# Renewable Energy, Financial Growth and Technological Progress: Analyzing the Dynamics of Sectoral Emissions in Pakistan

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## Abstract

*The study examined the role of renewable energy, financial growth, and technical progress in Pakistan's industrial, manufacturing, and service sector emissions. The study collected consistent time series data from 1975 to 2022 and employed the ARDL-Bounds testing approach to estimate the short- and long-term parameter estimates. The study assessed three broad models. The first model linked renewable energy to carbon emissions in the cement industry. Carbon emissions and renewable energy were negatively related. Further, a negative relationship exists between information and communication technologies (ICTs) and carbon emissions, with a one-unit increase in ICT reducing CO2 emissions by 0.135 units. A substantial and positive association was found between GDP per capita and CO2 emissions in Pakistan. At the same time, the square term decreases carbon emissions, supporting a country's environmental Kuznets curve (EKC) hypothesis. In the second model, high technology exports were positively connected with manufacturing CO2 emissions, while energy use's interaction term had a significant negative impact. Manufacturing CO2 emissions were positively correlated with renewable energy in the short and medium term. Financial development is assessed by money supply, which directly affects carbon emissions to support financial-led emissions in a country. The third model used GHG emissions as the dependent variable and focused on the service sector. The interaction term between energy consumption and clean fuel technology (CFT) was negative and significant, although GHG emissions and CFT were positively correlated. Non-renewable energy raised GHG emissions, while renewable energy decreased them.*


**Keywords**: Renewable Energy; Non-renewabel Energy; $CO^2$ Emissions; Technology; Economic Growth; Environmental Kuznets Curve.

## Introduction

Over the past three decades, global carbon dioxide (CO2) emissions have surged by approximately 80.19%, escalating from 20.6 million kilotons in 1990 to 37.12 million kilotons in 2021, as the World Bank (2022) reported. Consequently, there is a growing scientific interest in comprehending the factors behind CO2 emissions in various countries. Governments must explore viable alternatives to fossil fuels, aiming to reduce dependency, minimize geopolitical risks, and address the greenhouse effect, as evidenced by the effectiveness of green energies. Notably, before the Industrial Revolution, CO2 emissions remained relatively low (Androniciano & Georgescu, 2023). Pakistan's industrial output grew by 36.8% in May 2021

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compared to a notable 68.4% growth in the same month the previous year. Due to the nation's fast-paced industrial growth, a significant quantity of energy is required, mostly from conventional sources. However, relying too much on these traditional energy sources contributes to carbon dioxide emissions, which harms Pakistan's people's health and threatens the sustainability of the environment (Abbasi et al., 2022). Human activities, such as the combustion of fossil fuels and the incineration of biomass, contribute to the production of GHGs, which significantly impact air composition and the global climate (Shafiei & Salim, 2014).

Pakistan has considerable potential in renewable energy and is well-versed in operating nuclear power facilities using its resources. The nation's energy resources include wind (131,800 MW), hydro (59,000 MW), and solar (5.3 kWh/m2/day on average). Regarding nuclear energy, Pakistan has successfully operated five nuclear reactors and developed an independent fuel supply for its nuclear plants. In addition, Pakistan has sufficient human resources for the nuclear power industry (Qudrat-Ullah, 2022). Pakistan is a more vulnerable country to climate change. The importance of conserving, preserving, and reestablishing ecosystems and wildlife to meet the temperature targets outlined in the Paris Agreement is emphasized heavily during the Conference of Parties 28. This entails maintaining biodiversity and protecting GHG stores. Furthermore, by 2030, it is pledged to stop and reverse forest degradation and deforestation. It is projected that by taking this measure, world emissions will be reduced by 14%, and the capacity of forests to absorb more carbon will grow).

**Renewable and Non-Renewable Energy and Sectoral Emissions**

Nuclear power substantially contributes to the worldwide energy environment, accounting for 10.4% of total electricity generation, despite obstacles connected to public acceptance. The World Nuclear Association (WNA) reports that there has been a steady rise in nuclear generation worldwide over the past seven years, with an output of 311 TWh higher than in 2012. When compared to renewable energy sources like solar (24.5%), wind (34.8%), and hydropower (39.1%), nuclear power plants have the largest capacity factor—above 80%. This high capacity factor indicates that nuclear power has a promising future in the fight against CO2 emissions (Strike, 2021). Developed and developing nations have contributed to the trend of global CO2 emissions from the industrial and construction sectors, which are expected to return to 2019 levels in the next year. Due to a decline in the use of coal, industrial CO2 emissions fell in 2020 for the second year in a row, except in China. The transport sector continues to be the only one where worldwide CO2 emissions are substantially lower than in 2019. Even if electric car sales hit a record high in 2021, the demand for SUVs will increase simultaneously, negating the beneficial impact of reducing carbon emissions (Voumik et al., 2023). Pakistan is among the nations most susceptible to the deleterious consequences of climate change and atmospheric contamination. Pakistan's air was listed as the second most polluted in 2020 by German Watch, a research organization that made a report in 2019 that ranked Pakistan as the fifth most affected country by climate change over the preceding two decades. The nation must undertake a wide variety of adaptation and mitigation strategies in addition to shifting the energy sector to more carbon-neutral and less polluting options in order to lessen these effects (Butt et al., 2021). One of the most difficult tasks for global sustainable development is reducing carbon dioxide (CO2) emissions, which are exacerbated by economic expansion accompanied by industrialization (Dong et al., 2020). Economic expansion is pleasing but must not come at the cost of environmental pollution. Investigating the link between industrial CO2 emissions and economic growth can help formulate and implement strategies to meet the reduction targets (Meng et al., 2021). The Paris Agreement's approval has made achieving carbon neutrality a top concern for the world. Environmental economists have emphasized the importance of macroeconomic factors in fostering environmental sustainability within each economy. They contend that the large-scale release of carbon into the atmosphere, primarily due to human activities, is to blame for the rise in global temperatures (Li & Ullah, 2022). Around 76% of GHGs in the world are related to human activity, including CO2 emissions, a significant factor in climate change. Earth's temperature has risen by 1.1°C from pre-industrial times, causing catastrophic occurrences such as wildfires in Greece and Algeria, floods in London and Turkey, and droughts in Australia and Northern Nigeria. The world community is concerned about the continued extinction of land and marine species, increasing sea levels, and droughts becoming more frequent. These changes impact food shortages, animal migrations, health concerns, poverty, and displacement (Aminu et al., 2023). The world's significant reliance on non-renewable energy sources causes serious global worries and challenges, such as non-renewable energy source degradation, energy security, and environmental issues. As a result of these main concerns and challenges, governments have been paying attention to renewable energy in recent decades. According to the World Bank, this excessive dependence and attentiveness over time create many concerns regarding the energy industry's future and global socioeconomic and environmental problems (WDI, 2018). Sources of renewable energy and investments in renewable energy technologies have skyrocketed. Since 2004, the cost of renewable energy technology has dropped dramatically (Abbasi et al., 2020).

**Technological Advancement, Financial Development and Sectoral Emissions**

Global energy consumption increased significantly by 44% in the last four decades. Fossil fuel combustion, which is unnecessary, contributes significantly to CO2 emissions, which negatively impacts the environment and causes things like climate change. CO2 emissions have increased by 31% in the last 200 years, which has resulted in a 0.4–0.8 °C increase in average world temperature in the last century. Environmental pollution—caused mainly by CO2 emissions—has become a primary worldwide concern in recent years. Initiatives like the Kyoto Protocol, which went into effect in 2005 to reduce total GHG emissions from industrialized nations, show that governments are becoming increasingly aware of this issue (Qayyum et al., 2021). Economic growth is encouraged by financial development, which also leads the charge for green development and the setting up a low-carbon economy. Three main perspectives have emerged regarding the relationship between financial development and carbon emissions, major economic growth engines. This relationship has received much attention. First, there is the notion that financial development encourages company growth, which raises energy demand and consumption and, ultimately, carbon emissions. Second, some contend that financial development, through stimulating technical innovation, upgrading industries, and promoting economic expansion, can enhance energy efficiency, facilitate energy storage, and lower emissions. Thirdly, there's an opinion that there is no connection between financial progress and carbon emissions (Yang et al., 2023). A stable financial system facilitates smooth resource transfers, improves corporate operations' efficiency, and promotes strong economic growth. According to Yu and Qayyum (2021), the financial industry has a significant role in promoting economic growth and impacting environmental effectiveness. An established financial system actively promotes economic expansion and fosters the conditions necessary for prosperous economies. According to the United Nations Environment Programme (UNEP), climate finance refers to funding from public, private, or alternative channels, with potential application at local, national, or international levels. Sustainable finance incorporates climate finance within its framework, emphasizing environmental, social, and governance considerations in financial decision-making processes within the industry. Climate objectives have seen a 34% rise, reaching approximately $39 trillion (Aminu et al., 2023).

