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Research Article

Green Energy and Economic Development: A Macro Analysis

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Abstract

This study explores the relationship between renewable energy consumption and economic development in Pakistan from 2000 to 2022. Guided by the Neoclassical Growth Theory, Environmental Kuznets Curve (EKC), Porter Hypothesis, and Sustainable Development Theory, it employs the ARDL approach to capture both short- and long-term effects. GDP per capita serves as a proxy for economic development, while independent variables include carbon emissions, renewable energy use, gross fixed capital formation, labor force participation, and population growth. The findings reveal that renewable energy consumption, CO2 emissions, capital formation, labor force participation, and population growth all have a positive impact on GDP per capita, with capital formation and labor force participation being the most influential variables in the long-term. The findings support the EKC and the Porter Hypothesis and reinforce the role of labor as proposed by endogenous growth theories, offering insights for sustainable policy formulation in Pakistan.

Keywords: Renewable energy; economic development; labor force; Population growth; GDP per capita.

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1. Introduction

1.1 Background

The transition to renewable energy has become a central focus in global economic and environmental policy due to its capacity to foster sustainable development. Renewable energy sources—including solar, wind, hydropower, and biomass—are now recognized as more than just alternatives to fossil fuels. They serve as vital drivers of both economic development and environmental protection (Awan & Yaseen, 2017; Wang, Chen, & Kubota, (2019). This perspective aligns with the broader realization that climate action and equitable economic development must progress simultaneously. Empirical evidence confirms renewables' macroeconomic advantages. Bekun, Emir & Sarkodie, . (2019) disclosed their positive correlation with GDP growth, while IREA (2021) reports over 12 million global renewable energy jobs in 2020, particularly in construction, operations, and production. The advantages of the sector go beyond job creation, study conducted by Rojas-et al., (2018) highlights its contribution to the mobilization of private capital as well as technological innovations. Energy security also increases, according to Kirikkaleli, Güngör, &Adebayo. (2022), as local renewable investments mitigate volatility in the global fossil fuel markets. Shahbaz, et al., (2020) also highlight how less dependence on foreign energy insulates economies from global price volatility. Cost-effectiveness is another benefit. Bekun., Emir & Sarkodie (2019) associate reduced energy spending with greater disposable income and economic efficiency, whereas Le (2020) mentions renewables' enduring affordability for energy-intensive industries. Co-benefits to the environment—such as enhanced public health, agricultural production, and tourism opportunities—are extensively documented by Ntanos et al, (2018). However, the energy transition presents challenges, including substantial initial investments and workforce displacement in traditional energy sectors (Shahbaz et al., 2020). For developing nations like Pakistan, where energy access critically influences development, these obstacles require nuanced policy solutions that harmonize

sustainability with socioeconomic equity. The dilemma of Pakistan's economy is that the consumer is using costly energy produced by fossil fuels, have less resources to bear high one time cost of green energy, low public and private investment in green technologies, and less labor force participation ratio due to high rate of unemployment. In such a situation, a question arises how the goal of economic development can be achieved. This needs deeper investigation to bridge gaps. Hence, the primary research inquiry of this study is that *how renewable energy consumption, CO2 emissions, gross capital formation, labor force participation and population growth impact economic development (GDP per capita) in Pakistan?* To investigate this phenomenon, the current study aims at analyzing how renewable energy consumption, CO2 emissions, fixed capital formation, labor participation and population growth affect GDP per capita in Pakistan using time series data and employing various econometric techniques. In this analysis, GDP per capita is used as a proxy for economic development. This analysis would enable us to understand what factors are obstructing economic development in Pakistan.

1.4 Scope of the Study

This study focuses on Pakistan to investigate the interplay of important economic and environmental factors—renewable energy consumption, carbon emissions, gross fixed capital formation, and labor force participation —to shape macroeconomic performance. The analysis is broad enough to also include demographic dynamics, including population growth and energy access, that form an essential part of sustainable development. Although the study is confined to a single country case, the findings produced have important implications for wider policy issues in other developing economies facing comparable challenges.

1.5 Contribution of the Study

This study contributes to development economics in five ways.

First, it offers fresh empirical evidence on the interplay between renewable energy consumption, gross fixed capital formation, and carbon emissions for emerging economies. Second, it puts environmental economics and energy policy together to form a combined

analytical framework for sustainable development. Third, it tackles key yet under-researched drivers such as demographic pressures and fair energy distribution for inclusive growth. Fourth, it formulates implementable policy recommendations that reconcile emission mitigation with technological advancement and social equity. Fifth, it empirically confirms theoretical linkages among renewable energy, emissions, capital accumulation and economic development - providing policymakers with evidence-based action plans to attain UN's Sustainable Development Goals (SDGs). The rest of paper is structured as: Section 2: Critically review theoretical and empirical literature, identify research gap and formulate hypotheses. Section 3 illustrates methodological framework; Section 4 explains empirical results, and Section 5 discusses findings, policy implications, limitations, and future research directions.

