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The influence of renewable energy consumption and trade openness on carbon emissions in South Africa: an augmented autoregressive distributed lag method application

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Abstract. *This study examines the influence of renewable energy consumption and trade openness on CO2 emissions in South Africa. To do this, a recent and robust econometric approach, namely the augmented autoregressive distributed lag (ARDL) approach, is used on the World Bank (WDI, 2025) dataset from the period 2002 to 2021. The results show that in South Africa, an increase in renewable energy consumption significantly reduces CO2 emissions in the short and long term, while an increase in trade openness damages the environment in the short term. Therefore, in order to address the challenges of climate change, energy security and socio-economic development in South Africa, this study suggests increasing the production and use of renewable energy; implementing commercial strategies that guarantee development and improve environmental quality; a significant reduction in the use of fossil fuels.*

Keywords: Renewable energy consumption, Trade openness, Carbon emissions, South Africa, Augmented ARDL.

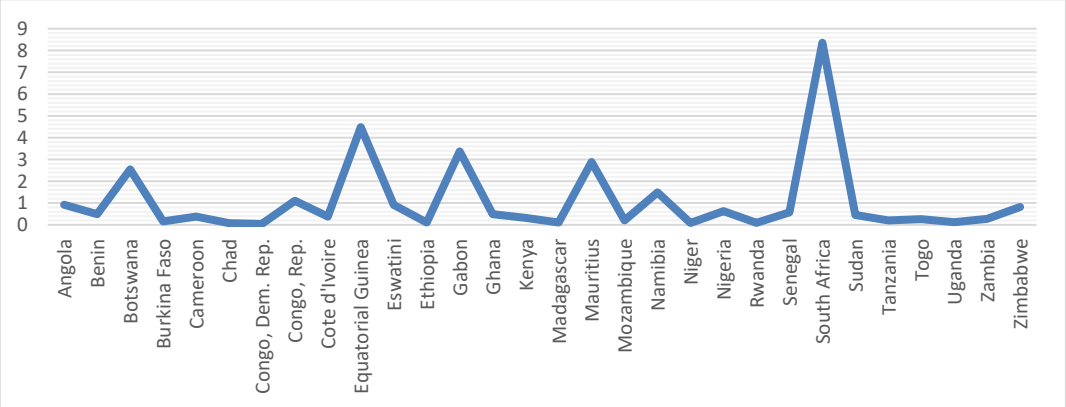
JEL Classification: C33, O13, Q42, Q54, Q58.

1. Introduction

Governments around the world have prioritized carbon reduction and carbon neutrality in order to tackle the growing threat of climate change. These goals are in line with the United Nations Sustainable Development Goals (SDG-13). These goals highlight the need to take action against climate change in order to reduce the harmful effects of human activities and the use of fossil fuels (Bekun, 2024). The impacts of pollution are not limited to humans, but also affect the overall harmony of the planet (Hassan et al. 2025). The problem of climate change, which causes various negative effects on a global scale, is one of the important research topics. It is necessary to determine the factors affecting CO2 emissions, which are the main determinants of climate change, and to take measures in this regard (Aydin, 2023). CO2, whose volume in the atmosphere has increased, is the main greenhouse gas (GHG) causing climate change. Climate change due to the increase in GHGs has a vast impact on health and the environment (Matenda et al. 2024).

In recent times, environmental degradation has gained prominence worldwide due to rising CO2 emissions. The international community has been confronted with global warming and climate change, which have had a widespread impact on human and natural systems. Global carbon emissions have shown a rapid increase over the years (Kgomo and Zhanje, 2025). Carbon emissions have significantly accelerated global warming in recent decades, thereby altering the Earth's atmosphere. Consequently, it is crucial to study the factors that contribute substantially to the increase in CO2 emissions (Amin et al. 2025: pp. 12605-12623). The need to reconcile economic growth with biodiversity conservation, as well as growing environmental concern about the impact of economic activities on CO2 emissions, has prompted the international community to develop common agendas on ecological sustainability and global warming issues over the past three decades (Perone, 2024).

Figure 1: *Trend in CO2 emissions in SSA countries between 2002 and 2021*



Source: Authors

This shows that the global increase in CO2 emissions observed through environmental degradation and global climate change is a source of great concern. It is important to note that although sub-Saharan Africa (SSA) accounts for no more than 3% of global carbon emissions, these emissions have been rising over the decades. This is due to ongoing

economic and institutional reforms aimed at stimulating economic growth, strengthening industrialization and diversifying activities, improving transport systems and responding to energy crises (Avom et al. 2020). However, among the SSA countries, South Africa stands out in terms of its emissions levels between 2000 and 2021 (Figure 1). Compared to other countries in the region, South Africa's CO2 emissions are high enough to suggest that it is the main contributor to CO2 emissions in SSA.

This therefore calls for the adoption, use and implementation of measures and policies aimed at curbing this global economic evil without hampering global economic growth rates (Egbe et al. 2024). The variables determining environmental degradation are similar to the determinants of energy consumption. The debate on environmental sustainability cannot be addressed without considering the type of energy to be used. The pace at which the world is industrializing, globalizing and developing economically has prompted many researchers to investigate the type of energy needed to preserve the environment (Justice et al. 2024). Renewable energy has emerged as a promising solution to the challenges of climate change, energy security and socio-economic development.

South Africa, with its abundant renewable energy resources, has made significant progress in the use of renewable energy over the past decade (Adebiyi and Moloi, 2024). There is no denying that the use of renewable energy has advantages in terms of preventing climate change and protecting the environment (Waris et al. 2023: pp. 72503-72513). It is widely accepted that the transition from fossil fuels to renewable sources is essential to reduce greenhouse gas emissions (Ganda, 2024; Huy, 2024: pp. 3845-3856). This will undoubtedly lead to more environmentally friendly technologies and sustainable methods in sectors such as agriculture, industry and transport. This would reduce emissions while promoting economic growth (Osabuohien-Irabor and Drapkin, 2022: pp. 52475-52498).