This study is unique in the following ways. First, this study examines the inverted U-shaped relationship between carbon emissions and Pakistan's sectoral growth. Earlier studies were limited to a single sector to verify the EKC hypothesis in a country (Khan et al., 2021; Ibrahim & Ajide, 2021). Second, the current study used non-renewable energy augmented with technology factors to assess Pakistan's carbon emissions at the sectoral level. In contrast, previous studies were limited to finding this relationship between the stated variables (Nain et al., 2017; Shahbaz et al., 2013; Mentel et al., 2022). Finally, this study incorporates the financial sector, clean fuel energy, and insurance coverage in carbon emissions modeling in Pakistan, while very few studies examine this relationship in Pakistan's context (Ali et al., 2023; Imran et al., 2024; Khan & Khan, 2023). The broad objective of the study is to examine the role of renewable energy, non-renewable energy, technology, FDI inflows, insurance, and financial indicators on sectoral emissions in Pakistan. The study is unique in different concepts, as it is the first to use energy-augmented technology in pollution modeling to verify technology-embodied emissions. Further, an inverted U-shaped relationship between sectoral growth and carbon emissions is assessed in Pakistan, which is very limited to the assessment in the previous country-wide literature (Shakoor et al., 2023; Amin et al., 2023). Finally, financial factors were also included in the study to verify the pollution halo/haven hypothesis in Pakistan's sectoral growth, which is less likely to be assessed in the earlier literature (Chishti, 2023; Farooq et al., 2023).

## Literature Review

The global energy mix is changing as the world discusses climate change and environmental issues. This change involves transitioning from nonrenewable to renewable energy sources to lessen carbon emissions, the primary cause of global warming. Understanding the impact of these energy sources on sectoral emissions is critical for climate change. This literature review seeks to synthesize current research on how these energy sources affect emissions across all sectors. Dogan and Ozturk (2017) looked at carbon emissions and nonrenewable and renewable energy in the United States for the period 1980 to 2014. They found that the research variables were cointegrated, and according to the ARDL results, using renewable energy reduces carbon emissions, while nonrenewable energy consumption increases environmental degradation. In the case of the United States of America, they discovered that the EKC assumption was not supported. Narayan and Doytch (2017) explored the link between renewable energy, nonrenewable energy, and economic growth using industrial and residential energy consumers from 1971 to 2011. Renewable energy sources mainly support the neutrality concept. Renewable energy is the only source of economic growth in developing countries. Bekhet and Othman (2018) investigated the function of renewable energy in validating the relationship between $CO_2$ and GDP in the context of Malaysian sustainable development. The findings revealed an inverted N-shaped relationship, indicating that green power energy reduces $CO_2$ emissions in Malaysia. Huang et al. (2021) examined the relationship between renewable energy and environmental degradation in major renewable energy use economies for the period of 2000-2015. The study used 2 step GMM model to find the relation among variables under consideration. According to empirical findings, renewable energy appears to positively impact environmental quality by reducing carbon emissions significantly. A one-percentage-point rise in renewable energy would significantly impact $CO_2$ emissions that cut by 0.5 percentage points. The author recommends that to achieve stable and sustained development, the countries' leaders need to devise policies to attract more international investors and facilitate the adoption of these technologies.

Huang et al. (2023) examined the links between fossil fuel energy consumption, industrial value-added, and carbon emissions in G20 countries from 1990-2020. The link between the variables was analyzed using the CS-ARDL estimator, and the results indicate significant differences between advanced and emerging economies regarding the factors impacting carbon emissions in G20 countries. Empirical results support the EKC theory across the board for advanced economies and the G20. However, in emerging economies, the EKC theory needs more evidence to support it. Halliru et al. (2020) explored the association between FDI, economic growth, and the environment in African countries. Panal data from 1970-2017 were used to measure the relationship among variables. The results confirmed the N-shaped EKC hypotheses between FDI and CO2 emissions in African countries. A comprehensive analysis of the relationship between income, innovation, use of renewable energy, and CO2 emissions in the BRICS economies between 1980 and 2016 was carried out by Khattak et al. (2020). The empirical results highlight how innovation has different effects in each country under study. Interestingly, the research shows that innovation-focused initiatives have only partially reduced carbon dioxide emissions in China, India, South Africa, and Russia, with Brazil being an exception. Moreover, causality estimations suggest a two-way relationship between innovation and CO2 emissions. Nasreen et al. (2020) examined the link between energy, growth, and environment in 18 Asian countries. They used data from 1980 to 2017 for analysis. The study's outcome showed that growth degrades the environmental quality in selected Asian countries. Anser et al. (2021) investigated the linkages between Green energy, Economic growth, and CO2 emissions in South Asian nations. They used panel data from 1985-2019 and confirmed the EKC Hypothesis for South Asian countries. Li et al. (2022) used the FMOLS& DOLS technique to analyze how green bond financing affects renewable energy index constructs in OECD nations using panel data from 2011-2019. Though investing in renewable energy companies may persuade investors to diversify their portfolios, they contended that effective regulation in the renewable energy sector might transform financial uncertainty into economic opportunities. Brigulaur (2023) Investigated the relationship between ICT and CO2 emissions for 34 OECD countries. The study used panel data from 2002 to 2019 and found a negative association between CO2 emissions and ICT. Jahanger et al. (2023) investigated the effects of renewable energy and technology on energy neutrality and energy efficiency in the top 10 manufacturing economies. The study suggests that energy efficiency and integrating renewable energy are crucial factors in reducing GHG emissions in the countries listed. Furthermore, the data shows a strong and positive association between the usage of technology and the decrease in GHG emissions. Furthermore, the results confirm that the EKC theory may be applied to the top 10 manufacturing nations. Jiang et al. (2020) discovered that financial development in eastern China significantly contributes to promoting industrial structure, while the central and western regions show no discernible impact on industrial structure promotion.

Khan et al. (2021) investigated the relationship between environmental parameters in the worldwide panel, considering technological advancement and institutional quality for a panel of 188 economies from 2002 to 2018. They employed static and dynamic GMM to determine the favorable effect of technological advancement, financial development, and the use of nonrenewable energy on carbon emissions, as well as the negative impact of renewable energy and foreign direct investment on carbon emissions. However, according to their findings, institutional qualities hurt carbon emissions. Karimi et al. (2021) examined the relationship between renewable energy, economic growth, and carbon emissions in Iran from 1975 to 2017. They employed a cointegration and NARDL technique, and the results show that renewable energy use and carbon emissions boost economic growth in the long run while decreasing renewable energy has the same effect; however, economic growth boosts renewable energy significantly. Khan et al. (2022) investigated global carbon emissions through commerce, quality institutions, and innovation for 176 world countries from 2000 to 2019. The results revealed that open trade and FDI lowered carbon emissions and that institutional quality indices had a significant impact on them. They also discovered that innovation has an increasing impact on emissions. Szetela et al. (2022) examined the link between renewable energy and CO2 emissions in top natural resource rent-depending countries from 2000 to 2015. The finding reveals that renewable energy has a large negative impact on per capita CO2 emissions.

Further, the study found that countries with a better rule of law, voice, and accountability reduce CO2 emissions faster when they use renewable energy. The link between GDP per capita and CO2 emissions is inverted U-shaped. Awosusi et al. (2022) investigated the relationship between globalization, renewable energy, rents, and CO2 emissions in Colombia from 1970 to 2017. The results show that globalization and renewable energy reduce CO2 emissions. Ping et al. (2023) explored the relationship between Green finance, renewable energy, financial development, FDI, and CO2 nexus under the impact of higher education using panel data for BRICS countries from 2000 to 2019. Panel ARDL was used to analyse the data. The outcomes showed that variables cointegrated. In the long run, all explanatory variables affect emissions, while, in the short run, only economic growth, renewable energy, and higher education influence emissions. The findings also reveal that higher education reduced CO2 emissions in both the short and long run. Amin et al. (2023) explored the relationship between auto transport, renewable energy, and GHG emissions in Pakistan by using PSLM data for the period 2018-2019. STIRPAT model was used to assess the relationship between the variables. They found a positive link between clean energy and GHG emissions. Yang et al. (2023) examined the relationship between carbon emissions and financial development. They found that upgrading the industrial constitution and financial development actively influence carbon emissions. The promotion of urban clustering by the industrial constitution and financial development regarding carbon emissions does not have an indirect influence.
Table 1 provides an overview of critical research that has been done in the field and looks at different aspects of environmental quality and the factors that affect it. The review addresses several factors that are important in influencing environmental results.

