURPOP_{it} + \epsilon_{it}$$

Equation 3:

$$\ln(REC_{it}) = \beta_0 + \beta_1 \ln(ERT_{i,t-1}) + \beta_2 \ln(R\&D_{i,t-1}) + \beta_3 \ln(IQ_{i,t-1}) + \beta_4 \ln(CO2_{i,t-1}) + \beta_5 \ln(URPOP_{i,t-1}) + \varepsilon_{it}$$

Equation 4:

$$\ln(REC_{it}) = \beta_0 + \beta_1 \ln(ERT_{i,t-1}) + \beta_2 \ln(R\&D_{i,t-1}) + \beta_3 \ln(GDPPC_{i,t-1}) + \beta_4 \ln(CO2_{i,t-1}) + \beta_5 \ln(URPOP_{i,t-1}) + \varepsilon_{it}$$

4. Results

Before conducting the regression analysis, principal component analysis was used to construct the institutional quality index, capturing six governance indicators: Government Effectiveness, regulatory quality, control of corruption, rule of law, voice and accountability, and political stability. From Table 2, Component 1 has an eigenvalue of 4.65475, capturing approximately 77.58% of the total variation. Component 2 explains an additional 8.3% of the variance, bringing the total variation explained to 85.88%. The remaining variation is captured by Components 3, 4, 5, and 6. According to ,, the component selected should have an eigenvalue greater than 1, as it explains more variance than a single observed variable. Additionally, most component loadings

for each variable should exceed 0.40 to maximize the explained variance. Therefore, based on Table 2 and Figure 2, Component 1 was retained to construct the institutional quality index.

Table 2 Principal component results

Component	Eigenvalue	Difference	Proportion	Cumulative
Comp 1	4.65475	4.15695	0.7758	0.7758
Comp 2	.497807	.0719915	0.0830	0.8588
Comp 3	.425816	.230646	0.0710	0.9297
Comp 4	.195169	.0573647	0.0325	0.9623
Comp 5	.137805	.0491543	0.0230	0.9852
Comp 6	.0886504	.	0.0148	1.0000
Number of obs	1,080			
Number of comp	6			
Trace	6			
Rho	1.0000			

Source: Author's calculation based on WGI data.

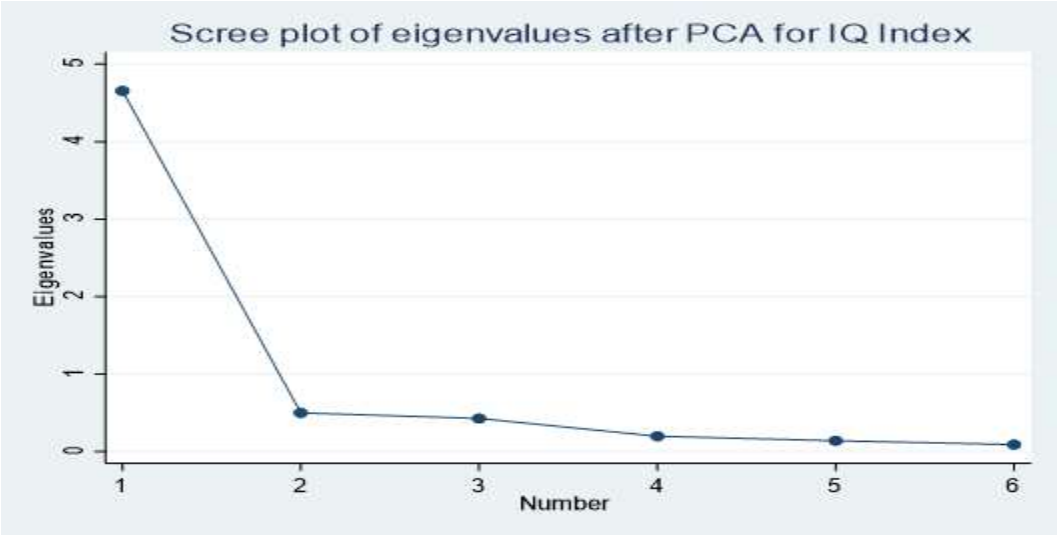

Fig. 2 Scree plot of eigenvalues after PCA for the Institutional Quality Index.

