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The Impact of Renewable Energy Consumption, Economic Growth and Exports on CO_2 Emissions in Pakistan: An ARDL Approach

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Abstract

The dynamic relationship among CO_2 emissions and Economic factors such as renewable energy consumption, GDP growth, and exports is an important aspect in view of environmental sustainability and economic development for developing countries like Pakistan. This research aims to explore the short-term and long-term relationship between CO_2 emissions and renewable energy, GDP growth, and exports in Pakistan. by using data from the year 1991–2022 and the ARDL technique of cointegration to check both long and short-term relationships among GDP, RE, exports and CO_2 emissions. and to check the stability and robustness of the model after estimation, a range of diagnostic tests is carried out. These include descriptive statistics, unit root tests, ARDL bounds testing. The results of the ARDL analysis reveal that Increased use of renewable energy significantly reduces CO_2 emissions in both the short and long term. GDP growth is associated with increased CO_2 emissions, both currently and with a lag, indicating a persistent relationship between economic activities and carbon emissions. In the short term, increased exports are associated with a decrease in CO_2 emissions, and in the long term, exports do not significantly affect CO_2 emissions. This paper, therefore, further contributes to what the literature provides through an in-depth analysis of how economic activities and environmental impacts interplay in Pakistan, emphasizing balanced economic and ecological policies for long-term sustainability.

Key words: Consumption of renewable energy; Economic growth rate; CO_2 emissions; ARDL; Export; Economic development; Sustainable environment

1. INTRODUCTION

The rise in global Carbon dioxide (CO_2) emissions has become a critical issue for environmental sustainability, especially concerning the youth worldwide and in developing countries. Pakistan has been on an upswing in economic escalation since long time, where the patterns of energy use and the produced CO_2 emissions are on the increase. Industrial growth is based on an increase in demand for manufacturing and exports, which call for the increased use of energy and subsequently higher emissions. the mechanization of most of its agricultural practices, which also involve a huge amount of energy for irrigation, further loads the emissions in Pakistan. the increase in population growing fast in urban areas puts a regular demand on infrastructural facilities and services that increase energy usage and, consequently, inflate the emission of GHGs (Ali et al., 2016). Transportation emissions are another major source of increased emission, as this sector is dependent on fossil fuels, which has been fueled further by urbanization and increase in population (Jamil, 2013).

1.1 Background and Significance

Adoption of renewable energy technologies has the potential to reduce the country's dependence on fossil fuels, lower CO_2 emissions, and enhance energy security (Mirza, Ahmad, & Majeed, 2021). But some of the factors that have hampered an actual switch toward renewable sources include financial constraints, technological barriers, as well as policy implementation issues in adopting countries (Siddiqui, 2004). This is usually explained by the Environmental Kuznets Curve (EKC) hypothesis that argues that CO_2 emissions first rise with economic growth but eventually tend to decrease when developing as more efficient economies adapt cleaner technologies. (Stern2004). An understanding of this relationship would be critical to designing policies that would foster economic growth in a sustainable manner within Pakistan.

The role of exports is significant within the economy of Pakistan and extends to CO_2 emissions. More often than not, the manufacturing of goods for export markets entails energy-intensive processes which further translate into emissions. As a result, exports can also lead to the growth of the economy, which in turn will force investment into cleaner technologies and greater efficiency in production processes (Din, Ghani, & Mahmood, 2013).

The government of Pakistan has adopted different policies and initiatives to encourage the promotion of renewable energy technologies. All these adoptions are not challenge-free, with financial constraints, technological challenges, and barriers in policy implementation. In balancing economic advancement with environmental stewardship, the fast-growing economy of Pakistan is at a great challenge. The reason it is important for developing countries to understand how much renewable energy is being consumed, along with economic growth, exports, and CO_2 emissions, relates to gaining that elusive balance between development and environmental protection. the current study will draw its importance to the readers by considering these variables in the specific context of Pakistan so as to derive salient insights capable of being used for policy formulation and strategic decision-making. This study thoroughly investigates the effect of renewable energy consumption with relation to GDP growth, exports, and the emission of CO_2 gases in Pakistan for an overall analysis in the dynamics of factors driving the eco-friendliness of the country.

1.2 Research Questions

The study seeks to answer the following key research questions:

i. What is the impact of renewable energy consumption on CO_2 in Pakistan?

ii. How does GDP growth influence CO_2 emissions, and is there evidence of the Environmental Kuznets Curve (EKC) in Pakistan?

iii. What role do exports play in affecting CO_2 in Pakistan?

iv. What policy measures can effectively promote renewable energy adoption and sustainable environment economic growth in Pakistan?

1.3 Research Objectives

The primary objectives of this research are:

i. To analyze the impact of renewable energy consumption on CO_2.

ii. To examine the relationship between GDP growth and CO_2.

iii. To investigate the effect of exports on CO_2.

iv. To provide policy suggestions based on the findings.

The structure of this research paper: Introduction, Literature Review, Methodology, Analysis Results and Discussion, Conclusion and Policy Recommendations, and References. By following this structured approach, the research paper ensures a clear and coherent presentation of the research.

2. LITERATURE REVIEW

2.1 Theoretical Framework

2.1.1 Environmental Kuznets Curve (EKC) Hypothesis

The Environmental Kuznets Curve (EKC) Hypothesis suggests an inverted U-shaped relationship between environmental degradation and economic growth.

Figure 1. presents the relationship between CO_2 emissions and economic growth according to the EKC hypothesis.

