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Renewable Energy Transition, Climate Risk, and Development Finance: Evidence from Pakistan Using ARDL and Causality Analysis

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Abstract

This study examines the dynamic relationship between greenhouse gas emissions, climate-related financial flows, and renewable energy development within Pakistan's evolving development finance landscape. Focusing on Foreign Direct Investment (FDI), Official Development Assistance (ODA), Trade Openness (TRD), and bilateral and multilateral agreements, the analysis evaluates how these factors shape Renewable Energy Capacity (REC) and influence the country's transition toward cleaner energy. The study also considers the role of Clean Energy Standard (CES) policies and the broader implications of carbon emissions for economic growth. Using unit root tests, the Autoregressive Distributed Lag (ARDL) framework, and Granger causality analysis, and grounded in Green Growth theory and the Environmental Kuznets Curve (EKC), the results show that ODA and trade positively affect REC in the long run, while FDI and CO2 emissions exert negative impacts. Short-run findings highlight the immediate adverse effect of carbon emissions on renewable energy development. Bilateral and multilateral agreements consistently emerge as strong drivers of renewable energy expansion. Overall, the results indicate that Pakistan's renewable energy transition is shaped by intertwined financial, policy, and environmental factors, underscoring the need for coordinated climate-aligned development strategies.

Keywords: Renewable energy transition, Climate risk, Development finance, Carbon emissions, Pakistan.

1 | Introduction

1.1 | Background of the Study

Climate change has become a critical global challenge, threatening environmental stability, social welfare, and economic development. Although its urgency is widely recognized, prior studies have insufficiently examined

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the dynamic mechanisms through which economic growth interacts with green growth and climate risks [1–3]. Achieving SDG-7 and SDG-13 requires international cooperation, technology transfer, and financial support to accelerate renewable energy adoption [4]. Pakistan has integrated climate concerns into national policy through mitigation and adaptation measures, including the 2012 climate policy and commitments under the Paris Agreement. These efforts accompany afforestation programs and initiatives to expand Renewable Energy Capacity (REC). Pakistan's energy transition is driven by government commitment, favorable renewable resources, and increasing private sector participation, reflected in large-scale renewable projects, distributed generation, energy storage, grid integration, and emerging technologies such as green hydrogen [5].

South Asian economies face persistent energy supply-demand imbalances and heavy reliance on imports despite diverse energy resources. Regional cooperation is therefore essential to reduce import dependence and accelerate renewable energy deployment [6]. Differences in renewable energy adoption also shape the effectiveness of climate adaptation policies across regions [7]. In the EU, high energy consumption and environmental pressures have intensified interest in renewable energy, aligned with SDG targets and COP26 commitments [8]. Pakistan's renewable energy potential spans legislative frameworks, technological advancements, investment opportunities, and successful initiatives in solar, wind, off-grid, and small hydropower. However, policy uncertainty, limited financing, infrastructure constraints, and technical barriers continue to hinder progress [9]. Green finance plays a pivotal role in shaping clean energy development, influencing emissions, biodiversity protection, and pollution control. Economic growth and urbanization remain major contributors to environmental degradation [10].

Pakistan's strategic partnership with China and engagement in multilateral platforms shape bilateral trade and associated risks [11]. International Financial Institutions (IFIs) such as the world bank, IMF, and ADB allocate multilateral aid based on political, economic, and bureaucratic considerations, with political instability positively influencing lending decisions. COVID-19 further increased Pakistan's reliance on IFI financing [12]. Pakistan aims to enhance access to Green Climate Fund resources by aligning its energy sector with net-zero pathways, enabling measurable emission reductions and green job creation [13]. Long-term renewable energy development is shaped by GDP, environmental progress, CO2 emissions, financial growth, and FDI, with nonlinear dynamics influencing renewable energy output [14].

Post-COVID-19 financing for renewable energy, particularly biogas, has become crucial for sustainable development, driven by perceived benefits, regulatory evaluations, and investor attitudes [15]. Despite global efforts, Pakistan's progress in biomass-based renewable energy remains limited, although projections show substantial potential for bioelectricity and CO2 reduction by 2050 [16]. CO2 emissions have risen sharply in Pakistan due to human activities. Renewable energy consumption, economic growth, and FDI significantly influence emissions, highlighting the need for stringent policies [17]. Pakistan's Alternative and Renewable Energy Policy targets 30% clean energy by 2030, with projections showing that renewable energy could meet future demand while reducing emissions from natural gas, furnace oil, and coal [18].

1.2 | Research Objectives and Question

This study focuses on three interconnected dimensions of Pakistan's renewable energy transition. First, it evaluates whether Foreign Direct Investment (FDI) provides sufficient support for expanding renewable energy generation capacity, given Pakistan's growing demand for clean energy and the structural constraints of its energy sector. Second, it investigates how bilateral and multilateral agreements shape the trajectory of renewable energy development, particularly through technology transfer, financial cooperation, and institutional commitments. Third, it examines the role of Clean Energy Standard (CES) policies in accelerating renewable energy deployment and strengthening long-term capacity expansion. These objectives collectively guide the central inquiry of the study: to determine the adequacy of FDI in driving renewable energy growth, to understand the extent to which international agreements influence the expansion of REC, and to assess how (CES) policies contribute to the overall development of Pakistan's renewable energy sector. Through this integrated analytical framework, the study seeks to clarify the financial, institutional, and policy mechanisms that underpin Pakistan's clean energy transition.

1.3 | Significant of the Study

The significance of this study is the importance of addressing climate change and pollution control through the reduction of CO2 emissions. It also analyzes the impact of renewable energy consumption, economic growth, FDI, bilateral and multilateral agreement and Official Development Assistance (ODA) for renewable energy on carbon emissions. The study suggests that stringent policies and strategies are needed to tackle environmental issues, making it relevant for policymakers, environmentalists and industries seeking to reduce their carbon footprint. The study aligns with the Government of Pakistan's commitment to increasing green energy capacity which aims to meet a significant portion of energy demand through renewable sources. This is crucial for Pakistan energy security and environmental sustainability. The study offers insights into how Pakistan can transition to cleaner energy sources and significantly reduce emissions from fossil fuels. It contributes to discussions on sustainable energy and environmental protection in Pakistan. Pakistan promises to reach 30% of its energy from clean sources by 2030 is a step toward using cleaner energy and reducing pollution. This change should significantly reduce the pollution from using natural gas, furnace oil and coal making the environment cleaner and more sustainable. The study also recognizes that Pakistan is changing its energy plans to focus more on alternative and renewable energy sources which shows they are adapting to new environmental goals.

