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The Impact of Foreign Direct Investment, Industrial Activity, Trade, and Energy Use on CO_2 Emissions in South Africa: Evidence from an ARDL Approach

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Abstract

This study investigates the effects of foreign direct investment (FDI), industrialization, trade openness, and electricity consumption on South Africa's CO_2 emissions from 1990 to 2022. In the analysis, based on the ARDL bounds testing, we examine both short-term and long-term relationships. The findings confirm a stable long-run cointegrating relationship. In the short run, both FDI inflows and trade expansion have a large impact on enhancing CO_2 emissions, which are consistent with the Pollution Haven Theory. But on the other side, industrial value-added and electricity consumption play an important part in reducing emissions throughout the long and short terms, implying the efficiency of production processes and the clean use of energy. No evidence of heteroskedasticity, and the CUSUM tests confirm parameter stability, as the diagnostic tests report no evidence of heteroskedasticity or serial correlation. The results indicate that policymakers should promote green FDI, incorporate environmental safeguards into trade policies, and diversify South Africa's energy mix to achieve green and emission-reducing economic growth.

Keywords: *CO_2 emissions, Foreign direct investment, Industrial activity, Trade openness, Energy consumption*

1. Introduction

Greenhouse gas emissions and their contribution to climate change will be among the central challenges of the 21st century. Of all pollutants, CO_2 (carbon dioxide) is the most abundant, contributing > 75% of total global GHG emissions (IEA, 2023); more than 90% of all CO_2 emissions are from the burning of fossil fuels. "South Africa is the most industrialized country on the continent and is one of the top 15 worldwide CO_2 emitters as its economy is largely based on carbon-intensive industries (e.g., coal-fired power, mining, and heavy manufacturing) (Bekun *et al.*, 2022). South Africa has experienced substantial economic changes during the past 30 years, including investment flows, an increasing level of FDI, increased factory outputs, expanded trade with other countries, and an increase in energy utilization. These developments have promoted economic growth, but questions about environmental sustainability have also been raised. FDI is a catalyst that brings about capital, technology, and jobs, but has also been recognized to lead to environmental stress, particularly in emerging economies with lax regulatory frameworks (Pollution Haven Hypothesis) (Williams *et al.*, 2022). In industrialized areas, both the production and mining industries are significant CO_2 emitters, particularly because they rely on coal-based energy (Kohler, 2013).

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Trade liberalisation has also opened the South African economy to the world economy and given renewed impetus to exports of resource-based products. Although this is good for economic performance, it can escalate emissions if it is not used judiciously (Aladejare, 2022). Energy use, specifically electricity use, is still the main source of carbon emissions, since more than 77% of electricity in the country is coal-based (IEA, 2023). This dependence on fossil energy heightens the concern over the extent to which energy use is a longrun contributor to environmental deterioration.

It is important to know how these economic activities relate to environmental results. In this context, this study looks at how FDI, industrial production, trade openness, and energy consumption impact CO_2 emissions in South Africa for the period of 1990–2022. By using the ARDL (AutoRegressive Distributed lag) model, accommodating small sample sizes and mixture orders of integration, the research reveals dynamics in the short term and relationships in the long term.

This research adds to the literature by encompassing four of the most important economic drivers in a single unified empirical model applicable to South Africa. The results appear to provide useful policy guidance on how economic growth objectives can be harmonized with environmental sustainability.

2. Literature Review

2.1. Theoretical Framework

The econometric literature on the relationship between economic activity and environmental quality has been extremely contentious in environmental economics. Three major theories prevail in this dialogue: EKC, PHH, and Energy-Led Growth Hypothesis.

The EKC theory suggests an inverted-U link between environmental destruction and economic growth (Grossman and Krueger, 1995). At the beginning of the development process (as countries industrialize), pollution increases with income, but once the society reaches a certain income level, it starts to invest in cleaner technologies and environmental regulation, so that emissions decrease. But evidence for EKC is mixed and very much country-specific.

According to the Pollution Haven Hypothesis, firms in industrialised countries move their pollution-intensive activities to countries with loose environmental regulations (Copeland and Taylor, 2004). This means that as FDI inflow rises, the environmental performance of the host country falls, particularly in countries with weak regulatory institutions.

The Energy-Led Growth Hypothesis postulates that energy consumption is a cause and outcome of economic growth (Stern, 2004). Energy use is an important force for CO_2 emissions, especially in fossil-fuel-based economies. This is particularly true within the South African context, where coal contributes more than 77% of the electricity produced (IEA, 2023). These perspectives provide us with an avenue to explore how the impacts of foreign direct investment (FDI), industrial activity, business activity, and energy use collectively impact CO_2 emissions in South Africa.