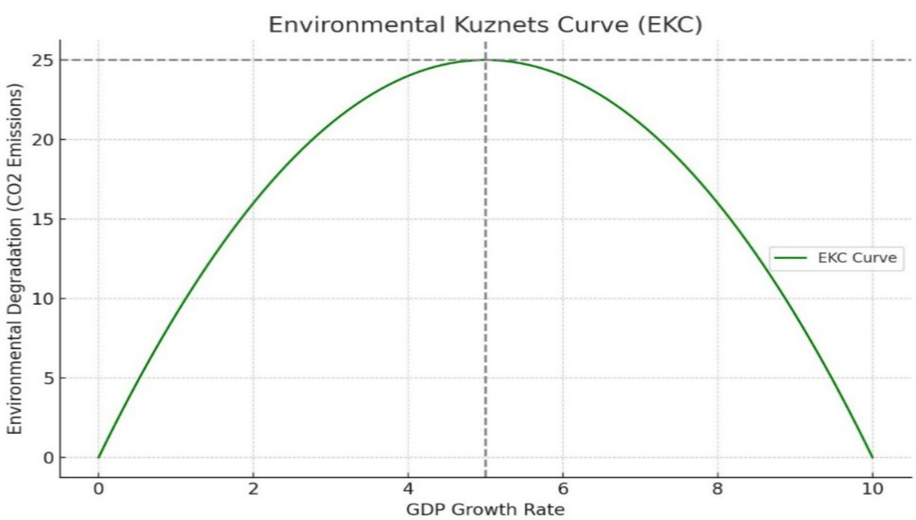

Figure 1
Environmental Kuznets Curve (EKC) Hypothesis
Source: Author's own compilation based on Power Bi Software

The Environmental Kuznets Curve (EKC) hypothesis, this theory indicates that during the early stages of economic development, as a country industrializes and consumes more energy, Carbon emissions tend to rise with increasing GDP. However, once a certain income level is achieved, the trend reverses, with further economic growth contributing to a decline in emissions. This reduction is attributed to the implementation of strict environmental policies by state, advancements in technology, and a shift towards less polluting sectors (Stern, 2004). In advanced stages of economic development, nations often adopt more sustainable practices, such as renewable energy sources and energy-efficient technologies, which further decrease CO_2 emissions (Grossman & Krueger, 1995).

2.1.2 Export-led Growth Hypothesis

The Export-led Growth Hypothesis posits that an increase in exports leads to overall economic growth. Figure 2. presents the relationship between export-led growth and CO_2 emissions.

According to this theory, increasing exports can stimulate economic growth. the environmental consequences of this growth are influenced by the type of goods being exported. In Pakistan, a significant portion of exports comprises energy-intensive industrials such as textile and agricultural products, which contribute to elevated CO_2 emissions (Munir & Khan, 2014). When a nation's export profile is heavily skewed towards such sectors, the economic benefits from exports can be accompanied by increased CO_2 emissions. Conversely, promoting the export of environmentally friendly products and services can help reduce the environmental impact associated with export-driven growth (Khan et al., 2019).

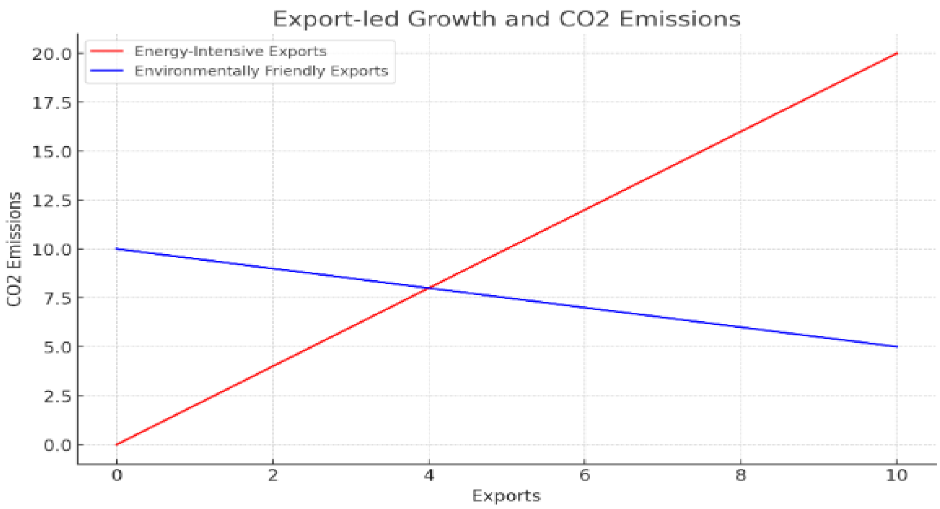

Figure 2
Export-led Growth and CO_2 Emissions Diagram

Source: Author's own compilation based on Power Bi Software

2.1.3 Renewable Energy and Carbon dioxide Emissions

This section explores the impact of renewable energy on carbon dioxide emissions. Figure 3 presents the relationship between renewable energy adoption and CO_2 emissions.

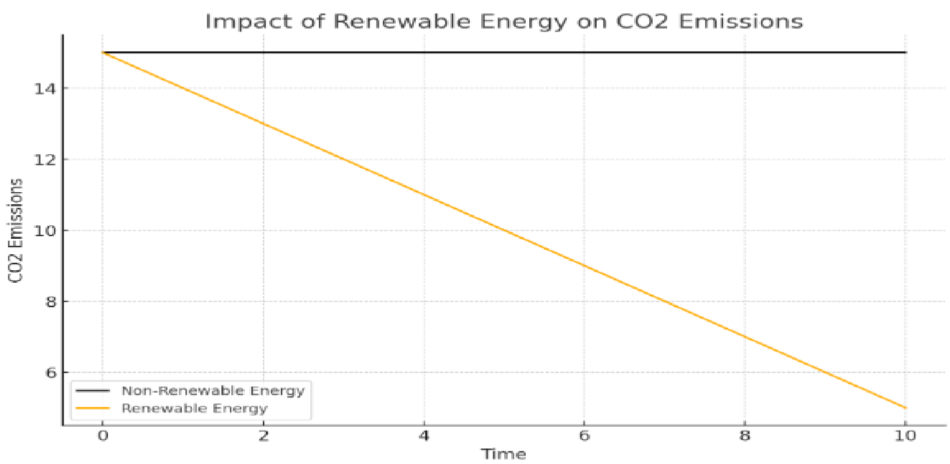

Figure 3
Renewable Energy and Carbon dioxide Emissions curve
Source: Author's own compilation based on Power Bi Software

Adopting renewable energy is crucial for reducing CO_2 emissions. Shifting from emissions to adoption of renewable energy sources can significantly alter the environmental impact of an economy. Investment in renewable energy infrastructure enables economies to reduce their dependence on fossil fuels, thereby fostering long-term environmental sustainability (Rehman et al., 2021).

