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Decoding the Link between Renewable Energy and CO2 Emissions: A VECM Analysis of Growth, Energy Consumption, and Population Influences

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Abstract:
This study investigates the dynamic interplay between carbon dioxide (CO_2) emissions, renewable energy consumption, economic growth, energy use, and population in Pakistan using annual data from 1990 to 2023. Employing a Vector Error Correction Model (VECM), the analysis captures both short-run dynamics and long-run relationships among these variables. The results confirm that all variables are integrated of order one, I(1), and co-integrated, indicating the existence of a long-term equilibrium relationship. Johansen co-integration tests reveal two co-integrating vectors, justifying the application of VECM. The error correction term is statistically significant, suggesting a stable adjustment toward equilibrium aftershocks. Findings highlight that increased renewable energy consumption is associated with reduced CO_2 emissions, while population growth and higher energy use contribute positively to emissions. Economic growth initially raises emissions but may later support reductions through technological advancement, consistent with the Environmental Kuznets Curve (EKC) hypothesis. The results underscore the importance of enhancing renewable energy deployment and energy efficiency to achieve sustainable economic growth while mitigating environmental degradation.

Keywords: CO_2 emissions, renewable energy, economic growth, energy use, population, VECM, Environmental Kuznets Curve, Pakistan, sustainable development

Introduction

The relationship between renewable energy and CO_2 emissions is shaped by various economic and demographic factors. In countries like Pakistan, rising energy needs driven by economic and population growth can increase emissions unless cleaner energy sources are adopted. Renewable energy offers a way to meet this demand while limiting environmental harm. Understanding how these elements interact is key to promoting sustainable development and effective climate policy. To fully grasp the importance of renewable energy, it is essential to understand the root cause of climate change chiefly the rise in atmospheric carbon dioxide. Climate change, driven largely by rising carbon dioxide (CO_2) levels, has become a critical global concern. CO_2 is a key heat-trapping greenhouse gas that results from the extraction and combustion of fossil fuels like coal, oil, and natural gas, as well as from wildfires and natural processes such as volcanic eruptions (NASA, 2025). The carbon in fossil fuels originates from ancient organic matter that absorbed CO_2 through photosynthesis millions of years ago; today, human activity is rapidly releasing this carbon back into the atmosphere, reversing a process that took eons (NOVAA, 2023).

This human-induced acceleration of carbon release is reflected in historical emission trends. Since the mid-20th century, fossil fuel emissions have steadily increased from around 11 billion tons annually in the 1960s to an estimated 36.6 billion tons in 2023 (NOVAA, 2023). This surge in emissions significantly contributes to global warming, as CO_2 absorbs outgoing terrestrial radiation, thereby increasing Earth's temperature. According to Benton (1970), a 10% rise in CO_2 levels can lead to a 0.3°C temperature increase, with projections from earlier decades warning of substantial warming if emission rates persist. This steady rise is especially prominent in densely populated metropolitan areas where energy demand is high.

The effects of this warming are not just theoretical they are already being felt across the globe. The consequences of climate change are far-reaching and threaten various aspects of life on Earth. Shifts in long-term environmental conditions defined as climate affect temperature, humidity, wind patterns, soil composition, and the hydrological cycle over decades (Ahmad et al., 2022). These changes negatively impact agriculture, livestock, rainfall distribution, plant development, and the overall food chain, particularly because plants form the foundation of life on Earth.

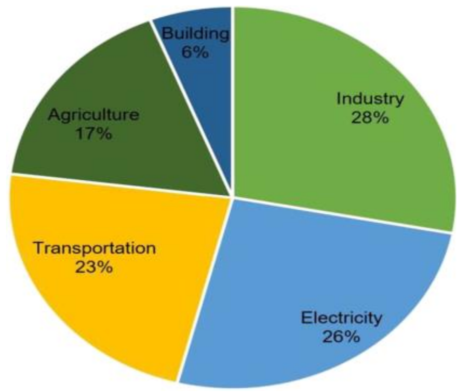
Recognizing the urgency of these threats, the international community has moved to implement policy solutions. In response to this growing crisis, the international community adopted the Paris Agreement, which aims to limit global warming to well below 2°C and preferably to 1.5°C above pre-industrial levels (United Nations, 2023). The agreement sets ambitious targets, including peaking emissions before 2025 and reducing them by 43% by 2030, alongside a longer-term goal of achieving net-zero emissions through a balance of emission reductions and carbon removals (Matemilola and Salami, 2023).

Achieving these targets will hinge on the large-scale deployment of renewable energy technologies. Renewable energy plays a central role in this transition, as it offers a cost-effective, sustainable alternative to fossil fuels, which are both environmentally damaging and finite (Olabi et al., 2022). With declining technology costs and increased awareness of climate risks, many developed nations are aggressively shifting towards renewable, solidifying their importance in the future energy mix (Jie and Rabnawaz, 2024).