2.Literature Review and Hypotheses Development

2.1 Theoretical Underpinning

The interdependence of renewable energy integration and economic development draws its foundation from several paradigms of economics. Malthusian economics holds that economic growth and increasing per capita income spur population growth, which can ultimately exhaust resources and reduce per capita wealth (Malthus, 1798). This view does not, however, capture the impact of technological innovation to overcome the limitations of resources. In Pakistan's perspective, this theory proves valid because high population growth dilutes national income per capita. The Neoclassical Growth Model (Solow, 1956) offers a broader context in that three classical growth drivers are specified: capital accumulation, the growth of the labor force, and technological advancement. In this model, energy resources, especially renewables, are utilized as key production inputs that boost industrial efficiency and production capacity. Pakistan's economy does not meet criteria of this theory because of high population growth, low accumulation of capital and low productivity of industrial sector due to low innovation and technological advancement. Romer's (1990) Endogenous Growth Theory advances this understanding by emphasizing

internal growth mechanisms, including (i) Policy frameworks, (ii) Educational attainment; (iii); Human. capital development, and (iv) private sector research investment. This theoretical approach suggests that institutional support for innovation can simultaneously promote economic advancement and environmental protection. As per this theory Pakistan's could not transform its labor force into human capital through education and training, trigger innovation due to poor investment in research and development and weak institutional mechanism. These factors significantly influence Pakistan's economic development trajectory. Another important theory, the Environmental Kuznets Curve hypothesis (Grossman & Krueger, 1995) offers an alternative explanation, introducing an inverted U-shaped association between economic growth and environmental quality. Empirical evidence illustrates that industrialization increases ecological degradation at first but later investments in clean technology and policy actions turn this situation around (Stern, (2006).; Accuracy & Ozturk, 2016; Wang & Su, 2019; Raza et al., 2024).The Porter Hypothesis (Porter & van der Linde, 1995) suggests that well-designed environmental regulation can increase innovation as well as industrial competitiveness. This has been more clearly demonstrated in renewable energy markets, where policy interventions have prompted technological innovations (Ambec et al., 2013; Bassen, Mayer, & Baltzer, (2017). Brundtland Commission's Sustainable Development approach (WCED, 1987) promotes equitable advancement on three fronts:

- Economic development
- Environmental resources protection
- Social equity

Recent research verifies the key role played by renewable energy to attain this balance. Technological Innovation Systems model (Bergek et al., 2008) explains the intricate dynamics of policy measures, institutional framework, and market forces driving the adoption of renewable technology (Yao, et al., (2019). This model offers important insights for countries transitioning towards sustainable energy systems.

2.2 Hypotheses Development

Building on these theories and empirical research, the study develop the following hypotheses:

H1: Renewable energy consumption positively correlates with GDP per capita (Economic development) in Pakistan.

H2: CO_2 emissions positively correlate with GDP per capita (Economic development) in Pakistan.

H3: Gross fixed capital formation positively correlates with GDP per capita (Economic development) in Pakistan.

H4: Labor force participation positively correlates with GDP per capita (Economic development) in Pakistan.

H5: Population growth positively correlates with GDP per capita (Economic development) in Pakistan.

These hypotheses provide a structured framework to analyze the interaction between renewable energy consumption, environmental policies, labor dynamics, population trends, and sustainable economic development in the context of Pakistan.

2.3 Research Gaps

Despite a substantial body of international literature examining the nexus between renewable energy and economic development, several critical gaps persist, particularly concerning Pakistan First, there is a lack of Pakistan-Specific Studies. Although global studies (e.g., Ben Aissa et al., 2014; Wang & Feng, 2019; Liu et al., 2018; Le, (2020) have consistently found positive correlations between renewable energy consumption and GDP growth, context-specific research focusing on Pakistan remains limited. Given the country's unique energy mix, economic structure, and policy landscape, tailored analysis is essential. Second, current academic literature neglected regional disparities The economic and environmental impacts of renewable energy adoption vary considerably

across regions within Pakistan, yet these differences are underexplored. Third, mostly previous international research has assessed the effectiveness of tools such as feed-in tariffs and carbon trading (Fischer & Personas, 2010; Liu et al., 2018; Flanagan, & Ucal, 2019), limited attention has been paid to how such instruments function in Pakistan's socio-economic and institutional environment. Fourth, previous studies provide unclear causal relationships. These studies mostly establish correlations but do not adequately address the direction of causality between renewable energy consumption, CO_2 emissions, and economic indicators (Glasure & Lee, 1995; Raza et al., 2020; Georgantzis, Martinez-Gomez,, & Ordoñez, 2020). More empirical work is required to determine these causal pathways. Fifth, previous studies focus on short-term economic relationships between macroeconomic variables (Kucukvar et al., 2017; Flanagan & Ucal, 2019; Kirikkaleli, Güngör & Adebayo, 2022), with insufficient emphasis on long-term sustainability, economic resilience, and employment transitions. Addressing these gaps will develop more policy-relevant understanding of the role that renewable energy can play in achieving sustainable economic development in Pakistan.

2.4 Conceptual framework

A conceptual model was constructed to determine statistical relationship between Renewable Energy Consumption, CO_2 Emissions, Gross Capital formation, Labor force participation population growth and Economic development, and it is shown in Figure 1.

