Investigating environmental quality and economic growth interdependency: An Environmental Kuznets Curve study of South Africa

A Dissertation

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by

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Declaration

I, **Bradley Nicolan Padayachee**, hereby declare that the work on which this thesis is based is my original work (except where acknowledgements indicate otherwise) and that neither the whole work nor any part of it has been, is being, or is to be submitted for another degree in this or any other university. I authorise the University to reproduce for the purpose of research either the whole or any portion of the contents in any manner whatsoever.

Signature:…Bradley Padayachee…………………………….

Date: 13 October 2024…………………………………….

Table of Contents

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Abstract

Economic growth at the expense of environmental quality has become an increasingly important policy concern since 2015, with the establishment of the Sustainable Development Goals at the United Nations Framework Convention on Climate Change in Paris. This study investigated the interdependency between environmental quality and economic growth in South Africa, within the framework of the Environmental Kuznets Curve (EKC) hypothesis, based on annual emissions and economic growth data from 1970 to 2018. The study examined the short and long run relationships of CO_2, NO_2, SO_2 and PM2.5 emissions with economic growth, respectively, utilising a time-series Autoregressive Distributed Lag estimation method in conjunction with classical unit root and cointegration techniques.

The study revealed that CO_2, NO_2 and PM2.5 has positive and statistically significant long run relationships with economic growth in South Africa. Additionally, CO_2 was found to be the only indicator of environmental quality that depicted a negative and statistically significant long run relationship with economic growth squared, thereby revealing a negative parabolic relationship with economic growth in accordance with the Environmental Kuznets hypothesis. Similarly, only CO_2 emissions portrayed an EKC relationship with economic growth in the short run, while NO_2 and PM2.5 were found to have linear relationships with economic growth.

Overall, only CO_2 was found to have a valid EKC relationship with economic growth in the long and short run for South Africa. The result reveals that incremental economic growth may result in diminishing CO_2 emissions as the country transitions from an industrial to a service-oriented economy. This result is linked to South Africa's reliance on coal for energy, its energy-intensive industrial economy, and the foundational relationship between these factors and economic growth.

The study recommends that South Africa explores policies aimed at enhanced emissions monitoring and improved regulatory threshold enforcement. Despite the results, the country should also seek to further diversify its energy sector and explore less carbon intensive alternatives without foregoing energy security.

List of Tables

List of Figures

List of Abbreviations

AfCFTA	African Continental Free Trade Agreement
APPA	Atmospheric Pollution Prevention Act of 1965
ARDL	Autoregressive Distributed Lag
CO2	Carbon Dioxide
DFFE	Department of Forestry, Fisheries, and the Environment
DOLS	Dynamic Ordinary Least Square
EDGAR	Emissions Database for Global Atmospheric Research
EKC	Environmental Kuznets Curve
FMOLS	Fully Modified Ordinary Least Squares
GDP	Gross Domestic Product
MEA	Multilateral Environmental Agreements
MIDP	Motor Industry Development Programme
MVA	Manufacturing Value Add
NAFTA	North American Free Trade Agreement
NDC	Nationally Determined Contributions
NEMA	National Environmental Management Act of 1998
NO2	Nitrogen Dioxide
PM 2.5	Particulate Matter under 2.5 micrometres
SDG	Sustainable Development Goal
SO2	Sulphur Dioxide
SPM	Suspended Particulate Matter
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organisation
USD	United States Dollar
ZAR	South African Rand

Chapter 1: Introduction

1.1. Background of the study

A lucrative industrial landscape and a diverse, dependable energy mix are essential components in catalysing sustainable economic growth and development. These are priority policy concerns for Africa, notably regarded as a highly resource endowed continent, while also comprising most of the worlds developing and least-developed nations. The urgent need for economic growth and development in the region has also brought to the fore a fervent desire to incorporate climate adaptation and mitigation initiatives into national and regional policies as the pressure intensifies for a unified global commitment toward climate targets. For developing countries, however, the challenge is compounded due to their limited capacity to absorb climate related impacts (Tenaw & Beyene, 2021). Energy, trade, and investment policies must incorporate measures to limit expected environmental degradation associated with industrialisation and development activities to ensure that the sustainability objective of future development is met.

