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The Effects of Energy Use, Economic Growth, and Rural Population Growth on CO2 Emissions in North African Countries

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Abstract---Air pollution can harm health. The consumption of non-renewable resources and economic activities cause pollution. Carbon dioxide emissions are commonly used as a measure of environmental degradation in previous research. Carbon dioxide emissions are on the rise in most countries, especially emerging ones. This environmental issue has raised concerns, prompting this study to examine how fossil and renewable energy consumption and economic growth affect carbon dioxide emissions. Another independent variable, rural population growth, also affects carbon dioxide emissions after stability and security in the study area, which was previously threatened by terrorism, especially in Algeria. This allowed for the return of populations to their original areas. Data from 1990 to 2021 in North African countries was analyzed using the ARDL model. The study concluded that increased fossil energy consumption and rural population growth could lead to increased carbon dioxide emissions over time. However, economic growth does not affect carbon dioxide emissions, while renewable energy consumption reduces carbon dioxide emissions. These findings are critical for policymakers in formulating policies. Renewable energy should replace fossil energy, which will reduce carbon dioxide emissions.

Keywords---Carbon dioxide emissions, rural population growth, ARDL model, North African countries.

1. Introduction

Climate change has an unfavorable public health effect, especially for highly vulnerable regions like North Africa. Its consequences include an increase in incidences of respiratory diseases, mortality from

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heat-related causes, and expansion of vector-borne diseases, which can be related to rising and extreme temperatures around the globe, weather events, and changing scenarios of disease distribution (Yuanying Chi et al., 2023).

Newer studies, including the 2022 report by the IPCC and findings from the WHO in 2021, substantiate the grievousness of these occurrences. Public health increasingly becomes jeopardized in rural areas with limited healthcare access, where issues are exacerbated. The highlighted health effects, together with the other environmental impacts, require concerted efforts in developing policy frameworks that combine the mitigation of climate change with protection of public health (Teboho Jeremiah Mosikari and al., 2020).

In terms of energy, North Africa includes countries that rely heavily on fossil fuels (Saeid Satari Yuzbashkandi et al., 2023), particularly Algeria, Libya, Morocco, and Tunisia. These countries still rely on oil and natural gas to meet their energy needs, despite their potential to harness renewable energy sources (Rania Miniesy and al., 2021). The region is also highly vulnerable to climate change, facing water scarcity, desertification, and heat waves, which have become increasingly serious threats (International Energy Agency., 2023) and (World Bank, 2024). These real geographic gaps impact sustainable development efforts across the region.

The relationship between rural population growth, energy consumption, and economic development is crucial to understanding the trajectory of carbon dioxide emissions in these countries (Samir Saidi et al., 2018). For example, rapid urban-rural migration trends have contributed to increased energy demands and corresponding environmental degradation (Hala Abou-Ali et al., 2016).

Studies such as those by (Belke et al., 2011) and (Pirlogea & Cicea, 2012) have emphasized the complex relationship between energy consumption and economic growth, demonstrating that energy consumption brings economic expansion; however, it involves considerable degradation of the environment. The nexus between these processes is further explored by (Grossman & Krueger, 1995), who underscore the importance of sustainable-growth models that tackle ecological infringement. However, despite all these studies, there is still a lack of information on separating rural from urban data when determining their contribution to carbon dioxide emissions. This study seeks to fill this gap by conducting a comprehensive analysis of how demographics and energy consumption in rural areas affect emissions in Morocco, Algeria, Tunisia, and Libya.

This study aims to identify the contribution of rural population growth to carbon dioxide emissions in the region; examine the impacts of fossil and renewable energy consumption on emissions; and examine how economic growth is linked to environmental degradation. These issues will serve as supporting points in the study to provide recommendations for formulating effective policies to achieve a just energy transition in North Africa and achieve a balance between economic growth and environmental change, among other things.