**Table 1: Litertaure on Green Power Sources and Economic Development**

| Author(s) | Data period | Countries | Findings |
|---|---|---|---|
| Usman (2023) | 1990-2017 | G-7 | Green power demand decreases carbon emissions |
| Adebayo & Ullah (2024) | 1990-2020 | Sweden | Renewable energy has fulfilled the decarbonization agenda |
| Zakaria and Bibi (2019) | 1984-2015 | South Asia | The pollution haven hypothesis is supported |
| Aminu et al. (2023) | 1995-2019 | Sub Saharan | Support Pollution Heaven hypothesis and EKC |
| Suhrab et al. (2023) | 1985-2018 | Pakistan | Renewable energy is carbon neutral |
| Saud et al. (2019) | 1980-2016 | BRI | Economic growth degrades environmental quality |
| Halliru et al. (2020) | 1970-2017 | African Countries | N-shaped EKC was found between FDI and CO2 emissions |
| Zoaka et al. (2022) | 1980-2018 | BRICS | Economic growth deteriorates environmental quality |
| Wang and Lee (2022) | 2000-2015 | China (27 provinces) | A positive link was found between clean energy and economic growth |
| Nathanial et al. (2020) | 1990-2016 | N 11 | Confirmed EKC hypothesis |
| Anser et al. (2021) | 1985-2019 | South Asian | Confirmed EKC hypothesis |
| Li and Haneklaus (2022) | 1979-2019 | G-7 | EKC exists in the long run |
| Nasreen et al. (2020) | 1980-2017 | 18 Asian | Growth deteriorates environmental quality |
| Perone (2024) | 1965-2020 | 27 OECD | Renewable energy decreases carbon emissions |
| Szetela et al. (2022) | 2000-2015 | 43 resource dependent countries | Carbon emissions can be mitigated through clean energy sources |
| Brigulaur (2023) | 2002-2019 | 34 OECD | ICT exports increase carbon emissions |
| Appiah-Otto & Acheampong (2021) | 2000-2016 | BRICS | Financial development increases carbon emissions |
| Ahmad et al. (2022) | 2005-2019 | USA | Agriculture insurance increases pollution levels |
| Amin et al. (2023) | 2018-2019 PSLM | Pakistan | A positive link was found between GHG emissions and Clean energy |
| Ozkan et al. (2023) | 1990-2019 | USA & EU | Renewable energy decreases GHG emissions |
| Voumik et al. (2023) | 1972-2021 | Kenya | Renewable energy is an environmentally friendly energy source |

Based on the information provided by the literature review, the study identifies the follwoing research gaps, i.e., according to numerous research (Usman, 2023; Adebayo & Ullah, 2024; Suhrab et al., 2023; Perone, 2024; Szetela et al., 2022; Voumik et al., 2023), there is a negative correlation between renewable energy and CO2 emissions. Financial development generally results in a degradation of environmental quality (Zakaria & Bibi, 2019; Saud et al., 2019; Appiah-Otto & Acheampong, 2021). Evidence for the EKC hypothesis can be found in the following studies (Aminu et al., 2023; Nathanial et al., 2020; Anser et al., 2021; Li & Haneklaus, 2022). The Pollution Haven concept is supported by Aminu et al. (2023) and Halliru et al. (2020). However, the results are mixed. It is necessary to perform dynamic research work that looks at several factors simultaneously under one framework, which is performed in this study to make the results more conclsuive. Although Pakistan has been researched in several contexts in the earlier literature, further research focusing on the nation alone is essential for fully understanding the unique impact of factors like financial development and renewable energy on the quality of its environment. Include timeframes that typically span the late 20th century to the present (e.g., 1990-2020, 1980-2017, 2000-2016). A few studies (Perone 2024, which spans 1965–2020, and Nasreen et al. 2020, which spans 1980–2017) feature lengthy periods. Previous studies covered the years 2019–2020. The Current study must incorporate the most recent data, particularly beyond 2020, to account for recent legislative changes, technology breakthroughs, and economic developments. Observing the long-term effects of factors over lengthy periods calls for more longitudinal studies, especially in emerging nations. The following are the research hypotheses of the study are developed based on the literature review, i.e.,

*H1:* Using renewable energy-augmented technology would help move toward cleaner production.

*H2:* An increase in inbound FDI, financial development, and chemicals used in industrial production would likely increase carbon emissions to support the pollution haven hypothesis.

*H3:* Coal and oil energy used would likely increase carbon emissions in Pakistan and

*H4:* The inverted U-shaped relationship between growth-specific factors and emissions will likely verify Pakistan's EKC hypothesis.

These hypotheses are supported by an extensive body of research that highlights the positive environmental effects of financial development, foreign direct investment, and renewable energy technology. By implementing these technologies, industries can attain more environmentally friendly manufacturing processes, thereby supporting the objectives of sustainable development. This study adds to our understanding of the relationship between environmental sustainability and economic growth by testing the EKC hypothesis in the context of Pakistan.

## Data and Methodology

The availability of sectoral data and energy components dictates the selection of the sample size. The study uses time series data for the period 1975-2022 of sectoral CO2 emissions, i.e., CO2 emissions from industries, manufacturing, GHG emissions from the services sector and, human capital, FDI, trade, high export technology, money supply, urban population, population growth, renewable and nonrenewable energy consumption in industries, and services sector to examine the long-run relationship between these variables for Pakistan. The data for variables are collected from WDI (2023). Table 2 lists the main variables used in the research, including the measurement methods for each variable and the expected direction of each variable's correlation with the dependent variable—in this case, CO2 emissions or environmental quality. The expected sign shows whether a positive (+) or negative (-) impact on environmental quality is predicted for the variable.

**Table 2: Variables Description**

| Variables | Measurement | Expected sign | Data source |
|---|---|---|---|
| **Environment Degradation** | CO2 | Dependent variable | WDI (2023) |
| **Greenhouse Gases** | GHG | Dependent variable | WDI (2023) |
| **Economic Growth** | GDPPC | + | WDI (2023) |
| **Renewable Energy Consumption** | REC | - | WDI (2023) |
| **Non-Renewable Energy** | NRE | + | WDI (2023) |
| **Financial Development** | FDI | - | WDI (2023) |
| **Technology** | ICT | - | WDI (2023) |
| **Square GDPPC** | SGDPPC | - | WDI (2023) |
| **Industrial GDP** | IVA | + | WDI (2023) |
| **Money supply** | MS | - | WDI (2023) |
| **Population growth** | PG | + | WDI (2023) |
| **Chemical use** | C Use | + | WDI (2023) |
| **Urban Population** | URB | + | WDI (2023) |
| **Manufacturing value added** | MVA | + | WDI (2023) |
| **High technology Export** | H.T.E | + | WDI (2023) |
| **Clean Fuel Technology** | CFT | - | WDI (2023) |
| **Transport and travel** | TT | + | WDI (2023) |
| **Insurance** | INS | - | WDI (2023) |
| **Service value added** | SVA | + | WDI (2023) |
| **Square of SVA** | SQ SVA | - | WDI (2023) |

This study based on EKC Hypothesis. According to the EKC hypothesis, there is a non-linear association between income and pollution. This is the EKC theory, which might be stated as follows:

E =f (Y ,Y^2 ,Z )

E is for environmental deterioration, Y stands for income, and Z stands for other factors that may have an impact on environmental degradation. The dependent variable CO2 emissions has frequently been employed. Economic development and the EKC hypothesis both frequently integrate economic growth. The study uses the following three different econometrics models

**Model 1: Carbon emissions from cement production**

$CO_{2(i)} = \alpha_{\circ} + \alpha_1$ NRE $_{ind}$ + $\alpha_2$ RE$_{ind}$ + $\alpha_3$ICT + $\alpha_4$ ICT*EU + $\alpha_5$ Ch.use + $\alpha_6$ FDI + α7 PG + $\alpha_8$ GDPPC + $\alpha_9$ SGDPPC+ei (1)