2.2. Empirical Literature Review

2.2.1. Foreign Direct Investment (FDI) and CO_2 Emissions

A number of studies find support for the Pollution Haven Hypothesis (PHH) in developing countries. For example, Williams *et al*. (2022) used a nonlinear ARDL model for South Africa and found that FDI has a significant positive impact on the ecological footprint. In essence, Williams *et al*. (2022) discovered that the movement of international capital to pollution-intensive sectors like mining and petrochemicals can adversely affect the environment.

Kivyiro and Arminen (2014) also assessed panel data from 12 Sub-Saharan African countries which explored the location choice of firms in developing countries with weak enacted environmental law, and found that when those countries received FDI, they increased CO_2 emissions. In South Africa, for example, FDI is thus heavily restricted to high-emitting sectors such as mining/energy (Aladejare, 2022).

However, other research suggests that FDI can also produce complementary environmental benefits. The "pollution halo hypothesis" suggests that a foreign multinational can adopt cleaner technology than a domestic competitor, and also better management practices (Zarsky, 1999). For example, Kılıçarslan and Akal (2021) found that in Turkey, FDI exerted a negative long-run effect on CO_2 emissions in the context of green technology transfer. This juxtaposition points to the heterogeneity of FDI-environment dynamics and the significance of institutional conditions in determining outcomes.

2.2.2. Industrial Activity and CO_2 Emissions

Economic activity is a key cause of CO_2 emissions behind much (though not all) development globally, including in South Africa. The industrial added value is positively correlated with emissions in the studies. In another study, the author Kohler (2013) used time series for South Africa and noticed that both manufacturing and mining are sources of rising CO_2 emissions, due to the predominance of fossil-fuel-related production.

Bekun *et al.* (2022) employed the ARDL bounds testing procedure and found industrial output to be found to be a major long-run driver of emissions for South Africa. Rapid urbanisation and a concentration of industrial activity in energy-hungry sectors have exacerbated the country's carbon footprint, the study said.

Other research focuses on the regional clustering of polluting industries. Oladunni *et al.* (2022) pointed out further that provinces where coal-fired power stations and heavy manufacturing are located, such as Mpumalanga, Gauteng, and KwaZulu-Natal, are the most polluted. These results reveal the spatial implications of industrialization and emissions in South Africa.

2.2.3. Trade and CO Emissions

The relationship between trade and environmental impact is complex. On one hand, trade can lead to higher emissions by stimulating the production of export goods that are energy-intensive (scale effect). On the other hand, it may decrease emissions if it results in technology transfer and less polluting production (technique effect).

For South Africa, Kohler (2013) showed that trade openness is linked with higher CO_2 emissions, mainly because of mineral and manufactured exports. These findings are reiterated by Aladejare (2022), who asserted that post-apartheid liberalization "opened" the South African economy to the world without any significant environmental protections in place.

Contrastingly, Shahbaz *et al.* (2013) provided proof that an EKC exists with trade and emissions, whereby further on, emissions decrease (peak) with trade liberalization as clean technologies are employed. This tipping point could be postponed, if not a dead point, in a coal-dependent country like South Africa.

2.2.4. Energy Use and CO Emissions

Energy use, and in particular electricity from fossil sources, is the single best predictor of CO_2 emissions. In a country like South Africa, which is coal-dependent, this relationship is particularly strong. IEA (2023) states that South Africa's power sector is roughly 77% coal-dependent, making South Africa the most carbon-intensive economy in Africa.

Argument for the energy-emissions nexus. Several lines of evidence support our model. Bekun *et al.* (2022) applied ARDL and revealed that In South Africa, using more energy has a statistically significant and beneficial effect on CO_2 emissions. Similarly, Mesagan *et al*. (2020) proved that the per capita electricity consumption is directly related to emissions in the industrial and transport sectors.

In addition, the relationship of energy consumption to other factors, i.e., trade and industrial output, can exacerbate emissions. For instance, the production for export of low-value and resource-intensive products, such as mining and metallurgical products, might heighten economic growth as well as environmental degradation.

2.3. Empirical Studies Using ARDL in South Africa and Similar Economies

The ARDL model has been increasingly adopted in environmental economics research because it tends to be more flexible for problems with sample size limitations and mixed integration orders. In the South African context, Kohler (2013) and Bekun *et al.* (2022) used the ARDL limits testing method and discovered the partnership throughout the long-term energy use, industrial growth, as well as emissions.

In other EGDEs, this kind of approach has been successful. Kılıçarslan and Akal (2021) used the ARDL model on Turkey and also found that FDI and energy consumption had immediate and long-term effects on CO_2. Likewise, Shahbaz *et al*. proved the practicability and applicability of using ARDL to see if the EKC hypothesis holds for China's environmental changes.

Your article contributes to this empirical literature by fitting a single ARDL framework with four explanatory variables– i.e., FDI, industrialization, trade, and energy use - tailored to South Africa.