Source: *Author's calculation based on WGI data.*

Table 3 Results of Fixed Effects Regression for Developing Countries

Dependent variable: Renewable Energy Consumption	**Model 1 (IQ)**	**Model 2 (GDP-PC)**
Environmental Taxes	0.105***	0.0109*
	(0.0136)	(0.0194)
Research and Development	0.148***	0.105***
	(0.0315)	(0.0277)
Quality of Institutions	0.0331***	
	(0.0109)	

GDP Per Capita		0.224***
		(0.0278)
CO2 Emissions	-1.148***	-1.241***
	(0.0592)	(0.0573)
Urban Population	0.000181	0.000366
	(0.00941)	(0.00830)
Constant	3.470***	2.450***
	(0.115)	(0.150)
Model	Fixed	Fixed
Hausman- Test chi2 -FE vs RE [Prob>chi2]	12.75 [0.0258]	10.42 [0.0247]
Modified Wald test for groupwise heteroskedasticity [Prob>chi2]	2093.32 [0.0000]	1772.34 [0.0000]
R-squared (Within)	0.7117	0.6845
Rho	.84161312	.85909912
F [Prob > F]	77.30 [0.0000]	71.83 [0.0000]
Mean VIF (from pooled model)	1.53	1.54
Wooldridge test for autocorrelation	181.327 [0.0000]	188.655 [0.0000]
Jochmans Portmanteau test [Prob > Chi-sq]	20.000 [1.0000]	20.000 [1.0000]
Observations	540	540
Number of countries	20	20

Source: *Author's calculations using Stata.*

Fixed effects regressions for developing countries further support these findings. Model 1 (IQ) and Model 2 (GDP-PC) are both highly significant (Model 1: $F = 77.30$; Model 2: $F = 71.83$; $p < 0.001$) with substantial explanatory power ($R^2 = 0.7117$ and 0.6845). The Hausman test confirms the appropriateness of the fixed effects specification, and mean VIF values (~1.5) indicate no multicollinearity concerns.

In Model 1, environmental taxes ($\beta = 0.105$, $p < 0.01$), R&D ($\beta = 0.148$, $p < 0.01$), and institutional quality ($\beta = 0.0331$, $p < 0.01$) are positively and significantly associated with renewable energy consumption, whereas CO_2 emissions show a strong negative association ($\beta = –1.148$, $p < 0.01$). In Model 2, environmental taxes are marginally significant ($\beta = 0.0109$, $p < 0.1$), while R&D ($\beta = 0.105$, $p < 0.01$) and GDP per capita ($\beta = 0.224$, $p < 0.01$) are positively and significantly associated with renewable energy consumption. CO_2 emissions continue to be negatively associated with renewable energy consumption ($\beta = –1.241$, $p < 0.01$). Urban population is insignificant in both models.

"Diagnostic tests indicate the presence of groupwise heteroskedasticity, as the Modified Wald test rejects the null hypothesis of homoskedasticity ($p < 0.001$). The Wooldridge test also rejects the null hypothesis of no first order serial correlation ($p < 0.001$), confirming serial correlation in the panel data. Accordingly, fixed effects models were estimated using Huber White cluster-robust standard errors at the country level to account for heteroskedasticity and within-country correlation of the disturbances; coefficient estimates from the robust and non-robust models were similar, with the robust specification adjusting the standard errors rather than the point estimates. The Jochmans Portmanteau test was additionally conducted as a diagnostic test for within-panel dependence."

Table 4 Optimal lag length for developing countries using panel VAR.