2.1.4 Technological Innovation and Diffusion Theory

This section examines how technological innovation and diffusion influence carbon dioxide emissions. Figure 4 presents the relationship between technological innovation and CO_2 emissions.

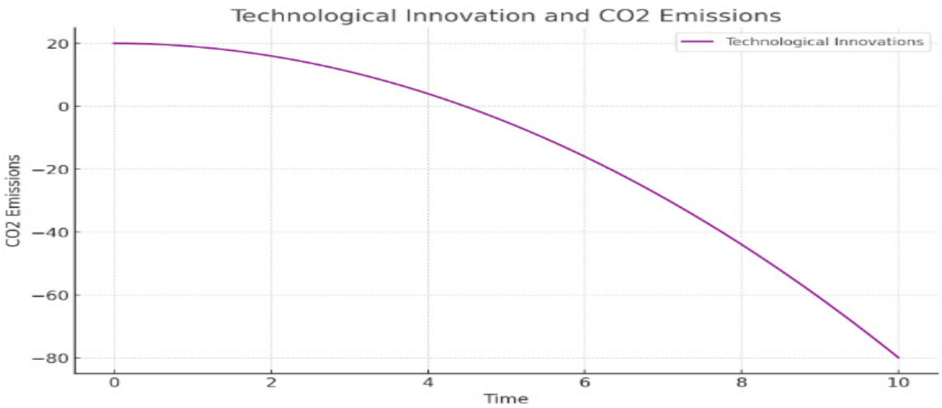

Figure 4
Technological Innovation and Carbon dioxide Emissions

Source: Author's own compilation based on Power Bi Software

The diffusion of clean and efficient technologies can enhance energy efficiency and reduce the carbon intensity of economic activities. The adoption of new technologies in energy production, transportation, and industry can lead to significant reductions in CO_2 emissions (Waheed et al., 2018). Government policies and incentives are vital in accelerating the adoption of innovative technologies and ensuring widespread diffusion (Iqbal et al., 2021).

2.1.5 Combined Theoretical Framework

This section integrates these theories to provide a comprehensive understanding of the factors influencing carbon dioxide emissions. Figure 5. presents the integrated theoretical framework.

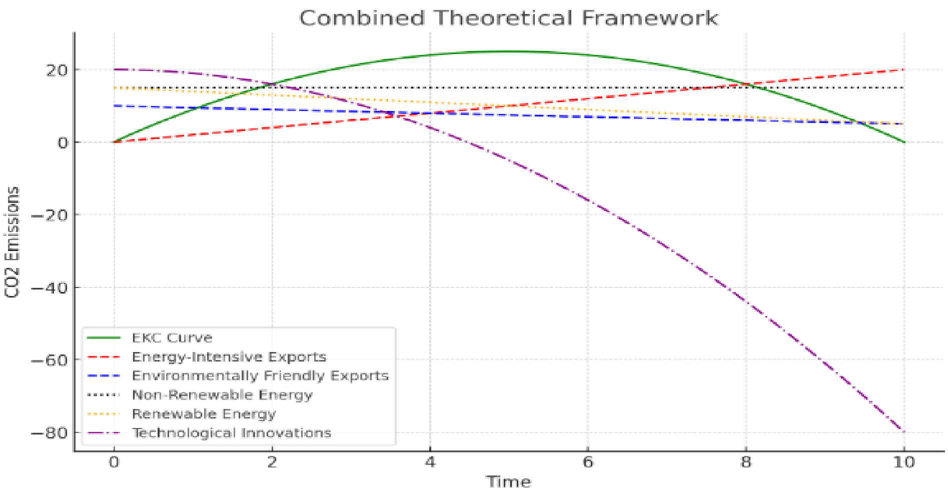

Figure 5
Integrated Theoretical Framework

Source: Author's own compilation based on Power Bi Software

2.2 Empirical Studies

Shafique et al. (2023) used panel data for Pakistan and China to analyze the determinants of CO_2 emissions. Their regression analysis and forecasts indicate that both energy consumption and production are significant positive contributors to CO_2 emissions, whereas energy intensity has a notable negative impact. Economic variables including GDP, positively influence CO_2 emissions, GDP growth unexpectedly shows an insignificant negative effect. Chien et al. (2021) found that renewable energy consumption is negatively associated with environmental degradation in Pakistan. Technological innovation is also very crucial for increasing energy efficiency and promoting cleaner production.

Khan et al. (2019) explored, technological advancements can significantly reduce CO_2 emissions and support a green economy. Shahbaz et al. (2015) investigated the impact of globalization on environmental quality in India, found that trade openness and globalization contribute to higher CO_2 emissions in developing countries. and Chien et al. (2021) similarly found that globalization is positively associated with CO_2 emissions in Pakistan. Tahir (2023) analyzed the relationship between trade, FDI, renewable energy consumption, electricity power consumption, economic growth, and CO_2 emissions in Pakistan from 1990 to 2022 by using the ARDL technique. The study revealed that REC, economic growth, and FDI have a significant impact on CO_2 emissions, highlighting the key roles of renewable energy and economic activities in shaping environmental outcomes.