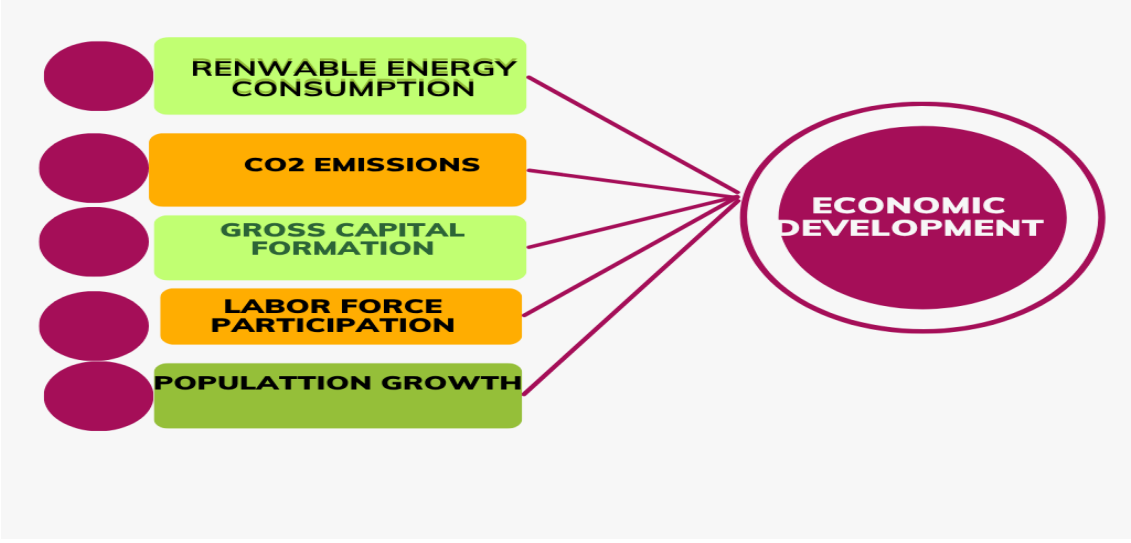

Fig 1: Research Model

3. Research Methodology

This study employs time-series econometric analysis to examine the relationship between renewable energy consumption and economic development in Pakistan using time series data spanning from 2000 to 2022. The quantitative methodology proves particularly suitable for analyzing time-dependent relationships between macroeconomic and environmental factors, facilitating both hypothesis validation and trend identification. The 22-year dataset provides sufficient temporal depth to yield reliable conclusions about how renewable energy policies affect economic outcomes. All data were obtained from secondary sources, primarily the World Bank's World Development Indicators (WDI) database, ensuring consistency and international comparability. Variable selection was guided by established economic theories and previous empirical studies. The research uses GDP per capita as the primary measure of economic development (dependent variable). Independent variables include:

- CO_2 emissions (environmental impact indicator)
- Renewable energy consumption (sustainability measure)

- Gross fixed capital formation (investment activity)
- Labor force participation rate (employment dynamics)
- Total population (demographic influence)

These carefully chosen metrics each serve specific analytical purposes: GDP per capita tracks economic development and welfare improvements, CO_2 emissions quantify environmental costs, renewable energy usage reflects clean energy adoption, capital formation shows investment patterns, labor statistics reveal workforce engagement, and population data capture demographic pressures on resources. Table 1 shows this study's variables, definitions and their sources

Table 1:

Variables, definitions and data sources

Abbreviation	**Variable**	**Description**	**Source**
GDP per capita	Gross Domestic Product per capita	National income divided by population	WDI
CO_2	CO_2 Emissions	Metric tons per capita	WDI
RENW	Renewable Energy Consumption	Share of renewables in total final energy consumption (%)	WDI
GFCF	Gross Fixed Capital Formation	Capital investment as % of GDP	WDI
LF	Labor Force Participation Rate	% of working-age population (15–64), ILO estimate	WDI
POP	Population growth	Total annual population growth.	WDI

The study first examines basic statistical measures to understand each variable's central tendency, variability, and distribution characteristics. This preliminary analysis reveals the dataset's fundamental patterns and identifies any anomalies. Before selecting the analytical

method, we assess each variable's stationarity through Augmented Dickey-Fuller (ADF) test. This crucial step determines whether the data remains stable in its original form (I (0)), becomes stationary after first differencing (I (1)), or shows mixed properties - information that directly informs our choice of modeling approach (Dickey D. A., Fuller W. A. (1979). Based on these stationarity findings, we used the ARDL (Autoregressive Distributed Lag) framework. The ARDL approach effectively handles this two-way relationship by using time-lagged independent variables, which account for delayed impacts and minimize reverse causality concerns. The ARDLs models were widely used in previous researchers for analyzing the link between energy consumption and economic growth (Zhang et al. (2015); Ntanos et al. (2018); Bekun, Emir, and Sarkodie (2019); Kirikkaleli, Güngör, and Adebayo (2022); and many more). The ARDL approach offers several distinct benefits compared to traditional cointegration techniques, as suggested by Pesaran and Shin (1998) and Hassler and Wolters (2006). In contrast to traditional procedures such as Engle-Granger two-step method (Engle and Granger, 1987) or Phillips-Hansen's fully modified OLS estimator (Phillips and Hansen, 1990), the ARDL model holds specific analytical overtures. Such flexibility is a great methodological enhancement over procedures necessitating rigorous integration order testing. Second, the ARDL specification jointly estimates short-run dynamics and long-run equilibrium relations in a single-step estimation procedure. This single-step procedure is more efficient and minimizes possible specification errors. Third, the model has asymptotically normal estimators, which makes hypothesis testing easier and also enhances the accuracy of statistical inferences regarding parameter significance. This property makes the ARDL approach particularly valuable for empirical economic analysis. Pesaran, Shin, and Smith (2001) also suggest a “bounds test”, which helps comparing the values of conventional F and t statistics with pairs of critical values (CV) to identify long-term cointegration between variables. Upon establishing a long-term equilibrium relationship, the study incorporates an Error Correction Model (ECM) to capture how short-run fluctuations adjust toward the long-run equilibrium