Lag Length	AIC	HQ	SC	FPE
1	-14.21976	-14.04305	-13.76829	6.674880e-07
2	-14.13542	-13.80409	-13.28891	7.262884e-07
3	-14.01686	-13.53090	-12.77531	8.178961e-07
4	-13.87661	-13.23602	-12.24001	9.414539e-07
5	-13.75653	-12.96131	-11.72489	1.062316e-06
6	-13.60936	-12.65953	-11.18269	1.232011e-06
7	-13.52799	-12.42353	-11.07063	1.338377e-06
8	-13.46925	-12.21017	-10.25250	1.422054e-06
9	-13.33965	-11.92594	-9.727858	1.622798e-06
10	-13.22215	-11.65381	-9.215316	1.830714e-06

Source: *Author's calculations using Stata.*

Table 4 presents the optimal lag length for the 20 developing countries using a Vector Autoregression (VAR) model. The selection was based on standard information criteria Akaike Information Criterion (AIC), Hannan Quinn (HQ), Schwarz Criterion (SC), and Final Prediction Error (FPE) to balance model fit and parsimony. Across all criteria, the lowest values occur at lag 1, indicating that a single year lag provides the best predictive performance. Higher lag lengths increase model complexity without improving fit, supporting the choice of a one year lag in the subsequent one-year lagged panel analyses.

Table 5 One-year lagged panel regression for 20 developing countries

Dependent variable: Renewable Energy Consumption	**Model 1 (Lag 1 IQ)**	**Model 2 (Lag1 GDP-PC)**
Lag1. Environmental Taxes	0.1744***	0.1276***
	(0.0145)	(0.0159)
Lag1. Research and Development	0.0098*	0.0877***
	(0.0294)	(0.0297)
Lag1. Quality of Institutions	0.1101***	
	(0.0101)	
Lag1. GDP Per Capita		0.1562***
		(0.0252)

Lag1. CO2 Emissions	-1.3692***	-1.396***
	(0.0326)	(0.0357)
Lag1. Urban Population	-0.1169***	-0.116***
	(0.0092)	(0.009)
Constant	3.2271***	2.197***
	(0.1211)	(0.2194)
R-squared	.796	0.766
F **[Prob > F]**	401.873 [0.0000]	337.889 [0.0000]
Observations	520	520
Number of countries	20	20

Source: *Author's calculations using Stata.*

The one year lagged panel regression results are reported in Table 5. Two models were estimated: Model 1 includes institutional quality (IQ), while Model 2 includes GDP per capita (GDP-PC) to address potential collinearity. Both models use one period lagged independent variables to estimate delayed associations with renewable energy consumption. The models are highly significant (Model 1: $F = 401.873$; Model 2: $F = 337.889$; $p < 0.0001$), explaining 79% and 76% of the variation in renewable energy consumption, respectively.

Environmental taxes exhibit positive and statistically significant one-year lagged associations with renewable energy consumption in both models (Model 1: $\beta = 0.1744$, $p < 0.01$; Model 2: $\beta = 0.1276$, $p < 0.01$), indicating a positive delayed relationship between environmental taxation and renewable energy consumption. R&D investment is also positively and significantly associated with renewable energy consumption, with a larger estimated coefficient in Model 2 (Model 1: $\beta = 0.0098$, $p < 0.1$; Model 2: $\beta = 0.0877$, $p < 0.01$), without implying a moderating effect of economic capacity.

Institutional quality in Model 1 is positively and significantly associated with renewable energy consumption ($\beta = 0.1101$, $p < 0.01$), whereas GDP per capita in Model 2 shows a positive and statistically significant association ($\beta = 0.1562$, $p < 0.01$), indicating positive delayed relationships for governance and economic resources. Lagged CO_2 emissions are negatively associated with renewable energy consumption in both models (Model 1: $\beta = -1.3692$, $p < 0.01$; Model 2: $\beta = -1.396$, $p < 0.01$), indicating a persistent negative delayed association between CO_2 emissions and renewable energy consumption. Urban population growth is also negatively associated with renewable energy consumption (Model 1: $\beta = -0.1169$, $p < 0.01$; Model 2: $\beta = -0.116$, $p < 0.01$), although the underlying mechanisms cannot be directly identified from the present specification.