Danish et al. (2017) utilized various econometric tools, including structural break unit root tests and the autoregressive distributive lag (ARDL) model, to analyze data from 1970-2011. They found that fossil fuel-based energy production is the main contributor to CO_2 emissions and suggested promoting renewable energy sources to mitigate this impact. Mahmood et al. (2019) employed three-stage least square and ridge regression methods on data from 1980-2014, revealing that economic growth and renewable energy consumption increase CO_2 emissions, while trade openness also contributes to higher emissions. Human capital, however, helps reduce emissions. Mirza and Kanwal (2017) They recommended increasing the renewable energy share in the energy mix to reduce emissions. Khan et al. (2020) also utilized the ARDL model on data from 1965-2015, concluding that both energy consumption and economic growth lead to higher CO_2 emissions in the short and long term. They emphasized the need for renewable energy adoption to curb emissions. Khan et al. (2019) applied dynamic ARDL simulations to data from 1971-2016, finding that energy consumption, financial development, and globalization positively affect CO_2 emissions, while urbanization and economic growth have mixed effects. Zaidi et al. (2018) used the ARDL model on data from 1970-2016 to reveal that renewable energy has an insignificant impact on CO_2 emissions, whereas natural gas and coal significantly increase them. They noted that economic growth contributes to emissions as well.

Danish et al. (2018) analyzed data from 1990-2015 using ARDL and VECM models, highlighting the significant impact of transport energy consumption and foreign direct investment (FDI) on CO_2 emissions from the transport sector. Tahir (2023) employed the ARDL technique on data from 1990-2022, showing that renewable energy consumption, economic growth, and FDI significantly affect CO_2 emissions, recommending strict policies to control pollution. Khan et al. (2019) used ARDL with structural break and error correction methods on data from 1972-2017, confirming the environmental Kuznets curve (EKC) hypothesis for Pakistan. They found that energy consumption and urbanization positively affect CO_2 emissions, while trade openness and financial development have mixed effects. Hussain et al. (2012) applied various econometric tests to data from 1971-2006, discovering a long-term relationship between CO_2 emissions, energy consumption, and GDP, but rejecting the EKC hypothesis for the period studied. d et al. (2018) analyzed impact of renewable and non-renewable energy consumption on CO_2 emissions in Pakistan by using data from 1970 to 2016. Their study, employed ARDL model, revealed that renewable energy consumption has a minor effect on CO_2 emissions, whereas non-renewable sources significantly increase to pollution. and economic growth positively influences CO_2 emissions in relation with renewable energy consumption, but not with non-renewable energy.

Abbas et al. (2021) analyzed the impact of traditional and renewable energy consumption, ecological footprint, urbanization, and transportation on CO_2 emissions in Pakistan using long-term data from 1970 to 2018 by employ the ARDL model alongside FMOLS and DOLS methods, and revealed that renewable energy significantly reduces CO_2 emissions. Bhattacharya et al. (2016) found that renewable energy consumption positively impacts economic growth and reduces CO_2 emissions. They utilized DOLS method. Apergis and Payne (2014) examined that renewable energy consumption decrease CO_2 emissions and increasing economic growth. Balaguer and Cantavella (2016) they examined the relationship between exports and CO_2 emissions in Spain, by using 1970 to 2014 data and employed the ARDL bounds testing approach. They found that exports initially increase CO_2 emissions, but over time, as exports become more technology-intensive and energy-efficient, the environmental impact decreases. Munir and Khan (2014) Their results showed that industrial value added and trade openness positively affect CO_2 emissions, while manufactured exports increase energy consumption and manufactured imports have a negative impact.

The ARDL approach, employed by Pesaran et al. (2001), ARDL widely used in time series analysis to examine the long-term and short-term relationship between variables. also used by Chien et al. (2021) and Dogan and Seker (2016), and they successfully utilized ARDL models to explore relationships between economic growth, energy consumption, and CO_2 emissions. This approach is useful particularly for its ability to handle small sample sizes and provide unbiased estimates of long-run relationships.

3. DATA AND METHODOLOGY

This section outlines the variables, and indicators, and data sources used in the study. Table 1 describes the key variables and indicators along with their respective data sources.

Table 1
Variables and indicators of the study and data sources

Variables and Symbols	Indicators
Gross Domestic Product (GDP) Rate	GDP growth (annual %)
Renewable Energy Consumption	Renewable energy consumption (% of total final energy consumption)
Exports	Exports of goods and services (% of GDP)
CO_2 Emissions	CO_2 emissions (metric tons per capita)

Note: Author's Own Estimation
Source: Author's compilation

3.1 Graphical Representation

Figure 6 presents the, Carbon dioxide emissions volatility and independent variables patterns in Pakistan.

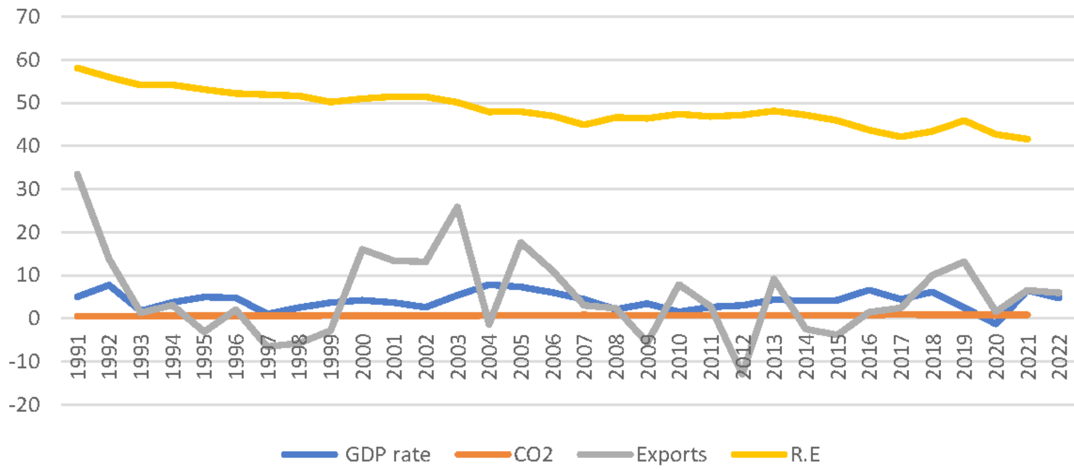

Figure 6
CO_2 Emissions and other Variables

Source: Author's compilation with the help of Excel

3.2 Methodology

3.2.1 Descriptive Statistic

The dataset encompasses key variables including CO_2 emissions, renewable energy consumption, GDP growth rate, and exports. Descriptive statistics offer an initial overview of these variables, detailing their central tendencies and dispersion.