2.4. Summary and Research Gap

From the above literature review, the framework confirms that FDI, industrial activity, trade, and energy consumption are the key factors affecting CO_2 emissions among developing countries. However, most of the reviewed studies evaluate these drivers separately or apply panel data that conceal the state-specific trends. Only a few studies have utilized recent time series data and ARDL modeling to test the linkages among the four drivers and CO_2 emissions in a South African network. This study looked at the short- and long-term connections between these factors and South Africa's

CO_2 emissions, attempting to fill in the gaps with data from 1990 to 2022. Also, the study significantly contributes to the current sustainable development and offers certain practical implications to link economic growth and environmental protection.

3. Data and Methodology

3.1. Data Description

This research investigates the impact of FDI (foreign direct investment), industrial activity (INDVA), trade (percentage of GDP-EXP01 that comes from exports of goods and services), and energy consumption (electric power consumption per capita-EPC) on carbon dioxide (CO_2) emissions in South Africa, in the period 1990 to 2022. The year-on-year data used was collected from the World Bank's World Development Indicators (WDI, 2023). The outcome variable is CO_2 emissions per person, which are measured in metric tons.

The selection of variables is motivated by economic and environmental theory. FDI is an external capital inflow that potentially may support both green investment and the dirty pollution industry. Industrial value added (% of GDP) embodies the degree to of industrialization impacts can have on the emissions, which come from production. Trade is captured via the exports to GDP ratio by representing the magnitude of openness of trade and its influence on the environment. Electricity consumption, which is shown with electric power consumption per capita (kWh) and can be used as a proxy for household and industrial electricity demand, is a known driver of emissions in fossil-fuel-based economies, such as South Africa.

Stationarity. We utilized the Phillips-Perron (PP) and Augmented Dickey-Fuller (ADF) unit root tests to check the series. Nothing came out as I(2) for any of the series, therefore justifying the utilization of the ARDL bound checking for cointegration analysis.

Table 1 shows the key variables used in the study, along with their abbreviations, units, and sources. The World Bank (WDI) provides the CO_2 emissions, FDI, industrial value added, and trade openness data. The IEA (2023) and WDI both provide the electricity consumption data. These things are the basis for the study of South Africa's economic and environmental interaction.

Table 1: Description of Data

Variable	Abbr.	Unit	Sources
Carbon emissions	CO_2	Metric tons per capita	World Bank (WDI)
Foreign direct investment net inflows	FDI	Current US$	WDI
Industrial value added as a percentage of GDP	INDVA	% of GDP	WDI
Exports of goods and services as a percentage of GDP	EXP01	% of GDP	WDI
Electric power consumption per capita	EPC	Kilowatt-hours per capita	WDI; IEA (2023)

The study looks at data from South Africa in an annual time series style from 1990 to 2022. The selected variables align with the concepts of the EKC, PHH, and ELGH models. All of the information comes from the World Bank's World Development Indicators (WDI) and the International Energy Agency (IEA). The variables used in the model, along with their definitions, measurement units, and data sources, are shown in Table 1. All variables were log-transformed in order to improve normality and reduce heteroskedasticity, which is a common practice for time series data.

3.2. Methodology

This study uses the autoregressive distributed lag (ARDL) bounds testing method. Pesaran, Shin, and Smith (2001) looked at the short- and long-term links between CO_2 and four other components. We measured FDI, INDVA, commerce (through EXP01), and energy use (through EPC) in South Africa from 1990 to 2022. We use ARDL because it can handle regressors of multiple orders of integration, I(0) and I(1), as long as neither of them is I(2). The long-run relationship looks like this in general:

$$CO_{2t} = \beta_0 + \beta_1 FDI_t + \beta_2 INDVA_t + \beta_3 EXPO1_t + \beta_4 EPC_t + \mu_t$$

We use the error correction version of the ARDL (p, q_1, q_2, q_3, q_4) model with consumption to find both the short-term and long-term changes in balance:

$$\Delta CO_{2t} = \alpha_0 + \sum_{i=1}^{p} \alpha_i \Delta CO_{2t-i} + \sum_{j=1}^{q_1} \gamma_j \Delta FDI_{t-j} + \sum_{k=0}^{q_2} \delta_k \Delta INDVA_{t-k} + \sum_{l=1}^{q_3} \phi_l \Delta EXPO1_{t-1} + \sum_{m=1}^{q_4} \psi_m \Delta EPC_{t-m}$$

$$+ \theta_1 CO_{2t-1} + \theta_2 FDI_{t-1} + \theta_3 INDVA_{t-1} + \theta_4 EXPO1_{t-1} + \theta_5 EPC_{t-1} + \in_t$$

Δ is the first-difference operator, α0 is the drift component, and 5t is the white-noise error term. The coefficients of the different variables demonstrate how they affect things in the short term, while the lagged level variables show how they affect things in the long term. The ARDL Bounds Test examines cointegration. The null hypothesis says that the variables don't have a long-term relationship. This test checks this. We compare the F-statistic to the important values that Pesaran *et al*. (2001) present. If the F-statistic is bigger than the upper bound, it means that cointegration is real.

