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Article

Macroeconomic Drives of Carbon Emissions in Jordan

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Abstract: This study investigates the dynamic relationship between carbon dioxide (CO_2) emissions, economic growth, energy consumption, and population in Jordan using annual data for the period from 1990 to 2022. A Vector Error Correction Model (VECM) is employed to examine both long-run equilibrium relationships and short-run adjustment dynamics. The results confirm the existence of a stable long-run relationship among the variables. Economic growth and energy consumption are found to exert positive and significant effects on CO_2 emissions, with energy consumption emerging as the dominant driver. Population growth also contributes positively to emissions, though to a lesser extent. Short-run dynamics and impulse response analysis reveal that shocks to energy consumption produce the most persistent upward effects on emissions. Overall, the findings underscore the dominant role of fossil-fuel-based energy use in driving emissions in Jordan and highlight the need for policies that promote energy efficiency and renewable energy to support sustainable growth.
Keywords: Carbon dioxide emissions; Energy consumption; Economic growth; VECM; Time-series analysis
JEL Classification: Q53, Q43, C32, O44, Q56.

1. Introduction

The relationship between energy consumption, carbon dioxide (CO_2) emissions, and economic growth has been a central topic in energy economics and environmental policy for several decades. Rapid economic expansion, population growth, and industrialization have significantly increased global energy demand, which remains largely dependent on fossil fuel resources. As a result, CO_2 emissions have risen sharply, intensifying environmental pressures (Zhang & Cheng, 2009; Wang et al., 2016; Acheampong, 2018; Dong et al., 2020). In response, many countries have entered a structural transition phase aimed at reducing reliance on fossil fuels through energy diversification, efficiency improvements, and the adoption of cleaner energy sources.

This transition has brought energy conservation and emissions mitigation policies to the forefront of international policy debates. A key unresolved issue concerns whether such policies hinder economic growth or instead support long-run sustainable development through technological progress, structural change, and efficiency gains. Although a substantial body of empirical literature has examined the nexus between energy consumption, economic growth, and CO_2 emissions, the findings remain mixed and highly context-dependent, offering no definitive consensus on the direction or strength of these relationships (Shahbaz et al., 2013; Bruns et al., 2014; Kalimeris et al., 2014; Destek & Sarkodie, 2019).

Theoretical and empirical literature generally classifies the energy–growth–emissions nexus into four competing hypotheses: neutrality, growth, conservation, and feedback hypotheses (Masih & Masih, 1996; Apergis & Payne, 2009; Narayan & Narayan, 2010). The neutrality hypothesis suggests the absence of causality between energy consumption, economic growth, and CO_2 emissions, implying that energy policies have negligible economic effects. The growth hypothesis posits that energy consumption is a key driver of economic growth, such that reductions in energy use may constrain output. By contrast, the conservation hypothesis assumes causality running from economic growth to energy consumption, indicating that energy-saving policies may be implemented with limited adverse effects on growth. Finally, the feedback hypothesis suggests a bidirectional relationship, where energy consumption and economic growth reinforce each other. Despite extensive empirical testing of these hypotheses, results remain inconclusive and vary across countries, time periods, and econometric methodologies (Squalli, 2007; Bruns et al., 2014).

Moreover, much of the existing literature focuses primarily on long-run equilibrium relationships, often neglecting short-run dynamics and transitional adjustment processes. Ignoring these temporal dynamics may obscure important transmission mechanisms through which economic growth influences energy consumption and emissions, and vice versa. This limitation is particularly relevant for economies undergoing structural change and facing frequent external shocks, where short-run responses may differ substantially from long-run outcomes (Enders, 2004; Lütkepohl, 2013; Acheampong, 2018).

Against this background, this study investigates the dynamic relationship between energy consumption, economic growth, and CO_2 emissions using a Vector Error Correction Model (VECM) complemented by impulse response function analysis. This framework enables the identification of both short-run and long-run causal relationships while capturing the dynamic responses of energy consumption and emissions to economic growth shocks over time (Johansen, 1991; Sims, 1980; Pesaran & Shin, 1998; Narayan & Smyth, 2008).

1.1 Motivation and Contributions

Jordan provides a particularly compelling case for analyzing the energy–growth–emissions nexus due to its structural energy vulnerabilities and evolving development challenges (Hrayshat, 2007; Alnsour et al., 2024). The Jordanian economy is characterized by extreme energy import dependence, with more than 90% of its primary energy supply sourced from abroad (Ministry of Energy and Mineral Resources [MEMR], 2020). This reliance exposes the country to international fuel price volatility, geopolitical risks, and persistent pressures on the trade balance and fiscal sustainability. At the same time, rapid population growth, urbanization, and rising living standards have intensified domestic energy demand, particularly in the residential, transport, and industrial sectors, contributing to a steady rise in CO_2 emissions.

Although Jordan has made notable progress in expanding renewable energy capacity and improving energy efficiency in recent years, fossil fuels continue to dominate the energy mix (Ministry of Energy and Mineral Resources [MEMR], 2020). Consequently, economic expansion and population growth remain closely intertwined with energy consumption and emissions dynamics, consistent with findings from the broader empirical literature (Acheampong, 2018; Dong et al., 2020). This creates a critical policy dilemma: how to sustain economic growth while meeting national and international commitments to emissions reduction and environmental sustainability.