Where

$CO_2$ = carbon emissions from cement production sector

$NRE_{ind}$ = non renewable energy use in cement industries

ICT = information communication technology

ICT *EU = interaction term

CH.use = chemical use in cement industries

FDI = foreign direct investment

PG = Population growth

GDPPC = Gross domestic product per capita

SGDPPC = square of gross domestic product per capita

ei = error term

**Model 2: Carbon emissions from manufacturing sector**

$CO_{2(m)} = \beta_0 + \beta_1 RE + \beta_2 NRE + \beta_3 HTE + \beta_4 HTE*EU + \beta_5 T + \beta_6 UP + \beta_7 MS + \beta_8 MVA + \beta_8 SMVA + \mu i$ (2)

Where

$CO_{2(m)}$ = Carbon emissions from manufacturing sector other than cement

RE = Renewable energy used manufacturing sector

NRE = Non-renewable energy use in the manufacturing sector

HTE = High technology export

HTE* EU = Interaction term

T = Trade

MVA = Manufacturing value added

UP = Urban population

MS = Money supply

SMVA = Square of manufacturing value added

**Model 3: Carbon emissionss from the services sector**

$GHG = \alpha_0 + \alpha_1 NRE_{(s)} + \alpha_2 RE_{(s)} + \alpha_3 CFT + \alpha_4 EU*CFT + \alpha_5 TT + \alpha_6 I + \alpha_7 SVA, + sq\ SVA + Ei$ (3)

Whereas

GHG = Greenhouse gases

$NRE_{(s)}$ = Non-renewable energy use in the service sector

$RE_{(s)}$ = Renewable energy use in service sector

CFT = Clean fuel technology

CFT*EU = Interaction term

TT = Travel & transport

I = Insurance

SVA = Services value added

SSVA = Square of services value added

And

$\alpha_i$ and $B_i$'s are the coefficient of variables

A unit root is a stochastic trend in a time series, sometimes known as a "random walk with drift." If a time series has a unit root, it has a recognisable systematic pattern. Unit root tests are used to determine whether a time series is stationary. If a change in time does not cause a change in the shape of a time series, it is termed stationary; unit roots are one source of non-stationarity. The Augmented Dickey-Fuller (ADF) test is used to identify if a time series dataset is stationary or non-stationary. By including higher-order autoregressive elements in the test equation, it is an extension the Dickey-Fuller test and addresses some of its drawbacks. If there is a unit root in the data, non-stationarity is present. The following autoregressive model serves as the foundation for the ADF test's general form:

$\Delta yt = \rho y(t-1) + \Sigma(\varphi i * \Delta y(t-i)) + \varepsilon t$ (4)

Where

$\Delta yt$ = difference operator

$\Delta y(t-i))$= lag value

$\Phi$ = coefficient

The ADF test's null hypothesis (H0) states that the time series is non-stationary and has a unit root. In other words, the data lacks stable statistical characteristics across time and has a stochastic trend. It is possible that the time series is stationary and devoid of a unit root, which is the alternative hypothesis (H1).

In this study, we employ the ARDL model, which looks at the short- and long-term impacts of different independent variables on dependent variables. The model enables us to comprehend the short- and long-term effects of changes in independent variables on dependent variables, reflecting both the abrupt changes and the slow adjustments towards equilibrium. ARDL (Autoregressive Distributed Lag) regression is employed to look at the long-term relationship between variables in a time series environment. It was developed by Pesaran, Shin, and Pesaran in 2001 and has grown in popularity as a result of the advantages it has over other methods, such as Johansen cointegration.

The ARDL method has the following major benefits:

1. Unlike some other cointegration techniques, such as Johansen, ARDL permits the mixing of variables that are stationary at the level (I(0)) and variables that are stationary at the first difference (I(1)) in the same model.
2. ARDL functions effectively even with finite data sizes, which is helpful when the amount of data that is available is constrained or limited. As a result, many real-world applications can benefit from ARDL, especially when long-time series data may not be easily accessible.
3. The ARDL approach yields unbiased estimates of the long-run connections between variables. When examining the long-term link between economic factors, this is essential for generating accurate and insightful conclusions. In econometrics, ARDL has emerged as a useful technique, especially when working with mixed-order integrated time series data and small sample sizes. It is a common choice for examining long-term correlations among variables due to its adaptability and robustness.

   The mathematical equation for ARDL model is given below:

**Model 1: Carbon emissions from cement production**

$$\Delta CO2 = \alpha_o + \alpha_1 CO2_{t-1} + \alpha_2 NRE_{t-1} + \alpha 3REt_{-1} + \alpha 4ICTt_{-1} + \alpha_5 ICT*EU_{t-1} + \alpha_6 Ch.\ Use_{t-1} + \alpha_7 FDIt_{-1} + \alpha_8 PG_{t-1} + \alpha_9 GDPPC_{t-1} + \alpha_{10}\ SGDPPC_{t-1} + \sum_{i=0}^{k} \alpha_i \Delta CO2 + \sum_{j=0}^{m} \alpha_j \Delta NRE + \sum_{k=0}^{o} \alpha_k \Delta RE + \sum_{l=0}^{p} \alpha_l \Delta ICT + \sum_{m=0}^{Q} \alpha_m \Delta ICT*NRE + \sum_{n=0}^{R} \alpha_n \Delta Ch.\ Use + \sum_{m=0}^{Q} \alpha_o \Delta FDI + \sum_{m=0}^{Q} \alpha_p \Delta PG + \sum_{m=0}^{Q} \alpha_q \Delta GDPPC + \sum_{m=0}^{Q} \alpha_r \Delta SGDPPC + e_i \quad (5)$$

Where $\alpha i$ are parameters and Δ is difference operator shows the short run impact.

The parameters to be estimated are represented by the coefficients $\alpha\ 0$ through $\alpha 9$ , which show the link between CO2 emissions and each independent variable. The size and direction of each independent variable's impact on CO2 emissions are captured by these coefficients, and unobserved factors that affect CO2 emissions but are not included in the model are represented by the error term (ei ).

**Model II: Carbon emissions from manufacturing sector**

$$\Delta CO_{2m} = \alpha_o + \alpha_1 CO2m_{t-1} + \alpha_2 NRE_{t-1} + \alpha 3REt_{-1} + \alpha 4HTEt_{-1} + \alpha_5 HTE*EU_{t-1} + \alpha_6 T_{t-1} + \alpha_7 UPt_{-1} + \alpha_8 MS_{t-1} + \alpha_9 MVA_{t-1} + \alpha_{10}\ SMVA_{t-1} + \sum_{i=0}^{k} \alpha_i \Delta CO_{2m} + \sum_{j=0}^{m} \alpha_j \Delta NRE + \sum_{k=0}^{o} \alpha_k \Delta RE + \sum_{l=0}^{p} \alpha_l \Delta HTE + \sum_{m=0}^{Q} \alpha_m \Delta HTE*NRE + \sum_{n=0}^{R} \alpha_n \Delta T + \sum_{m=0}^{Q} \alpha_o \Delta UP + \sum_{m=0}^{Q} \alpha_p \Delta MS + \sum_{m=0}^{Q} \alpha_q \Delta MVA + \sum_{m=0}^{Q} \alpha_r \Delta SMVA + e_i \quad (6)$$

Where $\alpha$i's are parameters and Δ shows the short run impact of independent variables on $CO_2$ emissions.

**Model III: Carbon emissionss from the services sector**

$$\Delta GHG = \alpha_o + \alpha_1 GHG_{t-1} + \alpha_2 NRE_{t-1} + \alpha 3REt_{-1} + \alpha 4CFTt_{-1} + \alpha_5 CFT*EU_{t-1} + \alpha 6TTt_{-1} + \alpha_7 It_{-1} + \alpha_8 SVA_{t-1} + \alpha_9 Sq\ SVA_{t-1} + \sum_{i=0}^{k} \alpha_i \Delta GHG + \sum_{j=0}^{m} \alpha_j \Delta NRE + \sum_{k=0}^{o} \alpha_k \Delta RE + \sum_{l=0}^{p} \alpha_l \Delta CFT + \sum_{m=0}^{Q} \alpha_m \Delta CFT*NRE + \sum_{n=0}^{R} \alpha_n \Delta TT + \sum_{m=0}^{Q} \alpha_o \Delta I + \sum_{m=0}^{Q} \alpha_p \Delta SVA + \sum_{m=0}^{Q} \alpha_q \Delta Sq\ SVA + e_i \quad (7)$$

Where $\alpha$i's are parameters and Δ shows the short run impact of independent variables on GHGemissions.