The Error Correction Model (ECM) is based on the ARDL model. It helps figure out how quickly things will get back to normal following a short-term shock. This is how the ECM looks:

$$\Delta CO_{2t} = \lambda_0 + \sum_{i=1}^{p} \lambda_1 \Delta X_{t-i} + \phi ECT_{t-1} + v_t$$

The first difference is Δ, the lagged error correction term is EC_{t-1}, the error term is v_t, and the speed of adjustment toward the long-run equilibrium is λ. The ARDL Bounds Test looks for cointegration by testing the null hypothesis that the variables are not linked in the long term. We look at the test statistic and compare it to important numbers from Pesaran *et al.* (2001). If the F-statistic is larger than the upper bound critical value, the null hypothesis is not true, which suggests that cointegration does exist. The Breusch-Godfrey LM test looks for serial correlation, the Breusch-Pagan-Godfrey test looks for heteroskedasticity, the Jarque-Bera test looks for normality of the residuals, and the Ramsey RESET test looks for functional form specification.

4. Findings

Table 2 shows the main statistics for the main variables that are being looked at. It shows the average, median, maximum, minimum, standard deviation, skewness, and kurtosis of the sample for CO_2 emissions, FDI, industrial value added, trade openness, and electricity use. These numbers show how wide and varied the industrial and environmental indicators were in South Africa throughout the time period being looked at.

Table 2: Descriptive Statistics

	CO_2	FDI	INDVA	EXP01	EPC
Mean	0.520524	4.45E+09	27.11604	25.34181	4115.654
Median	0.44	2.22E+09	26.01508	26.09825	4207.92
Maximum	1.42	4.07E+10	35.6076	33.37145	4716.42
Minimum	0.1569	-7.6E+07	23.33944	18.95515	3357.925
Std. Dev	0.33382	7.15E+09	3.362818	3.810063	364.9554
Skewness	1.239117	4.084542	0.92817	0.02712	-0.37037
Kurtosis	3.899155	21.27734	2.93409	2.243186	2.010587

The descriptive statistics help support the variables in this investigation. During that time, the average number for South Africa was 0.52 metric tons per person. In 1992, it was 0.16 metric tons per person, and in 2001, it was 1.42 metric tons. Skewness (1.24) and kurtosis (3.90) in Table 2 show that there are a few years with very high emissions, which means there is an outlier problem. Foreign Direct Investment (FDI) fluctuates significantly, with an average of $4.45 billion and a standard deviation of $7.15 billion. The very high skewness (4.08) and high kurtosis (21.28) indicate that FDI inflows were inconsistent, with some years receiving a much larger amount of capital than usual. The industrial value added (INDVA), which is the industrial part of GDP, had an average of 27.12 percent, with a range of 23.34 to 35.61 percent. The variable has a modest right-skewness with a mostly normal distribution. The series is mostly stable, but it does change a little bit. The export-to-GDP ratio (EXP01) for commerce had an average value of 25.34% and an almost symmetric distribution (skewness 0.03) with light tails (kurtosis = 2.24). This result means that trading probably didn't change much during the data period. Finally, the per capita electric power consumption (EPC) was 4,115 kilowatt-hours, which is slightly left-skewed with a moderate spread. This graph shows that, even though electricity usage has gone down in some years, it still seems to be a major factor in the economy. However, low consumption may limit its potential as a growth factor, possibly because of supply issues. When you look at all of these numbers together, they give you a basic idea of how South Africa's economy and environment did during the study period.

Table 3 shows the results of the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests, which were done to see if the variables were stationary. The findings show which series are stationary in levels (I(0)) and which are stationary after taking the first difference (I(1)). This information helps you choose the best econometric method and demonstrates that none of the variables are integrated in order two, I(2), which means that the ARDL limits testing method is the ideal one.

Table 3: Unit Root Test Results

Variables	ADF Level (p-Value)	ADF 1st Diff (p-Value)	PP Level (p-Value)	PP 1st Diff (p-Value)	Order of Integration
CO_2	0.9986	0.0000	1.0000	0.0001	I(1)
FDI	0.0008	0.0000	0.0009	0.0000	I(0)
INDVA	0.0099	0.0009	0.0002	0.0009	I(0)
EXP01	0.697	0.0000	0.8735	0.0000	I(1)
EPC	0.8744	0.001	0.824	0.0009	I(1)

It is crucial to test the stationarity of the data series before estimating the ARDL model to make sure that the variable is integrated of order two, I(2). If it is, the ARDL bounds testing approach should not be employed. We apply both the ADF and PP unit root tests in this study to find out the order of integration for all the variables. Table 3 also shows a summary of these outcomes.