The motivation for this study arises from two key gaps in existing literature. First, despite extensive international research on the energy–growth–emissions nexus, country-specific evidence for Jordan remains limited and fragmented. Many existing studies rely on cross-country panel analyses, which may obscure institutional, structural, and energy-market characteristics unique to small, energy-import-dependent economies such as Jordan (Destek & Sarkodie, 2019). Second, much of the empirical literature emphasizes long-run relationships while paying insufficient attention to short-run dynamics and adjustment mechanisms, which are particularly relevant for economies exposed to external shocks and energy supply disruptions.

This study contributes to the literature in several important ways. First, it provides new country-specific empirical evidence for Jordan using an extended time-series dataset covering the period 1990–2022. Second, it offers a comprehensive analysis of the nexus between energy consumption, economic growth, and carbon dioxide emissions by jointly examining both short-run dynamics and long-run equilibrium relationships within a unified framework. Third, by incorporating impulse response function analysis, it provides deeper insights into the dynamic transmission mechanisms through which economic growth and energy consumption affect emissions over time. Finally, by focusing on a small, energy-import-dependent economy, this study highlights how structural energy constraints shape the trade-off between economic growth and environmental sustainability, offering insights that are particularly relevant for developing economies facing similar challenges.

From a policy perspective, the findings of this study offer important insights for Jordan's energy and environmental strategies. By clarifying the nature and direction of causality among economic growth, energy consumption, and CO_2 emissions, the analysis enables policymakers to assess whether energy conservation and emissions-reduction policies are likely to constrain economic growth or can be implemented without adverse economic effects. Ultimately, the study supports evidence-based policymaking aimed at balancing economic development, energy security, and environmental sustainability.

2. literature Review

A substantial body of empirical research has examined the relationship between energy consumption, economic growth, and CO_2 emissions using a wide range of econometric techniques, time periods, and country samples. Despite the breadth of this literature, empirical findings remain mixed and often contradictory, reflecting differences in countries' development stages, energy structures, institutional settings, and methodological choices. Recent evidence also suggests that the stability of the energy–growth–emissions relationship may vary across contexts and time, which can contribute to continued inconsistency in empirical results (González-Álvarez & Montañés, 2023).

Early country-specific and time-series studies generally document a strong association between energy consumption, economic activity, and environmental degradation. For instance, Apergis and Payne (2009) analyzed six Central American countries over the period 1980–2004 using vector autoregressive (VAR) models, Granger causality tests, and impulse response analysis, and found a reinforcing relationship between energy consumption, economic growth, and CO_2 emissions. Similar evidence was reported by Saatci and Dumrul (2013) for Turkey, where both GDP and energy consumption were found to exert a significant positive impact on emissions, highlighting the emissions-intensive nature of economic growth in energy-dependent economies. More recent evidence continues to emphasize the importance of dynamic interactions between energy use and economic performance in large energy-consuming economies (Ren et al., 2022).

In contrast, other studies suggest that the g the relationship between energy use, economic activity, and environmental outcome may vary depending on structural and technological conditions. For example, Narayan and Narayan (2010) provide panel evidence from developing countries showing that economic growth can be associated with reductions in CO_2 emissions, consistent with the role of cleaner energy use, efficiency improvements, and structural transformation in weakening the emissions impact of growth. Such findings underscore the importance of country-specific energy structures and development pathways. Squalli (2007), focusing on OPEC countries, demonstrated substantial heterogeneity in the relationship across resource-rich economies, emphasizing the role of country-specific energy endowments and policy frameworks.

The direction of causality has also been a central focus in literature. Evidence from China indicates strong dynamic linkages between energy consumption, economic growth, and environmental outcomes. Using time-series techniques, Zhang and Cheng (2009) document a long-run relationship among energy use, GDP, and CO_2 emissions, highlighting the energy-dependent nature of economic growth in China. Country-specific evidence further underscores cross-country heterogeneity; for example, Baranzini et al. (2013) find a causal relationship between energy use and economic growth in Switzerland, reflecting the role of national energy structures and policy frameworks. At the global level, Burke et al. (2015) show that economic expansions are associated with disproportionately rapid increases in emissions-related pressures, whereas contractions lead to more gradual adjustments, pointing to asymmetric and dynamic responses over the business cycle. Recent time-series evidence also confirms that economic growth and energy consumption remain central contributors to climate-related environmental pressures in developing economies (Raza et al., 2023).

Despite these extensive findings, meta-analytical evidence suggests the absence of a universal conclusion. Kalimeris et al. (2014) and Bruns et al. (2014), using meta-analysis techniques, found no robust causal relationship between energy consumption and economic growth across the literature as a whole. These results underscore the sensitivity of empirical outcomes to model specification, sample selection, and country-specific characteristics.