1.4 | Delimitation of the Study

The study provides valuable insights into the impact of renewable energy consumption, economic growth and FDI on CO2 emissions and it's important to recognize its limitations. The study focuses primarily on these three factors and their impact on emissions, potentially overlooking other variables or complex interactions that affect carbon emissions. The study appears to be based on existing data and analysis, which might limit the exploration of real-time or dynamic factors that influence emissions. It doesn't delve deeply into the specific policy measures or technological advancements that could be employed to achieve the desired reduction in emissions and leaving room for further research in those areas. The study doesn't discuss potential challenges, obstacles or trade-offs associated with transitioning to green energy and reducing emissions. Understanding these challenges is crucial for practical implementation and policy development.

2 | Literature Review

We organize our literature review into two distinct but interlinked sections. The initial section will examine literature regarding to the reduction of carbon emissions, REC, FDI, and ODA in energy sector. In the second section, we will delve into the literature examining the impact of FDI, Bilateral and Multilateral Agreements, ODA, and Climate Finance Commitments (CFC) on REC. This exploration will also encompass legal and policy frameworks, along with access to information and technology.

2.1 | Renewable Energy Capacity and Carbon Emission Reduction

The existing literature provides extensive evidence on the complex interactions among FDI, REC, carbon emissions, and development finance, yet several conceptual and empirical gaps remain. Early foundational work such as Borensztein et al. [19] demonstrates that FDI can enhance economic growth through technology transfer, but only when host countries possess sufficient human capital. This finding is also verified by the study of Fakher [20]. This conditionality raises questions about the extent to which Pakistan, characterized by structural constraints, can effectively leverage FDI for renewable energy expansion. Kentor [21] further complicates this narrative by showing that large inflows of foreign capital may generate economic concentration, unemployment, and inefficient resource allocation, suggesting that FDI is not inherently growth-enhancing and may even exacerbate socio-economic disparities.

Energy access and sustainability have long been central to global development debates. Fecher [22] highlights the lack of political leadership in advancing renewable energy commitments at the World Summit on sustainable development, a challenge still relevant for Pakistan's policy environment. Similarly, Liming [23] notes that although China and India have made progress in renewable energy cooperation, such collaboration remains underdeveloped, an insight that parallels Pakistan's own limited regional energy coordination. Perry et al. [24] and Zhang et al. [25] emphasize that rising energy consumption continues to drive CO2 emissions, with Zhang's findings for China suggesting that emissions reduction policies need not compromise long-term growth, an argument applicable to Pakistan's policy dilemma.

The role of development assistance has also evolved. Woods [26] argues that emerging donors reshape global aid dynamics, offering alternatives to traditional Western financing. Minoiu et al. [27] distinguish between developmental and non-developmental aid, showing that only the former supports long-term growth. This distinction is crucial for Pakistan, where multilateral aid often reflects geopolitical interests rather than climate-aligned priorities. Sachs [28] underscores the importance of measurable global development goals, reinforcing the need for Pakistan to align renewable energy targets with international accountability frameworks. Environmental implications of FDI and economic growth have been widely studied. Lee [29] finds that while FDI supports economic growth in G20 countries, its environmental effects are complex and require targeted policy intervention. Dalla Longa et al. [30] illustrate how Kenya's climate commitments depend on cost-effective renewable technologies, offering a relevant comparison for Pakistan's own mitigation strategies. Ben Jebli et al. [31] show that renewable energy and tourism can jointly reduce emissions in Central and South America, whereas trade and growth increase them, mirroring Pakistan's challenge of balancing growth with environmental sustainability. Malik et al. [32] confirm the Environmental Kuznets Curve (EKC) hypothesis for Pakistan, indicating that emissions rise with income before eventually declining, while FDI and oil prices exert mixed effects on emissions.

The literature on Pakistan's energy sector further highlights structural constraints. Mele et al. [33] show that renewable energy can support economic recovery in Brazil, suggesting similar potential for Pakistan. Sikora [34] stresses the legal and financial complexities of the European Green Deal, underscoring the importance of coherent policy frameworks, an area where Pakistan continues to face fragmentation. Wang et al. [35] demonstrate that economic growth targets increase emissions in China, a dynamic likely present in Pakistan's growth-driven policy agenda. Raihan et al. [36] find that renewable energy reduces emissions in Peru, while agricultural expansion increases them, highlighting sector-specific trade-offs relevant for Pakistan's economy.

Recent studies deepen the understanding of renewable energy determinants. Appiah-Otoo et al. [37] show that renewable energy consumption and FDI jointly support growth in West Africa, while Iqbal et al. [38] reveal nonlinear effects of GDP, environmental technology, and financial development on renewable energy production in BRICS countries. Ali et al. [39] emphasize the importance of investor perceptions and regulatory frameworks for biogas adoption in Pakistan, whereas Raihan et al. [40] project substantial CO2 reductions through biomass-based energy by 2050. Tahir [17] confirms that renewable energy, economic growth, and FDI significantly influence Pakistan's emissions, reinforcing the need for stringent environmental policies. Raza et al. [41] demonstrate that Pakistan's renewable energy potential could meet future demand while reducing fossil-fuel emissions, aligning with national clean energy targets.

Table 1. Comparative evidence from recent studies.

Authors	Country	Time	Result and Conclusion
Appiah-Otoo et al. [37]	West Africa	1990-2021	Renewable energy consumption and FDI have a positive influence on economic growth.
Iqbal et al. [38]	BRICS countries	2000-2018	The renewable energy consumption and FDI exports are key terms of economic growth. Trade Openness (TRD) can have adverse effects on economic growth.

Table 1. Continued.