However, the adoption of renewable energy is not solely an environmental necessity it also aligns with economic imperatives. Energy is a fundamental driver of economic growth. There exists a positive, often linear, relationship between energy consumption and economic development. Over the past three decades, energy usage in developing countries has more than quadrupled, and this upward trend is expected to continue. Reliable and accessible energy services are essential not only for industrial growth but also for improving living standards. Various production and consumption activities increasingly rely on renewable energy, making it a key engine of sustainable economic development. Inadequate energy supply can hamper GDP growth, which is vital for national progress (Farooqi et al., 2022).

Understanding sector-wise emissions is crucial to targeting mitigation efforts effectively. According to the International Energy Agency (2020), CO_2 emissions are distributed unevenly across major economic sectors. The industrial sector is the largest contributor, accounting for 28% of global emissions. This is followed by the electricity sector at 26%, largely due to ongoing dependence on fossil fuels for power generation. The transportation sector contributes 23%, driven by emissions from vehicles, aviation, and shipping. Agriculture is responsible for 17%, largely from livestock, soil practices, and rice cultivation. Lastly, buildings contribute 6%, mostly through energy use for heating, cooling, and lighting. These figures highlight the need for a comprehensive, cross-sectoral strategy for emissions reduction one that incorporates cleans technologies, energy efficiency, and sustainable practices in all areas of economic activity.

In addition to sectoral dynamics, demographic trends such as population growth further complicate emissions reduction. Population growth also plays a significant role in shaping global emissions. According to Ritchie et al. (2023), each additional person increases carbon emissions, though the magnitude varies greatly depending on income and lifestyle. High-income countries tend to have disproportionately high per capita emissions. For instance, the United States, which comprises just 4% of the global population, accounts for 17% of global energy use and ranks among the highest in per-person carbon output. Conversely, low-income nations contribute far less, underscoring the importance of sustainable development strategies that decouple economic growth from carbon emissions. Similarly, urbanization as stated by Uttara et al. (2012) can exacerbate environmental issues if poorly managed. However, with strategic planning and governance, the negative impacts of urban growth can be minimized, promoting more sustainable urban environments.



Source: International Energy Agency (2020)

Given this context, countries like Pakistan have a critical opportunity to leverage renewable energy for a cleaner, more resilient future. Pakistan, in particular, holds vast untapped potential for renewable energy generation. The country has an estimated capacity of 60,000 MW from hydropower, 40,000 MW from solar energy, and an impressive 346,000 MW from wind power. Despite this potential, only 5.4% of Pakistan's current energy demand is met through renewable sources such as biomass, wind, and solar, with hydropower contributing an additional 25%. To bridge its energy gap and support growing demand, Pakistan has set a target to meet 30% of its energy needs from renewable sources by 2030. By capitalizing on its abundant renewable resources, Pakistan can reduce its energy deficit, advance sustainable development, and mitigate the environmental consequences of fossil fuel dependence. Accelerating efforts in this domain is essential for ensuring a clean, secure, and resilient energy future (Abbas and Aslam, 2023).

This study investigates the dynamic relationships between CO_2 emissions, renewable energy consumption, economic growth, energy use, and population in Pakistan, utilizing a Vector Error Correction Model (VECM) framework. By analyzing both short-run and long-run causal relationships among these variables, the research aims to provide a nuanced understanding of the energy-emission-growth nexus. Notably, this study fills a significant literature gap by offering a comprehensive empirical examination that integrates renewable energy, population, and disaggregated energy use in Pakistan's context. The findings are expected to yield valuable insights for policymakers, emphasizing the importance of sustainable energy policies in shaping Pakistan's environmental future and informing strategies for emerging economies. Ultimately, this research contributes to the development of evidence-based policies that balance economic growth with environmental sustainability.

Literature:

This literature review aims to critically examine existing empirical and theoretical research on the nexus between renewable energy consumption and CO_2 emissions, with a specific focus on how economic growth, total energy consumption, and population dynamics influence environmental sustainability in developing economies, particularly Pakistan.

