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The effects of GDP, Renewable Energy Consumption, Fossil Fuel Consumption, Foreign Direct Investment on Carbon Emissions in Botswana: Evidence from an ARDL Approach

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A B S T R A C T

This study investigates the relationship between economic growth, renewable energy consumption, fossil fuel consumption, foreign direct investment (FDI), and carbon dioxide (CO_2) emissions in Botswana within the Environmental Kuznets Curve (EKC) framework. Botswana has experienced sustained economic growth over the past decades, driven primarily by mining activities and foreign investment. However, this growth has also increased energy demand and environmental degradation due to the country's continued reliance on fossil-fuel-based electricity generation. Using annual time-series data from 1994 to 2024, the study applies the Autoregressive Distributed Lag (ARDL) model to estimate both short-run and long-run relationships among the variables. The findings reveal that GDP per capita and fossil fuel consumption significantly increase carbon emissions, while renewable energy consumption reduces environmental degradation in both the short run and the long run. The coefficient of GDP squared is negative and statistically significant, confirming the existence of the Environmental Kuznets Curve hypothesis in Botswana

INTRODUCTION

Balancing economic growth and environmental sustainability has become one of the most important policy concerns for developing economies. This challenge is particularly significant in resource-dependent countries such as Botswana, where economic growth has historically been driven by mining activities, industrial expansion, and foreign direct investment. Although Botswana has achieved impressive economic growth and improvements in living standards since the 1990s, the country continues to face rising environmental pressure associated with fossil-fuel dependence, increasing energy demand, and growing carbon dioxide emissions. Botswana's economy remains heavily dependent on the mining sector, particularly diamond mining, which contributes substantially to GDP, export revenues, employment generation, and industrial development. However, mining activities are energy-intensive and rely heavily on coal-based electricity generation. Coal continues to dominate Botswana's electricity generation system, accounting for more than 90 percent of electricity production. Consequently, economic expansion and industrialization have been accompanied by increased greenhouse gas emissions and environmental degradation.

At the same time, Botswana possesses considerable renewable energy potential, especially solar energy, due to its high solar radiation levels and favorable climatic conditions. The government has increasingly recognized the importance of environmental sustainability and energy diversification through policies such as the Renewable Energy Feed-In Tariff Programme, the Botswana Solar Programme, and climate mitigation strategies incorporated into national development plans. Despite these initiatives, renewable energy still contributes only a small share to the national energy mix. The Environmental Kuznets Curve (EKC) hypothesis provides an important theoretical framework for understanding the relationship between economic growth and environmental degradation. The EKC proposes that environmental degradation initially increases during the early stages of economic development because of industrialization, urbanization, and increased energy consumption. However, after a certain income threshold is reached, environmental degradation begins to decline as economies adopt cleaner technologies, strengthen environmental regulations, and shift toward environmentally sustainable production systems.

In Botswana's context, the EKC hypothesis is highly relevant because the country remains dependent on mining activities and fossil-fuel-based electricity generation while simultaneously pursuing economic diversification and renewable energy transition. Determining whether Botswana has reached or is approaching the EKC turning point is therefore important for sustainable development planning. Foreign direct investment also plays a major role in influencing environmental outcomes. On one hand, FDI may contribute positively through technology transfer, cleaner production methods, and renewable energy investment. On the other hand, FDI concentrated in mining and extractive industries may increase carbon emissions through energy-intensive industrial activities. The environmental impact of FDI therefore

depends largely on the sectoral composition of investment flows and the strength of environmental governance.

Similarly, fossil fuel consumption remains one of the primary drivers of carbon emissions in Botswana. The country's continued reliance on coal-fired electricity generation contributes significantly to greenhouse gas emissions and environmental degradation. In contrast, renewable energy consumption is expected to improve environmental quality through the substitution of fossil-fuel-based electricity with cleaner energy sources. Despite growing policy attention toward environmental sustainability and energy transition, empirical studies focusing specifically on Botswana remain limited. Most previous studies either examine the relationship between economic growth and environmental degradation in broader African contexts or focus on individual determinants such as energy consumption without integrating renewable energy, fossil fuel consumption, and FDI within a single empirical framework.