Authors	Country	Time	Result and Conclusion
Rej et al. [42]	India	1999-2018	Environmental-related technological innovation, FDI, and renewable energy have positive effect on climate change mitigation.
Leitão et al. [43]	Visegrad countries	1990-2018	The EKC is verified. The econometric results underscored the role of renewable energy consumption in fostering regional growth.
Raihan et al. [40]	Mexico	1971-2018	The study indicate that Economic growth, fossil fuel consumption, and urbanization have a negative influence on load capacity factor that leads to a reduction in environmental quality. Renewable energy sources and financial globalization positively affect the load capacity factor in both the long and short term.
Madaleno and Nogueira [44]	27 European Union (EU) countries	1994-2019	The study reveals that gross fixed capital human development and international trade positively contribute to economic growth. The study emphasizing the need for sustainable approaches and climate change mitigation and the importance of balancing economic growth with environmental sustainability.
Edo et al. [45]	Sub-saharan African economies	1980-2020	The analysis indicates that bilateral aid has a positive impact. Aid plays a complementary role in enhancing growth alongside the private and government sectors.
Hieu et al. [46]	Developing countries	1990-2020	Both renewable and non-renewable energy consumption contribute positively to economic growth.
Ali et al. [47]	Asian countries	1975-2020	The findings indicate that REC, NREC, labor force, and capital formation significantly impact long-term economic growth. NREC increases carbon emissions and REC decreases.
Kostakis and Arauzo-Carod [48]	G7 nations	1980-2018	The study emphasize that renewable energy generation was found to enhance environmental sustainability while globalization reduced pollution indicators. The economic complexity appeared to contribute to environmental degradation.
Amir et al. [10]	Pakistan	1991-2018	The study confirms a significant relationship between industrial CO2 emissions economic growth and added value which persists at different stages and undergoes extensive negative decoupling processes.
Raza et al. [41]	Pakistan	1981-2020	The study reveals a significant link between energy consumption and economic growth with agriculture economic output being the primary driver of increased energy use. Agriculture energy intensity and total agriculture land exhibit increasing returns to scale, while agriculture labor intensity has mixed effects.

Overall, the literature reveals several critical gaps. Although numerous studies examine the relationships among FDI, renewable energy, emissions, and development finance, few analyze these dynamics within a unified framework that incorporates bilateral and multilateral agreements, (CES) policies, and CFC. Moreover, existing research often focuses on isolated determinants rather than the combined financial, institutional, and policy mechanisms that shape REC in Pakistan. This study addresses these gaps by integrating development finance, policy frameworks, and environmental dynamics to provide a comprehensive understanding of Pakistan's renewable energy transition.

2.2 | Research Hypotheses

Based on the literature review, the following research Hypothesis can be formulated: 1) there is a positive relationship between renewable energy consumption and economic growth, with an increase in renewable energy use leading to higher economic growth, 2) FDI positively influences economic growth in developing countries with the influx of FDI contributing to economic expansion, and 3) the expansion of agricultural production and agro growth is associated with reduced carbon emissions, resulting in environmental improvement. These hypotheses aim to investigate the inter relationship between renewable energy, economic growth, carbon emissions and the role of FDI, agricultural production and urbanization in shaping the environmental and economic landscape in country.

2.3 | Research Gaps

After going through literature review, following research gaps have been identified: First, existing research often overlooks comprehensive view of international collaboration, renewable energy adoption, and climate action in Pakistan; it lacks a detailed exploration of policy implementation. Specifically, there is a gap in understanding the complexity of specific policy measures and their implementation strategies. Second, there is a research gap in exploring the long-term implications of relying on biomass-based sustainable energy, including the environmental, social, and economic considerations associated with its extensive use. Third, the study acknowledges the importance of bilateral and multilateral agreements; it lacks a dynamic analysis of how these agreements develop over time. Finally, there is a gap in understanding the specific ways and tools of green finance that contribute to supporting renewable energy initiatives. Building upon the above explanations, key contributions of this study are as follows: First, the study contributes by recognizing the need for a deeper exploration of policy measures and their implementation strategies in renewable energy adoption. Second, research can investigate the direct and indirect effects of various financial instruments on the deployment and success of renewable energy initiatives. Finally, this study contributes by highlighting the need to explore potential trade-offs and challenges in the transition to renewable energy.

3 | Theoretical Frameworks

3.1 | The Green Growth Theory

Green Growth Theory, as articulated by Jacobs [49], reframes environmental protection not as a constraint on prosperity but as a pathway toward it, directly challenging the traditional assumption that economic growth and environmental sustainability are incompatible. This theoretical shift is particularly relevant for economies like Pakistan, where growth pressures often overshadow environmental priorities. Smulders et al. [50] emphasize that achieving green growth requires balancing income expansion with ecological preservation, highlighting that technological innovation and efficiency improvements are essential for decoupling resource use from economic activity. Sandberg et al. [51] similarly argue that green growth relies on market-driven and technological solutions to reduce environmental pressures without slowing economic momentum. The World Bank [52] further broadens the concept by defining green growth as resource-efficient, clean, and resilient development, an approach that integrates natural capital management into economic planning. Collectively, these studies underscore both the promise and the limitations of green growth: while it offers a politically attractive narrative, its success depends on institutional capacity, technological readiness, and sustained policy commitment, all of which remain uneven in Pakistan's context.

3.2 | Environmental Kuznets Curve

The EKC provides a contrasting theoretical lens by proposing an inverted U-shaped relationship between economic growth and environmental degradation. Dasgupta et al. [53] show that environmental quality initially deteriorates as income rises due to weak regulation, high pollution intensity, and limited abatement capacity, but improves at higher income levels when societies begin valuing environmental protection and can afford cleaner technologies. Dinda [54] reinforces this pattern, noting that environmental pressure grows faster than income in early development stages but slows relative to GDP at higher income levels. Stern [55] offers a critical refinement, showing that EKC patterns are more robust for certain pollutants, such as particulates, than for others like carbon emissions, where economic growth continues to exert upward pressure. This nuance is crucial for Pakistan: while EKC dynamics may apply to localized pollutants, CO2 emissions linked to fossil-fuel dependence may not decline automatically with income growth, implying that policy intervention, not income effects alone, is necessary to achieve environmental improvements.

3.3 | Data Source

The study uses annual data from the World Development Indicators (WDI) for 1975-2022, ensuring consistency and comparability across all variables. REC is measured as the percentage of total final energy consumption, reflecting Pakistan's clean-energy uptake. ODA, reported in constant 2020 US dollars, captures external development financing, while FDI, expressed as a percentage of GDP, represents international capital inflows. Carbon emissions (CO2), measured in metric tons, indicate environmental pressure, and CFC, expressed as a percentage, reflect pledged climate-related funding. Trade Openness (TRD), measured as a share of GDP, serves as a proxy for bilateral and multilateral agreements influencing economic integration. Together, these variables provide a concise yet comprehensive dataset for examining how financial flows, environmental dynamics, and policy frameworks shape Pakistan's renewable energy trajectory.

3.4 | Model Specification

The analytical model examines how ODA, FDI, bilateral and TRD, CFC, and CO2 influence REC. The multivariate specification is expressed as *Eq. (1)*:

$$\mathrm{REC_t} = \beta_0 + \beta_1 \mathrm{ODA_t} + \beta_2 \mathrm{FDI_t} + \beta_3 \mathrm{CO2_t} + \beta_4 \mathrm{CFC_t} + \beta_5 \mathrm{TRD_t} + \varepsilon_t, \tag{1}$$

where REC represents Renewable Energy Capacity growth, ODA denotes Official Development Assistance for renewable energy, FDI captures foreign investment inflows, CO2 reflects emissions reduction efforts, CFC measures Climate Finance Commitments, and TRD proxies bilateral and multilateral agreements through TRD. The coefficients indicate the marginal effects of each independent variable on REC, and model validity is assessed through standard diagnostic tests.