However, there are conflicting theories on the anticipated economic development journey. One school of thought asserts that economic growth and environmental degradation are proportionally and positively related where they ebb and flow in relation to one another. Conversely, another school of thought, and a trending theory, is that an initial relationship exists between economic growth and environmental degradation that is proportional and positively related until a threshold of economic growth is observed. Whereafter, incremental economic growth becomes inversely proportional to environmental degradation with observable decreases in the latter. The phenomenon is hypothesized to owe its origins to a myriad of shifts in economic behaviour of industrialised nations such as a transition from industrial to service-oriented activities, environmentally conscious consumer practice, firmer environmental legislation, and/or technological advancement (Grossman & Krueger, 1991).

The latter theory, which is the focus of this study, is called the Environmental Kuznets Curve (EKC) hypothesis and is a forerunning framework for the analysis of the relation between economic growth and environmental quality (Tenaw & Beyene, 2021). According to AfDB (2022), South Africa boasts one of the highest levels of industrialisation-led economic growth potential on the continent, while also globally representing “the most carbon intensive non-oil producing developing country” (Ben Nasr et al., 2015), attributable to its coal dominant power sector and diverse extractive mineral industries. Therefore, South Africa is a unique candidate to investigate the existence of the EKC phenomenon from a developing country perspective.

1.2. Statement of Research Problem and Research Questions

Economic growth is a desirable outcome for all countries, and principally for developing nations, due to its precursory relationship with development. Sustainable development has become increasingly imperative, and an accepted definition is offered by UNWECD (1987) as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs".

The concept of economic growth suggests that it is succeeded by far-reaching socio-economic benefits, chiefly among them is economic prosperity. However, several studies have raised caution on unfettered economic growth absent of the requisite accountability that ensures that prosperity is equitable and sustainable (Elliot, 2013; S. M. N. Islam et al., 2003; Jabareen, 2008). For example, it is not guaranteed that economic growth will lead to environmental sustainability, financial inclusion, income equality, improved education, and public services. These outcomes are dependent on the robustness of national and regional policies, as well as the degree of institutional integrity and democracy. For this reason, a framework for sustainable development was established and deployed by the United Nations (UN) in 2015 which outlines 17 Sustainable Development Goals (SGDs) designed to address, among others: inequality, poverty, environmental quality, sustainability, and basic human rights, by 2030 (UNDP, 2023).

Africa is home to many nations that have been designated as "developing" and "least developed" by the UN, and these terms have become commonplace in discussions and research pertaining to sustainable development (UN DESA, 2023). The designation is based on predefined per capita income thresholds and updated annually in the United Nations World Economic Situation and Prospects (UN-WESP) report.

It is evident that industrialisation is a catalyst for economic growth and can be accompanied by technology transfers, economies of scale, human capital development, foreign direct investment, and other beneficial spillovers for the host nation (Szirmai, 2012; Szirmai & Verspagen, 2015). An imperative component for sustainable industrialisation is a dependable, scalable, and integrated energy supply network, as emphasised by Bhattacharya et al. (2016) . However, in Africa, more than 50% of energy is derived from the combustion of wood and other biomass material, with only 57% of the continent, on average, having access to a residential electricity supply (Longa & van der Zwaan, 2021).

Furthermore, as of 2022 only 6% of global energy consumption was attributable to African countries, making it apparent that the continent is in dire need to develop their energy infrastructure and are also negligible contributors to greenhouse gas emissions (IEA, 2024). However, conventional greenhouse gas emissions are not the only contributing factors to climate change and adverse impacts to human health. Africa's reliance on biomass combustion for energy, in the absence of an integrated energy network, and the region's propensity to be dependent on mineral resources for economic development are problematic.