Within this diverse body of research, four dominant hypotheses have emerged to characterize the energy growth emissions nexus (Masih & Masih, 1996). The neutrality hypothesis posits the absence of causality between energy consumption, economic growth, and CO_2 emissions, implying that energy policies have minimal economic consequences. The growth hypothesis suggests that energy consumption drives economic growth, indicating that energy conservation policies may reduce emissions at the cost of lower GDP. By contrast, the conservation hypothesis assumes causality running from economic growth to energy consumption, implying that emissions-reduction policies can be implemented with little or no adverse impact on economic growth. Finally, the feedback hypothesis proposes a bidirectional causal relationship, reflecting mutual dependence between energy use and economic activity.

The coexistence of these competing hypotheses, together with the mixed empirical evidence, highlights the importance of country-specific and dynamically grounded analyses. For economies such as Jordan characterized by high energy import dependence, rising energy demand, and growing environmental pressures understanding both the short-run dynamics and long-run equilibrium relationships among energy consumption, economic growth, and CO_2 emissions is particularly critical. This motivates the use of dynamic econometric frameworks capable of capturing adjustment processes and policy-relevant transmission mechanisms. This motivation is consistent with recent contributions emphasizing dynamic interactions and potential instability in the energy–growth–emissions relationship (Ren et al., 2022; González-Álvarez & Montañés, 2023; Raza et al., 2023)

3. Model, Data, and Methodology

3.1 Research Model

Building on the empirical literature, economic growth and energy consumption are widely recognized as key drivers of carbon dioxide (CO_2) emissions (Wang et al., 2016; Shahbaz et al., 2018). In addition, population growth plays a crucial role in shaping energy demand and emissions through increased residential energy use, transportation needs, and urban expansion. Ignoring demographic factors may therefore bias the estimated relationship between economic activity, energy consumption, and environmental outcomes.

Accordingly, this study specifies a multivariate model that relates CO_2 emissions to economic growth, energy consumption, and population size. To stabilise the variance, reduce heteroscedasticity, and allow for elasticity-based interpretation of coefficients, all variables are transformed into natural logarithms. The baseline long-run relationship is specified as follows:

$$\ln CE_t = \alpha + \beta_1 \ln GDP_t + \beta_2 \ln EC_t + \beta_3 \ln POP_t + \varepsilon_t \quad \ldots\ldots\ldots (1)$$

where ln denotes the natural logarithm, CE represents carbon dioxide emissions, GDP denotes real gross domestic product, EC refers to energy consumption, and POP represents total population. α is the intercept term, β_1, β_2, and β_3 are long-run elasticities to be estimated, ε_t is the error term, and t denotes the time period. A positive coefficient is expected for GDP, EC, and population, reflecting scale and demand effects on emissions.

Given the potential non-stationarity of macroeconomic and energy variables, the empirical analysis proceeds within a Vector Error Correction Model (VECM) framework. This approach enables the simultaneous estimation of both long-run equilibrium relationships and short-run adjustment dynamics among the variables.

3.2 Data and Variable Description

This study employs annual time-series data for Jordan covering the period 1990–2022, subject to data availability. All variables are sourced from the World Bank's World Development Indicators (WDI) to ensure consistency and reliability. Table 1 reports variable definitions, measurement units, data coverage, and sources.

Table 1: Description of Variables

Variable	Symbol	Definition	Unit of Measurement
Carbon Dioxide Emissions	CE	Carbon dioxide emissions from the combustion of fossil fuels and cement production, including emissions from solid, liquid, and gaseous fuels	Kilotons
Gross Domestic Product	GDP	Real gross domestic product measured at constant prices, representing the total value added by resident producers	Constant local currency (JOD)
Energy Consumption	EC	Primary energy consumption before transformation to end-use fuels, including domestic production and net imports	kg of oil equivalent per capita
Population	POP	Total mid-year population, reflecting demographic scale and demand pressure	Total population

The choice of variables is guided by economic theory and the empirical energy–environment literature. Carbon dioxide (CO_2) emissions are used as the dependent variable to capture environmental pressure resulting from economic activity and energy use. CO_2 emissions are the most widely adopted proxy for environmental degradation in energy economics, reflecting the dominant role of fossil fuel combustion in emissions generation (IPCC, 2021).

Economic growth, measured by real GDP, is included to capture the scale effect of economic activity on emissions. Higher income levels typically increase production, consumption, and energy demand, thereby exerting upward pressure on emissions, particularly in energy-import-dependent economies (Grossman & Krueger, 1995; Shahbaz et al., 2013). Energy consumption is incorporated as a key explanatory variable representing the direct emissions channel, as energy use especially from fossil fuels is the primary source of CO_2 emissions. From a production-theoretic perspective, energy is a fundamental input alongside capital and labour, implying a close link between energy use and emissions (Sadorsky, 2014; Wang et al., 2016).

Population is included to capture demographic scale effects not fully reflected by GDP. Population growth raises energy demand through residential consumption, transport, and infrastructure expansion, thereby increasing emissions pressure. In Jordan, where population growth has been amplified by both natural increase and migration flows, excluding population could lead to omitted-variable bias. This specification is consistent with the IPAT and STIRPAT frameworks, which identify population, affluence, and technology as core determinants of environmental impact (Dietz & Rosa, 1997; York et al., 2003).