The dependent variable, REC, is measured as the percentage share of renewable energy in total final energy consumption, reflecting the extent of clean energy adoption. Independent variables are operationalized using internationally recognized metrics: ODA in constant 2020 USD, FDI as a percentage of GDP, CO2 emissions in metric tons, and CFC as pledged financial resources dedicated to climate mitigation.

3.5 | Methodology

The empirical strategy of this study follows a structured time-series econometric approach designed to capture both short-run dynamics and long-run equilibrium relationships among REC, ODA, FDI, carbon emissions reduction, CFC, and bilateral and multilateral agreements. The analysis begins with unit root testing, where the Augmented Dickey–Fuller (ADF) procedure is applied to determine whether the variables exhibit stationarity. Identifying unit roots is essential because non-stationary series may produce spurious regression results, and the ADF test provides guidance on whether differencing is required to stabilize the statistical properties of each variable over time. After establishing the order of integration, Johansen's co-integration methodology is employed to examine whether the variables share a stable long-run relationship despite short-term fluctuations. The Trace and Maximum Eigenvalue statistics are used to determine the number of co-integrating vectors, allowing the study to assess whether the variables move together over extended periods. Evidence of co-integration justifies the use of an error-correction representation, linking short-run adjustments to long-run equilibrium.

Given the mixed integration orders typically observed in macroeconomic and financial variables, the Autoregressive Distributed Lag (ARDL) framework is adopted due to its flexibility in handling regressors with different lag structures and its suitability for small-sample time-series analysis. The ARDL approach does not require all variables to be integrated of the same order. The short-run dynamics are captured through the differenced ARDL specification in *Eq. (2)*:

$$\begin{aligned}\Delta \log \mathrm{REC_t} = {} & \mathrm{C_1} + \beta_1 \Delta \log \mathrm{REC_{t-i}} + \beta_2 \Delta \log \mathrm{ODA_{t-i}} + \beta_3 \Delta \log \mathrm{FDI_{t-i}} \\ & + \beta_4 \Delta \log \mathrm{CO2_{t-i}} \beta_5 \Delta \log \mathrm{CFC_{t-i}} + \beta_6 \Delta \log \mathrm{TRD_{t-i}} + \varepsilon_t.\end{aligned} \tag{2}$$

The corresponding long-run equation is expressed in *Eq. (3)*:

$$\begin{aligned}\mathrm{logREC_t} = {} & \mathrm{C_1} + \beta_1 \, \mathrm{logREC_{t-i}} + \beta_2 \, \mathrm{logODA_{t-i}} + \beta_3 \, \mathrm{logFDI_{t-i}} + \beta_4 \, \mathrm{logCO2_{t-i}} + \beta_5 \, \mathrm{logCFC_{t-i}} \\ & + \beta_6 \, \mathrm{logTRD_{t-i}} + \varepsilon_t\end{aligned} \tag{3}$$

To integrate both short-run and long-run effects, the combined ARDL representation is formulated in *Eq. (4)*, which includes both differenced and level terms:

$$\begin{aligned}\Delta \log \mathrm{REC_t} = {} & \mathrm{C_1} + \beta_1 \Delta \log \mathrm{REC_{t-i}} + \beta_2 \log \mathrm{REC_{t-i}} + \beta_3 \Delta \log \mathrm{ODA_{t-i}} + \beta_4 \log \mathrm{ODA_{t-i}} \\ & + \beta_5 \Delta \log \mathrm{FDI_{t-i}} + \beta_6 \log \mathrm{FDI_{t-i}} + \beta_7 \Delta \log \mathrm{CO2_{t-i}} + \beta_7 \log \mathrm{CO2_{t-i}} \\ & + \beta_8 \Delta \log \mathrm{CFC_{t-i}} + \beta_8 \log \mathrm{CFC_{t-i}} + \beta_9 \Delta \log \mathrm{TRD_{t-i}} + \beta_9 \, \mathrm{logTRD_{t-i}} + \varepsilon_t.\end{aligned} \tag{4}$$

The error-correction formulation, which incorporates the adjustment mechanism toward long-run equilibrium, is presented in *Eq. (5)*:

$$\begin{aligned}\Delta \log \mathrm{REC_t} = {} & \mathrm{C_1} + \beta_1 \Delta \log \mathrm{REC_{t-i}} + \beta_2 \log \mathrm{REC_{t-i}} + \beta_3 \Delta \log \mathrm{ODA_{t-i}} + \beta_4 \log \mathrm{ODA_{t-i}} \\ & + \beta_5 \Delta \log \mathrm{FDI_{t-i}} + \beta_6 \log \mathrm{FDI_{t-i}} + \beta_7 \Delta \log \mathrm{CO2_{t-i}} + \beta_7 \log \mathrm{CO2_{t-i}} \\ & + \beta_8 \Delta \log \mathrm{CFC_{t-i}} + \beta_8 \log \mathrm{CFC_{t-i}} + \beta_9 \Delta \log \mathrm{TRD_{t-i}} + \beta_9 \, \mathrm{logTRD_{t-i}} \\ & + \mathrm{ECT_{t-i}} + \varepsilon_t.\end{aligned} \tag{5}$$

The ARDL bounds testing procedure is then applied to determine whether the estimated long-run coefficients are statistically significant, testing the null hypothesis of no co-integration against the alternative of a long-run relationship. The Wald test is used to evaluate the joint significance of lagged level and differenced terms, ensuring that the dynamic structure of the model is appropriately specified.