(Glasure, & Lee, (1995). The error correction term quantifies the speed at which deviations from equilibrium are corrected after external shocks. To evaluate the soundness of the model, various diagnostic tests were applied. These include checks for heteroscedasticity (non-constant of error-terms) in a regression model, using the Breusch-Pagan test developed by Breusch and Pagan,1979) and White tests developed by Halbert White, (1980) for identifying heteroskedasticity, but more general than Breusch-Pagan. It can detect both linear and non-linear forms and Durbin-Watson statistic, articulated by Durbin and Watson (1950–1951) for testing for first-order autocorrelation (correlation between adjacent residuals) in the residuals of a regression. These assessments help confirm that the assumptions of classical regression hold and that the model is not affected by specification errors or omitted variables. One significant methodological issue in time series analysis is the risk of endogeneity, which can stem from reverse causality, omitted variables, or measurement errors. For instance, the interaction between renewable energy use and economic development appears to work in both directions. While renewable energy consumption may stimulate economic development, rising prosperity can also lead to changes in energy policies and usage patterns. However, no issue of endogeneity was found in the study's model.

4. Results

4.1 Descriptive Statistics

Table 2 presents key statistical measures for the study's main variables: per capita GDP (LGDP), CO_2 emissions (LCO2), renewable energy consumption (LRENEW), gross fixed capital investment (LGFCF), labor force participation (LLF), and population growth (LPOP). The GDP per capita values show stable distribution, with nearly identical average (26.30) and middle values (26.28). The negligible skewness measure confirms this balanced, symmetrical data pattern. LCO2 has a mean of 0.177 and a median of 0.178, with a slight negative skew (-0.35), suggesting a left-tailed distribution. Renewable energy consumption (LRENEW) shows a marginally positive skew and exhibits a near-normal distribution based on its skewness (-0.13) and kurtosis (2.69). LGFCF has a mean and

median around 24.37 and 24.39, respectively, showing stable investment patterns. Both LLF and LPOP indicate moderate variation, with LPOP exhibiting slightly heavier tails (kurtosis = 3.07), implying the presence of outliers. The Jarque-Bera test statistics suggest that all variables, except LRENEW, do not significantly deviate from normality.

Table 2:

Descriptive Statistics outcomes

Variable	Mean	Median	Max	Min	Std. Dev.	Skewness	Kurtosis	Jarque-Bera	Prob.	Obs.
LGDP	26.30	26.28	26.75	25.81	0.269	-0.13	1.96	4.43	0.109	92
LCO2	0.18	0.18	0.20	0.15	0.011	-0.35	1.90	6.54	0.038	92
LRENEW	3.86	3.85	3.94	3.74	0.051	-0.13	2.69	0.61	0.736	92
LGFCF	24.37	24.39	24.73	23.92	0.227	-0.45	2.22	5.35	0.069	92
LLF	17.92	17.95	18.20	17.61	0.166	-0.17	1.89	5.17	0.076	92
LPOP	1.96	1.99	3.09	1.20	0.468	0.50	3.07	3.80	0.149	92

Source: The author owns calculations using E-view software

4.2 Correlation Matrix

In Table 3, the correlation matrix reveals strong and positive correlations between GDP and key economic indicators. GDP (LGDP) is highly correlated with LCO2 (0.81), LGFCF (0.93), and LLF (0.99), supporting the notion that economic development is closely associated with industrial activity, gross fixed capital investment, and labor force participation. LRENEW also shows a moderate positive correlation with GDP per capita (0.49), suggesting that renewable energy contributes to economic performance. Interestingly, LPOP is moderately correlated with GDP per capita (0.77), while its negative relationship with LLF (-0.78) suggests a demographic trade-off in labor participation.

Table 3:

Correlation Matrix results

	LGDP	LCO2	LRENEW	LGFCF	LLF	LPOP
LGDP	1.000	0.813	0.487	0.927	0.990	0.774
LCO2	0.813	1.000	0.008	0.575	0.852	0.521
LRENEW	0.487	0.008	1.000	0.672	0.430	0.709
LGFCF	0.927	0.575	0.672	1.000	0.877	-0.742
LLF	0.990	0.852	0.430	0.877	1.000	-0.778
LPOP	0.774	0.521	0.709	-0.742	-0.778	1.000

Source: Author owns calculations using E-view Software.

The heat map of correlation analysis shows positive correlation in green color and negative correlation in red in Figure 2**.** This map shows that GDP (LGDP) is highly correlated with LCO2 (0.81), LGFCF (0.93), and LLF (0.99), while LRENEW also shows a moderate positive correlation with GDP per capita (0.49). However, LPOP is moderately correlated with GDP per capita (0.77), while its negative relationship with LLF (-0.78) demonstrates trade off in labor participation.