The ADF and PP tests of statistics all show that the series of CO_2 emissions, EXP01, and EPC are not stationary at levels, but they do become stationary at the first differences. This confirms the integration order of one, I(1). For example, the ADF \(p\)-values for CO_2, EXP01, and EPC at the level are 0.9986, 0.6970, and 0.8744, respectively, but fall well below 0.05 at first difference (0.0000, 0.0000, and 0.0010, respectively). The PP tests carry out similar outcomes. By contrast, foreign direct investment (FDI) and industrial value added (INDVA) are at levels (I(0)). The ADF and PP tests both give very low p-values below the 5% significance threshold, for example, 0.0008 for FDI and 0.0099 for INDVA. This means that the null hypothesis that there is no unit root under levels is rejected. The mixed order of integration (I(0,1)) across the variables supports the validity of the ARDL bound testing procedure in studying the long run and short run relationships among the investigated variables in this study.

Table 4 shows the results of the ARDL bounds test, which looks for a long-term cointegration relationship between the variables. We check the F-statistic against critical values at different levels of significance. We reject the null hypothesis of no cointegration again since the calculated F-statistic is higher than the top 1%, 2.5%, 5%, and 10% critical bounds. The result shows that the variables are related in the long term; hence, the ARDL model can be used in future research.

Table 4: ARDL Bounds Test				
F-Bounds Test		**Null hypothesis: No Level Relationship**		
Test Statistics	**Value**	**Signif.**	**I(0)**	**I(1)**
			Asymptotic: n=1000	
F-Statistics	7.512122	10%	2.2	3.09
K	4	5%	2.56	3.49
		2.5%	2.88	3.87
		1%	3.29	4.37

The observed F-statistic 7.512 is larger than the upper bound critical values at all significance levels (1%, 2.5%, 5% and 10%). For that matter, for instance, for a significance level of 5%, the upper-bound critical value (I(1)) is 3.49, well below the observed test statistic. Hence null hypothesis in the absence of a level relationship is turned down, which means that all Factors are integrated. Also, there exists Long-term cointegration in the way they are related to each other.

This result confirms the appropriateness of estimating both the long-run coefficients and the short-run dynamics using the ARDL model. It also corroborates the theory that economic variables such as FDI, industrial activity, trade, and energy consumption are collectively important in accounting for long-run changes in CO_2 emissions in South Africa.

The estimated long-run coefficients of the ARDL model are reported in Table 5. The findings reflect the long-run relationship between the explanatory variables and CO_2 emissions. Although the effects on CO_2 emissions of foreign direct investment (FDI) and trade openness are positive, they are insignificant, whereas those of industrial value added (INDVA) and electricity consumption (EPC) are significant and negative. The above conclusions illustrate that industrial growth and energy consumption structure improvement are two key factors that can lead to a minute decrease in carbon emissions.

Table 5: Long-run ARDL Coefficients				
Variables	**Coefficient**	**Std. Error**	**T-Statistic**	**Prob.**
FDI	9.31E-12	2.10E-11	0.442914	0.6673
INDVA	-0.104	0.037237	-2.79281	0.019
EXP01	0.021255	0.039934	0.532252	0.6062
EPC	-0.00054	0.00011	-4.91866	0.0006
C	4.771926	1.979951	2.410123	0.0367

The long-run ARDL estimation shows heterogeneous effects of the economic variables on CO_2 emissions for South Africa. The effect of FDI is positive but statistically insignificant (p = 0.6673). This means that FDI inflows don't have a big effect on emissions over time. This could be because South Africa has two types of investments, with FDI flowing into both clean and dirty industries, or due to the regulatory measures that dampen its environmental spillover. Unexpectedly, development in industry (INDVA) has a significant inverse association with CO_2 emissions (coefficient = -0.104, p = 0.0190), suggesting increased industrial activities would somehow lead to lesser emissions. Such a counterintuitive outcome may reflect that there have been structural changes in the industrial activity (e.g., an improvement in terms of energy efficiency, cleaner production technology, or a restructuring occurring in the direction of less carbon-intensive sectors). Open trade, which is approximated by the percentage of GDP that comes from exports (EXP01), however, appears to be positively related to emissions, albeit not statistically significant (p = 0.6062), which implies no long-run irreversible relationship between trade intensity and environmental quality. Most importantly, EPC per capita significantly and negatively affects CO_2 emissions (coefficient = -0.00054, p = 0.0006), a feature that is unexpected considering that South Africa is so coal-dependent. This could be due to recent energy efficiency advancements, shifts to cleaner fuels, or reduced per capita use owing to restricted supply. On the whole, the long-term outcomes confirm the intricate nature of the environmental impacts of such economic activities in South Africa and propose that the reduction in emissions can be achieved while still advancing local economic activities through technological enhancement and reform in energy services.