Table 6 Results of Fixed Effects Regression for Developed Countries

Dependent variable: **Renewable Energy Consumption**	**Model 1** **(IQ)**	**Model 2** **(GDP-PC)**
Environmental Taxes	0.286***	0.146***
	(0.0410)	(0.0959)

Research and Development	0.0405*	0.512***
	(0.0240)	(0.0686)
Quality of Institutions	-0.0161	
	(0.0605)	
GDP Per Capita		0.159
		(0.104)
CO2 Emissions	-1.196***	-1.193***
	(0.0959)	(0.0891)
Urban Population	-0.0648***	-0.0675***
	(0.0133)	(0.0134)
Constant	2.042***	1.639***
	(0.415)	(0.488)
Model	Fixed	Fixed
Hausman- Test chi2 -FE vs RE [Prob>chi2]	39.05 [0.0000]	23.86 [0.0000]
Modified Wald test for groupwise heteroskedasticity [Prob>chi2]	4299.02 [0.0000]	4600.74 [0.0000]
R-squared (Within)	.569	0.571
Rho	.95581016	.94270361
F [Prob > F]	136.24 [0.0000]	137.29 [0.0000]
Mean VIF (from pooled model)	1.47	1.67
Wooldridge test for autocorrelation	37.487 [0.0000]	37.964 [0.0000]
Jochmans Portmanteau test [Prob > Chi-sq]	20.000 [1.0000]	20.000 [1.0000]
Observations	540	540
Number of countries	20	20

Source: *Author's calculations using Stata.*

Table 6 presents regression results based on 540 observations from 20 developed countries, using two fixed-effects models that separately test institutional quality (Model 1) and GDP per capita (Model 2) due to high collinearity between the two variables. The Hausman test supports the use of fixed effects in both models, and VIF values below 2 confirm that multicollinearity is not a concern.

Both models are highly significant (F-statistics ≈ 136–137, $p < 0.0001$) and explain about 57% of the variation in renewable energy consumption. The very high Rho values (0.956 in Model 1 and 0.943 in Model 2) indicate that most variation is driven by differences between countries rather than changes within countries.

Environmental taxes are positively and significantly associated with renewable energy consumption in both models, with a larger estimated coefficient in Model 1. R&D is also positively associated with renewable energy consumption in both specifications, with a substantially larger estimated coefficient in Model 2. These coefficient differences should not be interpreted as evidence of moderation because no interaction terms are estimated. Neither institutional quality nor GDP per capita shows a statistically significant same year association with renewable energy consumption in developed countries.

CO_2 emissions exhibit a strong negative and statistically significant association with renewable energy consumption in both models. Urban population also shows a small but statistically significant negative association with renewable energy consumption. The constant terms are statistically significant in both models.

The same battery of diagnostic tests was run on the developed country models, with a similar outcome. The Modified Wald test rejects homoskedasticity in both models (χ^2 = 4299.02 and 4600.74, $p < 0.001$), and the Wooldridge test rejects the absence of first-order serial correlation (37.487 and 37.964, $p < 0.001$), so both problems are present here as well. Huber White cluster robust standard errors were therefore used at the country level in both models to account for these issues. The standard errors changed under this correction, as expected, but the coefficient estimates themselves stayed close to their non robust model, which fits with cluster robust standard errors affecting inference rather than the size of the estimated relationships. A Jochmans Portmanteau test was also run to check for within panel dependence, and neither model showed evidence of it.

Table 7 Optimal lag length for developed countries using VAR.

Lag Length	AIC	HQ	SC	FPE
1	-20.53550	-20.35879	-20.08403	1.206567e-09
2	-20.50307	-20.17173	-19.65656	1.246454e-09
3	-20.37857	-19.89261	-19.13702	1.412027e-09
4	-20.26387	-19.62328	-18.62728	1.584327e-09
5	-20.13123	-19.33602	-18.09960	1.810319e-09
6	-20.04246	-19.09262	-17.61579	1.980416e-09
7	-19.97612	-18.87166	-17.15441	2.119297e-09
8	-19.93605	-18.86796	-16.71929	2.210163e-09
9	-19.82474	-18.41103	-16.21295	2.476433e-09
10	-19.70214	-18.13380	-15.69531	2.807985e-09

Source: *Author's calculations using Stata.*

Table 7 reports the optimal lag length for the 20 developed countries using a VAR framework, evaluated through the AIC, HQ, SC, and FPE criteria. Consistent with the methodology of Saba and Biyase (2022), these criteria are used to balance model fit against unnecessary complexity. All four measures identify lag 1 as the optimal lag length, as it produces the lowest values across the criteria (AIC = –20.53550; HQ = –20.35879; SC = –20.08403; FPE = 1.206567e-09). This indicates that a one year lag provides the best-fitting and most parsimonious VAR model for the developed countries.