To ensure the reliability of the estimated model, a series of diagnostic tests are conducted. Autocorrelation tests evaluate whether residuals are correlated across time, while heteroskedasticity tests assess whether residual variance changes with the level of the regressors. The Jarque–Bera test is used to verify the normality of residuals. Model stability is examined through the Ramsey RESET test, which detects specification errors or omitted variables, and through CUSUM and CUSUMSQ procedures, which identify structural breaks or parameter instability over time. Robustness is further assessed through sensitivity analysis using Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS), both of which correct for endogeneity and serial correlation, providing more reliable long-run estimates. Finally, Granger causality tests are conducted to explore the direction of temporal relationships among variables, using the system of equations in *Eq. (6)* through *Eq. (11)*, each incorporating lagged values of REC, ODA, FDI, CO_2, CFC, and TRD to determine predictive causality within the multivariate framework.

$$\mathrm{REC_t} = \mathrm{C_1} + \beta_1 \mathrm{REC_{t-i}} + \beta_2 \mathrm{ODA_{t-i}} + \beta_3 \mathrm{FDI_{t-i}} + \beta_4 \mathrm{CO2_{t-i}} + \beta_5 \mathrm{CFC_{t-i}} + \beta_6 \mathrm{TRD_{t-i}} + \varepsilon_t, \tag{6}$$

$$\mathrm{ODA_t} = \mathrm{C_1} + \beta_1 \mathrm{ODA_{t-i}} + \beta_2 \mathrm{REC_{t-i}} + \beta_3 \mathrm{FDI_{t-i}} + \beta_4 \mathrm{CO2_{t-i}} + \beta_5 \mathrm{CFC_{t-i}} + \beta_6 \mathrm{TRD_{t-i}} + \varepsilon_t, \tag{7}$$

$$\mathrm{FDI_t} = \mathrm{C_1} + \beta_1 \mathrm{FDI_{t-i}} + \beta_2 \mathrm{REC_{t-i}} + \beta_3 \mathrm{ODA_{t-i}} + \beta_4 \mathrm{CO2_{t-i}} + \beta_5 \mathrm{CFC_{t-i}} + \beta_6 \mathrm{TRD_{t-i}} + \varepsilon_t, \tag{8}$$

$$\mathrm{CO2_t} = \mathrm{C_1} + \beta_1 \mathrm{CO2_{t-i}} + \beta_2 \mathrm{REC_{t-i}} + \beta_3 \mathrm{ODA_{t-i}} + \beta_4 \mathrm{FDI_{t-i}} + \beta_5 \mathrm{CFC_{t-i}} + \beta_6 \mathrm{TRD_{t-i}} + \varepsilon_t, \tag{9}$$

$$CFC_t = C_1 + \beta_1 CFC_{t-i} + \beta_2 REC_{t-i} + \beta_3 OA_{t-i} + \beta_4 FDI_{t-i} + \beta_5 CO2_{t-i} + \beta_6 TRD_{t-i} + \varepsilon_t, \quad (10)$$

$$TRD_t = C_1 + \beta_1 TRD_{t-i} + \beta_2 REC_{t-i} + \beta_3 OA_{t-i} + \beta_4 FDI_{t-i} + \beta_5 CO2_{t-i} + \beta_6 CFC_{t-i} + \varepsilon_t. \quad (11)$$

The analysis concludes with an Innovative Accounting Matrix, which supports impulse response functions and variance decomposition analysis. These tools quantify how shocks to one variable propagate through the system and how much each variable contributes to forecast error variance, offering deeper insight into the dynamic interdependencies that shape Pakistan's renewable energy transition.

4 | Results and Discussion

The descriptive analysis provides an initial overview of the statistical behavior of the variables used in the model, offering insight into their central tendencies, dispersion, and distributional characteristics. These patterns help clarify the stability of the data and the extent to which each variable fluctuates over the sample period, forming the empirical foundation for subsequent econometric estimation. *Table 2* summarizes the descriptive statistics for all variables.

Table 2. Shows descriptive statistics.

	REC	ODA	FDI	CO2	CFC	TRD
Mean	3.9415	21.3021	-0.5644	-0.4612	5.7611	3.4585
Median	3.9430	21.3704	-0.4865	-0.4669	5.7950	3.4915
Maximum	4.0619	22.1020	1.2997	-0.0850	6.3444	3.6506
Minimum	3.7400	20.0201	-2.7737	-0.6814	4.7662	3.2069
Std. Dev.	0.1002	0.4672	0.8402	0.1884	0.3732	0.1166
Skewness	-0.1922	- 0.5884	- 0.2056	0.2132	-0.8719	-0.4581
Kurtosis	1.6210	3.0145	3.5421	1.6669	3.3937	2.2158

Note: Carbon emission (CO2)

Table 2 shows that REC, measured as the percentage of total final energy consumption, exhibits a stable distribution with a mean of 3.94 and a very small standard deviation, indicating limited variation over time. ODA, expressed in constant 2020 US dollars, also displays low variability and a distribution close to symmetry. FDI, measured as a percentage of GDP, shows the highest dispersion among variables, with a wide range from –2.77 to 1.29 and a relatively large standard deviation, reflecting Pakistan's fluctuating investment environment. CO2, measured in metric tons, present a narrow range and slight positive skewness, suggesting modest variation in environmental pressure over the period. CFC, expressed as a percentage, show moderate variability with a negatively skewed distribution. TRD, measured as a share of GDP, remains relatively stable, with low dispersion and mild left skewness.

Table 3. Correlation matrix.

Variables	REC	ODA	FDI	CO2	CFC	TRD
REC	1					
ODA	-0.2448	1				
	(0.0935)					
FDI	-0.5882	-0.1978	1			
	(0.0000)	(0.1778)				
CO2	-0.9907	0.2277	0.5839	1		
	(0.0000)	(0.1196)	(0.0000)			
CFC	0.1899	-0.2951	-0.4123	-0.1207	1	
	(0.1959)	(0.0417)	(0.0036)	(0.4139)		
TRD	0.4213	-0.3935	0.2060	-0.4122	0.2320	1
	(0.0029)	(0.0057)	(0.1600)	(0.0036)	(0.1126)	

The correlation matrix in *Table 3* reveals several meaningful associations among the variables. REC shows a moderate negative correlation with ODA and a stronger negative correlation with FDI, indicating that higher external financing and investment inflows have historically not coincided with increases in renewable energy deployment. The relationship between REC and CO2 emissions is exceptionally strong and negative, confirming that greater reliance on renewable energy is closely linked with lower carbon emissions. CFC exhibit only a weak positive correlation with REC, suggesting that climate-related funding has had a limited direct association with renewable energy expansion. TRD, however, shows a moderate positive correlation with REC, implying that greater integration into international markets may facilitate technology transfer and support the growth of clean energy.

Table 4. Unit root test.