Table 6 shows the important short-run coefficients and the ECT of the ARDL model after removing variables that weren't relevant. The ECT coefficient is negative and significant, and it takes 61% of the time to adjust to long-run equilibrium. The pollution haven hypothesis is supported by the fact that foreign direct investment (FDI) has a short-term positive and significant influence on CO_2 emissions. Industrial value added (INDVA) and electricity consumption (EPC) have opposite significant negative effects, which means they help lower emissions. Trade openness (EXP01) still has a big and favorable effect on emissions over several periods.

Table 6: Short-Run Dynamics and Error Correction Model

Variables	Coefficient	Std. Error	T-Statistic	Prob.
CO_2(-1)*	-0.60742	0.213286	-2.8479	0.0173
INDVA(-1)	-0.06317	0.028299	-2.23222	0.0497
EPC(-1)	-0.00033	8.25E-05	-3.99117	0.0026
D(FDI)	1.51E-11	3.45E-12	4.378627	0.0014
D(FDI(-2))	-2.24E-11	8.08E-12	-2.76914	0.0198
D(INDVA)	-0.21242	0.042044	-5.05233	0.0005
D(EXP01)	0.035402	0.015588	2.271068	0.0465
D(EXP01(-1))	0.039427	0.014126	2.790993	0.0191
D(EXP01(-2))	0.036894	0.01139	3.23918	0.0089
D(EXP01(-3))	0.031669	0.008689	3.644602	0.0045
CointEq(–1)*	-0.60742	0.073873	-8.22248	0.0000

The ECM estimation shows marked short-run dynamics for CO_2 emissions and their determinants in South Africa. The error correction term (CointEq(–1)) is negative and significant at the 1% level (coefficient = -0.6074, $p < 0.01$). This means that these factors will stay in balance throughout the long run. This statistic shows that about 61% of any imbalance in CO_2 emissions goes back to the long-term equilibrium within a year. This means that the correction to the long-term equilibrium happens quite quickly.

In the short term, FDI has mostly a good effect on CO_2 emissions. The short-term effect of FDI is positive and statistically significant (coefficient = 1.51E-11, sign +, p = 0.0014), indicating that FDI inflow leads to emissions increasing due to the rise of the influx of FDI, which supports the Pollution Haven Hypothesis. The second lag of FDI, on the other hand, is estimated to have a significant negative effect (p = 0.0198), which may suggest a longer-term erosion or reversal of this effect due to long-term developmental or policy interventions.

Furthermore, industrial activity (INDVA) has a strong negative short-run impact on emissions (coefficient = -0.2124, $p < 0.01$), in line with the long-run results. This indicates that the increase in industrial value added may be a result of cleaner (more efficient) production processes, which could help to account for the role played by environmental regulations or the uptake of cleaner technologies in South Africa.

Trade openness (EXP01) shows a clear positive and important effect in all four subsequences ($p < 0.05$), meaning that when exports increase, CO_2 emissions also rise in the short term. This can be the result of high production intensity or transport, or a result of export trade.

On the other hand, electric power consumption (EPC) is statistically insignificant in the short run (p = 0.4215), suggesting that immediate transformation in the energy used does not substantially affect CO_2 emissions. This could be the result of lagged effects or structural factors, like inelastic demand or pricing interventions.

In general, in the short run, the data show that more foreign direct investment (FDI) coming in and expanding trade contribute to higher CO_2 emissions, while more industrial production means less CO_2 emissions. These outcomes show how important it is to take timely policy steps. in particular, in the short run as regards the greening of trade and foreign investment.

Table 7 compares this paper to previous studies with methodological approaches and main outcomes.

Table 7: Comparison with Other Published Papers

Study	Country	Methodology	Key Variables	Main Findings	Relevance to Current Study
This Study (2025)	South Africa	ARDL (1990-2022)	CO_2, FDI, INDVA, EXP, EPC	FDI and trade raise CO_2, in the short run; EPC and INDVA reduce CO_2, in the long run	Focused exclusively on South Africa; integrates four major economic drivers
Williams *et al.* (2022)	South Africa	NARDL	Ecological footprint, FDI, uncertainty	FDI increases ecological footprint; nonlinear effects observed	Confirms the asymmetric environmental impact of FDI in South Africa
Kohler (2013)	South Africa	ARDL	CO_2, energy use, GDP, trade	Energy use significantly raises CO_2; trade impact mixed	Confirms strong energy-emission link in SA, supports ARDL approach
Aladejare (2022)	Sub-Saharan Africa	Panel FMOLS and DOLS	CO_2, FDI, trade openness, GDP	FDI worsens emissions in weak institutions; trade has a mixed impact	Supports the Pollution Haven Hypothesis in the SSA region
Kivyiro and Arminen (2014)	SSA Panel	Johansen Cointegration	CO_2, FDI, energy, GDP	FDI increases CO_2, in energy-intensive economies	Reinforces the FDI-emission link in developing regions
Bekun *et al.* (2022)	South Africa	ARDL	CO_2, GDP, energy use, renewables	Fossil energy use raises CO_2; renewables reduce it	Confirms energy-emission relationship; advocates for cleaner energy
Shahbaz *et al.* (2013)	China	ARDL	CO_2, GDP, energy use, trade	Validates EKC; trade initially raises, then lowers CO_2	Provides a model precedent for exploring EKC in developing countries
Kılıçarslan and Akal (2021)	Turkey	ARDL	CO_2, FDI, complexity	FDI reduces CO_2, via tech transfer in high-complexity sectors	Shows FDI effects depend on sector & technology level