2. **Literature review**:

The relationships between rural population dynamics, energy consumption, economic development, and nature sustainability have been widely discussed in the literature, particularly in developing regions such as North Africa. Morocco, Algeria, Tunisia, and Libya face significant challenges in terms of economic growth, energy consumption, and their corresponding environmental impacts. Studies increasingly suggest that rural population growth leads to increased energy consumption and, consequently, carbon dioxide emissions. In North Africa, where agriculture remains a major economic sector, rural growth leads to increased agricultural production and household energy demand, leading to increased energy consumption. (Seadya Mohamed Ahmed and al., 2024) investigated the energy-economy-environment nexus in Somalia and found that rural growth through agricultural expansion significantly contributes to carbon dioxide emissions a finding that can be extrapolated to the North African environment. Similarly, (Soheila Khoshnevis Yazdi and al., 2019) demonstrated and linked the importance of urbanization and rural-urban migration in Asia, noting that energy consumption increases as rural populations flow into cities, leading to increased carbon dioxide emissions. These results suggest that further rural population growth in North Africa could lead to increased emissions, especially in areas with significant energy inefficiencies.

Of extensive examination is the dynamics connecting economic growth and CO2 emissions. Certainly, very many cases over the EKC framework have been tested in different regions of North Africa, among them tests on the validity of the EKC hypothesis. For instance, (Saidi Kais & Mounir Ben Mbarek, 2017)**,** in their study on Algeria, Egypt, and Tunisia, found that most CO2 emissions increased with economic growth in the initial phases. Notably, it was also proving that the effect becomes less in subsequent periods in support of the EKC hypothesis. The research indicated unidirectional causality from economic growth to energy consumption and CO2 emissions, with industrialization and increasing energy demand accounting for emissions. The research verifies the same argument made **by** (Kang et al., 2016) on the test of the EKC hypothesis in China; indeed, industrial growth and the intensity of using energy tend to lead to higher emissions. The adoption of renewable energy sources and energy efficiency measures could reverse this trend. These findings apply to North Africa since its economic growth is most often associated with energy-intensive industries and a dependence on fossil fuels.

Widespread CO2 producers are energy-consuming activities, particularly where fossil fuels are used to generate electricity and run industrial processes. (Zahed Ghaderi et al., 2023) (2019) argued that all these countries are affected by patterns of energy consumption in relation to urbanization and CO2 emissions, where apparent evidence indicates that energy urbanization increases energy demand, which directly leads to higher emissions. Such a pattern can also be observed in North African cities where industrialization and urban growth are characterized by a parallel rise in energy consumption. Apart from these two studies, (Sayed Kushairi and al. 2020) suggest that there is a relationship between energy consumption and economic growth at CO2 emissions levels in developed countries and developing economies. In fact, they found that for high-income countries, energy consumption and emissions show a similar average increase within economic growth, which is also true for the case of North Africa. (Nidhaleddine Ben Cheikh and al., 2021) also concluded that renewable energy could be used to mitigate emissions, despite the heavy dependency on fossil fuels by most North African countries. This necessitates a shift to cleaner sources of energy in order to ameliorate the impact of growing energy consumption on the environment.

Several studies have pointed to the enormous potential of renewable energy in mitigating carbon dioxide emissions and in breaking the link between economic growth and environmental degradation. (Xin Yang et al., 2016) argued that, despite the high energy intensity of industrial growth, renewable energy in China could help mitigate carbon dioxide emissions. These findings apply to North Africa, as Algeria, Morocco, Libya, and Tunisia have significant renewable energy potential, particularly in solar and wind power. For example, (Asif Raihan et al., 2024) noted that Egypt, a country similar to the rest, has abundant untapped solar resources. Such works argue for the necessary policy reforms to expand the renewable energy infrastructure needed to address the region's growing carbon footprint. Similarly, (Soheila Khoshnevis Yazdi and al., 2019) also argued that the widespread adoption of renewable energy in North Africa is undermining the positive environmental impacts of rapid urbanization. However, barriers to the widespread adoption of renewable energy in North Africa include high initial costs, a lack of adequate infrastructure, and weak regulations.