Table 2 presents descriptive statistics for CO_2 emissions, energy consumption, real GDP, and population over the sample period. The results indicate substantial variation across all variables, reflecting Jordan's economic expansion, demographic growth, and rising energy demand. CO_2 emissions and energy consumption display clear upward trends, accompanied by notable dispersion, consistent with increasing economic activity and energy use. Real GDP exhibits significant variability, capturing long-term growth alongside periods of adjustment, while population shows sustained and accelerating growth over time.

Table 2: descriptive statistics

Statistic	POP	CO_2	EC	GDP
Mean	6,985,542	18,992,202	1,486.75	21,500,563,647
Median	6,427,371	20,790,354	1,565.03	15,056,981,664
Maximum	11,256,263	26,164,846	2,044.91	48,764,963,380
Minimum	3,621,908	9,991,096	865.10	4,160,087,508
Standard Deviation	2,362,037	4,955,521	356.98	15,495,823,598
Skewness	0.522	−0.199	−0.266	0.450
Kurtosis	−1.026	−1.237	−1.383	−1.461
Observations	33	33	33	33

Overall, the descriptive statistics highlight strong scale and demand effects associated with economic growth and population expansion in Jordan. The observed variability in emissions and energy use supports the application of a dynamic econometric framework capable of capturing both short-run adjustments and long-run equilibrium relationships among the variables.

3.3 Methodology

This study employs annual time-series data for Jordan covering the period 1990–2022, determined by the joint availability of all variables. This period is particularly relevant, as it captures major structural changes in the Jordanian economy, including rapid population growth, increasing energy demand, economic liberalization, regional geopolitical shocks, and recent public-health and economic disruptions such as the COVID-19 pandemic.

The econometric analysis follows a structured sequence consistent with best practice in empirical studies examining the energy growth emissions nexus (Johansen, 1991; Enders, 2004; Shahbaz et al., 2018). First, the time-series properties of all variables are examined using unit root tests to determine their order of integration and to ensure that none of the series is integrated beyond the first order. Establishing stationarity is a necessary condition for avoiding spurious regression results and for selecting the appropriate multivariate framework.

Following the stationarity analysis, the optimal lag length is selected based on standard information criteria to capture the underlying data-generating process while preserving degrees of freedom. The Johansen cointegration test is then applied to examine whether a long-run equilibrium relationship exists among carbon dioxide emissions, economic growth, energy consumption, and population. The presence of cointegration implies that these variables move together over time despite short-run deviations.

When one or more cointegrating relationships are identified, a Vector Error Correction Model (VECM) is estimated. The VECM framework allows for the simultaneous modelling of short-run dynamics and long-run equilibrium adjustments, making it particularly suitable for economies such as Jordan that are exposed to frequent external shocks and structural changes. The error-correction term captures the speed at which deviations from long-run equilibrium are corrected over time. To ensure the robustness and reliability of the estimated model, a comprehensive set of diagnostic tests is conducted, including tests for serial correlation, heteroskedasticity, and residual normality. These diagnostics verify that the model satisfies standard econometric assumptions and that inference drawn from the results is valid. The dynamic properties of the system are further explored using impulse response functions, which trace the temporal response of CO_2 emissions and energy consumption to shocks in economic growth and population. Granger causality tests are also employed to identify the direction of causality among the variables. All econometric procedures are implemented using EViews 10, which is widely used in applied macro-energy and environmental economics research.

4. Analysis and Results

4.1 Unit Root Test

Prior to estimating the long-run and short-run relationships among carbon dioxide (CO_2) emissions, economic growth, energy consumption, and population, it is necessary to examine the time-series properties of the variables. Testing for stationarity is a fundamental step in time-series econometric analysis, as non-stationary variables may lead to spurious regression results and unreliable statistical inference (Granger & Newbold, 2014).

This study employs the Augmented Dickey–Fuller (ADF) unit root test due to its widespread use in energy–environment studies and its suitability for relatively small samples (Dickey & Fuller, 1981). The ADF test extends the standard Dickey–Fuller framework by incorporating lagged difference terms to control for serial correlation, which is common in macroeconomic and energy variables. In addition, the test allows for alternative deterministic specifications, ensuring consistency with the underlying data-generating process. The null hypothesis of the ADF test is the presence of a unit root, while rejection indicates stationarity.

The results in Table 3 show that CO_2 emissions, GDP, energy consumption, and population are non-stationary in levels, as the unit-root null cannot be rejected. After first differencing, however, all variables become stationary under the intercept and trend specification, indicating integration of order one, I(1). This common order of integration satisfies the conditions for applying the Johansen cointegration approach and supports the use of a Vector Error Correction Model (VECM) to examine both long-run equilibrium relationships and short-run dynamics. The presence of unit roots at levels is consistent with the behavior of macroeconomic, demographic, and energy variables in developing economies such as Jordan, where structural change and long-term trends are prevalent.