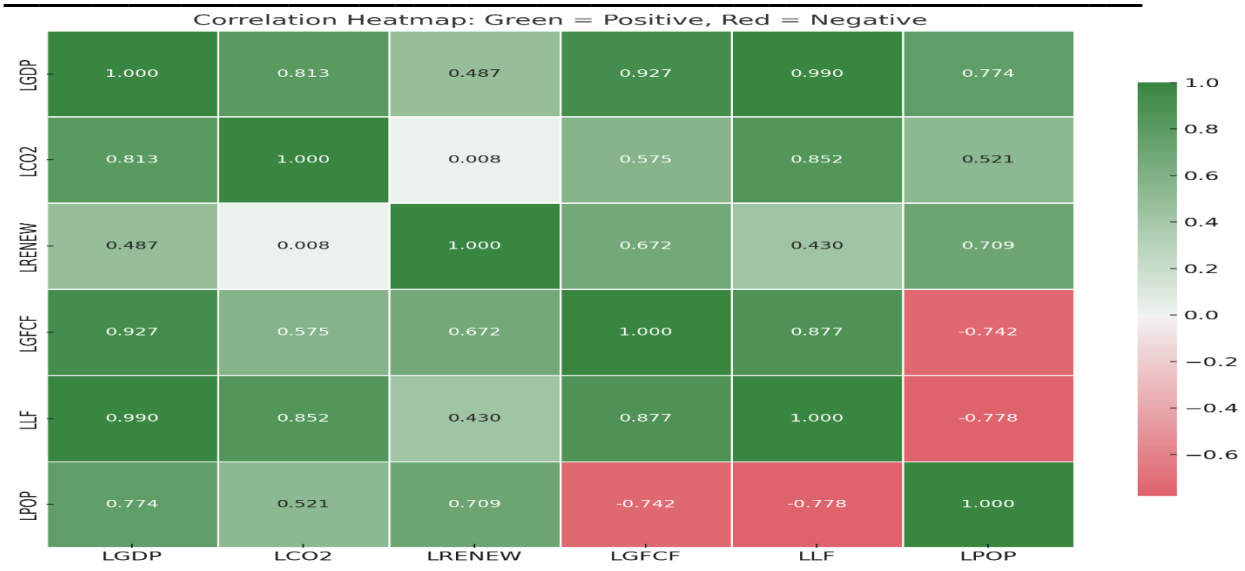

Fig 2: Positive and negative correlation**.**

4.3 Unit Root Test

Unit root tests (ADF and PP) were conducted to check the stationarity of variables. At level, most variables exhibited non-stationarity ($p > 0.05$). However, after first difference, the variables became stationary, confirming the presence of unit roots in their level form but not in their different form. This validation justifies the use of an ARDL model, which accommodates variables of mixed integration orders (Dickey & Fuller. (1979). Table 4 present Unit root tests outcomes.

Table 4:

Unit Root Test (ADF and PP) results

Variable	**ADF Level**	**ADF 1st Diff.**	**PP Level**	**PP 1st Diff.**
LGDP	1.000	0.014	1.000	0.026
LCO2	0.653	0.025	0.452	0.035
LRENEW	0.045	0.031	0.035	0.024
LGFCF	0.585	0.055	0.521	0.043

LLF	0.635	0.085	0.625	0.078
LPOP	0.146	0.035	0.685	0.024

Source: Author owns calculations using E-view Software**.**

4.4 ARDL Bounds Test

Table 5 provides the ARDL bounds test results. The computed F-statistic (9.5275) exceeds the upper bounds at all significance levels, indicating a statistically significant long-run relationship among the variables. This confirms the suitability of the ARDL model for estimating both short-run and long-run dynamics.

Table 45

ARDL Bounds Test outcomes

F-statistic	Lower Bound I (0)	Upper Bound I (1)
9.5275	2.08 - 3.06	3.00 - 4.15

Source: Author owns calculation using E-view Software.

4.5 ARDK Long-Run Estimation

The long-run estimates in Table 6 provide valuable insights into how key macroeconomic and environmental variables influence economic development in Pakistan, with GDP per capita serving as the dependent variable. These findings can be interpreted through the lens of established theories such as the Neoclassical Growth Theory, the Environmental Kuznets Curve (EKC), and the Sustainable Development Framework, while also offering policy-relevant implications for Pakistan's energy strategy. The coefficient for CO_2 emissions is positive and statistically significant (0.9045, $p < 0.05$), suggesting that higher emission levels are linked with increased economic development in the long run. This reflects Pakistan's continued dependence on fossil fuel-based energy sources such as oil, coal, and natural gas, which remain central to the country's industrial and transport sectors. Pakistan still imports and uses 90% of fossil fuel to support its energy sector and meet growing energy demand. While this growth-emissions link is typical in the early stages of the Environmental Kuznets Curve, it signals a potential trade-off between economic

development and environmental sustainability. This finding underscores the urgent need for Pakistan's energy policy to accelerate the transition away from carbon-intensive sources toward cleaner alternatives as suggested by Yousaf Raza, & Lin, 2022; Bai & Raza, 2024).