3.2.2 Unit Root Tests

Unit root tests were conducted using the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests to determine the integration order of each variable in the dataset.

3.2.3 Model Specification

The methodology of this study involves applying the Auto-Regressive Distributed Lag (ARDL) model to investigate the determinants of CO_2 emissions from 1991 to 2022. The ARDL model is selected for its suitability in handling small sample sizes and its flexibility in addressing variables with different integration orders, specifically I (0) and I (1). Unlike other cointegration methods, such as Johansen's approach, which necessitate pre-testing for unit roots and can be restrictive, the ARDL model does not require such pre-testing. This characteristic allows it to effectively model the relationships between variables regardless of their integration order. The ARDL approach thus provides a robust framework for analyzing both short-term and long-term dynamics. The general form of the ARDL (p, q) model is as follows:

$$CO_{2t} = \alpha 0 + \sum_{i=1}^{p} \alpha_i CO_{2t-i} + \sum_{j=0}^{q} \beta_j REC_{t-i} + \sum_{k=0}^{q} \gamma_k GDP_{t-k} + \sum_{l=0}^{q} \delta_l EXP_{t-l} + \epsilon_t \qquad (1)$$

Where: is the CO_2 emissions at time t, is the renewable energy consumption at time t-j, is the GDP growth at time t-k, is the exports at time t-l, α0 is the constant term, αi, βj, γk, and δl are the coefficients of the respective lagged variables, and is the error term. The long-run relationship represented by the following equation:

$$CO_{2t} = \beta_0 + \beta_1 \cdot Exports_t + \beta_2 \cdot RE_t + \beta_3 \cdot GDPRate_t + \varepsilon_t \quad (2)$$

Error Correction Model (ECM), ECM for our study is specified as follows:

$$\Delta CO_{2t} = \alpha_0 + \alpha_1 \cdot \Delta RE_t + \alpha_2 \cdot \Delta GDPRate_t + \alpha_3 \cdot CointEq(-1) + v_t \quad (3)$$

The coefficient of CointEq (−1) \{CointEq} (-1) CointEq (−1) (-0.375219) indicates that approximately 37.52% of the deviation from the long-run equilibrium is corrected each period, suggesting a relatively fast adjustment process. This rapid adjustment highlights the resilience of the system in restoring equilibrium after short-term shocks (Narayan, 2005). The ARDL bounds testing approach reveals a significant long-run relationship among the variables. results confirm a robust long-term association among renewable energy consumption, GDP growth, exports, and CO_2 emissions. Additionally, the error correction term (CointEq (-1)) is both significant and negative, suggesting that deviations from the long-term equilibrium are corrected at a rate of approximately 37.52% each period. This indicates a substantial and persistent adjustment process towards equilibrium following short-term shocks. Overall, these findings enhance our understanding of the directional influences between renewable energy consumption, GDP growth, exports, and CO_2 emissions in Pakistan, offering valuable insights into how these factors interact over the long term.

3.2.4 Diagnostic Tests

To ensure the robustness of the estimated models, we conduct several diagnostic tests, including: Serial Correlation, Heteroscedasticity, Cointegration Graph and Model Stability tests.

These tests help confirm the validity and reliability of the model and its estimates.

4. ANALYSIS, RESULTS AND DISCUSSION

4.1 Descriptive Statistics

Table No. 2 provides descriptive statistics, the mean values are 0.704 units for CO_2 emissions, 48.65 units for renewable energy consumption, 4.12% for GDP growth rate, and 5.40% for export growth rate. Median values are similar, except for export growth rate, which is notably lower at 2.92%, indicating a positive skew. The range of values shows that CO_2 emissions vary between 0.506 and 0.918 units, renewable energy consumption between 41.6 and 58.1 units, GDP growth rate from -1.27% to 7.83%, and export growth rate from -12.93% to 33.47%. The standard deviations indicate moderate variability for CO_2 emissions (0.099) and renewable energy consumption (4.13), higher variability for GDP growth rate (2.03), and substantial variability for export growth rate (9.75). Probability values are high for CO_2 emissions (0.719), renewable energy consumption (0.679), and GDP growth rate (0.815), indicating reliable measures, but lower for export growth rate (0.120), suggesting higher uncertainty. The dataset includes 31 observations for CO_2 emissions and renewable energy, and 32 for GDP and export growth rates, providing a robust basis for further analysis. These statistics lay the groundwork for exploring the interrelationships among these key economic and environmental variables.

Table 2
Descriptive Statistics

Variables and Statistics	CO_2	R. Energy	GDP rate	Exports
Mean	0.703968	48.65161	4.122296	5.396538
Median	0.710994	47.90000	4.239015	2.918966
Max	0.918473	58.10000	7.831256	33.46523
Min.	0.505906	41.60000	-1.274087	-12.92572
Std. Dev	0.098723	4.134962	2.027793	9.751152
Probability	0.719161	0.678787	0.814802	0.120248
Observations	31	31	32	32

Source: Author's compilation from EViews output

4.2 Unit Root Tests

Tables 3 and 4summarize the ADF and PP Unit Root Test. the order of integration is mixed, some variables are stationary at level and some at first difference which is supports using the ARDL modeling method The ARDL approach is suitable to effectively capture the relationship among CO_2 emissions, renewable energy consumption, GDP growth rate, and exports.