Table 3: Augmented Dickey–Fuller (ADF) Unit Root Test Results

Variable	Level t-statistic	P-value	Trend Assumption	Decision	First Difference t-statistic	P-value	Trend Assumption	Decision
LCO_2	−2.481	0.3333	Intercept & Trend	Can't reject H_0	−5.585	0.0008**	Intercept & Trend	Reject H_0
LGDP	−1.233	0.8798	Intercept & Trend	Can't reject H_0	−4.176	0.0165**	Intercept & Trend	Reject H_0
LEC	−1.241	0.8779	Intercept & Trend	Can't reject H_0	−5.137	0.0021**	Intercept & Trend	Reject H_0
LPOP	−2.102	0.2456	Intercept & Trend	Can't reject H_0	−4.892	0.0006**	Intercept & Trend	Reject H_0

*** significant at 1% level, ** significant at 5% level, * significant at 10% level.

4.2 Co-integration Test

Following the unit root analysis, all variables were found to be integrated of the same order, thereby permitting the application of the Johansen co-integration methodology developed by Johansen (1988) to investigate the presence of long-run equilibrium relationships among the variables. This multivariate approach employs two likelihood-ratio statistics, the trace test and the maximum eigenvalue test, to determine the number of co-integrating vectors within a vector autoregressive (VAR) framework. As reported in Table 4, the trace statistic rejects the null hypothesis of no co-integration at the 1% significance level, as the calculated value exceeds the corresponding critical value, while the null hypothesis of at most one co-integrating equation cannot be rejected. Consistent evidence is provided by the maximum eigenvalue test, which also rejects the null hypothesis of no co-integration at the 1% level but fails to reject the existence of at most one co-integrating vector.

Table 4: Results of the Johansen Co-Integration Test

Unrestricted Co-integration Rank Test (Trace)				
Null hypothesis No. of CE(s)	Trace Statistic	Critical Value	Prob.	Decision
None	44.416	24.275	0.0000***	Reject H_o
At most 1	10.762	12.320	0.0900	Can't Reject H_o
At most 2	0.055	4.129	0.8463	Can't Reject H_o
Unrestricted Co-integration Rank Test (Maximum Eigenvalue)				
Null hypothesis No. of CE(s)	Eigenvalue	Critical Value	Prob.	Decision
None	33.653	17.797	0.0001***	Reject H_o
At most 1	10.706	11.224	0.0616	Can't Reject H_o
At most 2	0.0255	4.129	0.8463	Can't Reject H_o

*** significant at 1% level, ** significant at 5% level, * significant at 10% level. Note: The lag length is 1 and detected according to all vector autoregressive criteria.

The convergence of results from both tests indicates the presence of a single co-integrating relationship among the variables, confirming that they are linked by a stable long-run equilibrium despite being individually non-stationary in levels. This finding suggests that deviations from long-run equilibrium are temporary and that the variables adjust over time to restore balance following short-run shocks. Consequently, the adoption of a Vector Error Correction Model (VECM) is econometrically appropriate, as it allows the simultaneous estimation of short-run dynamics and long-run adjustment mechanisms, with the lag length fixed at one according to all standard VAR lag selection criteria.

4.3 Vector Error Correction Model (VECM)

Given that all variables are stationary at first differences and a cointegrating relationship has been established, the appropriate econometric framework is the Vector Error Correction Model (VECM). The VECM extends the conventional VAR model by incorporating an error correction term (ECT), which captures the long-run equilibrium relationship among the variables while allowing for short-run dynamics. The coefficient of the error correction term, commonly referred to as the speed of adjustment parameter, indicates the extent to which deviations from long-run equilibrium are corrected over time. A negative and statistically significant adjustment coefficient implies convergence towards equilibrium following short-run disturbances (Wang et al., 2016). In this study, the VECM is specified with first-differenced variables, one lag length, and one co-integrating vector, consistent with the Johansen co-integration results. The VECM specification for carbon dioxide emissions is expressed as follows:

$$\Delta LCO_{2t} = \alpha + \sum_{i=1}^{n} \beta_i \, \Delta LGDP_{t-i} + \sum_{i=1}^{n} \rho_i \, \Delta LEC_{t-i} + \sum_{i=1}^{n} \omega_i \, \Delta LPOP_{t-i} + \mu ECT_{t-1} + \varepsilon_t \qquad (2)$$

where Δ denotes the first-difference operator, ln represents the natural logarithm, and α is a constant term. CO_2, GDP, EC, and POP refer to carbon dioxide emissions, gross domestic product, energy consumption, and population, respectively. The parameters β_i, ρ_i, and ω_i capture short-run dynamic effects, while ECT_{t-1} is the lagged error correction term derived from the long-run co-integrating relationship. The coefficient μ measures the speed at which the system adjusts back to long-run equilibrium following short-run shocks, and ε_t represents a white-noise error term. The estimated VECM results are reported in Table 5.