South Africa, which consumes the most electrical energy in Africa, is recognized as one of the most developed countries on the continent (Akinbami and Bodunrin, 2021: pp. 5077-5093). Despite limited oil and gas reserves in South Africa, the country compensates for this deficit by exploiting its large coal deposits to meet its energy needs. South Africa is gradually developing its renewable energy industry to mitigate CO2 emissions and provide sustainable and cost-effective electricity to its population (Matenda et al. 2024). South Africa is expanding its use of green energy technologies and increasing their share in the energy mix, resulting in substantial reductions in carbon emissions. Energy storage and grid flexibility technologies, by encouraging the inclusion of renewable energies in the energy system, are facilitating the elimination of fossil fuel-based electricity generation. The adoption of renewable energies in the electricity sector has contributed to the reduction of CO2 emissions.

Several studies have examined the link between renewable energy consumption and CO2 emissions. Some researchers have proven that the use of renewable energy reduces carbon emissions and improves environmental quality. The work of Al-Zubairi et al. (2025) in Arab countries; Tran et al. (2024) in ASEAN countries; Perone (2024) in OECD countries; Egbe et al. (2024) in G7 economies; Erdoğan et al. (2024) in Canada; Matenda et al. (2024) in South Africa; Rahman and Ferdaous (2024) in the MENA and OECD regions; Apergis et al. (2023) in Uzbekistan; and Dumrul et al. (2023) in Turkey corroborate this result.

However, others have found contradictory results suggesting that renewable energies contribute to increased environmental pollution. Studies by Singh et al. (2025) in 12 countries of Central and Eastern Europe and Hasni et al. (2023) in eighteen different Asia-Pacific Economic Cooperation economies corroborate this result.

Furthermore, with the increase in trade disputes related to the environment, global attention to environmental issues in international trade has intensified (Jiang and Jiang, 2025). Trade openness offers countries the opportunity to import advanced technologies for energy-efficient production and more environmentally friendly products, thereby contributing to further reductions in emissions (Ahakwa et al., 2024). The link between trade openness and CO2 emissions is a key area of research in these times of pressing global sustainability needs and ongoing discussions on climate change (Barkat et al. 2025: pp. 677-698). Trade openness can also play a role in this regard, as can the free flow of green technologies and environmentally sound practices across borders. The link between trade openness and environmental sustainability, primarily in the form of CO2 emissions, has attracted increasing attention.

The literature is nuanced and conveys mixed messages about the relationship between trade openness, which sometimes has a positive impact on environmental sustainability and other times extremely harmful effects, depending on various factors that are generally influenced by the level of development or primitiveness of a country's economy, the governance system in place, and technological progress (Sun and Qamruzzaman, 2025).

Indeed, trade openness damages the environment by increasing air pollution (Andriamahery et al. 2022; Wang et al. 2023; Mignamissi et al. 2024; Oumarou and Nourou 2024; Hassan et al. 2025; Barkat et al. 2025; Kgomo and Zhanje, 2025; Ünsal, 2025). On the other hand, conflicting results suggest that trade improves environmental quality (Udeagha and Ngepah, 2019; Aydin and Turan, 2020). Consequently, despite the existence of studies on the influence of renewable energy consumption on CO2 emissions on the one hand, and the impact of trade openness on CO2 emissions on the other, no consensus seems to have emerged. The literature is therefore nuanced and conveys mixed messages on the subject. In this context, the link between renewable energy consumption, trade openness and the environment is an innovative perspective discussed in the literature but absent for some SSA countries such as South Africa. Consequently, this study examines the following research questions:

1-Does renewable energy consumption really contribute to reducing CO2 emissions in South Africa?

2-Does trade openness have an effect on the increase in CO2 emissions in South Africa?

This research enriches the existing literature in four ways. First, despite the existence of several environmental quality indicators, the selection of CO2 is intriguing because of its multidimensional importance. Although many previous studies have been conducted on this topic, the study period and country examined in this research offer a new and distinctive perspective. Second, this research is important because it deepens our understanding of emissions dynamics and has major implications for environmental sustainability. Furthermore, a coherent and flexible approach to combating carbon emissions through energy transition, natural resource use and institutional improvement is essential for South Africa to achieve its emission reduction goals and meet global climate targets.

Thirdly, this article uses the robust and very recent econometric method known as augmented ARDL approach. To be precise, the augmented ARDL method differs from the traditional ARDL approach in several respects. The traditional ARDL method does not determine the statistical significance of all variables. The traditional ARDL method does not consider the statistical significance of all explanatory variables. As pointed out by Amin et al. (2025) and McNown et al. (2018), it is advisable to use an additional test statistic to determine the relevance of the explanatory variables and establish a precise cointegration between them. Furthermore, augmented ARDL is a method suitable for small samples, and no interference from endogenous explanatory variables is observed in the proposed test. The ARDL approach is suitable for producing short-term and long-term links when the sample size is small. Furthermore, it also follows the ordinary least squares (OLS) approach for cointegration between variables (Huang, 2022). Finally, fourthly, trade openness in this research is captured by the Squalli and Wilson (2011) indicator. Unlike the traditional indicator, this new measure takes into account two dimensions of openness. On the one hand, it considers the country's trade intensity in relation to the performance of its local economy and, on the other hand, its relative trade intensity in relation to the volume of world trade.

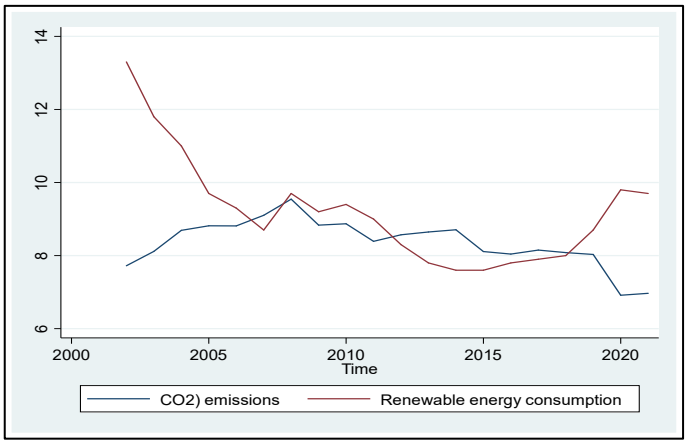
The rest of the article is organized as follows: Section 2 provides a review of the literature. Section 3 discusses the model, data and econometric method through the methodology. The fourth section presents the results and interpretations. Finally, the fifth section discusses the conclusions, suggestions and prospects for future research.

2. Literature review

2.1. Renewable energy consumption and CO2 emissions

Despite measures taken to control environmental degradation, carbon emissions continue to rise, damaging environmental quality.

Figure 2: *Trend in renewable energy consumption and CO2 emissions in South Africa*



Source: authors.