The juxtaposition of our study with previous literature reveals a mix of consistency and novelty in studying the economic factors of CO_2 emissions in South Africa and other developing countries in the Like community. Similar to Kohler (2013) as well as Bekun *et al.* (2022), this study corroborates the importance of the link between emissions and energy use in South Africa, with an interesting difference, however: while in these studies, there is a link between energy use and emissions that is good. This study obtains a negative long-run impact of electric power consumption, perhaps reflecting recent energy efficiency improvements or a diversification in energy mix.

Unlike Williams *et al.* (2022), who used the nonlinear ARDL (NARDL) and reported asymmetric influences of FDI on the environmental burden, the current research finds mixed short-run impacts of FDI and not of long-run significance on

CO_2 emissions. The implication is that any negative environmental effect of FDI is likely to be transitory, perhaps dampened over time by regulatory or technological changes.

Evidence from Kivyiro and Arminen (2014) and Aladejare (2022), which utilised panel data across Sub-Saharan Africa, is consistent with the Pollution Haven Hypothesis in that FDI is associated with greater pollution. Yet, the country-specific ARDL methodology used in the current paper provides more sophisticated evidence by revealing that FDI initially raises emissions in the short term, but it doesn't hold such a long-term effect, implying that the offset effect or adaptation and policy-driven effect exists in South Africa.

In addition, the negative link between industry and emissions found in this analysis differs from those of most studies, which usually report a positive link. This surprising finding could potentially be indicative of structural transformations in South Africa's industrial sector, the adoption of environmentally sound technologies, or changing patterns of compliance with environmental legislation.

Last but not least, the simultaneous presence of four major economic drivers—namely FDI, manufacturing activity, international trade, and energy use—in a single ARDL context offers a richer and more holistic perspective than in previous studies, where typically only one or two of these variables were taken into account. Such a multistaged design has increased the depths and policy implications of the present findings.

In sum, though the study has similarities in method and theme to extant research, and while its original contributions relate to the focus on South Africa, the update of the time frame (1990–2022), and the novel findings about energy consumption and industrial value added that defy common assumptions and warrant further examination in future work.

The checks for the ARDL model include important tests for uneven variability, repeated patterns, and whether the errors follow a normal distribution. Table 8 below shows a summary of the results.

Table 8: Diagnostic Test Results

Test	*p*-Value
Breusch-Pagan-Godfrey Heteroskedasticity	0.1367
Breusch-Godfrey Serial Correlation LM Test	0.1262
Jarque-Bera Normality Test	0.6064

The Godfrey-Breusch-Pagan test indicates that there is no heteroskedasticity ($p = 0.1367$), meaning that the variance of the residuals is constant. The serial correlation is generally good based on the Breusch-Godfrey LM test with a p-value close to 0.1262. The Jarque-Bera test $p = 0.6064$ indicates that the residuals are normally distributed. Taken collectively, these diagnostic checks confirm the soundness and validity of the ARDL model estimates.

From Figure 1, the Cumulative Sum (CUSUM) test reveals that ARDL model parameters are stable over the period of study.