The combustion of biomass for energy is responsible for the release of harmful suspended particulate matter (SPM), carbon dioxide (CO_2), nitrogen oxides (NO_2), and sulphur oxides (SO_2) which are not fully reacted in the combustion process (Obaidullah et al., 2012). Prolonged exposure to SPM, CO_2, SO_2, and NO_2 compounds have devastating effects on human health. De Koning,' et al. (1985) explains that regular exposure to these harmful chemicals and compounds lead to adverse health implications such as respiratory disease, ocular deterioration, and cancer. According to WHO (2023), it is estimated that, globally, 6.7 million premature deaths are attributable to air pollution per annum due to chronic exposure to SPM under 2.5 micrometres in diameter (PM2.5), CO_2, SO_2, and NO_2 compounds.

On the continent, South Africa has the highest energy consumption per capita and is the greatest contributor to commercial greenhouse gas emissions (>75%), largely due to its coal dependency for energy (IEA, 2019). More than 80% of South Africa's energy needs are met by coal combustion (Eskom, 2022). Additionally, South Africa is the highest emitter of NO_2 and SO_2 compounds on the continent, the former being ascribed to South Africa having the largest commuter vehicle complement, and both being key volatile compounds in the combustion of coal for power generation. This translates to 0.7 million and 1.5 million tonnes, respectively, of NO_2 and SO_2, being emitted per annum (Olufemi et al., 2018).

Furthermore, South Africa is the second largest emitter of PM2.5 on the continent following Nigeria (IEA, 2019). Altieri and Keen (2016) revealed in their study that approximately 7.4% of premature deaths in South Africa are attributable to chronic exposure to PM2.5 particulate matter and that it is estimated to have cost the country around USD20 billion in lost productivity in 2012. Carbon emissions also serve as a litmus test for environmental quality and is integral to any study pertaining to air quality. This is especially relevant considering South Africa is the largest carbon emitter (CO_2) on the content and 13th globally (Hassan, 2023).

Conversely, South Africa has been regarded as the African country to have shown consistently elevated levels of industrialisation over the past decade, highlighted as a top performer on the African Development Bank Group industrialisation index between 2010 and 2021 (AfDB, 2022). The country has featured consistently at the top of the Competitive Industrial Performance Score by the United Nations Industrial Development Organisation (UNIDO) and possesses the third highest share of manufacturing value add on the continent, indicating a thriving industrial landscape with potential for economic growth (Asche & Grimm, 2017; Signe, 2018; The Global Economy, 2025).

Therefore, South Africa's attractiveness for additional industrial-led economic growth and its notorious reputation as the major emitter of hazardous airborne compounds in Africa make it the model case for the investigation of economic-environmental linkages among developing economies.

The Environmental Kuznets Curve (EKC) hypothesis was introduced by Grossman and Krueger (1991), as an adaptation of Kuznets (1955) original theory. The study sought to investigate the economic-environmental effects of the North American Free Trade Agreement (NAFTA) using specific air pollutants as key indicators of environmental quality. Subsequently, the EKC hypothesis has been an integral and leading framework in a myriad of studies investigating economic-environmental linkages with further adaptations made by contributing authors to include other development parameters of interest.

Fundamentally the EKC framework proposes that environmental quality will assume an inverted U-shaped curve in relation to economic growth. The basis is due to the key assumption that early economic growth has a positive and significant relationship with environmental degradation, precipitated by the development of economies of scale during early industrialisation (Ahmed & Long, 2013). A threshold of economic growth is hypothesised to exist, whereafter the economy transitions from an industry dependent to a services dependent landscape. The transition is purported to be attributable to improvements in employment, technology, education, distribution of wealth and economic influence. A theorised consequence of this is that there is a change in consumer behaviour to more sustainable and environmentally friendly practices, as well as pressure from the citizenry on national government to implement more stringent environmental legislation as the populus becomes more environmentally conscious. Thereafter, incremental economic growth is met with a reduction in environmental degradation due, in part, to the implementation of environmentally benign production methods and technologies.