Variables	Level		First Difference		Remarks
	Intercept	Trend and Intercept	Intercept	Trend and Intercept	
REC	-0.792 (0.812)	-2.875 (0.179)	-5.237 (0.000)	-5.180 (0.000)	I(1)
ODA	-3.418 (0.015)	-3.617 (0.039)	-7.593 (0.000)	-7.596 (0.000)	I(0)
FDI	-2.070 (0.257)	-1.984 (0.595)	-6.875 (0.000)	-7.107 (0.000)	I(1)
CO2	-0.476 (0.886)	-3.843 (0.023)	-5.705 (0.000)	-5.643 (0.000)	I(1)
CFC	-2.281 (0.182)	-2.196 (0.480)	-3.036 (0.039)	-3.048 (0.131)	I(1)
TRD	-2.550 (0.111)	-2.697 (0.242)	-6.429 (0.000)	-6.360 (0.000)	I(1)

Note: Bracket value shows probability value.

To mitigate the issue of spurious correlation, it is crucial to transform non-stationary time series data into a stationary form. The results of various unit root tests, as reported in *Table 4*, are essential for this purpose. In this study, the Augmented Dickey-Fuller (ADF) unit root tests were employed, both with intercept and with intercept and trend. The outcomes of these unit root tests indicate that REC, FDI in the energy sector, CO2 emissions, climate finance assistance, and trade exhibit non-stationary at their levels. However, after applying the first difference, these series become stationary or are integrated at order one. On the other hand, ODA is found to be stationary at the level.

Table 5. Lag length criteria.

Lag	LogL	LR	FPE	AIC	SC	HQ
0	127.5144	NA	$1.61e^{-10}$	-5.5234	-5.2801	-5.4331
1	297.7123	286.2420*	$3.67e^{-13*}$	-11.6233	-9.9202*	-10.9971*
2	330.1331	45.6838	$4.73e^{-13}$	-11.461	-8.2977	-10.2876

Table 5 shows the lag length criteria for model selection of time series data. The analysis considers lag lengths 0, 1, and 2. For lag 0, there is no likelihood ratio (NA), as it doesn't involve comparing the current model to a restricted model. For lag 1, the LR statistic is 286.2420, and it is significant. The FPE, SC, and HQ are also provided for model evaluation. The Lag 1 provides a better balance between model complexity and fit.

Table 6. ARDL Long run and short run result.

Short Run Coefficients				
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
D(FDI)	0.003	0.003	0.981	0.333
D(CO2)	-0.501	0.032	-15.821	0.000
D(CFC)	0.009	0.008	-1.117	0.271
D(ODA)	-0.0002	0.003	-0.069	0.945
D(TRD)	0.064	0.016	4.081	0.000
CointEq(-1)	-0.299	0.075	-3.962	0.000
Long Run Coefficients				
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
ODA	0.001	0.004	0.229	0.820
FDI	-0.020	0.006	-3.298	0.002
CO2	-0.501	0.037	-13.384	0.000
CFC	-0.009	0.009	-0.901	0.373
TRD	0.043	0.017	2.514	0.016
C	0.899	0.442	2.033	0.049

Table 6 shows the results of long run and short ARDL model. The results show that ODA and trade have positive impact on REC in long run. FDI and carbon emissions have negative but significant impact on economic growth in the long run. While in short run FDI show insignificant positive relation with growth rate and CO2 have a negatively significant relation with renewable energy. CFC have also negative but insignificant impact on economic growth in long run and negatively insignificant in short run. Trade shows

positively significant relation with REC. The result showed that if there is 1% increase in FDI the economic growth would increase by 0.02% with a negative relation. It implies that a higher level of FDI might be associated with a reduction in economic growth. This negative relationship could be influenced by various factors, By the study of Kang et al. [56] it might be attributed to the fact that while FDI has the potential to stimulate economic growth by fostering technology integration, generating spillover effects, and enhancing productivity, the resulting technological innovations and improved managerial skills could enable host countries to reduce their dependence on renewable energy sources. The study of Latief et al. [57], emphasize a negative long-term association between FDI, GDP, and energy consumption. Pakistan's power and energy sector currently grapples with circular debt and relies on loan-based investments. Failure to repay these loans in the future may adversely impact Pakistan's economy, leading to further debt accumulation and potential adverse effects on energy consumption. The study of Cao et al. [58] suggest that FDI has a negligible impact on energy intensity in emerging countries. The influence of FDI on energy intensity varies between BRICS and non-BRICS nations, with innovation capacity moderating this relationship differently across diverse emerging economies. Higher innovation weakens the energy-saving impact of FDI in BRICS countries. Furthermore, CO2 has showed significant negative relation with economic growth both in short and long run. Ullah et al. [59], argued that Pakistan, an emerging economy, boasts a densely populated industrial sector contributing significantly to CO2 emissions. The recent energy crisis has prompted a shift towards alternative energy sources, particularly the exploration of renewable energy resources. Over the past decade, government policies have increasingly focused on addressing the reliance on fossil fuels for energy production, recognizing their finite nature and environmental impact. This has led to a growing emphasis on RE options and clean fuel technologies, both globally and within Pakistan, to not only address the energy shortage but also promote a cleaner environment. The adoption of REC has the potential to minimize CO2 emissions, aligning with sustainability goals. TRD showed a positively significant relation with REC in both long run and short run results

Table 7. Bound test.

F-Bounds Test				
Test Statistic	**Value**	**Signif.**	**I(0)**	**I(1)**
F-statistic	1.929	10%	2.08	3
K	5	5%	2.39	3.38
		2.5%	2.7	3.73
		1%	3.06	4.15
Actual Sample Size	**47**		**Finite Sample: n=50**	
		10%	2.259	3.264
		5%	2.67	3.781
		1%	3.593	4.981
			Finite Sample: n=45	
10%			2.276	3.297
5%			2.694	3.829
1%			3.674	5.019

The bound test results in *Table 7* indicate that the computed F-statistic (1.929) falls below all critical values at conventional significance levels, both for asymptotic and finite-sample bounds. This confirms that the null hypothesis of no long-run relationship cannot be rejected, implying that the variables do not exhibit co-integration within the ARDL framework.

Table 8. FMOLS and DOLS.