Table 5: Vector Error Correction Model (VECM) Results

Long-run Relationship	
Variable	Coefficient
CO_2 (-1)	1.0000
GDP (-1)	1.1369*
EC (-1)	1.3687**
POP (-1)	0.1366***
C	-10.7271
ECT	-0.045***
Short-run Relationship	
Variable	Coefficient
D(CO_2 (-1))	0.0236*
D(GDP (-1))	0.2512**
D(EC (-1))	0.8124*
D(POP (-1))	0.7026**

Note: ***, **, * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

The Vector Error Correction Model (VECM) results reported in Table 5 reveal strong and economically meaningful long-run and short-run relationships between CO_2 emissions, economic growth, energy consumption, and population, in line with environmental economic theory and prior empirical evidence. In the long run, economic growth exerts a positive and more-than-proportional effect on emissions, as reflected by a GDP elasticity of 1.1369, indicating that a 1% increase in output raises CO_2 emissions by approximately 1.14%. This result suggests that economic expansion remains closely tied to carbon-intensive production structures, a pattern widely documented in developing and energy-import-dependent economies where growth is driven by fossil-fuel-based industrialisation. Energy consumption displays an even stronger long-run elasticity of 1.3687, implying that a 1% increase in energy use leads to a 1.37% rise in emissions, confirming that energy use is the dominant transmission channel through which economic activity translates into environmental degradation. This finding is consistent with the energy–environment literature, which emphasises the central role of fossil-fuel-dominated energy systems in amplifying the environmental costs of growth. Population growth also contributes positively to emissions in the long run, although with a smaller elasticity of 0.1366, indicating that a 1% increase in population raises CO_2 emissions by about 0.14%. This modest but statistically significant effect aligns with the STIRPAT framework, suggesting that population growth increases aggregate energy demand and consumption pressures, even if its impact is less pronounced than that of income and energy use. The error correction term is negative and highly significant (–0.045), confirming the existence of a stable long-run equilibrium relationship and indicating that approximately 4.5% of deviations from equilibrium are corrected each period, which implies a slow adjustment process. Such gradual convergence reflects technological inertia, rigid energy infrastructure, and delayed policy responses, as documented in earlier VECM-based studies of the energy growth environment nexus.

In the short run, lagged changes in CO_2 emissions exhibit a small but significant persistence effect (0.0236), suggesting limited short-term inertia in emissions dynamics. Short-run changes in GDP positively affect emissions, with a coefficient of 0.2512, indicating that temporary economic expansions increase emissions, though to a lesser extent than in the long run, as production structures adjust only gradually. Changes in energy consumption have a large and immediate impact on emissions in the short run, as reflected by a coefficient of 0.8124, highlighting the rapid transmission of energy demand shocks into environmental outcomes. Population growth also has a positive and significant short-run effect on emissions (0.7026), suggesting that increases in population place immediate pressure on energy demand, transportation, and residential consumption. From a policy perspective, the more-than-proportional long-run elasticities of GDP and energy consumption indicate that economic growth remains fundamentally carbon-intensive, implying that growth-oriented development strategies will continue to exacerbate emissions in the absence of structural change. The dominant role of energy consumption underscores the urgency of accelerating the transition towards renewable energy, improving energy efficiency across sectors, and reducing reliance on fossil fuels through effective pricing and regulatory instruments. Moreover, the slow speed of adjustment captured by the error correction mechanism highlights the importance of early, credible, and sustained climate and energy policies to avoid long-term carbon lock-in. Finally, while population growth contributes positively to emissions, its relatively smaller long-run impact suggests that demographic pressures should be addressed through complementary policies such as urban planning, public transport development, and household energy efficiency improvements, ensuring that population dynamics do not undermine environmental sustainability.

4.4 Impulse Response Analysis

The main purpose of impulse response analysis is to trace the dynamic effects of a shock originating in one variable on the behaviour of other endogenous variables within the system over time. This approach is widely used in time-series and panel VAR/VECM frameworks to examine how economic, energy, and demographic shocks propagate through the economy and influence environmental outcomes (Sims, 1980; Lütkepohl, 2013). Specifically, impulse response functions describe the reaction of an endogenous variable to a one-standard-deviation shock in another variable, allowing both the direction and persistence of the response to be evaluated (Pesaran & Shin, 1998; Wang et al., 2016). By capturing the temporal adjustment path, impulse response analysis provides valuable insights into the magnitude and duration of the effects of sudden changes that may occur due to economic expansion, energy demand fluctuations, or demographic pressures (Apergis & Payne, 2010; Narayan & Smyth, 2008). Figure (1) illustrates the impulse response results of CO_2 emissions to shocks in gross domestic product, primary energy consumption, population, and its own innovations. The results indicate that CO_2 emissions respond positively to shocks in all explanatory variables, with energy consumption exerting the strongest and most persistent impact, highlighting the central role of fossil-fuel-based energy use in driving emissions dynamics (Ang, 2007; Lean & Smyth, 2010; Dogan & Turkekul, 2016). GDP shocks also lead to a gradual and sustained increase in emissions, reflecting the scale effect of economic growth on environmental pressure, a finding consistent with the energy growth environment literature (Sadorsky, 2014; Shahbaz et al., 2018). In addition, population shocks generate a continuous rise in CO_2 emissions, suggesting that demographic growth increases aggregate energy demand, transportation needs, and residential consumption, in line with the STIRPAT framework and previous empirical evidence (Dietz & Rosa, 1997; York et al., 2003). Finally, the gradual decay of the impulse responses over time indicates the presence of long-run equilibrium forces within the system, consistent with the error-correction mechanism identified in the VECM estimates and reflecting structural rigidities and slow adjustment in energy and environmental systems (Apergis & Payne, 2014; Narayan & Smyth, 2008).