Previous studies into the EKC hypothesis for South Africa has yielded conflicting and inconsistent results. It is further noted that no study of the EKC framework for South Africa exclusively considers key air pollutants linked to energy production/utilisation, anthropogenic and industrial activity such as carbon emissions (CO_2), SO_2, NO_2, and PM2.5. Understanding the relationship between these environmental indicators and economic growth, proxied by gross domestic product (GDP), in the context of the EKC framework will allow a more conclusive perspective on key economic activities, their environmental consequences and the implications emanating from the trajectory of national development. The outcome of such a study will inform crucial decisions for policy makers, industry leaders, further academic study, and future infrastructure investment strategies.

The following research questions can be derived from the narrative:

- Does a valid EKC relationship exist for CO_2, SO_2, NO_2, and PM2.5 pollutants and GDP per capita for South Africa?
- What policy recommendations can be suggested for South Africa based on the results of the EKC investigation for CO_2, SO_2, NO_2, and PM2.5 pollutants?

1.3. Statement of research objectives and hypotheses

The following study seeks to examine the impact of economic growth on environmental air quality in South Africa. The specific objectives of the study are:

- To investigate the existence of an EKC relationship between economic growth, measured by GDP per capita, and environmental air quality in South Africa, proxied by CO_2, SO_2, NO_2, and PM2.5 emissions per capita.
- To determine the resultant policy recommendation/s that can be suggested to address the outcome of the known relationship between economic growth and environmental air quality in South Africa.

Furthermore, the following hypotheses are derived from the above:

- Null hypothesis: Economic growth has no EKC relationship with CO_2, SO_2, NO_2, and PM2.5, respectively, in South Africa.
- Alternative hypothesis: Economic growth has an EKC relationship with CO_2, SO_2, NO_2, and PM2.5, respectively, in South Africa.

1.4. Limitations

The study will be limited to the period 1970 to 2018, and within the context of South Africa, for the variables considered. Inferences from the conclusions will not be applicable outside of this period, to countries other than South Africa, and for pollutants other than CO_2, SO_2, NO_2, and PM2.5.

1.5. Scope and Justification of the study

The following study seeks to investigate the plausible relationship between economic growth and environmental air quality in South Africa in context of the Environmental Kuznets Framework and discuss the policy implications for South Africa's future economic growth and development. Focus will be given to the availability of carbon dioxide (CO_2), sulphur dioxide (SO_2), nitrogen dioxide (NO_2), and Suspended Particulate Matter (PM2.5) concentration data for South Africa and will align with available Gross Domestic Product (GDP) per capita data, which will also inform the period/timeframe limitation of analysis.

The study aims to introduce an analyses of specific air pollutants – CO_2, SO_2, NO_2, and PM2.5 – which are commonly associated with industrial and anthropogenic economic activity within the EKC framework which has not been attempted and/or published exclusively in a South African context thus far.

Understanding the relationship between economic growth and environmental air quality will provide a useful perspective into the type of primary industrial activities that are currently driving the South African economy and whether economic policies should adapt, sustain and/or cease enabling specific industries as catalysts for growth. Furthermore, the study will support additional understanding into the anthropogenic activities which are supplementary to economic growth that may also be detrimental to the environment and possible alternatives to ensure continued, sustainable growth and development. These activities may take the form of public and commercial transport, domestic and commercial energy supply, mining activities and trade corridors, road/rail infrastructure, and manufacturing. Investigating the economic-environmental links for the pollutant variables will provide an outlook for the possible shocks of future economic activity on the fiscal efficacy and capacity of the national health system, and to inform strategies to manage the ramifications on human health. The study will, therefore, seek to contribute meaningfully to the existing empirical, academic, policy and practical bodies of knowledge.