## Results and Discussion

Table 3 shows the descriptive statistics of variables used in the study.

**Table 3: Descriptive statistics**

| Methods | CO2 | NRE | RE | ICT | ICT*NRE | C.USE | FDI | PG | GDPPC | SGDPPC |
|---|---|---|---|---|---|---|---|---|---|---|
| **Mean** | 111527.1 | 55.767 | 51.061 | 15.5 | 788.0 | 15.190 | 0.868 | 2.5907 | 2.0965 | 8.274 |
| **Median** | 99837.2 | 58.130 | 51.05 | 14.5 | 823.6 | 15.803 | 0.620 | 2.5586 | 1.9092 | 4.935 |
| **Maximum** | 198738.8 | 62.476 | 58.09 | 37.4 | 1745. | 16.794 | 3.668 | 4.4231 | 5.818 | 33.85 |
| **Minimum** | 59026 | 40.316 | 42.10 | 6.52 | 303.1 | 11.66 | 0.1027 | 1.204 | -2.970 | 0.0009 |
| **Std. Dev.** | 46351.7 | 6.0541 | 4.979 | 6.74 | 318.7 | 1.2812 | 0.771 | 0.8301 | 1.9928 | 8.5129 |
| **Observations** | 43 | 43 | 43 | 43 | 43 | 43 | 43 | 43 | 43 | 43 |

The descriptive statistics summary for CO2 emissions showed that the average CO2 emissions value for the dataset is approximately 111,527.1. The data may be slightly skewed since the mean of 111,527.1 is greater than the median of 99,837.2. The dataset illustrates the range of CO2 emissions with maximum emissions of 198,738.8 and a minimum of 59,026, as shown in the data. The data point dispersion from the mean is indicated by the standard deviation, which is 46,351.7. This suggests that emissions vary across variables. Similarly, a descriptive summary of nonrenewable energy showed that the mean value stands at 55.767 with a standard deviation of 6.0541, which advocates low variation in data for the period. Data for nonrenewable energy has a range of 62.476 – 40.316. Like CO2, the statistics shed light on the statistics of renewable energy. The range of renewable energy is 58.09-42.10, with a mean value of 51.061 and a standard deviation of 4.979. Information and communication technology, or ICT, measures how far technology has advanced. The data illustrates the range, central tendency, and variation in ICT development among the various regions. The FDI dataset's range is 3.667- 0.1027, and the mean and median of the data are 0.868 and 0.620, with a standard deviation of 0.771. The average population growth during the period is 2.59, with a 0.83 standard deviation. The average value of GDPPC is 2.0965, with a standard deviation of 1.9928. The range of the data is 5.818 – (-2.970). The data is normally distributed, as the probability value is greater than 5 percent.Table 4 show steh correlation matrix for Model-I.

**Table 4: Correlation Matrix**

| Variables | CO2 | NRE | RE | ICT | ICT_RE | CH__USE | FDI | PG | GDPPC | SGDPPC |
|---|---|---|---|---|---|---|---|---|---|---|
| **CO2** | 1.00 | 0.79 | -0.95 | 0.29 | 0.07 | 0.22 | 0.25 | -0.90 | 0.03 | 0.14 |
| **NRE** | 0.79 | 1.00 | -0.88 | 0.07 | -0.13 | 0.43 | 0.48 | -0.86 | -0.21 | -0.14 |
| **RE** | -0.95 | -0.88 | 1.00 | -0.10 | 0.13 | -0.24 | -0.41 | 0.91 | 0.02 | -0.07 |
| **ICT** | 0.29 | 0.07 | -0.10 | 1.00 | 0.97 | 0.32 | -0.38 | -0.13 | -0.03 | 0.15 |
| **ICT_NRE** | 0.07 | -0.13 | 0.13 | 0.97 | 1.00 | 0.27 | -0.46 | 0.09 | -0.04 | 0.12 |
| **CUSE** | 0.22 | 0.43 | -0.24 | 0.32 | 0.27 | 1.00 | -0.13 | -0.40 | -0.28 | -0.32 |
| **FDI** | 0.25 | 0.48 | -0.41 | -0.38 | -0.46 | -0.13 | 1.00 | -0.28 | -0.11 | -0.09 |
| **PG** | -0.90 | -0.86 | 0.91 | -0.13 | 0.09 | -0.40 | -0.28 | 1.00 | -0.03 | -0.10 |
| **GDPPC** | 0.03 | -0.21 | 0.02 | -0.03 | -0.04 | -0.28 | -0.11 | -0.03 | 1.00 | 0.82 |
| **SGDPPC** | 0.14 | -0.14 | -0.07 | 0.15 | 0.12 | -0.32 | -0.09 | -0.10 | 0.82 | 1.00 |

The results show a strong positive association between non-renewable energy and CO2 emissions, indicating that CO2 emissions increase in line with non-renewable energy usage. In contrast, a negative correlation exists between CO2 emissions and renewable energy and population growth. Rising renewable energy consumption and population growth could result in falling CO2 emissions. The connections between CO2 emissions and other explanatory variables, such as ICT, energy consumption, FDI, and GDPPC, are weaker. Additionally, the table indicates that the data do not exhibit substantial multicollinearity. Table 5 show sthe unit root estimates.

**Table 5: Unit Root Test**

| **Variable** | **Level** | | | **Ist difference** | **Order of integration** | | |
|---|---|---|---|---|---|---|---|
| | **None** | **Intercept** | **both** | **None** | **Intercept** | **Both** | |
| **CO2** | 3.1799 | 0.4078 | -5.0443 | --------- | ----------- | ----- | **I(0)** |
| **NRE** | 2.7197 | -4.0086 | --------- | -------------- | ---------- | ------- | **I(0)** |
| **RE** | -1.6620 | -0.9971 | -2.5450 | -4.8108 | ------------- | ------ | **I(1)** |
| **ICT** | 0.8951 | -0.0863 | -0.4265 | -6.4541 | -------- | ------ | **I(0)** |
| **C.Use** | 0.5120 | -3.2967 | -------- | -------- | ------- | ------- | **I(0)** |
| **FDI** | -1.8639 | -2.9961 | --------- | -------- | ------ | ------- | **I(0)** |
| **PG** | -1.9902 | --------- | --------- | -------- | ---------- | ------ | **I(0)** |
| **GDPPC** | -3.0517 | --------- | --------- | -------- | ---------- | ------ | **I(0)** |
| **ICT*NRE** | -1.6952 | -5.4163 | --------- | -------- | --------- | ------ | **I(0)** |
| **SGDPPC** | -3.6568 | --------- | --------- | -------- | ---------- | ------ | **I(0)** |

The Augmented Dickey-Fuller (ADF) unit root test results indicate that renewable energy exhibits stationarity after taking the first difference, while all other variables included in the model demonstrate stationarity at their original levels. Consequently, the findings suggest adopting the Autoregressive Distributed Lag (ARDL) technique for analysis. This technique accommodates the mixed order of integration among the variables, allowing for a comprehensive examination of their long-run relationships. Before utilizing ARDL, we check the lag length of the model. Table 6 shows the optimal lag length of the model.

**Table 6: Lag Length Criteria**

| **Lag** | **LogL** | **LR** | **FPE** | **AIC** | **SC** | **HQ** |
|---|---|---|---|---|---|---|
| | | | | | | |
| | | | | | | |
| 0 | -1194.880 | NA | 1.59e+13 | 58.77461 | 59.19256 | 58.92680 |
| 1 | -890.9995 | 444.7026* | 8.71e+08 | 48.82924 | 53.42663* | 50.50336* |
| 2 | -768.2330 | 119.7722 | 7.31e+08* | 47.71868* | 56.49551 | 50.91472 |

* indicates lag order selected by the criterion

Table 6 shows that the optimum lag length for the first model is one. Here is a breakdown of the criteria and selected lag orders: LR criteria Choose lag. 1, FPE determines the suggested two lags, AIC Criterion chooses two lags, SC selects lag 1, and HQ Criterion selects lag 1. As most of the criteria (LR, SC, and HQ) support a lag order of one, it is better to choose one as the ideal lag length. The ARDL Bounds test result shown in table 7.