The Environmental Kuznets Curve (EKC) hypothesis has long served as a theoretical framework for analyzing the relationship between economic development and environmental degradation. Recent studies have underscored the increasingly important role of renewable energy in curbing CO_2 emissions, particularly in the context of growing energy demands and population growth. Leal and Marques (2022) conducted an extensive review of over 200 EKC studies, emphasizing the growing integration of renewable energy consumption into empirical models assessing environmental impacts. Their analysis demonstrates how renewable energy consumption alters the trajectory and turning point of the EKC, enabling the decoupling of economic growth from emissions once a certain level of development is reached. However, they also note that in the early stages of economic growth, energy consumption, particularly from fossil fuels, remains a major driver of CO_2 emissions. As economies mature, renewable energy sources play a crucial role in reversing this trend, with factors such as technological advancement, climate finance, and structural economic shifts acting as mediators of this transition. This theoretical perspective provides a critical foundation for studies employing VECM (Vector Error Correction Model) methodologies, which explore both long-term and short-term dynamics among renewable energy consumption, CO_2 emissions, and economic variables—precisely the aim of the current research.

In a similar vein, Sarkodie and Strezov (2019) conducted a comprehensive meta-analysis of the EKC, validating its theoretical basis in explaining the inverted U-shaped relationship between economic growth and environmental degradation. Their findings highlight that at lower levels of income, economic growth and increased energy consumption—especially from fossil fuels—result in higher CO_2 emissions. However, as economies reach higher income levels, a shift toward renewable energy, cleaner technologies, and more stringent environmental regulations fosters emission reductions. This transition aligns with the EKC framework, where structural economic and energy transitions lead to environmental improvements. Their research further underscores the need to incorporate variables such as renewable energy, economic growth, and population dynamics when modeling the relationship between energy consumption and CO_2 emissions. This insight directly supports the use of VECM models to capture both the short- and long-run causal relationships between renewable energy, CO_2 emissions, and economic development, which is the focus of this study.

Naveed et al. (2021) provide a systematic review of the EKC, noting its evolution from a simple income-emissions model to a more complex one that includes energy types, population, and technological change. They argue that renewable energy adoption plays a key role in emission reductions in advanced economies, supporting the EKC's inverted U-shape. This aligns with the rationale for using econometric tools like VECM to explore the dynamic interactions between CO_2 emissions, renewable energy consumption, economic growth, and population dynamics, as addressed in the present study.

Similarly, Guo and Shahbaz (2021) critically evaluate the EKC hypothesis, questioning its universality across countries and pollutants. They contend that while the EKC may hold true in certain contexts, its validity is heavily influenced by the energy mix, particularly the transition from fossil fuels to renewable energy sources. The authors stress that renewable energy is indispensable for achieving long-term reductions in CO_2 emissions and flattening the EKC curve.

Their findings provide support for employing dynamic models like VECM to examine the joint effects of renewable energy, economic growth, energy consumption, and population on CO_2 emissions over time.

Shahbaz and Sinha (2025) discuss the applicability of the EKC in high-income countries but highlight its limited relevance in developing economies, where emissions continue to rise due to industrialization and increasing energy demands. They argue that factors such as energy consumption patterns, industrial structure, and institutional capacity play significant roles in shaping the relationship between economic growth and emissions. These authors further emphasize that renewable energy can shift the EKC by decoupling emissions from economic growth. Integrating renewable energy into development strategies is seen as essential for mitigating CO_2 emissions while supporting economic progress. This insight is directly relevant to the present study, as it examines how renewable energy adoption can influence CO_2 emissions in Pakistan, a developing economy with high growth and energy consumption rates.

Rehman et al. (2023) find a significant positive relationship between energy use, economic growth, and GDP with CO_2 emissions in China. Their long-run analysis shows p-values of 0.062, 0.000, and 0.100, respectively, indicating a substantial link between these variables and emissions. Both long- and short-run results confirm these associations. These findings are highly relevant to the present study, which investigates how similar dynamics in developing economies, such as Pakistan, can be influenced by renewable energy adoption to mitigate CO_2 emissions.

Husnain et al. (2023) provide key insights into how different energy sources influence economic growth. Their analysis reveals that renewable energy consumption (REC) supports economic development, where a 1% rise in REC leads to a 0.108% increase in economic growth. In contrast, non-renewable energy consumption (NREC) hampers growth, with a 1% increase causing a 0.263% decline in GDP across the full sample of countries. Notably, carbon emissions are also found to contribute positively to economic growth, with a 1% increase associated with a 1.085% rise in output. Although regional patterns vary, NREC demonstrates a positive long-run impact on economic growth within certain income groups. These findings underscore the nuanced role of energy structure in shaping economic outcomes and align closely with the focus of this study on how renewable energy, population, and overall energy consumption influence CO_2 emissions and growth trajectories in developing nations like Pakistan.