1.6. Organization of the study

The organisation of this study will take the form outlined in this section. Chapter one will encompass the introduction to the concept, the problem statement and questions, objectives and hypotheses, and justification for the study. Chapter two forms the literature review section and will cover similar research conducted in other areas of study, concepts underlying the current research, relevant theories and empirical facts that assist to formulate an understanding of the study. Chapter three underpins the research methodology section and entails discussions of the research approach, data sources, research design, data collection methods and the basis of the analytical framework to be used. Chapter four discusses the overall findings, analytical outcomes, and test results of the study. Chapter five provides a conclusion of the study, summarises whether the study achieved its intended objectives and/or answered the research questions posed and presents recommendations from the study and for future research on the topic. Finally, the study will be fulfilled with a presentation of the references used and appendices for supplementary information to and/or from the study.

Chapter 2: Literature Review

2.1. Introduction

The following chapter presents an overview of the relevant theory and concepts which underpin the research questions and the topic of research in this study.

2.2. Terms and concepts

Throughout the following study frequent references will be made to various key terms and concepts and it is therefore necessary that further expansion thereof is made in this chapter to provide a basis for productive analysis and discussion in latter chapters.

Sustainable development is a prevailing concept in this study and for which a brief explanation was provided in an earlier section. Sustainable development is defined as "development which meets the needs of the present without compromising the ability of future generations to meet their own needs" (UNWECD, 1987). It is explained by Monash University (2023) that the notion of sustainability in development discussions, although not a new concept at the time, featured prominently when it was formalised by the UN in their co-creation of the 17 sustainable development goals in 2015 by member states. These goals encompass the facets of sustainable development by creating localised, attainable goals which will advance the global objective. Sustainable development, additionally, emphasises the integration of social, political, financial, and environmental welfare for all, absent of bias and conflict.

Two prominently featured terms in the study are economic development and economic growth. Economic growth relates to the physical increase in the scale of the economy in terms of an increase in gross production capacity and is measured by the indicator – gross domestic product (GDP) per capita (Kuznets, 1973). Economic development relates to improvement of the composition and quality of physical outputs of the economy, which include institutional, political, and technical quality (Barbier, 1987). These terms are quite distinct and are often erroneously used interchangeably as it is possible for an economy to experience growth without development, and vice versa (Daly, 1987).

Industrialisation is referred to recurrently in the study and a definition is offered by AfDB (2023) as the promotion of industry in the form of increasing manufacturing and processing capability to add value to raw materials, and in so doing, advance human capital, employment, and social stability. Industrialisation is typically measured in terms of manufacturing value add

(MVA) per capita which is the net output of productive capacity after subtracting intermediate consumption (Elfaki et al., 2021).

2.3. Overview of the economic and environmental context

2.3.1. Industrialisation and brief sectoral overview of South Africa

The South African industrial sector attributes its origins primarily to the country's political legacy during Apartheid. The country's historically narrow policies combined with the industrial sector's focus targeting almost entirely domestic consumption led to the sectoral dominance of a few major firms, the crowding out of new entrants, and the recurrent need for government fiscal intercession due to market limitations precipitated by economic sanctions. It could also be argued that it was a period of inward industrialisation characterised by import substitution and catering for local demand, but as a response to political pressure rather than strategic policy or preference (Zarenda, 1989). Evidently, there was no inducement for efficient production processes and even less investment in human capital development and technological innovation. The nations survival during this period could only be attributed to its natural resource endowment. The establishment of South Africa's democratic government in 1994 together with the trade liberalisation that ensued, manufacturing and export of goods became more lucrative.