Empirical studies on the link between renewable energy consumption and CO2 emissions are summarized in Table 1. It is clear from the empirical literature (Table 1) that the link between renewable energy consumption and CO2 emissions is mixed. In South Africa, the evolution of these two variables over time shows that there is a negative correlation (Figure 2).

Indeed, it appears that between 2000 and 2020, whenever renewable energy consumption increases, CO2 emissions decrease, and vice versa.

2.1. Trade openness and CO2 emissions

Early research in the field of trade and climate change, such as that by Markusen (2013) and Copeland (2010), focused mainly on applying partial equilibrium or bilateral models to examine how a unilateral trade tax can mitigate cross-border environmental damage. This research indicates that trade policies can influence climate change through mechanisms such as greenhouse gas emissions, environmental regulation, and approaches to climate change adaptation and mitigation. It is appropriate to provide a brief summary of some information related to trade and climate change before reviewing previous research. Fundamentally, the relationship between trade and CO2 emissions exposes a duality that highlights very different dynamics. Trade can act as a driver of economic growth, leading to higher per capita income and the expansion of energy-intensive production processes.

Table 1: *Literature on the study of the link between renewable energy consumption and CO2 emissions*

Authors	Zone and period	Estimation method	Results
Al-Zubairi et al. (2025)	Pays arabes 2000-2020	FMOLS, DOLS and FGLS.	$RE \rightarrow -CO2$
Singh et al. (2025)	12 countries of Central and Eastern Europe 1990-2020	DF- GMM and one-step system GMM methods.	$RE \rightarrow +CO2$
Matenda et al. (2024)	South Africa 1990-2020	DOLS	$RE \rightarrow -CO2$
Perone (2024)	27 OECD countries 1965-2020.	The ARDL models of the PMG, MG, DFE, FMOLS, DOLS, CCEMG, GMM, PVAR and the Granger non-causality	$RE \rightarrow -CO2$
Egbe et al. (2024)	G7 economies 1990-2020.	The Dynamic Fixed Effect Autoregressive Distributive Lag and the Pooled Mean Group	$RE \rightarrow -CO2$
Erdoğan et al. (2024)	Canada 1965-2017.	ARDL	$RE \rightarrow -CO2$
Rahman and Ferdaous (2024)	Three distinct regions: SAARC, MENA and OECD 1998-2018	Panel ARDL causality tests, FMOLS, DOLS, and D-H.	In the MENA and OECD countries, RE$\rightarrow -CO2$ But has an insignificant effect in SAARC countries.
Wang et al. (2023)	24 countries with nuclear energy 2001-2020	The second-generation panel unit root test, the panel cointegration test, FMOLS, and the Dumitrescu and Hurlin test	$RE \rightarrow -CO2$
Tran et al. (2024)	ASEAN countries 2000-2020	Panel vector autoregression and Granger non-causality test in heterogeneous panels, as well as long-term estimation techniques	$RE \rightarrow -CO2$
Dumrul et al. (2023)	Turkey 1971-2006	Cointegration with Fourier Autoregressive Distributed Lag (ADL), DOLS and Fourier-Granger Causality tests	$RE \rightarrow -CO2$

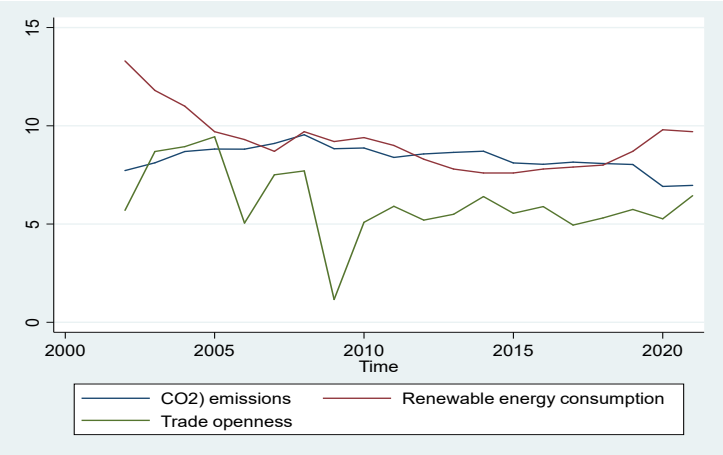
Authors	Zone and period	Estimation method	Results
Jiang and Khan (2023)	Belt and road innitiative countries 1995-2019	OLS, fixed effect, and GMM	$RE \rightarrow -CO2$
Waris et al. (2023)	19 G20 member countries 2000-2019	Dynamic fixed effects and GMM	$RE \rightarrow -CO2$
Hasni et al. (2023)	Eighteen different Asia-pacific economic cooperation economics economies 2000-2019	PMG-ARDL approach and Granger causality tests, the Pedroni tests.	$RE \rightarrow +CO2$
Sadiq et al. (2024)	Brics-1 countries 1990-2020.	AMG, CCMEG, CS-ARDL, and cross-sectionally augmented distributed lag (CS-DL)	A 1% increase in ER led to a 0.43% decrease in CO2 in the short term and a 0.23% to 0.55% decrease in the long term.
Jamil et al. (2022)	7 countries from the G-20 1990-2019	FMOLS and DOLS	A 1% increase in ER was linked to a 0.2% decrease in CO2
Ekwueme et al. (2021)	South Africa 1970- 2014	The unit root test of Zivot-Andrews and ADF, VAR, and Pesaran ARDL	In the long term RE→ $+CO2$. In the short term RE→ $-CO2$

Source: Compilations by the authors. Note: RE→+CO2 = renewable energy increases CO2 emissions; RE→-CO2 = renewable energy reduces CO2 emissions; ARDL = Autoregressive distributed lag; FMOLS= fully modified Ordinary least square; DOLS= Dynamic Ordinary least square; SAARC=Association for Regional Cooperation; MENA= Middle East and North Africa; OECD=Organization for Economic Cooperation and Development; RE=Renewable energy; ASEAN: Association of Southeast Asian Nations; PMG=pooled mean group; MG=mean group; DFE= dynamic fixed effect; CCEMG=common correlated effects mean group (CCEMG), GMM=generalized method of moment; PVAR= panel vector autoregression; OLS=Ordinary Least Square; CS-ARDL=cross-sectionally augmented ARDL; VAR= vector autoregressive; ADF=Augmented Dickey-Fuller.