Namahoro et al. (2021) provide a comprehensive assessment of the interplay between renewable energy consumption, economic growth, population dynamics, and CO_2 emissions. Their results reveal that while renewable energy consumption significantly reduces CO_2 emissions, both economic and population growth contribute to increased emissions at the regional level. The study further highlights the presence of both symmetric and asymmetric relationships between CO_2 emissions and its determinants, with considerable variation across countries. Additionally, the nature of causality between these variables differs between national and regional contexts. Importantly, the research also identifies a positive link between renewable energy consumption and economic growth at the regional level. These findings are pertinent to the current study, which explores the emissions-growth-energy-population nexus in developing economies such as Pakistan, underscoring the critical role of renewable energy in promoting environmental and economic sustainability.

Jianu et al. (2022) identify a strong positive relationship between greenhouse gas emissions per capita and key economic and consumption indicators, namely real GDP per capita, household final consumption per capita, and waste generation per capita. In contrast, the share of renewable energy in gross final energy consumption shows a weak but negative effect on emissions. Their findings also emphasize that the primary driver of rising emissions is the composition of household energy use, which is largely dependent on environmentally harmful fuels. These insights are closely aligned with the focus of this study on Decoding the Link between Renewable Energy and CO_2

Emissions, as they highlight how economic growth and energy consumption patterns—particularly in residential sectors—interact with emissions levels. The study reinforces the argument that increasing the share of renewable energy, especially in household energy consumption, is critical for reducing CO_2 emissions in developing economies like Pakistan.

Recent literature has increasingly emphasized the complex role of population dynamics and energy use in shaping environmental outcomes. Ahmad et al. (2022) found that trade openness, urbanization, and energy consumption significantly accelerate environmental degradation, suggesting that economic integration and urban growth contributes to higher CO_2 emissions. In the case of Pakistan, Muhammad et al. (2020) identified population density and energy consumption as major drivers of environmental decay, underlining the country-specific implications of demographic pressures. Extending this analysis across income groups, Pickson et al. (2024) observed that population density reduces CO_2 emissions in high- and lower-middle-income nations but intensifies them in low-income countries, pointing to the context-specific nature of the population-emissions relationship. These findings are central to the current study, which seeks to decode how renewable energy, economic growth, total energy use, and population trends jointly affect CO_2 emissions in developing economies like Pakistan.

The literature highlights the complex interplay between renewable energy, CO_2 emissions, economic growth, energy consumption, and population dynamics. While early development stages are associated with higher emissions, the adoption of renewable energy helps decouple growth from environmental degradation in later stages. Evidence from studies on Pakistan and other countries emphasizes that renewable energy plays a key role in reducing CO_2 emissions, though the influence of population factors varies by region and income group. These findings suggest that policies promoting renewable energy, while managing demographic growth, are essential for sustainable development in developing economies like Pakistan.

Methodology:

This study aims to explore the relationship between renewable energy consumption and CO2 emissions in Pakistan using time series data from 1990 to 2023. The dependent variable in this analysis is CO2 emissions from the power industry (denoted as Co2), while the independent variables include renewable energy consumption (RE), population growth (POP), energy use (EU), and GDP per capita (GDP). The analysis is performed using the Vector Error Correction Model (VECM), which is appropriate for assessing the short-run and long-run relationships between integrated variables.

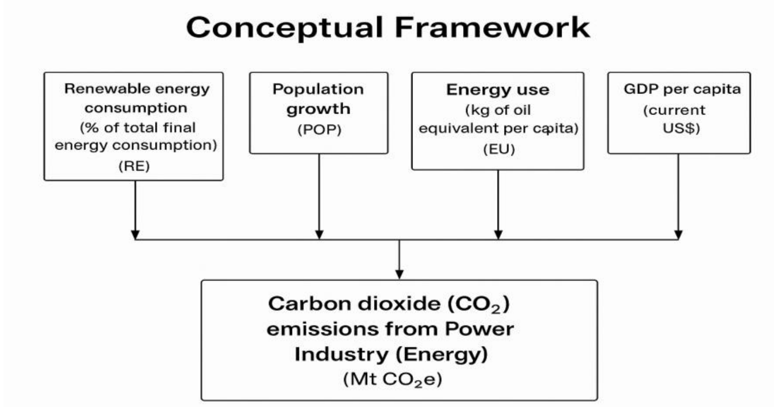
Data Description

This study utilizes annual time series data covering the period from 1995 to 2024 for Pakistan. The variables included in the analysis are as follows:

- **Dependent Variable:**
    - **Co2** (Carbon dioxide emissions from the power industry, Mt CO2e): This measures CO2 emissions resulting from electricity generation in the power sector.
- **Independent Variables:**
    - **RE** (Renewable energy consumption, % of total final energy consumption): This represents the proportion of renewable energy in the country's total energy consumption.
    - **POP** (Population growth, annual %): This measures the annual growth rate of Pakistan's population.
    - **EU** (Energy use, kg of oil equivalent per capita): This represents energy consumption per capita in the country.
    - **GDP** (GDP per capita, current US$): This measures the income level of the country, reflecting its economic activity.