**Table 7: ARDL Bounds Test Estimates**

| F-Bounds Test | | Null Hypothesis: No levels relationship | | |
|---|---|---|---|---|
| **Test Statistic** | **Value** | **Signif.** | **I(0)** | **I(1)** |
| **F-statistic** | 8.4259 | **10%** | 1.88 | 2.99 |
| **K** | 9 | **5%** | 2.14 | 3.3 |
| | | **2.5%** | 2.37 | 3.6 |
| | | **1%** | 2.65 | 3.97 |

The ARDL bounds test determines if there is a long-term relationship between the variables in a model. The assumption that no long-term link between the variables is the null hypothesis in the ARDL bound test. The ARDL bounds employ the F-statistic test to determine the presence or absence of a long-term relationship. The test's significance is evaluated by comparing these results with crucial values. At the one-percent significance level, the computed test statistic, 8.425, is greater than the upper bound critical value of 3.97. As a result, we can reject the null hypothesis and conclude that there are long-term relations between the variables. Table 8 shows the ARDL long-run estimates for Model –I.

**Table 8: ARDL Long-run Estimates for Model -I**

| **Dependent Variable: CO emissions** | | | | |
|---|---|---|---|---|
| **Variable** | **Coefficient** | **Std. Error** | **t-Statistic** | **Prob.*** |
| **NRE** | 0.562091 | 0.122048 | 4.605483 | 0.0441 |
| **RE** | -2.009527 | 0.115273 | -17.43274 | 0.0033 |
| **ICT** | -0.135804 | 0.008639 | -15.71912 | 0.0040 |
| **ICT*NRE** | -113.5611 | 362.8707 | -0.312952 | 0.7576 |
| **C.USE** | 0.618191 | 0.070606 | 8.755519 | 0.0128 |
| **FDI** | 0.016698 | 0.008352 | 1.999405 | 0.0561 |
| **PG** | 0.055094 | 0.012966 | 4.249061 | 0.0512 |
| **GDPPC** | 6400.773 | 3658.201 | 1.749705 | 0.0955 |
| **SGDPPC** | -2083.216 | 999.7522 | -2.083733 | 0.0502 |
| **C** | 712555.9 | 322512.8 | 2.209388 | 0.0390 |
| **R-squared** | 0.997927 | **Durbin-Watson stat** | | 2.420948 |
| **Adjusted R-squared** | 0.995855 | | | |
| **F-statistic** | 481.4541 | **Prob (F-statistic)** | | 0.000000 |
| **Diagnostic Test Estimates** | | | | |
| Jarque-Bera Normality Test | 1.851 (0.397) | Breusch-Godfrey Test (Autocorrelation) | | 1.232 (0.267) |
| Breusch-Pagan-Godfrey Test (Heteroskedasticity) | 2.340 (0.131) | | | |

The results show a positive coefficient (0.5621), which indicates that a unit rise in non-renewable energy usage is linked with a decrease in CO2 by 0.561. The t-statistic of 4.605 and the relevant probability of 0.0441 indicate that this relationship is statistically significant at 5%. The result implies that the Government of Pakistan has taken various steps to lessen its dependence on non-renewable energy sources in response to environmental concerns. The consumption of non-renewable energy declined due to increased investment in renewable energy sources. Environmental concerns are becoming more widely recognized, which could lead to a shift towards more sustainable energy sources.

Renewable energy negatively impacts carbon dioxide (CO2) emissions, and there is a statistically significant relationship between RE and CO2 emissions at the 1% significance level. Increasing renewable energy sources reduces CO2 emissions, and this association is statistically significant. The results are aligned with Perone's (2024) and Szetela et al.'s (2022) work. In past years, Pakistan had a notable rise in the production and use of renewable energy sources. As a result, Pakistan's energy mix has a larger share of renewable energy. In the production of electricity, the usage of fossil fuels like coal and natural gas is frequently replaced by the development of renewable energy sources. A transition towards renewable energy sources lessens dependency on carbon-intensive energy sources like fossil fuel burning, a major source of CO2 emissions, which reduces CO2 emissions.

The relationship between ICT and CO2 emissions is negative and statistically significant. One unit increase in ICT holds the other variable constant, and CO2 emissions decrease by 0.135 units. The result of the study is consistent with the work of Brigulaour (2023). On the other hand, the interaction between ICT and energy use and CO2 emissions is insignificant. ICT increases the overall efficiency of the organization and reduces waste. Applying smart grids and ICT-enabled energy management systems helps utilities manage electricity distribution better, reducing energy losses and CO2 emissions. Further, CO2 emissions and Chemical use have a positive, statistically significant connection—specifically, CO2 emissions rise by about 0.6182 units for every unit increase in chemical use. The relationship between chemical use and CO2 emissions is positive and significant. Manufacturing, chemicals, textiles, and cement are just a few industries that make up Pakistan's substantial industrial base. Chemicals are used in many industrial processes, and energy consumption, chemical reactions, and combustion can increase CO2 emissions.

A positive correlation between CO2 emissions and FDI, i.e., a unit increase in FDI is correlated with a 0.167 unit increase in CO2 emissions. FDI inflows are frequently accompanied by economic progress and modernization. FDI increases pollution, which supports the pollution heaven hypothesis for Pakistan's economy. Higher emissions may result from industries brought by FDI using energy-intensive procedures or producing goods using fossil fuels. Furthermore, FDI may encourage the expansion of energy and transportation infrastructure, which could increase CO2 emissions. Our findings match the results of Zakirya and Bibi (2019) and Khan et al. (2021).

Population growth and CO2 emissions are positively and significantly associated. The correlation coefficient value of 0.055 shows that for every unit rise in population growth, CO emissions increase by approximately 0.055 units, holding other variables equal. The relationship between GDPPC and CO2 emissions is positive and significant at a 10% level of significance, indicating that any increase in GDPPC leads to an increase in CO2 emissions in Pakistan. Furthermore, the square of GDPPC and CO2 emissions is negatively related. Any increase in SGDPPC lowers the CO2 emissions in Pakistan's economy. This relationship follows the EKC. This inverted U-shaped relationship between GDP per capita (GDPPC or SGDPPC) and CO2 emissions generally shows that as economies grow, emissions rise, peak, and fall.

The R-squared and Adjusted R-squared measures show how well independent variables explain the variations in the dependent variable. The very high R-squared value (0.997) indicates that the independent variables explain around 99.7% of the difference in CO2 emissions between them. By accounting for the quantity of predictors in the model, the Adjusted R-squared provides a more comprehensive assessment of the model's fitting ability. The F-statistic is used to assess the overall significance of a regression model. In this case, the F-statistic is considerably high (481.454), which shows that the model is significant. Table 9 show sthe ARDL short-run results.

**Table 9: Short Run Result**

| ARDL Error Correction Regression | | | | |
|---|---|---|---|---|
| **Variable** | **Coefficient** | **Std. Error** | **t-Statistic** | **Prob.** |
| **D(NRE)** | -1380.426 | 495.1363 | -2.787972 | 0.0114 |
| **D(RE)** | -4082.183 | 843.4265 | -4.839998 | 0.0001 |
| **D(ICT)** | 4230.656 | 2839.663 | 1.489844 | 0.1519 |
| **D(ICT*NRE)** | -81.79909 | 58.62094 | -1.395390 | 0.1782 |
| **D(C.USE)** | -1790.224 | 610.6293 | -2.931769 | 0.0082 |
| **D(FDI)** | 2757.006 | 982.4972 | 2.806121 | 0.0109 |
| **D(PG)** | -2235.481 | 2077.229 | -1.076184 | 0.2947 |
| **D(GDPPC)** | 683.8411 | 276.9960 | 2.468776 | 0.0227 |
| **D(SGDPPC)** | -320.3239 | 78.08776 | -4.102101 | 0.0006 |
| **ECM** | -0.2688 | 0.040001 | -6.719718 | 0.0000 |
| **R-squared** | 0.870843 | **Hetroskedasticity** | | 1.191 |
| **Adjusted R-squared** | 0.827791 | **Autcorrelation** | | 2.589 |
| **F-statistic** | 481.4541 | **Prob(F-statistic)** | | 0.000000 |

The short-run results are presented in the above table. It supports the EKC theory, even within this shorter timeframe. Renewable and non-renewable energy decrease carbon emissions, while FDI inflows and economic growth increase carbon emissions to support the pollution haven hypothesis and the monotonic increasing carbon emissions hypothesis in a country. The ECM (Error Correction Model) value also suggests a tendency towards long-term equilibrium adjustments. These adjustments occur at an annual rate of 26.88%. In other words, the results suggest a consistent pattern in the relationship between environmental degradation and economic growth over time. Furthermore, the transition towards a sustainable equilibrium occurs gradually and relatively steadily. Table 10 shows the lag length selection criteria for Model –II.