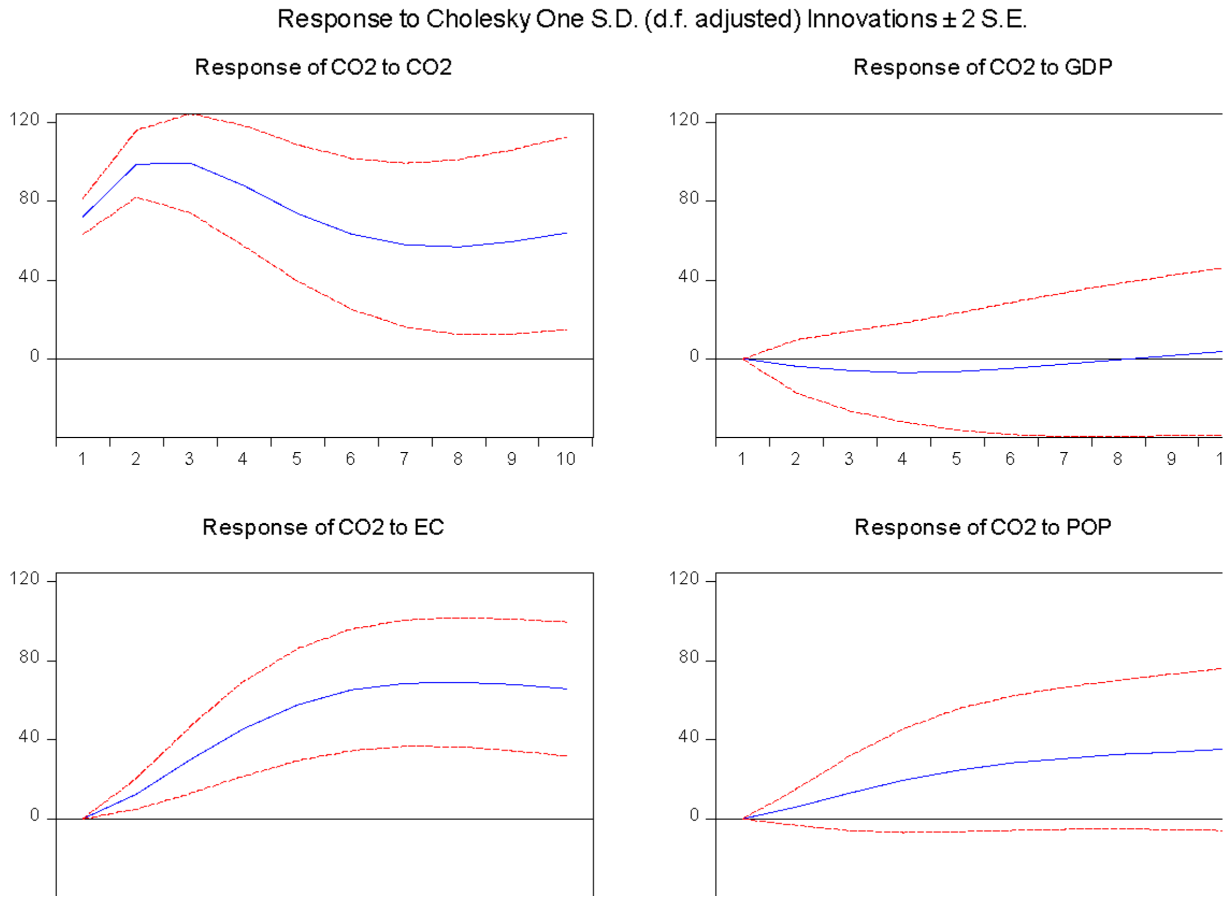

Figure 1: The Impulse Response Results

4.5 Causality Test

The Granger causality test is employed to examine the direction of predictive relationships among CO_2 emissions, economic growth, energy consumption, and population. The results reported in Table 6 reveal several statistically significant unidirectional causal linkages. Specifically, energy consumption Granger-causes CO_2 emissions at the 1% significance level, indicating that past variations in energy use contain significant explanatory power for future changes in emissions. This finding highlights the dominant role of energy consumption in driving environmental degradation and is consistent with the energy-led emissions hypothesis. In addition, economic growth Granger-causes CO_2 emissions at the 5% level, suggesting that expansions in output precede increases in emissions, thereby supporting the growth-induced emissions hypothesis. Population is also found to Granger-cause CO_2 emissions at the 1% significance level, implying that demographic pressures significantly contribute to future emissions through increased demand for energy, transportation, and residential services. In contrast, there is no evidence of reverse causality running from CO_2 emissions to energy consumption, economic growth, or population, indicating that environmental degradation does not play a predictive role in shaping these macroeconomic variables. Furthermore, no causal relationship is detected between economic growth and energy consumption, suggesting the absence of short-run feedback effects between these variables within the sample period. Overall, the Granger causality results provide empirical support for a unidirectional causality framework in which energy consumption, economic growth, and population act as key drivers of CO_2 emissions, reinforcing the conclusions drawn from the VECM and impulse response analyses and underscoring the importance of energy and demographic policies in emissions mitigation strategies.