This study therefore contributes to the literature by examining the relationship between economic growth, renewable energy consumption, fossil fuel consumption, FDI, and carbon emissions in Botswana using an extended EKC framework and the ARDL modelling approach. The study provides important policy insights for achieving sustainable economic development while reducing environmental degradation.

LITERATURE REVIEW

Environmental Kuznets Curve Hypothesis

The Environmental Kuznets Curve hypothesis originates from the work of Grossman and Krueger (1991) and proposes an inverted U-shaped relationship between economic growth and environmental degradation. According to the EKC framework, environmental degradation initially increases during the early stages of economic development due to industrialization, infrastructure expansion, and energy-intensive production systems, (Lovemore, T., & Thabeng, M. M. 2025).. However, after reaching a certain income threshold, environmental quality improves because higher-income economies adopt cleaner technologies, implement stronger environmental regulations, and increase investments in renewable energy and sustainable production systems, (Okurut, F. N., & Mbulawa, S. (2018).

The EKC relationship can be represented mathematically as:

$$CO_{2t} = \beta_0 + \beta_1 GDP_t + \beta_2 GDP^2_t + \varepsilon_t$$

Within the EKC framework, a positive coefficient for GDP and a negative coefficient for GDP squared indicate the existence of an inverted U-shaped relationship between economic growth and environmental degradation. Botswana provides an interesting context for testing the EKC hypothesis because economic growth has historically been driven by mining and fossil-fuel-based electricity generation. While this growth has improved income levels and industrial development, it has also increased environmental pressure through rising carbon emissions and fossil fuel consumption.

Demand-Side Renewable Energy Consumption

Botswana's energy and emissions profile underscores the importance of demand-side renewable energy efforts in shaping its environmental trajectory. The country depends heavily on coal to meet its electricity demands, with more than 90 percent of electricity supplied by coal-fired power plants (International Energy Agency, IEA,2023). The high usage of fossil fuels shows that changes in energy demand patterns can greatly influence carbon emission levels in the country. Demand-side renewable adoption, such as roof-top photovoltaic systems and solar water heaters, can lower the dependence on coal-generated electricity, thereby reducing carbon emissions through the direct substitution effect (Acheampong 2018).

Empirical literature

Renewable Energy Consumption and Environmental Quality

Renewable energy consumption has increasingly become a central issue in environmental economics literature because of its role in reducing greenhouse gas emissions. Renewable energy technologies such as solar, wind, and hydroelectric power generate significantly lower carbon emissions compared to fossil fuels Saad, (R., Plazas-Niño, F., Cannone, C., Yeganyan, R., Howells, M., & Luscombe, H. 2024). Empirical evidence suggests that renewable energy consumption improves environmental quality through the substitution effect, whereby cleaner energy sources replace coal and petroleum-based energy systems. In developing economies that remain highly dependent on fossil fuels, renewable energy transition is often viewed as a crucial pathway toward environmental sustainability, (Motsomi, M. O., & Oladiran, M. T. 2023). Botswana's substantial solar energy potential makes renewable energy transition particularly important. Increased renewable energy consumption could reduce dependence on coal-fired electricity generation while simultaneously improving energy security and environmental sustainability.

Fossil Fuel Consumption and Environmental Degradation

Fossil fuel consumption remains one of the largest contributors to carbon emissions globally. Coal, oil, and natural gas continue to dominate industrial production, electricity generation, transportation systems, and urban infrastructure development in many developing economies (Montsho, L. 2025). In Botswana, coal remains the primary source of electricity generation. The mining sector further intensifies fossil fuel dependence because mining and mineral processing activities require substantial electricity and industrial energy use. Consequently, increased fossil fuel consumption is expected to increase carbon emissions significantly (Tautsagae, M. K., & Wu, D. 2024). Energy Transition Theory argues that long-term environmental sustainability requires substantial restructuring of national energy systems away from fossil fuels and toward renewable energy technologies. This theory is highly relevant to Botswana because the country continues to rely heavily on coal despite possessing large renewable energy potential, (Cheeseman, K. 2025).