Data for these variables is sourced from reputable databases such as the World Bank and Pakistan's Ministry of Finance.

Conceptual Framework



Source: Author's own

The selection of variables in this study is grounded in their theoretical and empirical relevance to carbon dioxide (CO_2) emissions, particularly from the power industry. CO_2 emissions are used as the dependent variable because the power sector is a primary contributor to environmental degradation in Pakistan, largely due to its reliance on fossil fuels for electricity generation. This proxy for CO_2 emissions has also been used in previous literature, notably by Shahbaz et al. (2012), affirming its suitability for such analyses. Among the independent variables, renewable energy consumption (RE) is included to assess the potential of cleaner energy alternatives in mitigating emissions. The underlying logic is that a higher share of renewable in the energy mix should contribute to lower CO_2 emissions, aligning with global sustainability goals. This variable selection is supported by studies such as Sadorsky (2009) and Apergis and Payne (2010), who examined the role of renewable energy in reducing environmental degradation. Population growth (POP) is another critical factor, as an increasing population drives higher energy demand, infrastructure development, and urbanization—all of which intensify electricity consumption and emissions unless balanced by cleaner technologies. The inclusion of population and energy use per capita (EU) draws support from Dogan and Turkekul (2016), which highlighted these variables as key determinants of environmental impact. EU, in particular, serves as a proxy for industrial and technological advancement, indicating the intensity of energy consumption by individuals. Higher energy use, especially in fossil-fuel-dependent systems, tends to correlate with increased emissions. Lastly, GDP per capita (GDP) is incorporated to capture the scale and structure of economic activity, with the expectation that rising income levels may initially raise emissions through industrialization but could eventually lead to cleaner practices and technologies, as suggested by the Environmental Kuznets Curve (EKC) hypothesis. Together, these variables offer a comprehensive framework to examine both the economic and demographic influences on environmental outcomes in Pakistan, with a specific focus on the transition to renewable energy.

Descriptive Statistics:

Variable	Obs	Mean	Std.Dev	Min	Max
Co2	34	37.23524	11.29826	15.4769	57.4418
RE	34	48.75758	4.399931	41.6	58.1
EU	34	423.6022	27.8036	367.1218	472.5227

POP	34 3.343049	2.32332	.5839948	1.302164
GDP	34 1678.921	918.2593	432.6752	344.4555

This dataset spans 34 years, from 1990 to 2023, providing insights into a country's environmental, energy, demographic, and economic trends. The power industry's CO_2 emissions averaged 37.24 units, with notable fluctuations likely driven by shifts in energy policies or technological advancements. In contrast, renewable energy consumption remained consistently high, accounting for an average of 48.76% of total energy use, underscoring a strong national commitment to sustainable energy sources. Meanwhile, energy use per capita averaged 423.60 kg of oil equivalent, exhibiting moderate variation possibly due to improvements in energy efficiency or changes in the economic structure. The population grew steadily, with an average annual growth rate of 2.32%, indicating stable demographics. Economic performance, measured by GDP per capita, averaged $918.26, with significant variation over the period, ranging from $344.46 to $1,678.92, reflecting substantial economic development and fluctuations. Overall, the data highlights a trajectory of steady population and renewable energy trends alongside evolving patterns in emissions and economic performance.

Stationarity Tests:

To determine the stationarity of variables, the Augmented Dickey-Fuller (ADF) test was employed. Building upon the foundation of the Dickey-Fuller test, the ADF test accommodates more intricate models beyond the simple AR(1) framework. Its key advantage lies in handling larger and more complex time series models, making it an ideal choice for analyzing datasets with nuanced dynamics (santra, 2023). Augmented Dickey Fuller test assumes a AR(p) type time series model and it is represented mathematically as,

$$y_t = \mu + \sum_{i=1}^{p} \varphi_i \, y_{t-1} + \varepsilon_t$$

Subtracting yt-1 from both the side, we get:

$$\Delta y_t = \mu + \delta y_{t-1} + \sum_{i=1}^{p} \beta_i \, \Delta y_{t-1} + \varepsilon_t$$

Unlike the DF test, the ADF test equation includes extra lagged difference terms, making it suitable for analyzing more complex time series data (Santra, 2023). This test examine whether the time series contains a unit root, which would indicate non-stationarity.