This effect, known as the 'scale effect', is often accompanied by an increase in energy consumption and a consequent rise in CO2 emissions (Copeland and Taylor, 2004). In addition, trade can generate a 'composition effect' by altering global production and consumption patterns, leading to the production of high-emission goods (Khan et al., 2020). Furthermore, the 'pollution refuge hypothesis' introduces another level of complexity, suggesting that countries with less stringent environmental laws may focus on polluting sectors when faced with divergent standards. Generally, these sectors are capital-intensive in developed countries that enforce strict environmental policies. Furthermore, strong financing capacity may encourage the transfer of highly polluting production to developing countries (Barkat et al. 2025).

The empirical literature is summarized in Table 2. In South Africa, it is clear that the evolution of trade openness reveals a link that is difficult to determine in comparison with CO2 emissions (Figure 3). However, between 2010 and 2020, the increase in emissions is associated with an increase in trade.

Figure 3: *Evolution of key variables in the study over time*



Source: Authors

Unlike these studies, which use trade share (TS), i.e. the degree of openness, the composite indicator of Squalli et Wilson (2011)[(1)] is used in this research to capture South Africa's level of openness. This indicator is given by equation (1):

$$CTS = \frac{n(X+M)_i^2}{PIB \sum_{j=1}^{n}(X+M)_j} \quad (1)$$

The CTS represents the TS adjusted by the proportion of a country's trade level relative to average global trade. The data on exports X, imports M and GDP needed to construct the CTS indicator are taken from the World Development Indicators (Fankem and Oumarou, 2020).

Table 2: *Literature on the study of the link between trade openness and CO2 emissions*

Authors	Periods and Countries	Methods used	Results obtained
Zhou et al. (2025)	Emerging Countries 2003-2020	FMOLS, DOLS, PMG-ARDL, DCCEMG, and Driscoll–Kray	$TO \leftrightarrow CO2$
Barkat et al. (2025)	20 OECD countries 150-year, 1870-2019	CCE-MG and AMG estimators	$TO \rightarrow +CO2$
Sun and Qamruzzaman (2025)	BRICS + T countries 1990-2022.	DSUR, CS-APUR, ARDL	$TO \rightarrow +CO2$
Hassan et al. (2025)	South Asia 1990-2018	FE, RE, AMG, FMOLS, DOLS, CCEMG and AMG	$TO \rightarrow +CO2$
Kgomo and Zhanje (2025)	BRICS plus countries 2001-2020	Panel econometric methods such as the panel autoregressive distributed lag	$TO \rightarrow +CO2$
Ünsal (2025).	Nine developing countries 1990-2020	Heteroscedasticity detection, the method Huber-Eicker-White is used for estimation to estimate the coefficients correctly.	$TO \rightarrow +CO2$
Fang et al. (2025)	Australia 1990-2023	ARDL	$TO \rightarrow +CO2$
Keşap et al. (2025)	five developing Organization of Turkic States (OTS) members 1993-2021	This study employs panel data methods, AMG and CCEMG estimation	$TO \rightarrow +CO2$
Mignamissi et al. (2024)	Africa	STIRPAT model. 2SLS	$TO \rightarrow +CO2$

Authors	Periods and Countries	Methods used	Results obtained
Oumarou and Nourou (2024)	SSA 2002-2019	GMM, 2SLS	$TO \rightarrow +CO2$
Wang et al. (2023)	122 countries 1998-2018.	Pesaran CD test, CIPS unit root test, Pedroni cointegration test, FMOLS, Dumitreschu-Hurlin causality test and DOLS	$TO \rightarrow +CO2$
Duodu and Mpuure (2023)	SSA 1990-2020	GMM and the Dumitrescu and Hurlin (D-H) causality test	Trade reduces environmental pollution by approximately 0.10% and 0.79% in the short and long term, respectively.
Andriamahery et *al.* (2022)	ASS 1990-2017	GMM	$TO \rightarrow +CO2$
Nguyen et *al.* (2020)	33 emerging economies 1996-2014	Model STIRPAT, ARDL	$TO \rightarrow +CO2$
Udeagha and Ngepah (2019)	South Africa 1960-2016	ARDL	$TO \rightarrow -CO2$

Source: authors. Notes: TO↔CO2= bidirectional relationship between trade openness and CO2 emissions; TO→-CO2= trade openness reduces CO2 emissions; TO→+CO2= trade openness increases CO2 emissions; GMM=Generalized Method of Moments; CO2= carbon dioxide, SSA= Sub-Saharan Africa; FMOLS= Fully Modified Ordinary Least Squares, DOLS= Dynamic Ordinary Least Squares, ARDL= Autoregressive Distributed Lag model,, STIRPAT= Stochastic Impact by Regression on Population, Affluence and Technology, BRICS= Brazil, Russia, India, China and South Africa,, OECD = Organization for Economic Co-operation and Development; DCCEMG = Common-correlated effect mean group; DSUR = Dynamic Seemingly Unrelated Regression; CS-APUR = Cross-Sectionally Augmented Panel Unit Root; 2SLS = Two-Stage Least Squares estimation; FE = Fixed Effects; RE = Random Effects; AMG = Augmented Mean Group; CCEMG = Common Correlated Effects Mean Group Approaches.

3. Methodology

3.1. Econometric model used

This research explores the influence of renewable energy consumption and trade openness on CO2 emissions in South Africa. Based on the study by Amin et al. (2025), an empirical model is developed (equation 2), where CO2 depends on renewable energy consumption, trade openness, natural resources, real income, inward foreign direct investment, fossil fuel consumption and governance (Control of Corruption, Government Effectiveness, Regulatory Quality, Rule of Law, Voice and Accountability, Political Stability and Absence of Violence). This research covers the period 2002-2021. The sample was selected based on the availability of data across the different variables. The estimation model is given by the following equation (2):

$$CO2_t = \propto_0 + \propto_1 REC_t + \propto_2 TO_t + \propto_3 NRR_t + \propto_4 GDP_t + \propto_5 FDI_t + \\ + \propto_6 FEC_t + \propto_8 GOV_t + \mu \qquad (2)$$

In equation (2), carbon dioxide emissions are denoted by CO2, which is an environmental variable, REC is renewable energy consumption, TO is trade openness, NRR represents natural resource rent, GDP gross domestic product per capita, FDI is foreign direct investment inflows, FEC represents fossil energy consumption, and GOV is the synthetic

indicator of institutional quality. The explanation and sources of the above indicators are discussed in Table 3.