Foreign Direct Investment and Environmental Outcomes

The relationship between FDI and environmental quality remains theoretically ambiguous. The Pollution Haven Hypothesis suggests that multinational corporations may relocate pollution-intensive production

activities to developing countries with relatively weak environmental regulations. Under this framework, FDI increases environmental degradation by promoting energy-intensive industrial production, (Dube, O. P. (2013).,. Conversely, the Pollution Halo Hypothesis argues that FDI may improve environmental quality through technology transfer, cleaner production systems, and environmentally efficient management practices (Bouzahzah, M. 2022). In Botswana, FDI inflows are concentrated mainly in mining and extractive industries, which are highly energy-intensive and environmentally damaging. Consequently, the environmental impact of FDI is likely to depend on whether investment flows are directed toward carbon-intensive activities or environmentally sustainable sectors (, Achuo, E., & Ojong, N. 2025).

Global and African Empirical Literature

Empirical evidence regarding the EKC hypothesis remains mixed across countries and regions. Several studies support the existence of the EKC relationship, while others find that economic growth continues to increase environmental degradation without evidence of a turning point (Maswabi, M. G., Chun, J., & Chung, S. Y 2021). Research focusing on African economies increasingly highlights the role of renewable energy consumption in improving environmental quality. Studies have consistently shown that renewable energy reduces carbon emissions even at relatively low levels of renewable energy penetration. Similarly, fossil fuel consumption has consistently been found to exert a strong positive effect on carbon emissions across both developed and developing economies. However, Botswana-specific evidence remains limited. Most existing studies focus primarily on descriptive analysis and policy discussion rather than integrated econometric modelling. There is therefore limited empirical evidence examining the combined effects of economic growth, renewable energy consumption, fossil fuel consumption, and FDI on carbon emissions in Botswana, (Hlongwane, N. W., Daw, O. D., & Sithole, M. S. 2023). This study addresses these gaps by employing an extended EKC framework and ARDL modelling approach to estimate both short-run and long-run relationships among the variables.

METHODOLOGY

Data Sources and Variables

This study uses annual time-series data for Botswana covering the period from 1994 to 2024. The data were obtained from secondary sources including the World Bank World Development Indicators, the International Renewable Energy Agency (IRENA), and the International Monetary Fund. The dependent variable is carbon dioxide emissions measured in metric tons per capita. The explanatory variables include GDP per capita, GDP squared, renewable energy consumption, fossil fuel consumption, and foreign direct investment. GDP per capita measures economic growth and is included together with GDP squared to test the Environmental Kuznets Curve hypothesis. Renewable energy consumption is measured as the percentage share of renewable energy in total energy consumption. Fossil fuel consumption measures the percentage share of fossil

fuels in total energy consumption, while FDI is measured as net inflows as a percentage of GDP.

Model Specification

The study employs the Autoregressive Distributed Lag (ARDL) modelling approach developed by Pesaran, Shin, and Smith. The ARDL framework is appropriate because it allows estimation regardless of whether variables are integrated of order I(0) or I(1), provided none are integrated of order I(2). The estimated econometric model is expressed as follows:

$$\ln CO_{2t} = \beta_0 + \beta_1 \ln GDP_t + \beta_2 (\ln GDP_t)^2 + \beta_3 \ln REP_t + \beta_4 FDI_t + \beta_5 FF_t + \varepsilon_t$$

The ARDL bounds testing procedure is used to determine the existence of a long-run equilibrium relationship among the variables. Once cointegration is established, both long-run coefficients and short-run error correction dynamics are estimated.

Unit Root and Cointegration Tests

Before estimating the ARDL model, stationarity tests were conducted using the Augmented Dickey-Fuller (ADF) unit root test. The results indicated that carbon emissions, GDP per capita, GDP squared, and FDI were integrated of order I(1), while renewable energy consumption and fossil fuel consumption were stationary at levels and integrated of order I(0). The mixture of I(0) and I(1) variables confirmed the suitability of the ARDL modelling framework.

Diagnostic and Stability Tests

Diagnostic tests including the Breusch-Godfrey serial correlation test, Breusch-Pagan heteroskedasticity test, Jarque-Bera normality test, and Ramsey RESET test were conducted to assess the reliability and adequacy of the estimated model. The stability of the ARDL coefficients was further examined using the CUSUM and CUSUMSQ tests.

RESULTS

Lag Order Selection and Unit Root Results

The lag order selection criteria identified lag one as the optimal lag structure for the ARDL model based on the Akaike Information Criterion, Schwarz Criterion, and Hannan-Quinn Criterion. The Augmented Dickey-Fuller unit root test results confirmed that the variables were integrated at a mixture of I(0) and I(1), thereby satisfying the requirements for ARDL estimation.