Table 8 One-year lagged panel regression for 20 developed countries

Dependent variable: Renewable Energy Consumption	**Model 1 (Lag 1 IQ)**	**Model 2 (Lag1 GDP-PC)**
Lag1. Environmental Taxes	-0.3347***	-0.1647***
	(0.0232)	(0.0232)
Lag1. Research and Development	0.3399***	0.9251***
	(0.0791)	(0.0842)
Lag1. Quality of Institutions	0.4958***	
	(0.0571)	
Lag1. GDP Per Capita		0.3102***
		(0.0456)
Lag1. CO2 Emissions	-1.691***	-1.3608***
	(0.1122)	(0.1386)
Lag1. Urban Population	-0.0546**	0.088***
	(0.0276)	(0.0326)
Constant	7.974***	9.535***
	(0.2718)	(0.684)
R-squared	0.562	.581
F **[Prob > F]**	132.054 [0.0000]	134.02 [0.0000]
Observations	520	520
Number of countries	20	20

Source: *Author's calculations using Stata.*

Table 8 reports the results of two one year lagged panel regression models for 20 developed countries using 520 observations. Both models use one period lagged independent variables to examine delayed associations with renewable energy consumption. The models are highly significant (F-statistics ≈ 132–134, $p < 0.0001$) and explain a substantial share of the variation in renewable energy consumption ($R^2 = 0.562$ in Model 1; $R^2 = 0.581$ in Model 2).

Lagged environmental taxes exhibit a significant negative association with renewable energy consumption in both models, contrasting with the positive same year associations observed in the fixed effects results. This sign reversal indicates that the one-year delayed association differs from the same year relationship; it should not be interpreted as a long run effect without a formally specified and validated cointegration model.

Lagged R&D expenditure is positively and significantly associated with renewable energy consumption in both models, with a larger coefficient in Model 2. Institutional quality also has a large and significant positive lagged association in Model 1. In Model 2, lagged GDP per capita is positive and highly significant, indicating a positive delayed association between economic capacity and renewable energy consumption.

Lagged CO_2 emissions display a strong and consistently negative association with renewable energy consumption in both models. The lagged association of urbanization varies across specifications: it is negative in Model 1 but positive in Model 2, indicating that the relationship is sensitive to model specification.

Both models include large and significant constant terms. Overall, the one-year lagged results indicate positive delayed associations for R&D, institutional quality, and GDP per capita, while also revealing negative associations for CO_2 emissions and heterogeneous urbanization effects in developed countries.

5. Discussion

Taken together, the results show that environmental taxes, R&D, institutional quality, and economic growth relate to renewable energy consumption differently in developing versus developed countries, and not always in the way the hypotheses predicted. None of the four factors behaves identically across the two groups: some matter right away in developing countries, some only show up in developed countries after a year's delay, and one factor even switches sign depending on the time horizon. The rest of this section works through each factor in turn.

For developing countries, environmental taxes are positively linked to renewable energy consumption whether they are measured in the same year (Model 1: $\beta = 0.105$, $p < 0.01$; Model 2: $\beta = 0.0109$, $p < 0.10$) or with a one year lag ($\beta = 0.1744$ and 0.1276, both $p < 0.01$). This supports H1b and fits with Pigouvian taxation theory, where taxing pollution raises its relative cost and pushes consumption toward cleaner alternatives. It also lines up with, who found that environmental taxes in ASEAN developing economies were associated with more capital going into renewable energy, Also in China, higher environmental taxes have encouraged investment in renewable energy technologies, enabling a gradual shift away from coal and other fossil fuels .

The findings for developed countries are more complex and less consistent. Taxes are positive and significant in the same year (Model 1: $\beta = 0.286$; Model 2: $\beta = 0.146$; both $p < 0.01$), supporting H1a and consistent with the Double Dividend idea that tax revenue can be recycled into environmental goals,,,. With a one year lag, however, the sign flips: taxes become negative and significant in both models ($\beta = -0.3347$ and -0.1647, both $p < 0.01$). For example, in Greece, environmental taxes help curb fossil fuel use while also contributing substantially to public revenues—roughly 10% of the national budget—that are subsequently channeled toward renewable energy infrastructure. This reinvestment accelerates the country’s clean-energy transition .