Fully Modify Least Square (FMOLS)				
Variables	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
ODA	0.008	0.006	1.308	0.198
CO2	-0.509	0.019	-26.826	0.00
FDI	0.000	0.004	0.095	0.923
CFC	0.0314	0.007	4.330	0.000
TRD	0.059	0.024	2.454	0.013
C	3.154	0.191	16.542	0.000
(DOLS)				
Variables	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
ODA	0.019	0.018	1.055	0.302
CO2	-0.491	0.037	-12.358	0.000
FDI	0.002	0.011	0.224	0.825
CFC	0.040	0.015	2.584	0.016
TRD	0.131	0.064	2.060	0.050
C	2.613	0.617	4.232	0.000

Table 8 shows the results of a FMOLS and DOLS regression analysis with coefficients, standard errors, t-statistics, and probability values for the specified variables. In FMOLS the coefficient for CO2 is -0.509 and statistically significant. The negative coefficient implies an inverse association between CO2 emissions and the dependent variable REC. The coefficient for CFC is 0.0314 indicates that CFC exhibits a positive and statistically significant influence on the REC. The positive coefficient, along with the statistically significant t-statistic, suggests that TRD has a positive and statistically significant impact on the REC. In DOLS result CO2 with coefficient of -0.491 suggests that there is a negative relationship between CO2 emissions and REC. In simple terms as CO2 emissions decrease, REC tends to increase. The positive coefficient of 0.040, along with a statistically significant t-statistic (2.584), indicates that CFC has a positive impact on REC. CFC appears to contribute positively to the growth of REC. The positive coefficient and the marginally significant t-statistic indicate that TRD has a positive impact on REC.

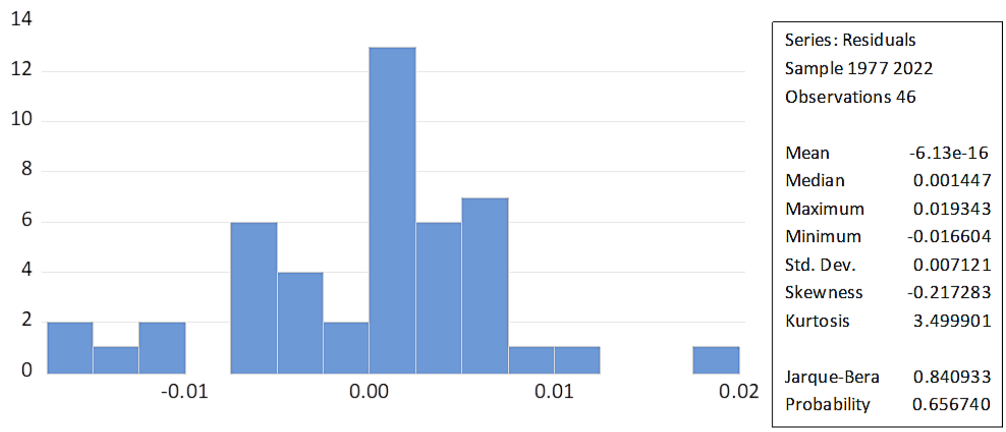

Fig 1. Normality test.

Fig. 1 show that the residuals are normally distributed as evident from the Jarque-Bera test.

Table 9. Diagnostic estimates.

	Value	Df	Prob.
t-statistic	1.521	33	0.138
F-statistic	2.313	(1, 33)	0.138
Likelihood ratio	3.116	1	0.077
F-Test Summary			
	Sum of Sq.	**Df**	**Mean Squares**
Test SSR	0.000	1	0.000
Restricted SSR	0.002	34	6.71E-05
Unrestricted SSR	0.002	33	6.46E-05

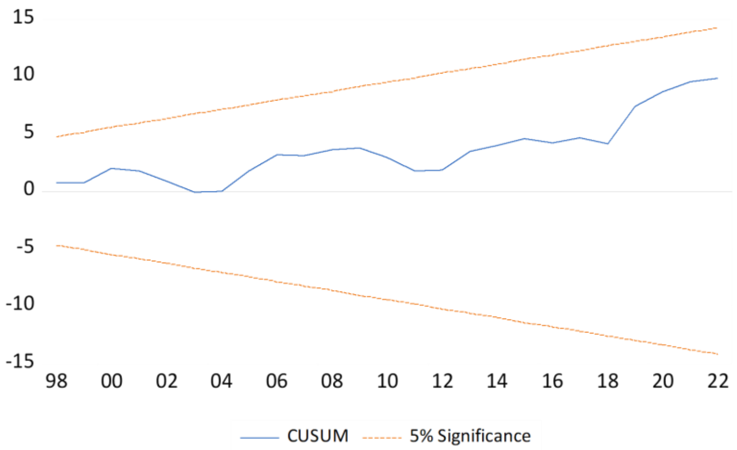

Fig 2. CUSUM test.

Fig. 2 shows the CUSUM graph which lies within given significance level showing that the model is stable, and the outcomes are free from any technical issue.

Table 10. Granger causality.

Null Hypothesis	F-Statistic	Prob
ODA ↔REC	0.356	0.703
REC↔ ODA	6.493	0.000
CO2 ↔REC	0.172	0.843
REC ↔CO2	0.224	0.800
FDI ↔REC	1.409	0.255
REC ↔FDI	0.203	0.817
CFC ↔REC	0.262	0.770
REC ↔CFC	0.361	0.699
TRD ↔REC	0.172	0.843
REC ↔TRD	1.416	0.254
CO2 ↔ODA	4.579	0.016
ODA ↔CO2	0.217	0.805
FDI ↔ODA	0.023	0.977
ODA ↔ FDI	0.735	0.486
CFC ↔ODA	0.445	0.644
ODA ↔CFC	2.934	0.027
TRD ↔ODA	1.992	0.149
ODA ↔TRD	0.180	0.835
FDI ↔CO2	0.568	0.571
CO2 ↔FDI	0.192	0.826
CFC ↔CO2	2.217	0.077
CO2 ↔CFC	1.194	0.313
TRD ↔CO2	0.267	0.767
CO2 ↔TRD	1.156	0.325

Table 10. Continued.

Null Hypothesis	F-Statistic	Prob
CFC↔FDI	1.808	0.177
FDI ↔CFC	0.434	0.651
TRD ↔FDI	0.433	0.651
FDI ↔TRD	0.367	0.695
TRD ↔CFC	2.712	0.078
CFC ↔ TRD	2.395	0.059