Renewable energy consumption also exhibits a positive but marginally significant coefficient (0.5438, $p \approx 0.0786$), suggesting that renewables contribute to economic development, albeit less strongly than conventional energy sources. This result aligns with the Porter Hypothesis (Ambec, Cohen, Elgie, & Lanoie, (2013)., which posits that environmentally friendly innovations can enhance productivity and competitiveness over time. However, the relatively weaker influence reflects Pakistan's still-developing renewable energy infrastructure. Despite initiatives like the Alternative and Renewable Energy Policy 2019, actual deployment remains modest. Strengthening regulatory frameworks, expanding grid access for solar and wind power, and reducing institutional barriers are essential to fully harness the growth potential of renewables as reported by (Luqman, Ahmad & Bakhsh, 2019; Leitao., Shahbaz., & Apergis, (2023). Raza & Cucculelli, 2024). The coefficient on gross fixed capital formation is positive and highly significant (0.3427, $p < 0.01$), indicating that investments in infrastructure and productive assets play a central role in Pakistan's long-run economic development. This result supports the Neoclassical Growth Theory, which emphasizes the importance of capital accumulation in enhancing productive capacity. Continued public and private investment in renewable energy projects—such as hydropower dams, solar farms, and transmission networks—could further align capital formation with green growth objectives (Georgantzis, Martinez-Gomez. & Ordoñez, 2020). Labor force participation has a strong and highly significant impact on economic development (0.2467, $p < 0.01$). This reinforces the importance of human capital in Pakistan's growth trajectory. The finding is consistent with endogenous growth models, which highlight labor efficiency as a key growth driver. Pakistan's energy policy can indirectly benefit from this insight by promoting job creation

in clean energy sectors, such as solar panel installation, energy auditing, and sustainable construction, thus linking labor market policies with green economic transformation.

The positive and statistically significant effect of population (0.0859, $p < 0.05$) implies that demographic growth modestly supports economic development. However, this impact is relatively limited, pointing to the dual challenges of resource pressure and employment generation. In light of this, energy policy must consider the implications of population growth on energy demand and incorporate measures to ensure equitable energy access and long-term sustainability, as emphasized in the Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 8 (Decent Work and Economic Growth). These results provide robust empirical support for the integration of green energy strategies into Pakistan's long-term economic planning. By aligning energy policy with growth objectives and sustainability goals, Pakistan can move toward a development pathway that is both economically viable and environmentally responsible.

Table 6:

Long-Run findings of ARDL Model

Variable	Coefficient	Std. Error	t-Stat	Prob.
LCO2	0.9045	0.3831	2.361	0.0207
LRENEW	0.5438	0.3051	1.783	0.0786
LGFCF	0.3427	0.1171	2.926	0.0045
LLF	0.2467	0.0218	11.292	0.0000
LPOP	0.0859	0.0397	2.162	0.0337
C	1.2849	0.8362	1.537	0.1285

* GDP per capita is dependent variable**.**

Source: Author owns calculations using E-view software.

The ARDL model long-run outcomes are presented in Figure 3 to illustrate individual visual impact of each variable on GDP per capita.

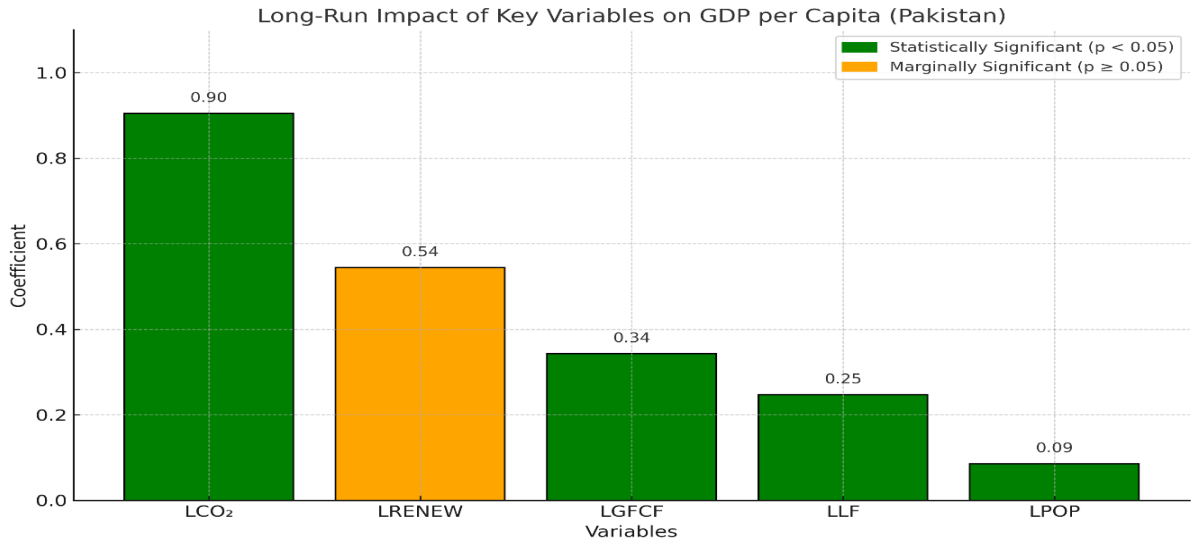

Fig 3: Long run impact of variables on GDP per capita

This figure shows the long-run effects of each variable on GDP per capita in Pakistan. Green bars indicate statistically significant relationships ($p < 0.05$), while orange bars represent marginally significant results ($p \geq 0.05$).

4.6 Short-Run Estimation

We used Error Correction Model (Glasure, & Lee, (1995) to determine short-term results, which are presented in Table 7. indicate that CO2 emissions, capital formation, and population growth significantly influence GDP per capita, while Renewable energy and labor force participation have positive but marginal effects on dependent variable in the short-term. The short-term results almost match with long-term ARDL's outcomes. The error correction term is negative and highly significant, confirming model convergence toward long-term equilibrium.