Table 3: *Variables with measurements*

Variables	Symbols	Definition	Source
CO2 emissions (metric tons per capita)	$CO2$	Carbon dioxide (CO_2) emissions per capita, which serves as an indicator of environmental deterioration.	World Development Indicators
Renewable Energy Consumption	REC	Renewable energy consumption is the share of renewable energy in total final energy consumption.	World Development Indicators
Trade Openness	TO	The trade intensity composed by Squalli and Wilson (2011) is used to describe the degree of openness of SSA countries.	World Development Indicators
Total natural resources rents (% of GDP)	NRR	Total natural resources rents are the sum of oil rents, natural gas rents, coal rents (hard and soft), mineral rents, and forest rents.	World Development Indicators
GDP per capita growth (annual %)	GDP	Gross domestic product is the total income earned through the production of goods and services in an economic territory during an accounting period. This indicator denotes the percentage change over each previous year of the constant price (base year 2015) series in United States dollars.	World Development Indicators
Foreign direct investment, net inflows (% of GDP)	FDI	Foreign direct investment are the net inflows of investment to acquire a lasting management interest (10 percent or more of voting stock) in an enterprise operating in an economy other than that of the investor.	World Development Indicators
Fossil fuel energy consumption (% of total)	FEC	Fossil fuel comprises coal, oil, petroleum, and natural gas products.	World Development Indicators
Governance	GOV	These indicators are: Control of Corruption, Government Effectiveness, Regulatory Quality, Rule of Law, Voice and Accountability, Political Stability and Absence of Violence	World Governance Indicators

Source: Compiled by the authors.

3.2. Estimation strategy

The autoregressive distributed lag (ARDL) approach, introduced by Pesaran et al. (2001), has been widely used in previous studies (Fang et al. 2025; Perone, 2024; Egbe et al. 2024; Erdoğan et al. 2024; Rahman and Ferdaous, 2024; Apergis et al. 2023; Udeagha and Ngepah, 2019). The reason is that the test is very flexible as it allows regressors to be at level or in first difference, assuming that the regressor must be in first difference (Amin et al. 2025). ARDL is the best technique for finding variable integrations as it is well suited to a small sample of data (Osabohien et al. 2018).

The augmented ARDL approach offers many benefits. First, the sequence of incorporation of the model's indicators, including the dependent variable, can vary, but they must not exceed one (i.e., they must not be I(2)). Second, it is an appropriate method for small data sets. Thirdly, according to Perasan et al. (2001), endogenous explanatory factors have no indirect impact on the suggested test. And finally, fourthly, the approaches provide long-term coefficients (Pakrooh et al. 2025). Equation (2) is presented in the form of an ARDL error correction model, as is equation (3):

$$\Delta CO2_t = \beta_0 + \sum_{i=1}^{q} \beta_{1i}\Delta CO2_{t-i} + \sum_{i=0}^{p} \beta_{2i}\Delta REC_{t-i} + \sum_{i=0}^{u} \beta_{3i}\Delta TO_{t-i} + \sum_{i=0}^{v} \beta_{4i}\Delta NRR_{t-i} + \sum_{i=0}^{w} \beta_{5i}\Delta GDP_{t-i} + \sum_{i=0}^{x} \beta_{6i}\Delta FDI_{t-i} + \sum_{i=0}^{y} \beta_{7i}\Delta FEC_{t-i} + \sum_{i=0}^{z} \beta_{8i}\Delta GOV_{t-i} + \alpha_1 CO2_{t-1} + \alpha_2 REC_{t-1} + \alpha_3 TO_{t-1} + \alpha_4 NRR_{t-1} + \alpha_5 GDP_{t-1} + \alpha_6 FDI_{t-1} + \alpha_7 FEC_{t-1} + \alpha_8 GOV_{t-1} + \mu_t \quad (3)$$

The ideal lag times for each variable are indicated by q, p, u, v, w, x, y, and z in equation (3), with the lag times selected using Akaike's information criteria (AIC). The range of the calculated parameters is $[\beta_0 \ldots\ldots \beta_8]$ and $[\alpha_1 \ldots\ldots \alpha_8]$. Initially, two tests are suggested to analyze cointegration between indicators: the t-test on the explained lagged indicator and the F-test assessing the relevance of indicators for all lagged variables. In addition, it contains two degenerate cases.

For case 1, although the F-test shows statistical significance, the coefficients of the explanatory variables ($\beta_0 \ldots\ldots \beta_8$) are not. Event 2 occurs if the F-test shows significance, but the coefficient of the explanatory variables (β_1) is not. To avoid the second degenerate case, it is imperative that both T and F tests are significant(2).

However, Goh et al. (2017) argued that this assumption does not accurately reflect cointegration, as unit root tests often have insufficient power. If the estimates of the F and T statistics exceed their critical thresholds, it can be inferred that all included indicators exhibit cointegration. Furthermore, when establishing equation (3) to obtain long-term results, an error correction model is calculated in parallel in order to obtain the coefficients of the error correction term(3).

4. Results and interpretations

4.1. Descriptive analyses

The descriptive statistics (Table 4) for the main variables analyzed are shown in the table below and reveal the same number of observations (20) for all variables. The average CO2 emissions for South Africa are around (8.356). Renewable energy consumption averages 9.215, while trade openness averages around 6.071**.** Furthermore, natural resource rents have an average value of 1.425. Governance has the lowest average value (0.202) and also the lowest maximum value (0.388). Gross domestic product has the highest average value (9.935) and the highest maximum value (11.877). Foreign direct investment has an average value of 1.653 with a maximum and minimum value of 9.660 and 0.205 respectively. Fossil

fuel consumption has an average of 9.668, with a maximum and minimum of 9.650 and 8.260 respectively.

Table 4: *Descriptive statistics of variables*

Variable	Obs	Mean	Std. Dev.	Min	Max	Skewness	Kurtosis	J-B	Probability
CO2	20	8.356	0.652	6.914	9.545	0.343	2.772	34.922*	0.113
REC	20	9.215	1.477	7.600	13.3	-0.750	3.121	32.543*	0.144
TO	20	6.071	1.801	1.161	9.440	2.151	5.871	61.912*	0.173
NRR	20	1.425	0.886	0.187	3.831	1.136	3.532	32.721*	0.233
GDP	20	9.935	3.338	6.815	11.877	1.811	4.111	6.989*	0.177
FDI	20	1.653	2.039	0.205	9.660	2.543	7.111	15.771*	0.411
FEC	20	9.668	1.388	8.260	9.650	1.311	8.523	17.524*	0.239
GOV	20	0.202	0.133	-0.016	0.388	1.324	6.341	19.625*	0.134

Source: authors. Note: *, **, and *** indicate significance at the respective thresholds of 1%, 5%, and 10%.