Table 1. Unit Root Test Results

Variable	Level	First Difference	Order of Integration
CO_2	0.4281	0.0003	I(1)
GDP	0.5174	0.0012	I(1)
GDP^2	0.6035	0.0008	I(1)
REC	0.0324	—	I(0)
FF	0.0417	—	I(0)
FDI	0.2815	0.0143	I(1)

The results demonstrate that none of the variables were integrated of order I(2), validating the use of the ARDL bounds testing approach.

ARDL Bounds Test for Cointegration

The ARDL bounds test was conducted to examine whether a long-run equilibrium relationship exists among carbon emissions, economic growth, renewable energy consumption, fossil fuel consumption, and FDI.

Table 2. ARDL Bounds Test Results

Test Statistic	Value
F-statistic	5.214
K	5

Significance Level	I(0) Bound	I(1) Bound
10%	2.26	3.35
5%	2.62	3.79
1%	3.41	4.68

The calculated F-statistic of 5.214 exceeds the upper critical bound at all significance levels, leading to rejection of the null hypothesis of no cointegration. This confirms the existence of a long-run equilibrium relationship among the variables.

Long-Run ARDL Estimation Results

The long-run ARDL results reveal that GDP per capita has a positive and statistically significant effect on carbon emissions in Botswana. This implies that economic growth initially increases environmental degradation through industrialization, increased energy demand, and fossil fuel dependence.

However, the coefficient of GDP squared is negative and statistically significant, confirming the existence of the Environmental Kuznets Curve hypothesis.

Table 3. Long-Run ARDL Estimation Results

Variable	Coefficient	Probability
GDP	0.4285	0.0214
GDP^2	-0.000021	0.0291
REC	-0.1846	0.0182
FF	0.3927	0.0113
FDI	0.0678	0.0417
Constant	-3.5142	0.0220

The estimated EKC turning point was approximately USD 10,200. Botswana's average GDP per capita during the study period remained below this threshold, implying that the country is still located on the upward-sloping segment of the EKC.

Renewable energy consumption exhibits a negative and statistically significant relationship with carbon emissions. Specifically, a 1 percent increase in renewable energy consumption reduces carbon emissions by approximately 0.18 percent in the long run.

Fossil fuel consumption demonstrates a strong positive effect on carbon emissions, confirming that Botswana's coal dependence contributes substantially to environmental degradation.

Similarly, FDI exerts a positive and statistically significant impact on carbon emissions, supporting the Pollution Haven Hypothesis. This suggests that foreign investment inflows directed toward mining and extractive industries increase environmental pressure.

Short-Run ARDL Error Correction Results

The short-run ARDL results indicate that economic growth continues to increase carbon emissions in the short run.

Table 4. Short-Run ARDL Error Correction Results

Variable	Coefficient	Probability
ΔGDP	0.2143	0.0338
ΔGDP^2	-0.000011	0.0456
ΔREC	-0.0964	0.0301
ΔFF	0.2416	0.0287
ΔFDI	0.0315	0.0362
ECM (-1)	-0.6842	0.0010
Constant	-1.8426	0.0197

Renewable energy consumption reduces carbon emissions in the short run, while fossil fuel consumption and FDI increase environmental degradation.

The error correction term is negative and statistically significant, indicating convergence toward long-run equilibrium. The coefficient of -0.6842 implies that approximately 68.4 percent of short-run disequilibrium is corrected within one year.

Diagnostic and Stability Tests

The diagnostic tests confirmed that the ARDL model is econometrically sound and reliable.

Table 5. Diagnostic Test Results

Test	Statistic	Probability	Decision
Breusch-Godfrey LM Test	1.842	0.184	No Serial Correlation
Breusch-Pagan Test	1.516	0.231	No Heteroskedasticity
Jarque-Bera Test	0.964	0.617	Residuals Normally Distributed

Test	Statistic	Probability	Decision
Ramsey RESET Test	1.274	0.291	Model Correctly Specified

The CUSUM and CUSUMSQ stability tests further confirmed parameter stability throughout the study period.

Granger Causality Results

The Granger causality analysis revealed that GDP per capita, renewable energy consumption, and fossil fuel consumption Granger-cause carbon emissions.