Table 7:

Short-Run Coefficients

Variable	Coefficient	Std. Error	t-Stat	Prob.

LCO2	0.7890	0.3677	2.145	0.0350
LRENEW	0.1977	0.1147	1.724	0.0887
LGFCF	0.1200	0.0422	2.843	0.0057
LLF	0.0668	0.0380	1.759	0.0824
LPOP	0.0253	0.0116	2.174	0.0327
CointEq (-1) *	-0.0234	0.0011	-21.13	0.0000

Source: Author owns calculations using E-view Software**.**

4.7 Granger Causality Tests

Table 8 shows unidirectional causality from renewable energy consumption, gross fixed capital formation, and labor force participation to GDP, while no feedback causality from GDP per capita is detected. This suggests that policies targeting these drivers can influence economic development, while GDP per capita does not Granger-cause these variables in the short term.

Table 8:

Granger Causality Test outcomes

Null Hypothesis	F-Statistic	Prob.	Conclusion
LRENW does not Granger Cause LGDP	3.6721	0.0487	Causality exists
LGFCF does not Granger Cause LGDP	8.0312	0.0038	Strong causality
LLF does not Granger Cause LGDP	4.6957	0.0249	Causality exists
Others	< 3.37	> 0.05	No causality

Source: Author owns calculations using E-view software.

4.8. Diagnostic Tests

Diagnostic tests (Table 9) confirm the model's validity, indicating that no issues of serial correlation, heteroscedasticity, or non-normality are detected, suggesting robustness of the estimates and goodness of fit of the model and validity of results.

Table 9:

Diagnostic Statistics

Tests	p-Value	Conclusion
Breusch-Godfrey LM	0.1458	No serial correlation
Breusch-Pagan-Godfrey	0.4615	No heteroscedasticity
Jarque-Bera	0.3154	Residuals are normally distributed

Source: Author owns calculation using E-view software.

4.9 Theoretical and empirical nexus

4.9.1 Hypotheses testing

Empirical analysis provides strong support for the Neoclassical Growth Theory, which emphasizes capital formation, labor force participation, and technological progress as key components of economic development. The positive and significant long-run relationships between GDP per capita and gross fixed capital formation, labor force participation, and CO_2 emissions indicate that capital accumulation and labor input continue to be primary drivers of economic development in Pakistan. These findings align with Solow's (1956) assertion that productivity growth is closely tied to these fundamental production inputs. Similarly, the significant impact of labor force participation on GDP per capita growth substantiates Hypothesis 4, affirming the importance of productive human capital in fostering economic development. This is consistent with both Neoclassical and Endogenous Growth Theories (Romer's 1990;1994; Schilirò, ,2019) emphasis on internal growth factors like human capital.

The role of renewable energy in economic growth, although only marginally significant, offers partial support for the Environmental Kuznets Curve (EKC). The moderate but positive relationship between renewable energy consumption and GDP suggests that as Pakistan develops economically, it is gradually transitioning toward cleaner energy sources. This lends support to Hypothesis 1, albeit at a weaker level of

statistical significance. It implies that income growth can facilitate the adoption of cleaner technologies, albeit with lags typical of developing economies.

The Porter Hypothesis postulates that environmental regulation can spur innovation and improve competitiveness is indirectly supported (Ambec, et al., (2013; Awan, 2014);Saravia-Matus, (2020). We noted contradiction in the Neoclassical model and Environmental Kuznets Curve model. The EKC assumes emissions eventually decline with growth, while the Neoclassical model doesn't inherently account for environmental externalities (Awan, 2013; Luqman, Ahmad & Bakhsh, 2019; Raza & Cucculelli, 2024). The observed unidirectional Granger causality from renewable energy to GDP per capita implies that innovations in clean energy contribute to economic development. However, because the study did not measure regulatory quality, Hypothesis 2 cannot be fully confirmed or rejected based solely on the current analysis (Yousaf Raza & Lin (2022). This may be due to institutional investment preferences or weak environmental regulations, which did not measure in this research (Bassen, Mayer & Baltzer, (2017).

Likewise**,** Hypothesis 3, which relates institutional stability and public policy frameworks to renewable energy deployment, cannot be empirically tested using the current dataset, as it lacks direct institutional variables. Nevertheless, the significant long-run contribution of renewable energy suggests an enabling policy or market environment, pointing to the possible relevance of Technological Innovation Systems (TIS) theory (Bergek, et al., (2008). Interestingly, Hypothesis 5 is rejected. Population growth in this study shows a positive and significant impact on GDP, both in the short and long run, contrary to Malthusian theory. Rather than diminishing per capita output, population increases appear to support labor supply and consumer demand, reflecting demographic dividends rather than constraints (Bekun, Emir & Sarkodie, (2019). The Sustainable Development Theory is reinforced through the empirical validation of the positive contributions of both renewable energy and labor force participation to GDP growth. These findings affirm that economic development need not come at the cost of environmental or social objectives, but can instead be part of an integrated growth trajectory (Georgantzis,

Martinez-Gomez, & Ordoñez, (2020; Awan, 2020; Raza & Cucculelli, (2024). Table 10 shows hypothesis testing results.