**Table 10: VAR lag length selection Criteria for Modle -II**

| Lag | LogL | LR | FPE | AIC | SC | HQ |
|---|---|---|---|---|---|---|
| 0 | -1161.439 | NA | 3.11e+12 | 57.14337 | 57.56131 | 57.29556 |
| 1 | -858.4089 | 443.4588* | 1.78e+08* | 47.23946 | 51.83685* | 48.91358* |
| 2 | -747.8556 | 107.8569 | 2.71e+08 | 46.72467* | 55.50150 | 49.92070 |

* indicates lag order selected by the criterion

Table 10 shows that most of the criteria (LR, FPE, SC, and HQ) imply a lag order 1, showing that the optimal lag length for the model is 1. The AIC criteria suggest a lag order of two. As a result, it is better to conclude that the ideal lag length for model is one, as it is supported by more criteria used to determine the lag length. Table 11 shows the ARDL Bounds estimate for Model –II.

**Table 11: ARDL Bounds Test Estimates**

| F-Bounds Test | | Null Hypothesis: No levels relationship | | |
|---|---|---|---|---|
| **Test Statistic** | **Value** | **Signif.** | **I(0)** | **I(1)** |
| **F-statistic** | 5.9196 | 10% | 1.63 | 2.75 |

| | | | | |
|---|---|---|---|---|
| **k** | 9 | 5% | 1.86 | 3.05 |
| | | 2.5% | 2.08 | 3.33 |
| | | 1% | 2.37 | 3.68 |

Table 11 displays the results of the ARDL bound test, which determines whether a long-term link is present between the variables. The test confirms this by matching the calculated F-statistic with critical values. In this instance, at a one percent significance level, the F-statistic of 5.9196 exceeds the upper bound critical value of 3.68. As a result, the null hypothesis of no long-term association between the variables is rejected, proving that such a relationship exists. Table 12 show sthe ARDL long-run Estimates for Modle -II.

**Table 12: ARDL Long Run Estimates for Modle -II**

| Variable | Coefficient | Std. Error | t-Statistic | Prob.* |
|---|---|---|---|---|
| **RE** | -0.045378 | 0.007550 | -6.010152 | 0.0039 |
| **NRE** | 0.539350 | 0.138253 | 3.901191 | 0.0175 |
| **H_T_E** | 18.79129 | 4.835952 | 3.885748 | 0.0178 |
| **MS** | 0.026055 | 0.010378 | 2.510584 | 0.0660 |
| **H_T_E*NRE** | -0.309006 | 0.079536 | -3.885128 | 0.0178 |
| **MVA** | 0.006106 | 0.002557 | 2.388258 | 0.0753 |
| **SMVA** | -0.000398 | 0.000163 | -2.439660 | 0.0712 |
| **TRADE** | 0.003626 | 0.002015 | 1.799729 | 0.1463 |
| **URB** | -0.083469 | 0.035622 | -2.343179 | 0.0791 |
| **R-squared** | 0.999904 | **Durbin-Watson stat** | | 2.246493 |
| **Adjusted R-squared** | 0.999062 | | | |

Table 12 suggests that renewable energy and CO2 emissions are negatively and significantly correlated, which implies that if all the other variables are held constant, a one-unit increase in renewable energy leads to a decrease in CO2 emissions by 0.045 units. When renewable energy sources generate power, they emit few or no greenhouse gases. For instance, energy from the sun and wind produce electricity without releasing CO2. As a result, Pakistan lowers its CO2 emissions per unit of power produced by increasing its use of renewable energy, which helps lower CO2 emissions overall. Our findings are linked with the work of Adebayo and Ullah (2024) and Usman (2023). Non-renewable energy and CO2 emissions are positively and significantly related to each other. An increase in non-renewable energy by one unit corresponds to a significant increase of 0.539 units in CO2 emissions, holding other variables constant. Similar findings were reported by Huang et al. (2023) and Dogan and Ozturk (2017). Pakistan mostly depends on natural gas and coal for industrial operations and power production. Due to their abundance and low cost, these non-renewable energy sources are appealing for supplying the nation's expanding energy needs. However, burning coal and natural gas results in large atmospheric emissions of CO2, which increases air pollution and contributes to climate change.

CO2 emissions increase by approximately 18.791 units for every unit rise in high-technology export, a statistically significant value. There is a positive correlation between the money supply and CO2 emissions. CO2 emissions increase by 0.026 units for every unit increase in money supply, even though the relationship is not statistically significant at the traditional 5% level but is significant at the 10% significance level. The interaction term between high technology export and energy use hurts CO2 emissions. A one-unit increase in interaction term leads to a decrease in emissions by 0.309 units. This relationship is significant at a 5% level of significance. Manufacturing value added is positively and significantly related to carbon emissions, while its squared term is negatively related to CO2, which verifies the validity of EKC. This inverted U-shaped relationship between manufacturing value added (MVA and SMVA), and CO2 emissions generally show that as economies grow, emissions first increase, reach their highest level, and then decline. Aminu et al. (2023) reported a similar result for Sub-Saharan countries. The coefficient shows that trade openness and the dependent variable have a positive association, which is significant at the 5% level. Pakistan trades mostly less carbon-intensive goods and commodities. For example, Pakistan might export agricultural products, often with smaller carbon footprints than heavy industries like steel manufacturing. Similarly, Pakistan imports more than it exports. Because of the nature of the traded commodities and services, trade openness changes may not substantially impact CO2 emissions. The association between urban population and CO2 Emissions is negative. CO2 emissions decrease by about 0.083469 units for every unit increase in the urban population. This relationship is significant at the 10% level but not statistically significant at the 5% level. Table 13 show sthe ARDL short-run Estimates for Modle –II.

**Table 13: ARDL Short Run Estimates**

| Variable | Coefficient | Std. Error | t-Statistic | Prob. |
|---|---|---|---|---|
| **D(RE)** | -0.045378 | 0.002248 | -20.18855 | 0.0000 |
| **D(NRE)** | 0.321010 | 0.063913 | 5.022647 | 0.0074 |
| **D(H_T_E)** | 11.18399 | 2.210848 | 5.058686 | 0.0072 |
| **D(MS)** | 0.026055 | 0.003381 | 7.705302 | 0.0015 |
| **D(H_T_E*EU)** | -0.184966 | 0.036445 | -5.075170 | 0.0071 |
| **D(MVA)** | 0.005022 | 0.000845 | 5.946190 | 0.0040 |
| **D(SMVA)** | -0.000223 | 4.85E-05 | -4.603432 | 0.0100 |
| **D(TRADE)** | -0.001947 | 0.000608 | -3.200500 | 0.0329 |
| **D(UP)** | 0.053944 | 0.010246 | 5.264791 | 0.0062 |
| **CointEq(-1)*** | -0.803475 | 0.057928 | -13.87034 | 0.0002 |
| **R-squared** | 0.991695 | **Autocorrelation** | | 0.187 |
| **Adjusted R-squared** | 0.975086 | | | |
| **Hetroskedasticity** | 0.9075 | **Normality** | | 0.6725 |

The results show a negative and significant relationship between renewable energy (re) and carbon emissions. One unit increase in RE decreases CO2 emissions by 0.045 units. This relationship between CO2 emissions and RE is significant at the 1% level of significance. Our results match those of Suhrab et al. (2023). Nonrenewable energy (NRE) and CO2 emissions are positively and significantly correlated with each other in the short run. When one unit increase in NRE leads to an increase 0.32 units of CO2 emissions. Similarly, the relationship between high technology export and CO2 emissions is positive, while its interaction term and CO2 has a negative and significant relationship with carbon emissions. This relationship implies that technological advancements and economic activities associated with high-technology exports may contribute to increased carbon emissions. This could be due to increased production processes, energy consumption, and transportation associated with high-tech industries. Manufacturing value-added and CO2 emissions have a direct relationship. However, the square of manufacturing value added and carbon emissions are inversely related. This relation also verifies the validity of the EKC in the short term. Table 14 show sthe ARDL Bounds test estimates for Modle –III.