R&D spending comes out positive for both groups and at both time horizons, which makes it the steadiest result in the paper, supporting H2a and H2b. In developing countries, it is significant right away ($\beta = 0.148$ and 0.105, $p < 0.01$) and stays significant a year later ($\beta = 0.0098$, $p < 0.10$; $\beta = 0.0877$, $p < 0.01$). In developed countries, the same year effect is small in Model 1 ($\beta = 0.0405$, $p < 0.10$) but much larger in Model 2 ($\beta = 0.512$, $p < 0.01$), and it grows further with the lag ($\beta = 0.3399$ and 0.9251, both $p < 0.01$). This fits Endogenous Growth Theory and earlier work showing R&D pays off for renewables in both OECD and emerging economies , , . For example, R&D investment in countries such as Brazil has facilitated the development and adoption of locally adapted renewable energy technologies, helping to address existing infrastructural and

technological gaps and promote technology diffusion Similarly, advanced economies such as Japan benefit from larger R&D budgets and more developed technological ecosystems, which can support the development and deployment of advanced renewable energy solutions, including offshore wind and smart-grid technologies .

Institutional quality is positive and significant for developing countries both in the same year ($\beta = 0.0331$, $p < 0.01$) and with a lag ($\beta = 0.1101$, $p < 0.01$), supporting H3b and matching and . The interpretation here is fairly intuitive: better functioning institutions in developing economies likely make it easier to carry out renewable energy policy rather than just announce it like Egypt, reforms under the Renewable Energy Law of 2014 enhanced investment security and simplified licensing procedures, enabling large scale initiatives such as the Benban Solar Park, one of the world's largest solar installations, despite limited financial resources . In developed countries, institutional quality shows no same-year effect ($\beta = -0.0161$, $p > 0.10$), so H3a is not supported in the same year. It does turn up positive with a one-year lag ($\beta = 0.4958$, $p < 0.01$). regulatory delays can temporarily hinder renewable energy expansion; for instance, in several EU nations, the deployment of onshore wind and solar projects can take 6 to 9 years due to extensive governmental permitting processes.

Economic growth, measured through GDP per capita, is positively and significantly associated with renewable energy consumption ($\beta = 0.224$, $p < 0.01$ in Model 2), supporting Hypothesis H4b and Green Growth Theory . A reasonable reading is that richer developing economies simply have more room in their budgets for renewable energy investment, though the reverse could also be true, and this specification cannot tell the two apart such as Morocco provides a relevant example through the Noor Ouarzazate Solar Complex. The project contributed to local economic activity, generating 8,504 jobs during construction, including 6,077 positions for Moroccan workers, while around 30% of total project costs benefited domestic contractors.

For developed countries, GDP per capita is not statistically significant in the same year specification ($\beta = 0.159$, $p > 0.10$), indicating that H4a is not supported in the same year. However, the coefficient becomes positive and significant in the one year lagged model ($\beta = 0.3102$, $p < 0.01$), suggesting that the effect of higher income on renewable energy consumption may materialize over time. This finding is broadly consistent with the Environmental Kuznets Curve (EKC) framework, which suggests that environmental conditions may worsen during earlier stages of economic growth; however, as economies reach higher levels of development, stronger preferences for environmental protection, greater technological capabilities, and increased financial resources can improve environmental outcomes and encourage the transition toward cleaner energy sources. The European Union's NextGenerationEU recovery package provides a relevant example, as it allocated substantial resources to green investment following the COVID 19 pandemic and illustrates how greater economic capacity can support renewable energy expansion over time .

Overall, the findings show clear differences between developed and developing countries in the relationships between environmental taxation, institutional quality, and renewable energy consumption. Environmental taxation remains positive across the models for developing countries but varies across time periods in developed countries. Institutional quality is significant in both the same-year and lagged models for developing countries, while its effect appears only after one year in developed countries. R&D expenditure is the most consistent factor, showing a positive

relationship with renewable energy consumption across both country groups and time periods. These results indicate that the factors influencing renewable energy consumption differ according to countries' levels of development and the time period considered.