Table 10 shows the Granger causality relationship between different observed variables. There is a significant causality relationship between REC and ODA. The REC led growth hypothesis has an F-statistic of 6.493 with a probability of 0.000. This implies that historical REC values offer substantial insights for anticipating future ODA levels. A temporal correlation suggests that alterations in REC may coincide with subsequent adjustments in ODA. This correlation may stem from the impact of renewable energy projects on decisions related to development assistance. A substantial Granger causality connection exists between CO2 emissions and ODA, as evidenced by an F-statistic of 4.579 with a probability of 0.010. This supports the emissions-driven growth hypothesis. The results show that historical levels of CO2 emissions offer meaningful insights for predicting future ODA levels. The findings suggest a temporal linkage between environmental concerns related to CO2 emissions and subsequent decisions regarding ODA. This may signify an acknowledgment that environmental sustainability plays an integral role in achieving development assistance goals. The result shows Granger causality relationship is established between ODA and CFC with an F-statistic of 2.934 and a probability of 0.027. It is observed that an increase in ODA influences CFC. This implies that past values of ODA offer insights for predicting future levels of CFC. The connection suggests interdependence between development assistance decisions and environmental policies. A substantial Granger causality relationship is identified between CFC and CO2 emissions. This implies that past levels of CFC provide meaningful information for predicting future levels of CO2 emissions. The observed relationship supports the growth conversion hypothesis. This could suggest that efforts in climate finance or lack thereof are associated with subsequent changes in CO2 emissions. The growth conversion hypothesis may propose a dynamic where financial support for climate-related initiatives influences the transition toward sustainable and lower carbon-emission growth patterns. The significant Granger causality relationship between TRD and CFC implies interdependence between trade dynamics and climate finance decisions. Economic activities related to trade may influence the allocation of climate finance assistance and policies and support for climate-related initiatives might impact trade dynamics. This connection underscores the potential linkages between international trade and climate finance, highlighting the importance of considering economic factors in shaping climate-related policies.

Table 11. Impulse response function.

Period	REC	ODA	FDI	CO2	CFC	TRD
1	0.0222	0.000	0.000	0.000	0.000	0.000
2	0.0261	-0.0031	-0.0060	-0.0004	-0.0018	0.0010
3	0.0257	-0.0050	-0.0094	-0.0001	-0.0022	0.0015
4	0.0243	-0.0027	-0.0086	0.0002	-0.0006	0.0025
5	0.0239	-0.0006	-0.0067	0.0013	0.0011	0.0036
6	0.0239	-0.0008	-0.0059	0.0029	0.0018	0.0044
7	0.0235	-0.0018	-0.0059	0.0047	0.0019	0.0049
8	0.0226	-0.0019	-0.0058	0.0061	0.0023	0.0056
9	0.0217	-0.0013	-0.0051	0.0073	0.0029	0.0063
10	0.0208	-0.0008	-0.0044	0.0086	0.0035	0.0068

In the context of our research, we conducted impulse response analysis to describe the impact of random innovations among the variables under study. We investigated the responses of REC, ODA, FDI, CO2 emissions, and TRD to random innovations. *Table 11* illustrates the impulse response of REC to innovations in relation to the other study variables. Our findings reveal that the response of ODA to innovations in REC is both significant and consistently decreasing within a 10-period horizon. Conversely, the response of renewable energy to FDI exhibits a significant negative trend within the same 10-period horizon. Furthermore, the response of CO2 emissions to REC is positively significant within a 10-period horizon. Notably, the response of CFC to REC is positively significant, particularly within the preceding 6 years. Lastly, TRD demonstrates a positively significant effect on REC over10-period horizon.

Table 12. Variance decomposition analysis.

Period	REC	ODA	FDI	CO2	CFC	TRD
1	100.000	0.000	0.000	0.000	0.000	0.000
2	95.900	0.7783	2.947	0.015	0.277	0.082
3	91.490	1.738	6.183	0.009	0.407	0.169
4	90.335	1.583	7.401	0.009	0.320	0.352
5	90.314	1.293	7.350	0.060	0.298	0.685
6	90.195	1.102	7.037	0.276	0.331	1.059
7	89.634	1.020	6.826	0.718	0.361	1.439
8	88.741	0.968	6.659	1.347	0.472	1.867
9	87.657	0.897	6.432	2.137	0.525	2.352
10	86.384	0.826	6.152	3.101	0.668	2.868

The variance decomposition results in *Table 12* show that shocks to REC remain the dominant driver of its forecast variance, though their influence gradually declines from 100% to about 86% over ten periods. Among the other variables, FDI and CO2 emerge as the most influential contributors to REC's variability, with FDI rising to over 6% and CO2 increasing to more than 3%, while ODA, CFC, and TRD play comparatively minor but steadily growing roles in shaping long-run fluctuations in REC.

5 | Conclusion and Policy Recommendations

5.1 | Conclusion

This study demonstrates that Pakistan's REC is shaped by a complex interaction of financial flows, environmental pressures, and international economic linkages. The empirical results show that while TRD and ODA contribute positively to renewable energy development in the long run, FDI and rising CO2 emissions exert adverse effects, reflecting structural dependence on carbon-intensive investment and energy systems. Short-run dynamics reveal additional constraints, including the limited immediate impact of FDI and climate finance commitments, underscoring the need for policies that differentiate between short-term volatility and long-term structural change. Granger causality and impulse-response patterns further confirm strong interdependencies among renewable energy, development assistance, emissions, climate finance, and trade, highlighting the importance of coordinated policy action. Overall, the findings suggest that Pakistan's energy transition requires a comprehensive strategy that aligns investment policies, environmental regulation, and international cooperation. Strengthening climate-aligned investment frameworks, reducing carbon emissions, addressing structural issues such as circular debt, and expanding renewable energy deployment are essential for achieving sustainable growth. Integrating environmental considerations into development assistance, trade policy, and climate finance decisions will be critical for building a resilient, low-carbon economic trajectory.

5.2 | Policy Recommendation

The study highlights the adverse long-term impact of FDI on economic growth, emphasizing the importance of attracting sustainable and environmentally friendly investments. Policymakers should focus on encouraging FDI in green and renewable energy projects to mitigate the negative environmental effects associated with traditional energy sources. Despite the limited impact of climate finance commitments on economic growth, there is a crucial need to fortify climate finance strategies. Policymakers should explore innovative financing mechanisms and collaborations to support sustainable development, particularly within the renewable energy sector. Addressing circular debt in the energy sector is imperative, given its pivotal role in promoting renewable energy. Policymakers should explore alternative financing models to ensure a stable and sustainable energy supply, working towards resolving financial challenges in the power sector for long-term energy security. The positive and significant relationship between trade and REC in both short and long terms underscore the importance of trade policies. Policymakers should persist in fostering an open and conducive trade environment to facilitate the import and export of renewable energy-related technologies and products. Recognizing the adverse impact of carbon emissions on economic growth, there is a critical need to expedite the transition to cleaner energy sources. Policymakers should prioritize and incentivize the adoption of renewable energy technologies, encouraging a shift away from fossil fuels.

Authors' Contributions

S. R.: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Writing-original draft, Visualization, and Validation. The author has read and agreed to the published version of the manuscript.

Data Availability

The data is available on request from the corresponding author.

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Conflict of Interest

There are no competing interests to declare.

Consent for Publication

The author has given consent for the publication of this manuscript.

Ethics Approval and Consent to Participate

The author confirms that this research did not involve human participants or animal subjects.

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