ADF Test Results:

Initial Null hypothesis:

$$\mathrm{H_0 = Each\ X_t \sim I(1)}$$

Initial Alternative hypothesis:

$$\mathrm{H_1 = \exists X_t \sim I(0)}$$

Initially we fail to reject the null hypothesis because the entire variables were found non-stationary at level. After that we take 1^{st} difference of variable,

Null hypothesis after 1^{st} difference

$$\mathrm{H_0 = \Delta\, X_t \sim I(1)}$$

Alternative hypothesis after 1^{st} difference

$$\mathrm{H_1 = \Delta X_t \sim I(0)}$$

Variable label	Notation after integration	Order of integration	ADF result	P-value	Critical value at 1%	Critical value at 5%	Critical value at 10%
Co2	L1. D_co2	I(1)	-3.567	0.001	-2.650	-1.950	-1.602
RE	L1. D_re	I(1)	-3.966	0.000	-2.654	-1.950	-1.602
EU	L1. D_eu	I(1)	-3.899	0.001	-2.650	-1.950	-1.602
POP	L1. D_pop	I(1)	-4.091	0.000	-2.650	-1.950	-1.602
GDP	L1. D_gdp	I(1)	-3.652	0.001	-2.650	-1.950	-1.602

The table shows the results of Augmented Dickey-Fuller (ADF) unit root tests for the variables CO_2, RE (Renewable Energy), EU (Energy Use), POP (Population), and GDP. The test is used to determine whether each time series is stationary or not. A non-stationary series can produce misleading results in time series analysis, so it is important to transform it into a stationary one if necessary. From the table, all variables were found to be non-stationary in their original levels but became stationary after taking the first difference. This is indicated by the notation "L1. D_variable" and the order of integration being I(1) for all variables. The ADF test statistics for each variable (ranging from -3.567 to -4.091) are all more negative than the critical value at the 5% significance level (-1.950), and all p-values are well below 0.05. This means that the null hypothesis of a unit root after 1st difference is rejected at conventional levels of significance, confirming that the differenced variables are stationary.

Co-integration test:

Co-integration analysis is employed to assess whether a long-term equilibrium relationship exists among a set of variables. The Johansen co-integration test is particularly suitable when all variables are integrated of the same order, typically I(1) (Research Gate, 2021). In this study, all the variables were found to be non-stationary at level but became stationary after first differencing, confirming they are integrated of order one, I(1). Therefore, the Johansen co-integration test was applied to examine the presence of any long-run equilibrium relationships among the variables.

Johansen Co-integration Test Result:

Trend: Constant				Number of observation: 34	
Time: 1990 to 2023				Number of lag: 04	
Trace Statistics					
Rank	Params	Log Likelihood (LL)	Eigen value	Trace Statistics	Critical Value (5%)
0	80	-244.02388	…	118.2433	68.52
1	89	-212.77559	0.9012	55.7467	47.21
2	96	-196.96076	0.69009	24.117	29.68
3	101	-191.18604	0.34803	12.5676	15.41
4	104	-186.42117	0.29739	3.0379	3.76
5	105	-184.90224	0.10641	…	…
Maximum Eigen value Statistics					
Rank	Params	Log Likelihood (LL)	Eigen value	Max-Eigen Statistics	Critical Value (5%)
0	80	-244.02388	…	62.4966	33.46
1	89	-212.77559	0.9012	31.6297	27.07
2	96	-196.96076	0.69009	11.5494	20.97
3	101	-191.18604	0.34803	9.5297	14.07

4	104	-186.42117	0.29739	3.0379	3.76
5	105	-184.90224	0.10641	…	…

The Johansen co-integration test was conducted using a constant trend assumption with a sample covering the years 1990 to 2023, comprising 34 observations and employing 4 lags. The results of both the Trace and Maximum Eigen-value statistics indicate the presence of co-integrating relationships among the variables. Specifically, the Trace statistic suggests that there are at least two co-integrating vectors, as the test statistics for ranks 0 and 1 (118.24 and 55.75, respectively) exceed the 5% critical values (68.52 and 47.21). Similarly, the Maximum Eigen-value statistic supports this conclusion, with values of 62.50 and 31.63 for ranks 0 and 1, surpassing their corresponding critical thresholds of 33.46 and 27.07. However, for rank 2, both the Trace (24.12) and Maximum Eigen-value (11.55) statistics fall below the 5% critical values, indicating that the presence of more than two co-integrating vectors is not supported. Therefore, it is concluded that there are two long-run equilibrium relationships among the variables, justifying the use of a Vector Error Correction Model (VECM) to analyze both the short-term dynamics and long-term relationships within the system as stated by Enders (2003).