Overall, the descriptive statistics show little variation. Skewness, kurtosis and Jarque-Bera (J-B) tests are used to verify the normality of the data. The first refers to a measure of asymmetry, the second deals with the precision and amplitude of the peak of the curve, while the third establishes whether the asymmetry and kurtosis of the data are consistent with a normal distribution. The assumptions of skewness and kurtosis require a mean different from zero and a mesokurtic distribution. Descriptive statistics clearly indicate that CO2, REC, TO, NRR, GDP, FDI, FEC, and Gov in our selected country show little fluctuation over the period. Therefore, the fluctuations appear appropriate for further empirical evaluation.

Table 5: *Correlation matrix between variables*

Variables	CO2	REC	TO	NRR	GDP	FDI	FEC	Gov
CO2	1.000							
REC	-0.172	1.000						
TO	0.131	0.323	1.000					
NRR	-0.055	-0.116	-0.143	1.000				
GDP	0.208	-0.030	-0.423	0.342	1.000			
FDI	-0.294	0.033	0.045	0.732	0.055	1.000		
FEC	0.039	-0.871	-0.392	0.352	0.890	0.123	1.000	
Gov	0.614	0.546	0.399	-0.247	-0.578	-0.320	-0.664	1.000

Source: Authors

Table 5 provides a description of the correlations between the different analysis variables. The correlation matrix shows the existence of correlations between the different variables used. The correlations between CO2 emissions and renewable energy consumption, and between CO2 emissions and trade openness, are -0.172 and 0.131 respectively. The correlations between CO2 emissions and natural resources, and between CO2 and gross domestic product, are -0.055 and 0.208 respectively. Furthermore, the highest correlations appear between gross domestic product and fossil fuel consumption (0.890) and between governance and CO2 emissions (0.614). This proves that there is no multicollinearity between the independent variables. However, the weakest correlations appear between renewable energy consumption and fossil fuel use (-0.871), between governance and gross domestic product (-0.578), and between trade openness and gross domestic product

(-0.423). Nevertheless, the correlations between the different variables analyzed are not high enough to cause the problem of multicollinearity.

4.2. Unit root tests

Although different integration orders of variables can be subjected to the augmented ARDL bounds test, it must be ensured that no variable is I(2). This study is based on unit root tests, integrating all relevant variables, to analyze the time series data. As previously indicated, the ARDL cointegration technique is only valid for time series that are stationary at the level or at the first difference. Unit root tests such as Im-Pesaran-Shin (Im et al., 2003), CADF and CIPS are designed to deal with cross-sectional dependencies. Table 6, which focuses on South Africa, shows significant results for unit root tests. This suggests a strong argument against the null hypothesis of the existence of a unit root for certain variables. For example, variables such as CO2, REC, TO, NRR and FDI show stationary processes at level I(0), which means that differentiation is not necessary to achieve stationarity. Although the unit root test results for other variables such as GDP, FEC, and GOV are not statistically significant, they suggest the presence of a unit root in the series.

Table 6: *Unit root test results*

Country: South Africa				
Variables	**Im-Pesaran-Shin**	**CADF**	**CIPS**	**Stationary Level**
$CO2$	-1.34***	-1.56	-1.77	I(0)
REC	-1,32***	-6.88	-1.92	I(0)
TO	2.22***	-3.86	-2.31	I(0)
NRR	-1,53	-5.01	-4.77	I(0)
GDP	2,27	2.54	7.32	I(1)
FDI	2,91	-3.21	2.71	I(0)
FEC	-1,01	5.55	2.45	I(1)
Gov	-1,23	-1.11	-1.72	I(1)

Source: Authors. Notes: Im-Pesaran-Shin unit panel root test (Null hypothesis= All panel contains unit root). Pesaran's CADF panel unit root test in presence of cross section dependence (Null hypothesis= all series are non-stationary). Pesaran panel unit root test in the presence of cross-section dependence (Null hypothesis= (homogeneous non-stationary). *Refers to 10 %, ** is 5 %, and *** is 1 % significance level.

Furthermore, based on the augmented ARDL method, we find that none of the variables in our model exhibit stationarity at second difference, while all do at first difference. Consequently, we will perform the cointegration test.

4.3 The cointegration test for the augmented ARDL method

Given that CO2 emissions, renewable energy consumption, trade openness, natural resource rents, foreign direct investment, fossil fuel consumption, gross domestic product and governance are either stationary at level or stationary at their first difference, we use the ARDL cointegration method to estimate equation 3. Table 7 shows the results of the bounds cointegration test.

The estimated F statistic is shown in Table 7, along with the critical limits for 10%, 5% and 1% respectively. The decision rule states that if the F statistic of the test exceeds the threshold value for a certain significance level (1%, 5% or 10%), the null hypothesis is rejected, and vice versa.

Table 7: *Cointegration Test Results*

F-statistics	Significance (%)	Critical bounds	
		I(0)	I(1)
5.633*	1	5.12	5.23
	5	4.22	5.39
	10	3.67	3.77

Source: Authors. Notes: *Represents a 1% level of significance

According to the evaluated model, , $f(CO2 = REC, TO, NRR, GDP, FDI, FEC, Gov)$,, where CO2 emissions represent the dependent variable; renewable energy consumption and trade openness represent the variables of interest; natural resource rent, foreign direct investment, fossil fuel consumption, gross domestic product and governance are the control variables, we also conclude that there is a long-term correlation between the selected variables, given that the F statistic determined exceeds their maximum critical values, leading us to reject the null hypothesis of non-cointegration. These results on the existence of a long-term relationship between the different variables in this study corroborate the empirical investigations found by Sadiq et al. (2024) in the BRICS-1 countries (Brazil, Russia, India and China) between 1990 and 2020; Perone (2024) in 27 OECD countries between 1965 and 2020; Bekun (2024) in South Africa between 1975 and 2020; Egbe et al. (2024) in G7 economies (France, Germany, Canada, Italy, and the United Kingdom) over the period 1990-2020; Erdoğan et al. (2024) in Canada between 1965 and 2017; and Amin et al. (2025) in China between 1990 and 2019.