Agricultural lands, mostly rural areas, release vast amounts of CO2 as a result of land-use changes, deforestation, and methane emissions from livestock. (Rawshan Ara Begum et al., 2020) studied the relationship between economic growth, deforestation, and CO2 emissions in Malaysia and found that agricultural expansion directly aggravates CO2 emissions through deforestation. This is very important in terms of North African countries because agricultural growth generally increases emissions through similar pathways such as land degradation and deforestation. According **to** (Ana María Loboguerrero et al., 2019), this is further confirmed by the agricultural contribution to the emission of CO2 in Somalia as the country is found to have significant agricultural value added to being a major contributor to environmental degradation. Thus, continued expansion of lands under agriculture, as expected to occur in the North African environment where population grows in rural areas, could contribute to further emissions. In addition, industrial growth, especially in energy-intensive sectors, like the cement and steel industry, within urban centers has compounded emissions within the region.

Considering the environmental issues that affect North Africa, many studies documented and proposed possible policy measures for emission reduction through energy efficiency, renewable energy adoption, and sustainable agriculture practices. In the recommendations of (Soheila Khoshnevis Yazdi and al., 2019), they advised policymakers to improve on urban planning and to integrate energy-efficient technologies towards reducing environmental costs due to urbanization. Their findings suggest that newly emerging cities may adopt emissions-reducing measures even within this policy applicable to North African countries. In a further argument, (Teboho Jeremiah Mosikari and al., 2020) endorsed investment in renewable energy infrastructure development within North African countries, particularly with respect to solar and wind energy resources, thereby reducing dependence on fossil fuels. The policies, including carbon taxes, emissions trading schemes, and subsidies for renewable energy technologies, are emphasized to play an important role by (Sayed Kushairi Sayed Nordin & Siok Kun Sek, 2020) as a means for achieving long-term emission reductions. Also, (Bingjing Yang et al., 2023) discussed proper integrative measures between economic growth and the application of energy conservation efforts so that rebound effects that can interfere with the intended emission reductions will be avoided.

The studies that were reviewed reveal very complicated and interdependent relationships among rural population growth, energy consumption, economic growth, and CO2 emission in North Africa. Ignoring all these, economic growth and energy consumption, as such, contribute highly to CO2 emissions, while renewable energy adoption complemented with energy efficiency improvements and sustainable agricultural practices can reduce these emissions. The results support a move towards cleaner energy systems and the adoption of policies that will foster sustainable development. Future research should be concerned with understanding how increased use of renewable energy and energy efficiency improvements could grow in North Africa and allow the decoupling of economic growth from CO2 emissions and produce a sustainable future.

3. Methodology and data

This research analyzes the impacts of fossil energy use, renewable energy use, economic expansion, and rural population growth on carbon dioxide emissions in four selected developing countries: Morocco, Algeria, Tunisia, and Libya. These countries are the most affected by climate change. The study period is between 1990 and 2021. Rural population expansion, economic growth, and fossil and renewable energy use are the independent variables, while carbon dioxide emissions are the dependent variable and represent an indicator of environmental degradation. They indicate rising carbon dioxide levels, while emissions indicate increased environmental degradation. Accordingly, the specification model is defined as follows.

$$Y_{it} = \alpha_i + \sum_{k=1}^{p} \beta_k Y_{it-k} + \sum_{k=0}^{q} \gamma_k X_{it-k} + \epsilon_{it} \quad (1)$$

For our study, we include five variables provided by the World Bank, Carbon dioxide (CO_2) emissions are expressed in thousands of metric tons of CO_2, GDP is reported in constant 2015 US dollars.

Renewable energy (RENE) consumption, expressed as a percentage of total final energy consumption, reflects the share of energy derived from renewable sources in the overall energy consumption. Similarly, fossil fuel energy consumption (FOSF), also expressed as a percentage, indicates the proportion of total energy sourced from fossil fuels. Finally, the rural population (RURP) is expressed as the total number of individuals living in rural areas, This study used logarithms of the variables to help choose appropriate time series models and estimate the direct elasticities of coefficients.

A panel data analysis requires unit root testing to determine the order of integration for each variable. This study will apply two methods for the unit root test: the Im, Pesaran, and Shin W-statistic (IPS) and the Augmented Dickey-Fuller (ADF) test. The tests will be performed on both the level and first differences of the variables. After conducting the unit root tests, a panel cointegration test will be carried out to examine the existence of a long-term relationship between the variables. Pedroni (1999) and Maddala and Wu (1999) introduced this panel cointegration methodology. Pedroni's approach focused on panel cointegration with heterogeneous intercepts and coefficients, while Maddala and Wu concentrated on aggregating individual tests to obtain a global test statistic for the entire panel. Panel cointegration analysis can improve the efficiency of estimators.