Table 3
ADF Unit Root Rest

Variables	Probability value at level	Probability value 1st Difference	Level of integration
CO_2 emissions	0.4181	0.0116	1(1)
R. Energy	0.4409	0.0002	1(1)
GDP rate	0.0013	-	1(0)
Exports	0.0002	-	1(0)

Source: Author's compilation from EViews output

Table 4
Phillips-Perron Unit Root Test

Variables	Probability value at level	Probability value 1st Difference	Level of integration
CO_2 emissions	0.4122	0.0009	1(1)
R. Energy	0.4192	0.0000	1(1)
GDP rate	0.0015	-	1(0)
Exports	0.0002	-	1(0)

Source: Author's compilation from EViews output

Table 5 shows the results of the Lag Order Selection Criteria, which indicate that the optimal lag length for the ARDL model is 1.

Table 5
Lag Order Selection Criteria

Lag	LogL	LR	FPE	AIC	SC	HQ
0	-167.2309	NA	2.409428	12.23078	12.42109	12.28896
1	-116.5652	83.23652*	0.205693*	9.754654	10.70623*	10.04556*
2	-105.9172	14.45086	0.326253	10.13694	11.84977	10.66057
3	-83.86393	23.62845	0.262071	9.704566*	12.17866	10.46092

Source: Author's compilation from EViews output

4.3 Estimation Results of ARDL Model for CO_2 Emissions

Table 5 presents ARDL results, The ARDL model estimating the determinants of CO_2 emissions from 1992 to 2022, with 30 adjusted observations, highlights several key findings. The model selected is ARDL (1, 0, 1, 1), based on the Akaike Information Criterion (AIC). The dependent variable, CO_2, exhibits significant persistence, with the coefficient of CO_2 (-1) at 0.625, showing a strong positive autocorrelation. Among the dynamic regressors, EXPORTS shows negative and statistically significant relationship with CO_2, suggesting that higher exports correlate with lower CO_2 emissions, potentially due to technological or efficiency improvements. Conversely, R_E (presumably renewable energy) has a negative effect on CO_2 emissions, while its lagged effect is positive, implying a complex interaction with CO_2. The GDP_RATE has a positive effect on CO_2 emissions in both current and lagged terms, reflecting that economic growth is associated with increased CO_2 emissions. The constant term, C, is also positive and significant. The model explains approximately 97.4% of the variation in CO_2 emissions (R-squared = 0.9739) with a high F-statistic (143.2626) and a very low p-value (0.000), affirming the overall model fit. The Durbin-Watson statistic of 2.417 suggests no significant autocorrelation in the residuals. Overall, the results imply a strong relationship between economic activities, renewable energy, exports, and CO_2 emissions, highlighting the intricate dynamics at play.

Table 6
ARDL Model Results

Variable	Coefficient	Std. Error	t-Statistic	Prob.*
CO_2 (-1)	0.624781	0.144460	4.324935	0.0003
EXPORTS	-0.000936	0.000412	-2.272822	0.0327
R_E	-0.017256	0.002686	-6.424926	0.0000
R_E (-1)	0.008509	0.003964	2.146707	0.0426
GDP_RATE	0.003783	0.001788	2.116071	0.0454
GDP_RATE (-1)	0.005281	0.001626	3.246698	0.0036
C	0.658887	0.275263	2.393669	0.0252
R-squared	0.97394	Mean dependent var		0.71057
Adjusted R-squared	0.96714	S.D. dependent var		0.09319
S.E. of regression	0.01689	Akaike info criterion		-5.12291
Sum squared resid	0.00656	Schwarz criterion		-4.79597
Log likelihood	83.8437	Hannan-Quinn criter.		-5.01832
F-statistic	143.262	Durbin-Watson stat		2.41697
Prob(F-statistic)	0.00000			

Source: Author's compilation from EViews output

Table 7 presents the ARDL long-run form and bounds test analysis, using the dependent variable Δ (CO_2) and the model ARDL (1, 0, 1, 1). This table investigates the relationships among CO_2 emissions, exports, renewable energy consumption, and GDP growth rate over the sample period from 1991 to 2022.The Conditional Error Correction Regression indicates that the CO_2 (-1), exports, R_E (-1), and GDP_RATE (-1) variables significantly impact CO_2 emissions at different levels, reflecting both short-term and long-term effects. The constant term in the model, with a coefficient of 0.658887 (p-value = 0.0252), indicates a persistent baseline level of CO_2 emissions that remains even after accounting for changes in other factors.

The significant negative coefficient for lagged CO_2, at -0.375219 (p-value = 0.0161), suggests that deviations from the long-run equilibrium are corrected at a rate of 37.52% each period, reflecting a relatively rapid adjustment back to equilibrium. An increase in exports, with a coefficient of -0.000936 (p-value = 0.0327), reduces CO_2 emissions, potentially due to the adoption of eco-friendly technologies or a shift to less carbon-intensive goods. Renewable energy usage, both in the short term (-0.017256, p-value = 0.0000) and long term

(-0.008747, p-value = 0.0226), consistently shows a significant negative effect on CO_2 emissions, emphasizing its crucial role in reducing emissions.

Table 7
ARDL Long Run Form and Bounds Test

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	0.658887	0.275263	2.393669	0.0252
CO_2 (-1) *	-0.375219	00.144460	-2.597387	0.0161
Exports**	-0.000936	00.000412	-2.272822	0.0327
R_E (-1)	-0.008747	00.003578	-2.444664	0.0226
GDP_ RATE (-1)	0.009063	0.002186	4.146574	0.0004
D(R_E)	-0.017256	0.002686	-6.424926	0.0000
D(GDP_ RATE)	0.00378	0.00178	2.11607	0.0454

Levels Equation: Case 3: Unrestricted Constant and No Trend

Variable	Coefficient	Std. Error	t-Statistic	Prob.
Exports	-0.002494	0.001524	-1.636845	0.1153
R_E	-0.023312	0.002233	-10.44104	0.0000
GDP_ RATE	0.024155	0.011702	2.064240	0.0505

EC = CO_2 - (-0.0025*EXPORTS -0.0233*R_E + 0.0242*GDP_ RATE). Source: Author's compilation from EViews output

Conversely, GDP growth, with a coefficient of 0.009063 (p-value = 0.0004), is associated with increased emissions, displaying the need for policies that balance economic growth with environmental protection. The levels equation shows that, in the long run, while exports do not significantly affect CO_2 emissions (-0.002494, p-value = 0.1153), renewable energy has a robust negative impact (-0.023312, p-value = 0.0000), and GDP growth continues to increase emissions (0.024155, p-value = 0.0505). These findings underline the necessity of integrating renewable energy and sustainable practices into economic policies to achieve long-term environmental sustainability. Policy recommendations include promoting renewable energy, encouraging sustainable export practices, and decoupling economic growth from carbon emissions through green technologies and energy efficiency measures.