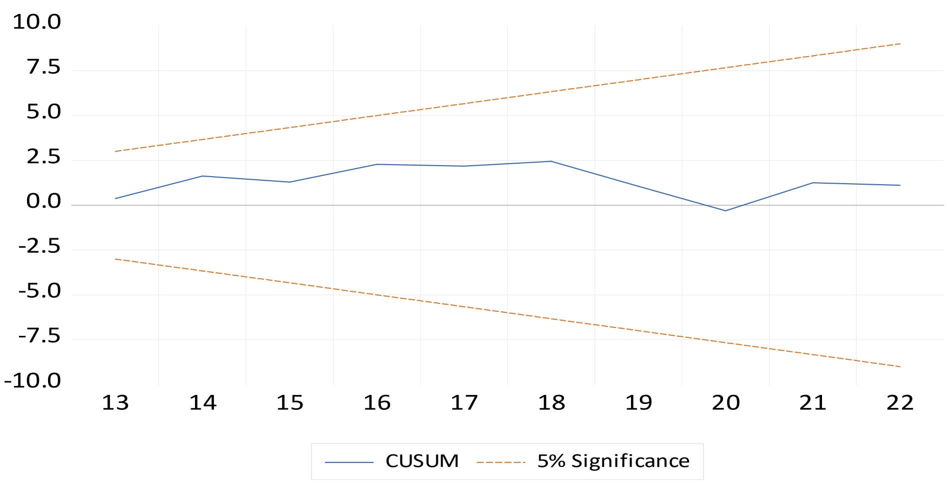

Figure 1: CUSUM Test for Parameter Stability

The solid blue line in Figure 1 indicates the cumulative sum of recursive residuals, and the dashed red lines show the 5% significance limits. This is the result of the CUSUM test to see if the model parameters are stable. From 1990 to 2022, the blue curve does not leave these "critical strips," which shows that there is no structural break or instability in the model coefficients. This proof shows that the ARDL model's estimated associations stay the same throughout time, which means that the empirical results are strong.

Figure 2 shows the CUSUM of Squares test statistics, which support the idea that the variance structure in the model residuals stays the same during the sample period.

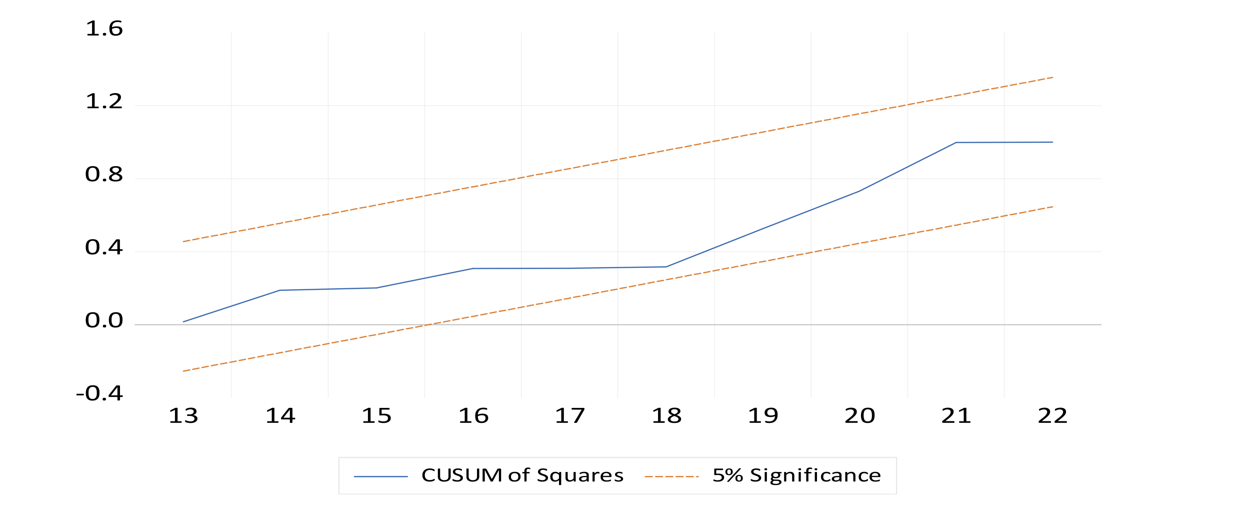

Figure 2: CUSUM of Squares Test

Figure 2 displays the CUSUM of Squares test, with the solid blue line showing the total of the squared recursive residuals, and the dashed red lines marking the 5% significance level. Since the solid blue line is entirely between these critical limits, there is no evidence for instabilities in the variance of the model errors or heteroskedasticity. The evidence suggests that the variance of the ARDL model residuals is constant, which means that ARDL estimates of the model are reliable and robust.

5. Conclusion and Policy Recommendations

This study examines at how FDI, industrialization, trade openness, and energy use affect CO emissions in South Africa from 1990 to 2022. It uses a bound testing approach to the cointegration technique. The long-run cointegration connection between these variables is steady, according to empirical evidence. This supports the ARDL approach.

In the short term, FDI and trade openness have been reported to significantly raise CO emissions, validating the PHH and suggesting the environmental problems associated with the rapid economic opening up. On the contrary, industrial activity and electricity consumption have substantial negative effects on emissions, both in the short term and the long term, which means that more efficient production and use of clean energy have occurred, which is probably due to technological changes and policy interventions. The policy implication of this study is straightforward: South Africa needs to focus on attracting green FDI driven by environmentally friendly technologies and regulation in pollution-intensive industries. Trade policy should include environmental standards as a measure to counteract negative externalities associated with export expansion. First, energy policy needs to set goals for diversifying the energy matrix, becoming more efficient, building up infrastructure for clean energy, and intentionally cutting greenhouse gases.

On the whole, this research has shed light on striking a balance between economic development and conservation in South Africa. The role of other factors (e.g., renewable energy adoption, environmental regulations, sector-specific) could be considered in future research to provide a more comprehensive influence estimation for policy reference.

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