6. Conclusion

This study examines the key drivers of renewable energy consumption across 40 developed and developing countries over the period 1995–2021 using balanced panel data. Fixed effects models and one year lagged panel specifications reveal substantial heterogeneity across the two country groups. Environmental taxes and R&D are positively associated with renewable energy consumption in the same year fixed effects models for both groups. In the one year lagged specifications, environmental taxes remain positive in developing economies but become negative in developed economies, while R&D remains positively associated with renewable energy consumption in both groups. Institutional quality and GDP per capita are positively associated with renewable energy consumption in the developing country models and show positive one year lagged associations in developed economies despite statistically insignificant same year fixed effects estimates. These results distinguish same year from one year delayed associations across the two country groups. Overall, the hypothesis assessment shows that the proposed relationships receive stronger and more consistent support in developing countries, while several relationships in developed countries emerge only with a one year delay.

This study is subject to several limitations. A key limitation is the restricted availability of comprehensive data, particularly for environmental taxation and R&D, which constrained country coverage and may limit the generalizability of the findings. In addition, the exclusive reliance on quantitative methods may not fully capture the socio-political, cultural, and stakeholder-related factors influencing renewable energy consumption.

Future research should therefore expand country coverage through more comprehensive datasets, particularly for developing economies and underrepresented regions such as the MENA region and Asia. Further studies could also integrate quantitative and qualitative approaches to better capture contextual influences on renewable energy consumption. Moreover, sector specific analyses in areas such as energy, transportation, agriculture, and manufacturing could provide more detailed evidence on the drivers and constraints of renewable energy adoption.

The findings also have important policy implications. Environmental taxation may function not only as a corrective fiscal instrument but also as a source of financing for renewable energy investment. Governments could introduce energy transition credit schemes and allocate environmental tax revenues to green skills development, clean energy enterprises, and renewable energy infrastructure. In parallel, renewable energy mandates could be used to increase the share of electricity generated from renewable sources within clear and progressively adjusted regulatory frameworks.

Given the positive association between R&D and renewable energy consumption, greater policy attention should also be directed toward research funding, innovation hubs, and collaboration among universities, industry, and public institutions. Finally, institutional effectiveness could be strengthened through improved monitoring, regulatory coordination, and digital technologies,

while fossil fuel subsidies could be gradually reduced and public support redirected toward renewable energy projects where appropriate to national economic and institutional conditions.

From a managerial perspective, businesses should align their products, services, and operations with recognized green standards, increase the use of renewable energy within their supply chains, and encourage suppliers to adopt more sustainable practices. Such measures can help firms respond to growing consumer demand for environmentally responsible products, comply with evolving environmental regulations, strengthen corporate reputation, and facilitate entry into international markets. Collectively, these actions may also support greater renewable energy use, green investment, energy security, and broader sustainability goals.

This study contributes to the renewable energy literature by developing a more integrated theoretical understanding of the factors shaping renewable energy consumption across different levels of economic development. Its main theoretical contribution is to bring together fiscal, technological, institutional, and economic perspectives within a single comparative framework, rather than treating these mechanisms in isolation. In doing so, the study extends the application of Pigouvian Taxation Theory, Double Dividend Theory, Endogenous Growth Theory, Institutional Theory, and Green Growth Theory by demonstrating the value of examining their relevance jointly across heterogeneous country contexts. The study further contributes by incorporating a temporal dimension into this theoretical framework, recognizing that the influence of policy, institutional, and economic factors may not emerge within the same period. This broadens the interpretation of renewable energy transition theories from static and single factor explanations toward a more dynamic and multidimensional framework that accounts for differences in development level and adjustment over time.

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Author Contributions

Yasmeen S. A. Abdelmoaty contributed to the conceptualization, methodology, data collection, formal analysis, and preparation of the original manuscript. Dina Yousri contributed to supervision, conceptual development, and review and editing of the manuscript. Both authors read and approved the final manuscript.

Data Availability

The data used in this study were obtained from publicly available sources, including the World Bank, International Monetary Fund, OECD, and Worldwide Governance Indicators. The datasets supporting the findings of this study are available from the corresponding author upon reasonable request.

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