Table 10:

Hypotheses Testing outcomes

Hypothesis	**Statement**	**Result Based on Findings**	**Status**
H1	Countries with higher GDP per capita are more likely to adopt renewable energy.	Moderately supported via correlation and weak significance in long-run ARDL results.	Partially Accepted
H2	Strong environmental regulations correlate with innovation in green energy technologies.	Not directly tested; causality suggests indirect support	Inconclusive
H3	Capital investment in green energy sector accelerates green energy technology adoption.	Not directly tested; implied via positive long-run RE effect	Inconclusive
H4	Labor force participation is positively associated with economic development.	Strong positive relationship in both short- and long-run estimates	Accepted
H5	Population growth negatively influences economic development.	Positive and significant relationship found	Rejected

Source: Author owns calculations using E-View software**.**

5. Discussion

5.1 Main findings

This research provides valuable insights regarding the relationship between renewable energy consumption and economic development in Pakistan. Long-run evidence indicates that GDP per capita is positively correlated with carbon emissions, renewable energy consumption, gross fixed capital formation, labor force participation, and population growth. Such findings indicate that economic development in Pakistan continues to remain based on industrial production, capital accumulation, and labor market development. The long-lasting effect of CO_2 emissions on both short- and long-term studies suggests that, in spite of environmental issues, traditional energy sources continue to make a significant contribution to the nation's economic growth (Awan, 2013; Bai Raza, 2024). On the other hand, the small but positive influence of renewable energy shows a slow transition towards cleaner sources of energy. The ARDL bounds test established a long-run relationship between the variables, and diagnostic tests ensured the validity of the model. The short-run dynamics further reinforce the idea that capital formation and population growth exert immediate effects on economic development, while renewable energy consumption and labor force participation show delayed but positive influence (Awan, 2016;Accuracy & Ozturk,2016; Rojas-Valdivia,-Sánchez., & Gutiérrez-Trashorras, 2018) Notably, the significant and negative error correction term confirms the convergence of the system to long-term equilibrium, indicating that short-term deviations from the growth path are corrected over time. Granger causality analysis reveals unidirectional causality from renewable energy, investment, and labor force to economic growth, but not vice versa. This absence of feedback effects implies that while these drivers affect GDP per capita, economic growth alone does not influence them directly in the short run. This asymmetry reinforces the importance of proactive policy design rather than reactive economic management as suggested by Pollin, et al., 2009; Awan, Yaseen, 2017: Bassen, Mayer, & Baltzer, 2017; Bilan, et al., 2019; Raza, Cucculelli, 2024)

5.3 Policy Implications

The findings have profound implications for policymakers in Pakistan. First, the significant impact of renewable energy on economic development, albeit modest, suggests that promoting clean energy technologies can serve dual purposes: advancing environmental goals and supporting GDP per capita. Policy instruments such as subsidies for solar and wind energy, tax incentives for green investments, and infrastructure support for energy diversification could accelerate this transition.

Second, the dominant contribution of gross fixed capital formation to GDP growth confirms that capital-intensive investments, and especially in manufacturing, infrastructure, and technology, need to continue as the central part of national development strategies. To strengthen the contribution of renewable energy to growth, we will need to increase investment, strengthen financing systems, and facilitate grid integration of clean power. Third, the fact that the labor force has been such a central contributor to economic development underscores the role of human capital. Spending on education, technical training, and health care is become essential in boosting labor productivity and underpinning long-term economic performance. Economic policies should support green infrastructure and workforce training to maximize the economic benefits of the energy transition. Fourth, while a rising population can temporarily stimulate economic growth, it also requires careful long-term strategies to ensure job opportunities for the expanding workforce. Governments must focus on well-structured urban development, employment generation, and robust public services. Additionally, managing the demands of a growing population involves sustainable energy consumption and environmentally conscious urban planning to avoid worsening ecological degradation.

5.4 Limitations and suggestions for future research.

Despite valuable contribution and robustness of findings, there are certain limitations in this research. The study mainly relies on annual data, which, while it is sufficient for long-

term trend analysis, may obscure short-term deviations. Additionally, the use of CO_2 emissions as a proxy variable for industrial activity may not fully incorporate the multi-faceted nature of environmental degradation. The ARDL model, although good for small samples and mixed integration orders, does not address structural breaks or nonlinear relationships that may present in the data. Further, the scope of the study is confined to macro-level indicators, which may limit insights into sectoral or regional differences within Pakistan.

In the light of the above limitations, the following suggestions are made for future research. Future research can expand upon this work by incorporating panel data from multiple developing countries to compare the energy-growth dynamics across different institutional and economic settings. Moreover, future studies could explore nonlinear and asymmetric effects of renewable energy using threshold or nonlinear ARDL models. Additionally, integrating variables such as energy prices, technological innovation, and institutional quality could provide a more comprehensive framework for understanding the pathways through which renewable energy affects economic development. Examining disaggregated renewable energy sources—such as solar, hydro, or wind—could also yield more granular policy insights.

5.5 Conclusions

In conclusion, this study affirms the positive and significant role of renewable energy, capital formation, labor force, and population in fostering economic growth in Pakistan. While carbon-based energy remains a dominant driver, the evidence supports the growing relevance of renewable energy in shaping sustainable development. Policymakers must harness this momentum by adopting forward-looking policies that promote clean energy, strengthen investment frameworks, and invest in human capital to ensure long-term, inclusive economic growth. The continued dependence on non-renewable sources could not solve Pakistan's energy crisis and harness economic development in the long run.

Data availability statement

The data of this research could not be made available due to ethical restrictions..

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