The results found are therefore conclusive and support the existence of cointegration relationships among the variables examined. Thus, a cointegration relationship is established between the different variables in our model. Consequently, we now assume that the results predicted in the next section are accurate, consistent and economically significant.

4.4. Long-term and short-term results of the augmented ARDL estimation

Table 8 presents the results of several diagnostic procedures. We use several diagnostic tests, namely the Jarque-Bera normality test; the LM test for serial correlation; the ARCH test for heteroscedasticity; and the Ramsey test for model specification. We use these tests following the modelling approach from general to specific. After completing the diagnostic tests, we arrive at the ideal model exactly as in Amin et al. (2025).

Table 8 presents a description of the long-term and short-term results for renewable energy consumption, trade openness, natural resource rents, foreign direct investment, fossil fuel consumption, gross domestic product, and governance. With regard to the environmental impacts of renewable energy consumption, the results indicate that an increase in the use of renewable energy reduces CO2 emissions in South Africa. These results corroborate the findings of Perone (2024) in OECD countries; Egbe et al. (2024) in G7 economies; Matenda et al. (2024) in South Africa; Al-Zubairi et al. (2025) in Arab countries; and Rahman and Ferdaous (2024) in the MENA and OECD regions, who found that renewable energy consumption plays an important role in mitigating carbon emissions. However, these results contradict a body of research. For example, in Uzbekistan, non-renewable energy consumption, natural gas and oil consumption have a positive impact on per capita

CO2 emissions in the short and long term (Apergis et al. 2023). However, some authors have found that renewable energies contribute to increased environmental pollution, such as Singh et al. (2025) in 12 countries of Central and Eastern Europe; Hasni et al. (2023) in eighteen different Asia-Pacific Economic Cooperation economies. Consequently, South Africa has an interest in consuming renewable energy, which is the best strategy for pursuing the mission of limiting the temperature increase to 2 degrees Celsius and thus guaranteeing an intact environment for future generations. Furthermore, the signatory countries to the protocol and the main producers of renewable energy have a responsibility to implement appropriate measures to achieve the established goals. The consumption of renewable energy could overcome the problem of environmental degradation and achieve sustainable development (Jiang and Khan, 2023).

Table 8: *Results of the augmented ARDL estimation*

Estimations	Variables	Coefficient	Std.Err.	Probability
Long run results	$1.CO2$	-1.551**	-2.513	0.044
	REC	-0.071***	-1.668	0.000
	TO	0.022	-2.213	0.712
	NRR	0.012***	-6.431	0.032
	GDP	0.002***	3.341	0.000
	FDI	0.009**	1.234	0.046
	FEC	0.055***	4.321	0.000
	Gov	0.021*	-2.326	0.092
Short run results	$Adjust.Term\ (CO2)$	-1.675***	-2.555	0.039
	ΔREC	-0.067***	-1.951	0.001
	ΔTO	0.003*	-3.921	0.09
	ΔNRR	0.038***	-9.231	0.000
	ΔGDP	0.001*	6.291	0.092
	ΔFDI	0.006*	1.422	0.081
	ΔFEC	0.305	2.541	0.000
	ΔGov	0.014***	-1.183	0.009
	ECM	-0.091***	-1.032	0.000
Diagnostic tests	Ramsey	3.001	-	0.412
	Jarque-Bera	1.023	-	0.124
	Arch	2.015	-	0.543
	LM	3.662	-	0.244

Source: authors. Notes: *refers to 10 %, ** is 5 %, and *** is 1 % significance level

It has also been determined that trade openness has a positive impact in both the long and short term. However, only the short-term result is significant. This result is quite revealing, since unlike highly advanced countries such as China, Germany and the USA, South Africa is in its early stages of development and uses less sophisticated techniques to reduce carbon emissions. These results corroborate those found by Andriamahery et al. (2022) in SSA; Wang et al. (2023) in 122 countries around the world; Mignamissi et al. (2024) in Africa; Oumarou and Nourou (2024) in SSA; Hassan et al. (2025) in South Asia; Barkat et al. (2025) in 20 OECD countries; Kgomo and Zhanje (2025) in the BRICS plus countries; and Ünsal (2025) in nine developed countries. Furthermore, these results contradict the findings of Udeagha and Ngepah (2019) in South Africa and Aydin and Turan (2020) in the BRICS countries.

The link between natural resources and CO2 emissions has remained a crucial environmental conjecture (Khan and Hassan, 2024). A major debate in environmental

economics concerns the impact of natural resources on CO2 emissions (Khan et al. 2024, Han et al. 2024, Wang et al. 2024). However, there seems to be no consensus on the actual effect of abundant natural resources on CO2 emissions. In our results, natural resource rents show a direct and statistically significant correlation with CO2. These findings illustrate the unsustainable use of natural resources in South Africa, considering that this country is one of Africa's major mining powers. Furthermore, the relentless demand for energy and other materials in South Africa has put considerable pressure on its natural resources. The findings are consistent with those of Amin et al. (2025) in China; Destek and Sarkodie (2019) for developed countries; Bekun et al. (2019) for European Union countries; and Baloch et al. (2019) in the BRICS economies. Furthermore, the direct link between natural resources and CO2 emissions in South Africa may stem from its heavy dependence on its abundant natural resources. This phenomenon leads to unsustainable exploitation and use of natural resources and reinforces the country's dependence on fossil fuel imports.

Furthermore, South Africa is considered to be a country that has recently entered a phase of rapid development, unlike other countries in sub-Saharan Africa. Table 8 also illustrates a statistically significant positive correlation between GDP growth and CO2 emissions in South Africa. In other words, with a significance level of 1% and 10%, there is a 0.002% and 0.001% increase in CO2 in the long term and short term, respectively, for each 1% increase in gross domestic product. As the relationship between GDP and CO2 emissions shows a positive correlation in the short and long term, an increase in GDP leads to an increase in CO2 emissions. Therefore, it can be argued that South Africa has become one of Africa's major economies in recent decades, requiring sustained growth in energy consumption to support its economic expansion. In the context of studies conducted for South Africa, these findings corroborate those found by Ekwueme et al. (2021). Globally, these results corroborate the findings of Amin et al. (2025) in China and Egbe et al. (2024) in G7 economies (France, Germany, Canada, Italy, and the United Kingdom).