Pedroni (1999) proposed two types of statistical tests for panel cointegration: panel statistics and group statistics. Various statistics are included within the panel dimension, such as the panel v-statistic, panel rho-statistic, panel ϱϱ-statistic, and panel ADF-statistic. For the group dimension, the statistics include the group rho-statistic, group ϱϱ-statistic, and group ADF-statistic.

This study employs the panel ARDL approach to examine the short-run and long-run relationships between the independent and dependent variables. The panel data analysis is considered superior to temporal analysis, particularly when multiple countries are involved.

Time series analysis is utilized in this research due to the inclusion of data from four countries, rather than just one. Additionally, this approach does not require an extended time span. The Error Correction Model (ECM) is employed to capture the short-run dynamics. The research adopts the panel ARDL technique over the Johansen co-integration method because it is suitable regardless of whether the integration order is I(0), I(1), or a combination of both. Three ARDL estimators PMG, MG, and DFE are used in this study. The MG and MG estimators allow for the calculation of both short-run and long-run coefficients across multiple years and countries. However, the PMG estimator cannot estimate long-run coefficients for individual countries. Similarly, the DFE estimator is not effective in providing accurate coefficients for individual nations**.** Equation 2 calculates the coefficients for both the short-run and long-run.

In Equation 2, i=1, ..., n is the number of countries, t=1, ..., T is the number of years and ε is the error term. Δ is the 1st variation factor, and k is the ideal lag length. The model to estimate the long-run impacts of economic growth, energy use and rural population growth on CO2 emissions is as follows:

$$\begin{aligned}\ln(CO_{2,it}) = {} & \alpha_i + \gamma_t + \beta_0 \ln(GDP_{it}) + \beta_1 \ln(RENE_{it}) + \beta_2 \ln(FOSF_{it}) + \beta_3 \ln(RURP_{it}) \\ & + \sum_{k=1}^{p} \theta_k \ln(CO_{2,i,t-k}) + \sum_{k=0}^{q} \lambda_k \ln(GDP_{i,t-k}) + \sum_{k=0}^{q} \mu_k \ln(RENE_{i,t-k}) \\ & + \sum_{k=0}^{q} \nu_k \ln(FOSF_{i,t-k}) + \sum_{k=0}^{q} \xi_k \ln(RURP_{i,t-k}) \\ & + \epsilon_{it} \qquad (2)\end{aligned}$$

λ is the coefficient of the ECT in Equation 3. It measures the speed of adjustment to equilibrium. The value must be significantly negative, then we can confirm there is an existence of long-run relationships between the independent variables and the dependent variable.

$$\Delta\ln(CO_{2,it}) = \alpha_i + \gamma_t + \sum_{k=1}^{p} \delta_k \Delta\ln(CO_{2,i,t-k}) + \sum_{k=0}^{q} \lambda_k \Delta\ln(GDP_{i,t-k}) + \sum_{k=0}^{q} \mu_k \Delta\ln(RENE_{i,t-k}) + \sum_{k=0}^{q} \nu_k \Delta\ln(FOSF_{i,t-k}) + \sum_{k=0}^{q} \xi_k \Delta\ln(RURP_{i,t-k}) + \lambda \mathrm{ECT}_{i,t-1} + \epsilon_{it} \quad (3)$$

4. Findings

4.1 Descriptive statistics

Based on the summary statistics in the table1, this table highlights the diverse characteristics of the variables under study. While Gross Domestic Product (LGDP) appears fairly symmetric and normally distributed, Renewable Energy (LRENE) is notably volatile and negatively skewed. In contrast, Fossil Fuel consumption (LFOSF) is exceptionally stable, with very little variation in the dataset.
The Jarque-Bera test formally confirms these distributional properties. It indicates that only LGDP adheres to a normal distribution, while all other variables significantly deviate from it. This non-normality, especially in LRENE, is a key consideration for subsequent econometric modeling and hypothesis testing.