Vector Error Correction Model (VECM)

After confirming co-integration, the study proceeds to estimate the Vector Error Correction Model (VECM). The VECM is suitable for analyzing both the short-run dynamics and the long-run relationships between the dependent and independent variables. The VECM can be written as follows:

$$\Delta Co2_t = \alpha_1 + \beta_1 \Delta RE_t + \beta_2 \Delta POP_t + \beta_3 \Delta EU_t + \beta_4 \Delta GDP_t + \gamma_1 ECM_{t-1} + \varepsilon_t$$

Where:

- Δ represents the first difference operator (change in the variable),
- α_1 is a constant term,
- $\beta_1, \beta_2, \beta_3$ and β_4 are the short run coefficient of the differenced independent variables,
- γ_1 is the coefficient of the error correction term (ECM), which shows the speed of adjustment to long run equilibrium,
- ECM_{t-1} is the lagged error correction term, and
- ε_t is the error term that is also called residual.

The **ECM** captures the deviations from the long-run equilibrium in the previous period and indicates how quickly the system returns to equilibrium after a shock. If the ECM coefficient is statistically significant, it suggests that the system adjusts towards the long-run equilibrium.

VECM Results:

Equation	Parms	RMSE	R^2	Chi^2	Prob > Chi^2
D_co2	17	2.8069	0.7657	35.95294	0.0047
D_re	17	.776462	0.8714	74.53762	0.0000
D_eu	17	65.5627	0.7981	43.47471	0.0004
D_pop	17	5.93881	0.8650	70.48345	0.0000
D_gdp	17	.077823	0.8952	93.98683	0.0000

Vari	Coeffi	Std. Err	z	prob > | z |	95% confi − Interwal lower	95% confi − Interwal Upper
D_Co2						
_Ce1.L1	0.0478995	0.0514093	0.93	0.351	-0.0528609	0.1486599
co2.LD.	-0.7496847	0.2850064	-2.63	0.009	-1.308287	-0.1910825
co2.L2D.	-0.5843128	0.366091	-1.6	0.11	-1.301838	0.1332124

co2.L3D.	-0.6429879	0.3690043	-1.74	0.081	-1.366223	0.0802474
RE						
LD.	0.538532	1.719689	0.31	0.754	-2.831997	3.909061
L2D.	-0.8330052	1.582377	-0.53	0.599	-3.934408	2.268397
L3D.	0.8269053	1.333631	0.62	0.535	-1.786963	3.440773
EU						
LD.	0.0151518	0.2896251	0.05	0.958	-0.552503	0.5828066
L2D.	-0.0234561	0.2851833	-0.08	0.934	-0.5824051	0.5354928
L3D.	0.2755618	0.2522075	1.09	0.275	-0.2187558	0.7698793
POP						
LD.	0.6418035	6.596718	0.1	0.922	-12.28753	13.57113
L2D.	2.054043	7.482696	0.27	0.784	-12.61177	16.71986
L3D.	1.205744	5.748864	0.21	0.834	-10.06182	12.47331
GDP						
LD.	-0.0050649	0.0107432	-0.47	0.637	-0.0261213	0.0159915
L2D.	-0.0033816	0.0107815	-0.31	0.754	-0.02451	0.0177498
L3D.	-0.0280827	0.0163611	-1.72	0.086	-0.0601498	0.0039845
Constant	2.124225	2.556396	0.83	0.406	-2.886219	7.134668
D_re						
_ce1 L1.	-0.0409444	0.0142212	-2.88	0.004	-0.0688174	-0.0130714
co2 LD.	-0.037749	0.0788403	-0.48	0.632	-0.1922732	0.1167752
co2 L2D.	0.1292575	0.1012705	1.28	0.202	-0.069229	0.327744
co2 L3D.	0.1384238	0.1020764	1.36	0.175	-0.0616422	0.3384899
RE						
LD.	0.4709054	0.4757116	0.99	0.322	-0.46147	1.403283
L2D.	0.178769	0.437728	0.41	0.683	-0.67916	1.036699
L3D.	-0.2002597	0.3689176	-0.54	0.587	-0.9233248	0.5228055
EU						
LD.	0.158118	0.080118	1.97	0.048	0.0010892	0.3151459
L2D.	0.0384578	0.0788893	0.49	0.626	-0.1161623	0.1930779
L3D.	-0.0572449	0.0697673	-0.82	0.412	-0.1939862	0.0794965

POP						
LD.	0.0430496	1.824827	0.02	0.981	-3.533546	3.619645
L2D.	0.2330895	2.069912	0.11	0.91	-3.823864	4.290043
L3D.	-0.7450179	1.590288	-0.47	0.639	-3.861925	2.371889
GDP						
LD.	0.0012328	0.0029719	0.41	0.678	-0.0045919	0.0070576
L2D.	0.0096579	0.0029825	3.24	0.001	0.0038124	0.0155034
L3D.	0.0085028	0.0045259	1.88	0.06	-0.0003678	0.0173735
Constant	0.6729955	0.7071668	0.95	0.341	-0.713026	2.059017