The introduction of programmes and policies such as the Motor Industry Development Programme (MIDP) in 1995, with the objective of promoting foreign direct investment, intentionally led to the reinvestment of key global manufacturers with a domestic base of operations, and the importation of modern technology and efficient production processes (Green, 2009). While policies played a significant role in reinvigorating domestic industrialisation, South Africa benefitted greatly from its inexpensive electricity supply, achieved by an abundance of coal reserves and ease of access to high quality mineral resources. According to Bell and Farrell (1997), the minerals-energy complex in South Africa comprising mining, electricity production, chemicals and metal processing industries continues to play a pivotal role in the economic development of the country, a notion supported by Zalk (2014).

Furthermore, and as emphasised in an earlier section, South Africa has delivered remarkable levels of industrial progress since its trade liberalisation efforts of the early 1990's. According to AfDB (2022), in 2021 South Africa had an industrial development score of 0.84, the measure encompassing a weighted average of economic elements such as performance, direct and indirect determinants, collectively comprising 19 measured economic attributes. South Africa is closely followed by Morocco (0.83), Egypt (0.78), Tunisia (0.77), and Mauritius (0.66). Over the period 2010 to 2021, South Africa was consistently at the top of the index. It is anticipated that South Africa will serve as a gateway into Southern Africa, yielding additional industrial growth for the country, when regional economic strategies and trade agreements such as the 2018 African Continental Free Trade Agreement (AfCFTA), Agenda 2063 and the African Union (AU) 2011 Action Plan for the Accelerated Industrial Development of Africa are fully embraced. The goal is the multilateral prosperity of partner nations by recognising, exploring and/or co-creating regional advantages in infrastructure, knowledge, and human capital.

South Africa's current key economic sectors comprise agriculture, tourism, mining, manufacturing, energy, and transport, according to the Government of South Africa (2023). These are presumed to be identified key economic drivers and not indicative of any sizable contribution to GDP. Based on 2022 annual GDP data, South Africa's manufacturing sector featured as the prevailing industrial sector at 13% contribution to overall GDP (Stats SA, 2023). This was closely followed by other industrial and ancillary sectors such as transport and mining with 9% and 5%, respectively. A breakdown of 2022 annual sector specific value add to GDP can be seen in Figure 1, below. Astonishingly, South Africa's services sector contributes collectively more than 50% toward overall GDP providing an indicative view of the state of economic development of the country.

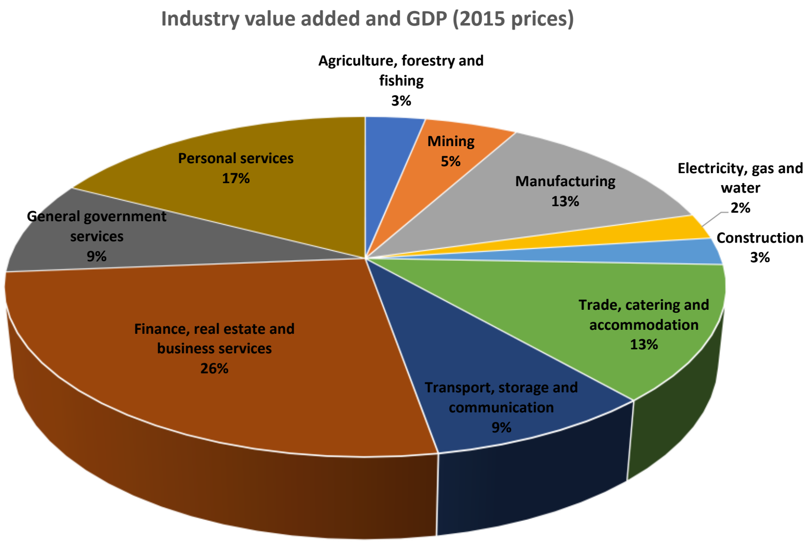

Figure 1: 2022 GDP sectors for South Africa, adapted from (Stats SA, 2023)