Table 1: Summary Statistics

Variables	LCO2	LFOSF	LGDP	LRENE	LRURP
Mean	3,8781	4,5304	24,9192	1,2469	15,4657
Median	3,8993	4,5253	24,8479	1,7525	15,6855
Maximum	5,2021	4,6052	26,0330	3,1355	16,4279
Minimum	2,6928	4,4000	23,5913	-2,3026	13,8917
Std. Dev.	0,6239	0,0640	0,5920	1,6739	0,9627
Skewness	0,2143	-0,0439	-0,0404	-0,7454	-0,3966
Kurtosis	2,3671	1,2560	2,4735	2,2069	1,5299
Jarque-Bera	3,1164	16,2631	1,5131	15,2072	14,8821
Probability	0,2105	0,0003	0,4693	0,0005	0,0006
Sum	496,4013	579,8915	3189,6634	159,6046	1979,6063
Sum Sq. Dev.	49,4329	0,5210	44,5042	355,8394	117,6923
Observations	128	128	128	128	128

Table 2 reveals several significant relationships between the variables, with the log of CO_2 emissions (LCO_2) showing a particularly strong connection to economic activity. The correlation between LCO_2 and the log of GDP (LGDP) is exceptionally high and positive (0.955), indicating that economic growth is almost perfectly coupled with an increase in carbon emissions within this dataset. As anticipated, LCO_2 also has a moderate positive correlation with the log of fossil fuel consumption (LFOSF) at 0.755 and a strong positive correlation with the log of the rural population variable (LRURP) at 0.339. Conversely, the log of renewable energy consumption (LRENE) shows a strong negative correlation with LCO2 (-0.859), indicating its potential role in mitigating emissions.

The interaction between energy sources and economic growth presents a more complex picture. There is a very strong inverse correlation between renewable energy and fossil fuel consumption (LRENE and LFOSF: -0.902), strongly suggesting a direct substitution effect; as the use of one energy source increases, the other decreases significantly. Interestingly, while GDP is moderately correlated with higher fossil fuel use (0.593), it exhibits a moderately strong negative correlation with renewable energy use (-0.723). This may imply that, historically, economic growth in the context of these data has been driven by non-renewable energy, and that the scale of renewable energy adoption has not yet been sufficient to reverse this trend. The moderately positive correlation between GDP and LRURP (0.492) further reinforces the relationship between population dynamics, economic expansion, and energy consumption patterns.

Table 2: Correlation of the variables

Variables	LCO2	LFOSF	LGDP	LRENE	LRURP
LCO2	1	0,755033	0,955069	-0,859429	0,339914
LFOSF	0,755033	1	0,593117	-0,902129	-0,192355
LGDP	0,955069	0,593117	1	-0,723625	0,492398
LRENE	-0,859429	-0,902129	-0,723625	1	-0,140789
LRURP	0,339914	-0,192355	0,492398	-0,140789	1

4.2 Panel Unit Root Test and Cointegration Test

4.2.1 Panel unit root

The results presented in Table 3 summarize the findings from both the ADF-Fisher Chi-square and IPS unit root tests for the panel data variables. According to the test statistics and associated p-values, the variables LCO_2, LFOSF, LGDP, and LRENE are all non-stationary at their levels but become stationary after first differencing, as indicated by their highly significant results (p-values = 0.0000) for both tests. This means they are integrated of order one, I(1). In contrast, the variable LRURP exhibits stationarity at level, as shown by its p-values (0.0362 for ADF and 0.06196 for IPS), which allow rejection of the unit root hypothesis at the 5% significance level. Thus, LRURP is integrated of order zero, I(0). These results suggest a mix of integration orders among the variables, highlighting the need for subsequent econometric analysis that can accommodate both I(0) and I(1) series, such as a panel ARDL approach.