Table 8 displays the results of the Bounds Test, the null hypothesis for this test posits that no long-term relationship exists among the variables. The results indicate a significant long-run relationship between CO_2 emissions, exports, renewable energy consumption, and GDP growth rate. The test statistic value of 7.177494 exceeds the upper bound critical values at all conventional significance levels (10%, 5%, 2.5%, and 1%), with the upper bounds being 3.77, 4.35, 4.89, and 5.61, respectively.

Table 8
F-Bounds Test
Null Hypothesis: No levels relationship

Test Statistic	Value	Signif.	I (0)	I (1)
F-statistic	7.177494	10%	2.72	3.77
K	3	5%	3.23	4.35
		2.5%	3.69	4.89
		1%	4.29	5.61

Source: Author's compilation from EViews output

Table 9 presents the ARDL Error Correction Regression analysis for CO_2 emissions, with the model ARDL (1, 0, 1, 1), spans from 1991 to 2022 and reveals crucial insights into both short-term dynamics and long-term equilibrium adjustments. The significant positive constant term indicates a persistent level of CO_2 emissions. The negative coefficient for D(R_E) suggests that increases in renewable energy consumption immediately reduce CO_2 emissions, emphasizing the effectiveness of renewable energy in mitigating emissions. Conversely, the positive coefficient for D(GDP_RATE) indicates that short-term economic growth increases emissions, highlighting the challenge of balancing economic expansion with environmental sustainability. The highly significant negative error correction term (CointEq (-1)) shows that approximately 37.52% of deviations from the long-term equilibrium are corrected each period, indicating a rapid adjustment back to equilibrium. The model fits well with an R-squared of 0.808672, and diagnostic statistics such as the F-statistic and Durbin-Watson statistic confirm its robustness and lack of autocorrelation issues. These findings underscore the importance of integrating renewable energy and sustainable practices into economic policies to achieve long-term environmental sustainability.

Table 9
ARDL Error Correction Regression

ECM Regression
Case 3: Unrestricted Constant and No Trend

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	0.65888	0.11573	5.69314	0.0000
D(R_E)	-0.01725	0.00228	-7.55164	0.0000
D(GDP_RATE)	0.00378	0.00128	2.93736	0.0074
CointEq (-1) *	-0.37521	0.06586	-5.69690	0.0000
R-squared	0.80867	Mean dependent var		0.01061
Adjusted R-squared	0.78659	S.D. dependent var		0.03439
S.E. of regression	0.01588	Akaike info criterion		-5.32291
Sum squared resid	0.00656	Schwarz criterion		-5.13609
Log likelihood	83.8437	Hannan-Quinn criter.		-5.26314
F-statistic	36.6306	Durbin-Watson stat		2.41697
Prob(F-statistic)	0.000000			

Source: Author's compilation from EViews output

The F-statistic 412164 is provided to assess the overall significance of the regression model, with a corresponding p-value of 0.0041, indicating significant heteroscedasticity (Table 10). the Obs*R-squared value is 16.05299 with a p-value of 0.0135, further confirming heteroskedasticity. However, the Scaled explained SS value of 9.308379 and its p-value of 0.1570 suggest that not all tests uniformly indicate heteroskedasticity.

Table 10
Heteroskedasticity Test: Breusch-Pagan-Godfrey

F-statistic	4.41216	Prob. F (6,23)	0.004
Obs*R-squared	16.0529	Prob. Chi-Square (6)	0.013
Scaled explained SS	9.30837	Prob. Chi-Square (6)	0.157

Source: Author's compilation from EViews output

Table 11 shows the Breusch-Godfrey Serial Correlation LM Test results. The F-statistic is 1.955840 with a p-value of 0.1759, and the Obs*R-squared value is 2.449307 with a p-value of 0.1176. Both p-values are above 0.05, suggesting that there is no significant chance of serial correlation at up to 1 lag. These diagnostic tests indicate that while there is evidence of heteroskedasticity in the model, serial correlation is not a concern. Adjustments for heteroskedasticity, such as using robust standard errors, should be considered to improve model reliability.

Table 11
Breusch-Godfrey Serial Correlation LM Test

Breusch-Godfrey Serial Correlation LM Test: Null hypothesis: No serial correlation at up to 1 lag			
F-statistic	1.955840	Prob. F (1,22)	0.1759
Obs*R-squared	2.449307	Prob. Chi-Square (1)	0.1176

Source: Author's compilation from EViews output

Model Stability Test

Figure 7 presents the results of the CUSUM test.

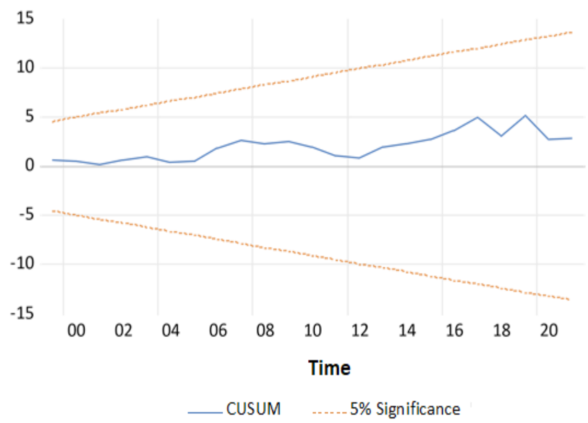

Figure 7
CUSUM graph

Source: Author's compilation from EViews output

Cointegration Graph

Figure 8 presents the cointegration graph, which illustrates the long-term relationship between the variables in the study.