Table 6. Granger Causality Results

Null Hypothesis	F-Statistic	Probability	Decision
GDP does not Granger Cause CO_2	4.182	0.028	Reject Null
REC does not Granger Cause CO_2	3.764	0.041	Reject Null
FF does not Granger Cause CO_2	5.314	0.012	Reject Null
FDI does not Granger Cause CO_2	2.147	0.139	Fail to Reject Null

Fossil fuel consumption exhibited the strongest causal relationship with carbon emissions, emphasizing the central role of coal dependence in Botswana's environmental degradation.

DISCUSSION

The findings provide strong empirical support for the Environmental Kuznets Curve hypothesis in Botswana. Economic growth initially increases carbon emissions because of industrialization, mining expansion, urbanization, and fossil-fuel dependence. However, the negative coefficient of GDP squared suggests that environmental degradation may eventually decline once Botswana reaches higher income levels and adopts cleaner production systems. The estimated EKC turning point of approximately USD 10,200 indicates that Botswana has not yet reached the income threshold required for environmental improvements associated with the EKC. Consequently, economic growth currently remains carbon-intensive. The negative relationship between renewable energy consumption and carbon emissions confirms the importance of renewable energy transition in improving environmental quality. Botswana's substantial solar energy potential creates important opportunities for reducing coal dependence and supporting sustainable development.

The strong positive effect of fossil fuel consumption highlights the environmental risks associated with Botswana's continued reliance on coal-fired electricity generation. Fossil fuel consumption was found to be among the strongest determinants of carbon emissions in both the short run and the long run. Similarly, the positive relationship between FDI and carbon emissions supports the Pollution Haven Hypothesis. This finding suggests that foreign

investment flows directed toward mining and extractive industries contribute to environmental degradation through energy-intensive industrial production. Overall, the findings emphasize that achieving environmental sustainability in Botswana requires substantial energy transition, stronger environmental regulation, and environmentally sustainable investment policies.

CONCLUSIONS AND RECOMMENDATIONS

This study examined the relationship between economic growth, renewable energy consumption, fossil fuel consumption, foreign direct investment, and carbon dioxide emissions in Botswana between 1994 and 2024 using the ARDL modelling approach. The findings confirm the existence of a long-run equilibrium relationship among the variables. Economic growth and fossil fuel consumption were found to increase carbon emissions significantly, while renewable energy consumption improves environmental quality by reducing emissions. The study further confirmed the Environmental Kuznets Curve hypothesis through the positive coefficient of GDP and the negative coefficient of GDP squared. However, Botswana remains below the estimated EKC turning point, implying that economic growth continues to worsen environmental degradation at the current stage of development. Fossil fuel dependence, particularly coal-based electricity generation, remains a major driver of carbon emissions.

The findings also demonstrate that FDI contributes positively to carbon emissions, suggesting that investment inflows concentrated in mining and extractive industries intensify environmental pressure. Based on these findings, several policy implications emerge. First, Botswana should accelerate renewable energy transition policies by increasing investment in solar energy infrastructure and reducing dependence on coal-fired electricity generation. Second, environmental regulations should be strengthened to encourage cleaner industrial production and improve energy efficiency. Third, Botswana should promote environmentally sustainable foreign investment by encouraging FDI inflows into renewable energy, green manufacturing, and environmentally friendly technologies rather than carbon-intensive industries. Fourth, national development planning should integrate environmental sustainability objectives into economic growth strategies. Economic diversification beyond mining activities will be essential for reducing long-term environmental pressure.

Finally, policymakers should strengthen institutional capacity and environmental governance systems to ensure effective implementation of climate mitigation and sustainable development policies. In conclusion, Botswana's long-term environmental sustainability depends largely on its ability to successfully transition toward renewable energy systems, diversify the economy beyond fossil-fuel-intensive industries, and implement environmentally sustainable development strategies. Coordinated efforts among government institutions, private sector stakeholders, researchers, and international development partners will therefore be essential for ensuring that future economic growth occurs alongside environmental protection and sustainable energy transition.

FURTHER STUDY

This research still has limitations, so further research is needed on the topic of The effects of GDP, Renewable Energy Consumption, Fossil Fuel Consumption, Foreign Direct Investment on Carbon Emissions in Botswana: Evidence from an ARDL Approach in order to perfect this research and increase insight for readers.

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