It appears that FDI has a positive impact on CO2 emissions in South Africa. These results are consistent with theoretical predictions and certain empirical investigations, thus supporting the pollution haven hypothesis in South Africa. In the literature, these results have been found by Sabir et al. (2020) and Demena and Afesorgbor (2020). Furthermore, some authors have found the contradictory hypothesis, namely the pollution halo hypothesis (Bildirici and Gokmenoglu, 2020). With regard to fossil fuel consumption, the results show that the use of these energies contributes significantly to increasing CO2 emissions in South Africa. In fact, a 1% increase in fossil fuel use leads to an increase in CO2 emissions in South Africa of 0.055% in the long term and 0.305% in the short term. In addition, the production of goods in South Africa is increasingly reliant on fossil fuels, which exacerbates the degradation of their environment.

According to Bekun (2024), fossil fuel consumption has adverse effects on environmental sustainability in South Africa. Similarly, Khan et al. (2024) demonstrate that an increase in CO2 emissions is due to the use of oil, gas and coal in their study on the United States, China, Romania and Thailand. Alongside the growth and globalization of the world economy since the first industrial revolution, the production and use of fossil fuels have led to an increase in CO2 emissions and, ultimately, significant environmental degradation

(Dumrul et al. 2023). In the case of South Africa, it appears that despite economic growth based on fossil fuels, these fuels contribute significantly to increasing CO2 emissions and consequently to climate change and, in turn, to environmental degradation. Therefore, it would be preferable for South Africa to reduce its dependence on fossil fuels and opt for renewable energies in order to meet the increase in energy demand. To achieve this, the most important approach is to invest in technologies that are sustainable in the long term from an ecological point of view. With regard to governance outcomes, it can be observed that weak institutional quality indicators in South Africa have negative repercussions on their environment by increasing CO2 emissions. According to Aka et al. (2024), the quality of institutions determines the energy transition in SSA. Some studies suggest that the quality of institutions is a determinant of CO2 emissions (Hussain and Dogan, 2021; Khan and Rana, 2021). Therefore, the adoption of effective institutional procedures and robust rule of law practices can help raise awareness among businesses about compliance with CO2 emission restrictions (Muhammad and Long, 2021). It would be preferable for South Africa to further improve its level of governance.

5. Conclusion, policy implications and research perspectives

In the current context, it is clear that the change caused by the global increase in CO2 emissions has become a major issue that could compromise sustainability on a global scale. Several researchers and academics have therefore focused on investigating the link between economic variables and environmental quality. It is in this context that this study was conducted for South Africa, which is the main contributor to CO2 emissions in SSA according to World Bank data. The main objective of this research is to assess the influence of renewable energy consumption and trade openness on CO2 emissions in South Africa. Several contributions have been made in this research to demonstrate its relevance in the current context.

Firstly, despite the existence of several indicators of environmental quality, the selection of CO_2 as the dependent variable is intriguing due to its multidimensional importance. Although many previous studies have been conducted on this topic, the temporal dimension (2002-2021) and geographical scope (South Africa) of this research offer a new and distinctive perspective. Secondly, this research is important because it deepens our understanding of emissions dynamics and has major implications for environmental sustainability. Furthermore, a coherent and flexible approach to improving the environment through renewable energy consumption, improved trade policies, natural resource use, reduced fossil fuel use, and improved governance is essential for South Africa to achieve its emission reduction goals and meet global climate targets. Thirdly, this research uses the most recent econometric method, namely the augmented distributed lag autoregressive (ARDL) approach, unlike previous research which uses the traditional ARDL approach. Fourthly, trade openness in this research is captured by a recent measure which, unlike the traditional indicator or degree of openness, takes into account two dimensions of a country's openness. This measure takes into account, on the one hand, the trade intensity of a given country in relation to the performance of its local economy and, on the other hand, the relative trade intensity of that country in relation to the volume of world trade. The study's

empirical investigations highlight that an increase in renewable energy consumption significantly reduces CO2 emissions in the short and long term, while an increase in trade openness damages the environment in the short term. Furthermore, the results show that fossil fuel consumption, FDI, natural resources and governance contribute to environmental degradation in South Africa.

Therefore, in order to create an environment conducive to long-term, inclusive and environmentally sustainable economic growth, this study suggests increasing the production and use of renewable energy; implementing policies and commercial strategies that guarantee development without neglecting the environmental aspect. Furthermore, it would be preferable for South Africa to reduce its dependence on fossil fuels and opt for renewable energies in order to meet the increase in energy demand. Effective management of inward FDI and natural resources is important for reducing CO2 air pollution in this country. Furthermore, taking into account the effects of governance (control of corruption, government effectiveness, regulatory quality, rule of law, voice and accountability, political stability and absence of violence) on CO2 emissions, it seems imperative for South Africa to improve the quality of its institutions.

Furthermore, this study used methods that provide long-term and short-term coefficients, although they do not establish causal links between the variables used. Future research could use alternative estimation techniques to determine whether past values of variable X, such as renewable energy consumption, trade openness or natural resources, can predict future values of variable Y, such as environmental quality as measured by CO2 emissions. In this case, we recommend that future studies use the non-causality test to address the issue of causality between variables. Future studies could also conduct analyses at the level of other countries and use other indicators of environmental quality.

Notes

(1) According to these authors, trade openness, commonly measured by the trade share $TS = X + M/GDP$ In hundreds of studies published to date, the world's largest trading nations, such as the United States, the United Kingdom, Japan and Germany, are systematically considered closed economies, regardless of the data set used. But is it normal to classify countries such as the United States, the world's leading trading power, Japan and Russia as closed economies? The obvious explanation is that the TI and related indicators are one-dimensional measures of trade openness and, as such, penalize large economies by classifying them as closed. Based on this observation, they suggested a composite measure of trade share that more fully reflects reality by combining two important dimensions of trade openness: trade share and the relative importance of a country's trade level relative to total world trade.

(2) However, according to McNown et al. (2018), the first degenerate case can be ruled out by assuming that the regressor is I(1).

() In addition, a vector error correction model (VECM) is used to examine explicit and implicit causality, provided that a long-term correlation is actually observed between the variables. This process also makes it possible to examine long-term and short-term relationships, which manifest themselves not only between dependent variables, but also between independent variables.

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