Table 6: The Granger's Causality Test Results

Null hypothesis	F-statistic	P-Value
LEC does not Granger Cause LCE	5.701	0.0083***
LCO2 does not Granger Cause LEC	0.980	0.4541
LGDP does not Granger Cause LCO2	5.293	0.0108**
LCO2 does not Granger Cause LGDP	1.253	0.3409
LGDP does not Granger Cause LEC	0.644	0.6414
LCO2 does not Granger Cause LPOP	.27895	.57891
LPOP does not Granger Cause LCO2	18.4279	0.0001***
LEC does not Granger-cause LGDP	1.560	0.2474

*** significant at 1% level, ** significant at 5% level, * significant at 10% level. Note:

5. Conclusion and Policy Implications

This study provides clear evidence that economic growth, energy consumption, and population are key drivers of CO_2 emissions in Jordan within a dynamic macroeconomic framework. The findings consistently confirm the existence of a stable long-run equilibrium relationship among the variables, indicating that emissions, output, energy use, and population evolve together over time rather than independently.

In the long run, economic growth, energy consumption, and population are all found to exert statistically significant positive effects on CO_2 emissions. The estimated elasticities reveal that both GDP and energy consumption have more-than-proportional impacts on emissions, highlighting the persistent carbon-intensive nature of economic activity and the strong dependence of growth on fossil-fuel-based energy systems.

Although the contribution of population growth is smaller in magnitude, its positive and significant effect suggests that demographic pressures reinforce emissions through increased demand for energy, transportation, housing, and public services. The negative and statistically significant error-correction term further confirms the validity of the long-run relationship and indicates a gradual speed of adjustment toward equilibrium. This slow convergence implies that shocks to emissions tend to persist over time, reflecting structural rigidities in energy infrastructure, technological inertia, and delays in policy implementation.

These findings contribute to the literature by providing country-specific and dynamic evidence for Jordan, addressing the limited empirical focus on small, energy-import-dependent economies.

The short-run dynamics and impulse response functions provide additional insight into the transmission mechanisms underlying these relationships. In particular, shocks to energy consumption generate the strongest and most persistent increases in CO_2 emissions, both immediately and over the adjustment horizon, underscoring the central role of the energy system as the dominant driver of environmental degradation.

Shocks to economic growth also lead to rising emissions, although their effects are comparatively weaker and more gradual, reflecting the slower adjustment of production structures and capital stocks. Population shocks similarly result in a sustained increase in emissions, indicating that demographic changes exert immediate pressure on energy demand and consumption patterns.

Together, these dynamic responses reinforce the view that energy consumption acts as the primary channel through which economic and demographic forces translate into environmental outcomes. The Granger causality analysis further strengthens this conclusion by revealing unidirectional causality running from energy consumption, economic growth, and population to CO_2 emissions, with no evidence of reverse causality.

From a policy perspective, these findings carry important implications for sustainable development and climate policy. The strong and persistent link between economic growth and emissions indicates that growth-oriented development strategies, if pursued without structural transformation, are likely to intensify environmental pressures.

This underscores the need to decouple economic growth from carbon emissions through a shift toward less energy-intensive sectors, cleaner production technologies, and low-carbon innovation. The dominant role of energy consumption highlights the urgency of accelerating the transition toward renewable energy sources, improving energy efficiency across industrial, residential, and transport sectors, and reducing dependence on fossil fuels.

Policy instruments such as carbon pricing, energy subsidy reforms, emissions trading schemes, and targeted support for clean energy investments can play a crucial role in facilitating this transition. Moreover, the slow speed of adjustment toward long-run equilibrium emphasizes the importance of early, credible, and sustained policy interventions, as delayed action risks locking economies into carbon-intensive development paths and increasing the long-term cost of transition.

The positive contribution of population growth to emissions further suggests that environmental policy should be complemented by integrated urban planning, investment in public transportation, and improvements in household energy efficiency.

Finally, this study opens several promising avenues for future research. Subsequent work could extend the analysis by incorporating renewable energy consumption, technological innovation, or environmental policy stringency indicators to examine their moderating or mitigating effects on the growth energy emissions nexus.

Future studies may also explore nonlinearities and asymmetric responses using threshold, regime-switching, or quantile-based approaches to capture heterogeneous effects across different stages of development or emissions levels.

In addition, disaggregated analyses at the sectoral or regional level could provide deeper insights into the specific channels through which energy use and economic activity affect emissions. Such extensions would contribute to a more nuanced understanding of how economies can reconcile economic growth objectives with long-term environmental sustainability and climate mitigation goals.

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