The Vector Error Correction Model (VECM) output provides insights into both the short-run dynamics and long-run equilibrium relationships among the variables CO_2 emissions (D_co2), renewable energy consumption (D_re), GDP (D_gdp), energy usage (D_eu), and population (D_pop). The model fit is strong across all equations, with high R-squared values (ranging from 0.77 to 0.90) and statistically significant chi-square statistics, indicating that the explanatory variables jointly have a meaningful impact on each dependent variable. The error correction term (_ce1 L1) is particularly important in understanding how quickly each variable returns to long-run equilibrium after a shock. In this case, the error correction term is statistically significant and negative only in the equation for renewable energy (D_re), with a coefficient of -0.0409 and a p-value of 0.004. This suggests that deviations from the long-run equilibrium are corrected primarily through changes in renewable energy consumption. In contrast, the error correction term is not significant in the CO_2 equation, implying that CO_2 emissions do not significantly adjust back to equilibrium in the short run.

Looking at the short-run dynamics, the CO_2 emissions equation (D_co2) shows a significant negative relationship with its own lagged values. Specifically, the first lag of CO_2 (LD) has a coefficient of -0.7497 and is statistically significant ($p = 0.009$), indicating a self-correcting behavior where increases in CO_2 are followed by reductions in subsequent periods. Other variables such as renewable energy, GDP, energy usage, and population do not have statistically significant short-term effects on CO_2 emissions in this model. In the renewable energy equation (D_re), GDP plays a notable role. The second lag of GDP (L2D) has a positive and statistically significant effect on renewable energy (coefficient = 0.0097, $p = 0.001$), suggesting that economic growth supports renewable energy deployment with a lag. Energy usage (eu) also have a significant and positive short-run effect on renewable energy, as seen with the first lag of EU (coefficient = 0.1581, $p = 0.048$). These results highlight the importance of economic and policy factors in driving renewable energy consumption in the short term.

Overall, the model indicates that renewable energy is the most responsive variable in the system, adjusting both to long-run equilibrium deviations and to changes in GDP and environmental policies. CO_2 emissions, on the other hand, exhibit inertia and are primarily influenced by their own past values, with minimal short-term influence from other variables. This suggests that while policy and economic growth can effectively stimulate renewable energy, their impact on emissions may be more gradual, requiring sustained efforts over time.

Conclusion:

This study uses a Vector Error Correction Model (VECM) to examine the dynamic and long-run relationships between CO_2 emissions, renewable energy consumption, GDP, energy usage, and population. The findings reveal that renewable energy consumption is the most responsive variable, adjusting significantly to correct long-run imbalances and responding positively in the short run to changes in economic growth and energy usage. In contrast, CO_2 emissions exhibit strong inertia, responding primarily to their own past values with limited short-term responsiveness to external variables like renewable energy or policy interventions. The results suggest that renewable energy plays a crucial intermediary role, linking economic growth and environmental regulation to long-term environmental outcomes. However, its effects on emissions are not immediate, indicating that the transition to a lower-carbon future is gradual and path-dependen**t**. In the short term, economic and policy efforts may boost renewable adoption, but reducing emissions requires sustained, long-term strategies that go beyond short-term interventions.

Policy Recommendations:

Based on the findings of this study, four key policy recommendations emerge to effectively link renewable energy expansion with long-term CO_2 emissions reduction. First, governments should prioritize the **strengthening of long-term support for renewable energy development**. The model shows that renewable energy responds positively to both economic growth and environmental regulation, indicating that consistent policy incentives—such as subsidies, tax breaks, and long-term investment commitments—can significantly boost renewable adoption and contribute to the energy transition. Second, **environmental regulations must be reinforced and strategically designed** to stimulate clean energy use. The short-run significance of environmental regulation on renewable energy suggests that strong, enforceable policies—such as emissions caps, carbon pricing, and renewable mandates—are effective levers for influencing energy choices. These policies not only provide clear market signals but also help embed sustainability into institutional and industrial frameworks.

Furthermore, since CO_2 emissions exhibit inertia and are not immediately responsive to renewable energy growth, policymakers should **implement complementary measures that directly target emissions.** These may include phasing out fossil fuel subsidies, enforcing stricter emissions standards, and investing in carbon capture technologies. Such direct interventions are essential to ensure that gains in renewable energy use translate into meaningful reductions in emissions over time. Lastly, it is crucial to adopt a **comprehensive, multi-sectoral strategy for decarburization.** The limited responsiveness of CO_2 emissions to short-run changes highlights the need for a broader policy framework that integrates energy, industry, transportation, and urban planning. Sustainable infrastructure development, energy efficiency improvements, and behavioral change initiatives can work together with energy policy to drive long-term environmental outcomes and support climate targets.

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