| Table 14: ARDL Bounds Estimates for Modle -III | | | | |
|---|---|---|---|---|
| **F-Bounds TestNull Hypothesis: No levels relationship** | | | | |
| **Test Statistic** | **Value** | **Signif.** | **I(0)** | **I(1)** |
| **F-statistic** | 7.881395 | 10% | 2.26 | 3.34 |
| **K** | 8 | 5% | 2.55 | 3.68 |
| | | 2.5% | 2.82 | 4.02 |
| | | 1% | 3.15 | 4.43 |

Table 14 shows that the F-statistic (7.881) value is greater than the upper bound critical value at 1% (4.43), so we reject our null hypothesis of no cointegration and conclude that there is a long-run relationship among the stated variables. Table 15 shows the ARDL long-run estimates.

| Table 15: ARDL Long-run Estimates | | | | |
|---|---|---|---|---|
| **Method: ARDL** | | | | |
| Selected Model: ARDL(1, 0, 1, 2, 1, 2, 2, 0, 2) | | | | |
| **Variable** | **Coefficient** | **Std. Error** | **t-Statistic** | **Prob.*** |
| **INSURANCE** | 0.008078 | 0.003007 | 2.686752 | 0.0142 |
| **CFT** | 0.081015 | 0.032425 | 2.498544 | 0.0213 |
| **RE** | -0.021480 | 0.002316 | -9.275998 | 0.0000 |
| **NRE** | 0.028253 | 0.014002 | 2.017817 | 0.0572 |
| **EU_CFT** | -0.000201 | 8.47E-05 | -2.370791 | 0.0279 |
| **SVA** | 0.002193 | 0.001573 | 1.394773 | 0.1784 |
| **SQ_SVA** | 0.000677 | 0.000322 | 2.098360 | 0.0488 |
| **TRANSPORT SERVICES** | 0.000759 | 0.000353 | 2.149833 | 0.0440 |
| **C** | 5.371061 | 2.470897 | 2.173729 | 0.0419 |
| **@TREND** | 0.006126 | 0.004397 | 1.393011 | 0.1789 |
| **R-squared** | 0.999664 | **Adjusted R-squared** | | 0.9993 |
| **F-statistic** | 2974.360 | **Durbin-Watson stat** | | 2.5319 |
| **Prob(F-statistic)** | 0.000000 | | | |
| *Note: p-values and any subsequent tests do not account for model selection. | | | | |

There is a positive and statistically significant relationship between GHG emissions and insurance. The GHG emissions are predicted to grow by 0.008 units for every unit increase in insurance. This relationship is statistically significant at the 5% level, as indicated by the t-statistic of 2.687. Our findings are aligned with the work of Ahmad et al. (2022) and Appiah-Otto (2021). GHG emissions and clean fuel technology are positively correlated. The dependent variable increases by an estimated 0.081 units for every unit increase in clean fuel technology (CFT). This relationship is statistically significant at the 5% level, as indicated by the t-statistic of 2.499. Its interaction term with energy use has a negative and significant impact on GHG emissions. Similar results were reported by Amin et al. (2023).

Renewable energy (RE) and GHG emissions are negatively and significantly associated; however, nonrenewable (NRE) and GHG emissions are positively correlated. One unit increase in RE leads to a decrease in GHG emissions by 0.021 units. The results are significant at a 1% level of significance. According to the NRE coefficient, an increase of one unit is linked to a 0.028 unit rise in the dependent variable. However, the p-value of 0.057 indicates that the finding is only marginally significant at the 5% level. These results match the Ozkan et al. (2023) and Voumik et al. (2023) findings.

Service value-added, and GHG emissions are positively related, but this relationship is statistically insignificant. However, the square of Service value added is positively and significantly related to each other. The service sector utilizes relatively cleaner fuel technologies, leading to a decoupling of economic growth from GHG emissions. Advancements in information technology allow service providers to operate with lower energy consumption and reduced emissions intensity. Table 16 show sthe ARDL short-run estimates for Modle –III.

**Table 16: Short run result**

| ARDL Error Correction Regression | | | | |
|---|---|---|---|---|
| **Selected Model: ARDL(3, 3, 3, 3, 3, 3, 3, 2, 2)** | | | | |
| **Variable** | **Coefficient** | **Std. Error** | **t-Statistic** | **Prob.** |
| **D(INSURANCE)** | -0.009148 | 0.001979 | -4.622712 | 0.0036 |
| **D(CFT)** | 0.074221 | 0.013122 | 5.656240 | 0.0013 |
| **D(RE)** | -0.024099 | 0.001371 | -17.57625 | 0.0000 |
| **D(NRE)** | 0.034392 | 0.006146 | 5.596273 | 0.0014 |
| **D(EU_CFT)** | -0.001684 | 0.000232 | -7.268405 | 0.0003 |
| **D(SVA)** | -0.010045 | 0.001245 | -8.069404 | 0.0002 |
| **D(SQ_SVA)** | 0.001508 | 0.000213 | 7.068220 | 0.0004 |
| **D(TRANSPORT)** | 0.000694 | 0.000292 | 2.379224 | 0.0548 |
| **CointEq(-1)*** | -0.283485 | 0.025440 | -11.14317 | 0.0000 |
| **R-squared** | 0.982410 | **Hetroskedasticity** | | 2.5583 |
| **Adjusted R-squared** | 0.954266 | **Normality** | | 0.2930 |

In the short run, insurance has a negative impact on GHG emissions. One unit increase in insurance decreases GHG emissions by 0.009 units. Clean fuel technology, nonrenewable energy, and transport have positive impacts on GHG emissions. These relationships are statistically significant at 5%. Further, there is a negative link between services value added (SVA) and GHG emissions in the short run, while its square is positively related to GHG emissions. The positive correlation between the square of SVA and GHG emissions and the negative correlation between SVA and GHG emissions can be attributed to technological, regulatory, and economic reasons. The inverse association observed between SVA and GHG emissions may suggest that the relative significance of energy-intensive businesses is diminishing as the service sector expands. Compared to manufacturing, the service sector's emissions intensity is often lower. The error correction term (- 0.2834) indicates how short-term retreats from the long-run equilibrium relationship between variables are corrected. Within the framework of the ARDL model, the error correction term captures the process of adjusting toward long-term equilibrium after short-term fluctuations. Values of the error correction term indicate a 28.34% rate of adjustment.

## Conclusion and Recommendations

This study examines carbon emissions and economic growth at the sectoral level using data from 1975 to 2020 for Pakistan's economy. Similar to Khan et al. (2020) and Wang and Lee (2022), carbon emissions are positively associated with non-renewable energy. Perone (2024) and Szetela et al. (2022) found a negative and statistically significant association between renewable energy and carbon emissions. Further, the results show that ICT significantly negatively influenced $CO_2$ emissions, with a 0.135 unit decline for every unit increase in ICT. GDP per capita (GDPPC) was positively and statistically significantly correlated with $CO_2$ emissions. The EKC hypothesis confirmed that GDPPC squared negatively affects $CO_2$

emissions. High technology exports (HTE) were negatively and statistically significantly associated with energy consumption in the second model, whereas CO2 emissions were positively associated with HTE in the first model. The negative association between $CO_2$ emissions and renewable energy sources persists, but a positive correlation exists between renewable and non-renewable sources. Financial expansion correlated with carbon emissions, whereas trade openness did not. Further, confirmation of the EKC hypothesis in the correlation between industrial value-added and $CO_2$ emissions, with the squared term showing a negative impact. GHG emissions were included in the third model to describe the service sector's environmental impact. Insurance and GHG emissions correlated positively and statistically, supporting Appiah-Otto (2021) and Ahmad et al. (2022). In contrast to renewable energy, Ozkan and Voumik (2022) observed a positive correlation between non-renewable energy and GHG emissions. First, service value added increased GHG emissions but not much. The correlation became positive and statistically significant after computing the square. This shows that greener technology is initially deployed in the service sector's economic boom, reducing emissions.

These findings suggest that policymakers should establish regulations encouraging renewable energy consumption and penalizing non-renewable manufacturers. Cleaner technology adoption, including cleaner fuel technology, ICT exports, and high-tech exports, may improve environmental performance and reduce emissions intensity. Businesses should be financially rewarded for investing in renewable energy and energy efficiency. The government should finance R&D and encourage stakeholders to seek sustainable techniques to minimize industrial emissions. Participating in international treaties and carbon trading mechanisms may assist in maintaining development. Tracking success and finding improvement possibilities requires regular data collection and analysis. Cleaner manufacturing industries need technical help for using green power fuels.

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