Table 3: IPS w-stat and ADF test results

Variables	ADF		Order of integration	IPS		Order of integration
	Statistic	Prob.		Statistic	Prob.	
LCO2	55.269	0.0000	I(1)	-6.718	0.0000	I(1)
LFOSF	39.946	0.0000	I(1)	-5.023	0.0000	I(1)
LGDP	35.627	0.0000	I(1)	-4.3060	0.0000	I(1)
LRENE	50.339	0.0000	I(1)	-6.168	0.0000	I(1)
LRURP	16.466	0.0362	I(0)	-2.061	0.0196	I(0)

4.2.2 Panel cointegration test:

The panel co integration test results, as presented in Table 4, provide mixed evidence across different statistics; however, the most robust indicators support the existence of a long-run relationship among the variables under investigation. Under the within-dimension framework (assuming common autoregressive coefficients), the Panel PP-statistic and Panel ADF-statistic yield statistically significant results at the 5% level, with values of -1.8077 (p = 0.0353) and -2.2687 (p = 0.0116), respectively. In contrast, the Panel v-statistic (-0.2417; p = 0.5955) and Panel rho-statistic (0.0713; p = 0.5284) do not indicate statistical significance. Despite the mixed outcomes, the significant results from the more powerful PP and ADF tests provide substantial support for the presence of co integration in the panel.

In the between-dimension results (allowing for heterogeneous autoregressive coefficients), the evidence for co integration becomes even more compelling. The Group PP-statistic (-2.3022; p = 0.0107) is significant at the 5% level, and the Group ADF-statistic (-2.5457; p = 0.0055) is significant at the 1% level, reinforcing the conclusion of a long-run equilibrium relationship. However, the Group rho-statistic (0.2875; p = 0.6131) remains statistically insignificant. Taken together, these findings, based on Pedroni's methodology, allow for the rejection of the null hypothesis of no cointegration and justify the use of dynamic panel techniques PMG estimators to analyze the long-run relationships among the variables.

Table 4: Panel co-integration results

Alternative hypothesis: common AR coefs. (within-dimension)		
	Statistic	Prob.
Panel v-statistic	-0,2417	0,5955
Panel rho-statistic	0,0713	0,5284
Panel PP-statistic	-1,8077	****0,0353**
Panel ADF-statistic	-2,2687	****0,0116**
Alternative hypothesis: common AR coefs. (between-dimension)		
	Statistic	Prob.
Panel rho-statistic	0,2875	0,6131
Panel PP-statistic	-2,3022	****0,0107**
Panel ADF-statistic	-2,5457	***0,0055**
* and** show the significance levels of 1% and 5%, respectively		

The long-run estimation results presented in **Table 5: Pooled Mean Group (PMG) Estimations** provide significant insights into the drivers of CO_2 emissions. The variable **LFOSF** (log of fossil fuel consumption) has a **positive and statistically significant coefficient of 2.0524 (p = 0.0086),** indicating a strong link between fossil fuel use and increased CO_2 emissions. Similarly, **LRURP** (log of rural population growth) also exhibits a **positive and highly significant coefficient of 2.1546 (p = 0.0000),** suggesting that rural population expansion contributes substantially to environmental degradation, likely due to reliance on biomass and inefficient energy practices. In contrast, **LGDP** (log of GDP) shows a **statistically insignificant effect (0.0134; p = 0.7531)**, implying that economic growth does not have a direct and significant long-run impact on CO_2 emissions in the observed context.

The coefficient of **LRENE** (log of renewable energy consumption) is **negative (-0.1086)** and **marginally significant at the 10% level (p = 0.0887).** This suggests that increasing the share of renewable in the energy mix may help reduce CO_2 emissions over time, although the effect is relatively modest. The limited significance could reflect the still-developing status of renewable energy infrastructure in the sampled countries. Additionally, the **constant term (C)** is **strongly negative and significant (-36.0026; p = 0.0000)**, indicating the influence of omitted fixed factors that vary across countries but remain stable over time.

It is also important to highlight that among the estimation techniques applied **Pooled Mean Group (PMG), Mean Group (MG), and Dynamic Fixed Effects (DFE)** the **PMG estimator is deemed the most appropriate** for this study. PMG combines the advantages of allowing for heterogeneity in short-run dynamics across countries while imposing homogeneity in the long-run coefficients. This balance makes PMG particularly well-suited for panel data structures where countries differ in adjustment speeds but may share similar long-run equilibrium relationships, providing more reliable and consistent estimates than MG or DFE approaches.