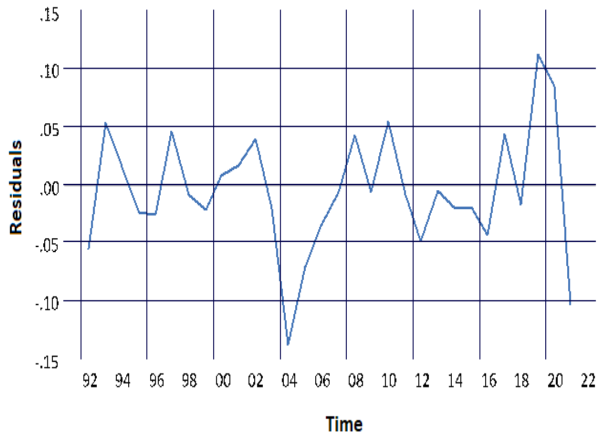

Figure 8
Cointegration graph

Source: Author's compilation from EViews output

The Cusum graph indicate that the ARDL model's coefficients remain stable over time, while the cointegration graph confirms a long-run equilibrium relationship among the variables. These results collectively support the robustness and validity of the ARDL model.

DISCUSSION

The findings not only align with existing literature but also offer new insights into these relationships. The observed positive relationship between GDP growth and CO_2 emissions supports the Environmental Kuznets Curve (EKC) hypothesis, which posits that while economic development initially leads to increased environmental degradation, it ultimately contributes to environmental improvements as economies evolve and adopt more sustainable practices. This trend is well-documented in the literature, with studies such as Munir and Khan (2014) identifying similar patterns in Pakistan. This research analyzed the critical role of renewable energy in mitigating CO_2 emissions, a finding that aligns with the work of Rehman et al. (2021). Their study revealed that positive shocks in renewable energy consumption leads to decrease in CO_2 emissions, while negative shocks have the opposite effect. Our results corroborate this asymmetric impact, further emphasizing that a substantial share of renewable energy in the energy mix is pivotal for long-term environmental sustainability.

The impact of exports on CO_2 emissions, as revealed in this study, underscores the potential of export-led growth strategies to align with sustainable development goals. This finding extends the work of Tahir (2023), who also explored the relationship between economic activities and CO_2 emissions. By integrating exports into our analysis, we provide a more comprehensive understanding of how trade can be leveraged to achieve environmental benefits. This research suggests that export-oriented policies, particularly those promoting green technologies and environmentally friendly products, can significantly contribute to reducing CO_2 emissions.

In the short run, the ECM Model results offer additional insights. The negative and significant coefficient of the ECT confirms the existence of a long-term equilibrium relationship, indicating that deviations from this equilibrium are corrected over time. This adjustment speed is critical for understanding the dynamic interplay between GDP growth, exports, renewable energy share, and CO_2 emissions. The short-run dynamics indicate that GDP growth initially exacerbates CO_2 emissions; however, this effect diminishes as the economy adjusts towards the long-term equilibrium. This observation aligns with the transitional phase outlined in the EKC hypothesis, which suggests that while economic development may initially increase environmental degradation, the negative impact gradually lessens as the economy progresses and adopts more sustainable practices. The short-run results also indicate that increases in renewable energy share quickly leads to reductions in CO_2 emissions, highlighting the immediate benefits of renewable energy adoption. This underscores the importance of policies that not only increase the share of renewable energy in the long run but also provide incentives for rapid adoption in the short run. Our methodological approach, using the ARDL model and F-bounds testing, ensures the robustness of our findings. This approach has been validated by previous studies, including those by Pesaran et al. (2001) and Narayan (2005).

CONCLUSION

This research explores a thorough analysis of the relationship between GDP growth, exports, renewable energy share, and dependent variable CO_2. in Pakistan from 1991 to 2022. by Utilizing the ARDL model and bounds testing approach, our findings reveal a significant long-term equilibrium relationship among these variables. The analysis underscores the pivotal roles of economic growth, trade, and renewable energy in influencing Pakistan's environmental trajectory. The results confirm a positive association between GDP growth and CO_2, thereby supporting the EKC hypothesis. This underscores the need for sustainable economic policies that mitigate environmental degradation while fostering economic development. The significant reduction in CO_2 emissions associated with an increased share of renewable energy emphasizes the importance of integrating renewable energy sources into Pakistan's energy policy. This finding aligns with the global push towards renewable energy adoption as a means to combat climate change. The positive impact of exports on reducing CO_2 emissions suggests that trade policies should be oriented towards promoting sustainable export practices.

Policy Recommendations

Based on these findings, several policy recommendations emerge to mitigate CO_2 emissions in Pakistan:

Incentivize Renewable Energy: Implement subsidies and tax incentives for renewable energy projects to increase the share of renewable energy in the national energy mix. This can involve both large-scale renewable energy plants and decentralized solutions such as solar panels and wind turbines for rural areas.

Promote Energy Efficiency: Introduce regulations and incentives to enhance energy efficiency in industrial, residential, and transportation sectors. This can include mandating energy-efficient building codes, offering rebates for energy-efficient appliances, and promoting public transportation.

Sustainable Trade Practices: Formulate policies that promote the export and production of environmentally friendly products, including support for industries engaged in eco-friendly and green technologies, while ensuring that export activities adhere to strict environmental standards.

Public Awareness Campaigns: Launch public awareness campaigns to educate citizens about the benefits of renewable energy and energy conservation. Behavioral changes driven by increased awareness can significantly reduce household and industrial energy consumption.

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