Table 5: Long-run estimation results Pooled Mean Group (PMG) Estimations

Variables	PMG	
	Coefficient	Prob.
LFOSF	2,0524	*0,0086
LGDP	0,0134	0,7531
LRENE	-0,1086	***0,0887
LRURP	2,1546	*0,0000
C	-36,0026	*0,0000

* and*** show the significance levels of 1% and 10%, respectively

Table 6 presents the short-run estimation results using the PMG approach, revealing that the error correction term (ECT) is negative as theoretically expected (–0.3859), but statistically insignificant (p = 0.3134), indicating a weak adjustment toward long-run equilibrium in the short run. Among the explanatory variables, only D(LGDP) and D(LRENE(-1)) are statistically significant, with coefficients of 0.4570 (p = 0.0000) and 0.0981 (p = 0.0176), respectively, suggesting that short-term economic growth increases CO_2 emissions, while the positive impact of lagged renewable energy use may reflect inefficiencies in transitioning away from carbon-intensive systems. In contrast, D(LCO2(-3)) and D(LRURP(-3)) show no significant effect (p = 0.9082 and 0.3532, respectively), indicating a limited short-run influence of past emissions and rural population growth. Overall, the findings emphasize that while economic activity and renewable energy use have measurable short-term effects on emissions, the system lacks a strong corrective mechanism to restore equilibrium, highlighting the need for more effective long-term environmental and energy policies.

Table 6: Short-run estimation results

Variables	PMG	
	Coefficient	Prob.
ECT	-0,3859	0,3134
D(LCO2(-3))	0,0140	0,9082
D(LGDP)	0,4570	0,0000
D(LRENE(-1))	0,0981	0,0176
D(LRURP(-3))	-5,6083	0,3532

5. Discussion

This study has provided a nuanced empirical analysis of the determinants of CO_2 emissions in North Africa, revealing a significant divergence between short-run pressures and long-run environmental outcomes. The findings underscore that the region's path to sustainable development is constrained by a complex interplay of energy consumption patterns, economic activity, and demographic factors. In the long run, the primary drivers of environmental degradation are the continued reliance on fossil fuels and, notably, the growth of the rural population. The highly significant positive coefficients for both fossil fuel consumption and rural population highlight a structural challenge where both industrial energy systems and traditional rural livelihoods contribute substantially to the carbon footprint. Conversely, the adoption of renewable energy is confirmed to be a mitigating factor, albeit with moderate statistical significance, validating its importance in any long-term decarbonization strategy.

A critical finding of this analysis is the profound disconnect between the region's short-term dynamics and its long-term environmental goals. The statistically insignificant Error Correction Term (ECT) suggests a weak or non-existent automatic adjustment mechanism, meaning that shocks driving up emissions are not quickly corrected. This inertia is particularly concerning given that short-term economic growth is the most potent driver of increased emissions. This creates a classic policy dilemma: the immediate pursuit of economic expansion directly undermines long-term climate targets. Furthermore, the paradoxical short-run positive impact of lagged renewable energy consumption points to the transitional costs of greening the grid, where the carbon-intensive manufacturing and installation of infrastructure, or the supplementary role of renewables, may temporarily increase emissions before net benefits are realized.

The policy implications derived from these results are clear and pressing. First, the lack of a strong self-correcting mechanism indicates that market forces alone will be insufficient to steer North African economies toward a sustainable trajectory. Proactive, deliberate, and robust government intervention is essential. Policies must address the primary long-run drivers of emissions by creating aggressive frameworks to phase out fossil fuels while simultaneously developing targeted programs to modernize energy consumption in rural areas. This could include promoting access to clean cooking technologies and off-grid solar solutions to reduce reliance on biomass and inefficient energy sources.

Finally, policymakers must navigate the short-run trade-offs with strategic foresight. While promoting economic growth, they must implement measures to decouple this growth from emissions, such as carbon pricing or stringent efficiency standards. The short-term environmental cost of deploying renewables must be anticipated and managed by ensuring that new capacity genuinely displaces fossil fuels rather than merely supplementing them. Ultimately, this research demonstrates that achieving a low-carbon future in North Africa requires an integrated policy approach that aligns immediate economic needs with the long-term imperatives of environmental sustainability and addresses the unique challenges posed by both industrial and rural sectors.

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