2.3.2. International, Regional, and Domestic Environmental policies

Over the past 50 years countries have increasingly entered into multilateral environmental agreements (MEA), protocols and ratified conventions. These are intended to serve as a means of collectively addressing climate change and environmental conservation initiatives, thus ensuring maximisation of efforts, knowledge sharing and pooling of resources. Presently, there exists approximately 729 MEAs with numerous interlinkages resulting in subsequent addendums, protocols, and conventions (Chambers, 2008; Mitchell, 2003a). However, only 20 MEAs relate to air pollution abatement, with the balance split almost evenly between other forms of pollution reduction and species conservation initiatives. While there has been mixed observable outcomes for many MEAs, environmental treaties and protocols, it is inaccurate to assume that the apparent failure and/or success of the initiative is directly attributable to its efficacy or rigor of application. Rather, Mitchell (2003a) suggests that success or failure of these international environmental agreements vests in the relative rates of mitigation versus degradation, and what may appear as a policy failure may be attributable to an evolving rate of degradation compared to mitigation outcomes, and vice versa for successful results.

International climate agreements took their basis from the notable Montreal Protocol of 1987 which sought to phase out ozone depleting substances and is the first MEA to have been ratified by every nation globally. It also aimed to prevent an anticipated 2.5^{o}C global average temperature increase by 2000 (USDOS, 2023). An amendment to the Montreal Protocol took the form of the Kigali Amendment in 2016 which sought to prevent a further 0.5^{o}C global average temperature increase by 2100 via the mass phaseout of hydrofluorocarbons, another type of harmful refrigerant gas in commercial use at the time. Thereafter, the United Nations Framework Convention on Climate Change (UNFCCC) was agreed upon in 1994 with the goal of radically reducing greenhouse gas emissions emanating from anthropogenic sources to pre-1990 levels (UNCC, 2023b). More recently, the promulgation of the UN SDGs in 2015 brought to the fore the importance of member nations to include elements of the SDGs, especially SDG 13 on climate action, within their national development plans and policies (UNDP, 2023). Furthermore, the famed Paris Agreement, ratified in 2016 at the UN Climate Change Conference (COP21), places the onus on signatories to utilise all efforts to collectively limit, via Nationally Determined Contributions (NDC), global average temperature increase to less than 2.5^{o}C above pre-industrial levels, as a minimum goal, and possibly, to less than 1.5^{o}C above pre-industrial levels, as an ultimate goal, by 2025 (UNCC, 2023a). This is envisaged to be achieved by concerted efforts to reduce greenhouse gas emissions, financial contributions, and capacity building. A comprehensive database of all international environmental agreements and their respective linkages was developed by Mitchell (2003b) as part of a project concluded in 2020.

Regionally, African countries took a progressive stance toward environmental conservation shortly after obtaining their respective independence. The 1960's were marked by the ratification of several climate related MEAs and protocols, beginning with the Arusha Manifesto in 1961 which comprised an agreement by African nations to commit to sharing knowledge, promoting skills development, and financial contributions toward environmental conservation efforts (Noe et al., 2017). Closely following the Arusha Manifesto, the African Charter for the Protection and Conservation of Nature was developed in 1963, and was followed by the Algiers Convention of 1968, both of which formed an improvement to the intentions of the Arusha Manifesto (AU, n.d.). Recently, the Maputo Convention of 2003, although focus was on the promotion of women's rights, equality, and dignity, also sought to affirm sustainable development practices, enhance natural resource conservation efforts, and implement social development initiatives as a knowledge sharing objective (UNEP, 2023).

According to Naiker et al. (2012), air quality legislation and policies in South Africa prior to 1994 were ineffective. Post democratic transition, legislation was comprehensively and systematically reassessed to align with progressive international standards, summarised in Table 1 below. Environmental regulation in South Africa is administered by the Department of Forestry, Fisheries, and the Environment (DFFE) which also experienced significant structural reforms over the years. As a significant policy reform, national government ceded administration powers for environmental management and control to the local government level. This was signified by the introduction of the National Environmental Management Act of 1998 (NEMA), recognising the ineffectiveness, lack of context and retroactive approach of national administration on localised industrial activities under the outdated Atmospheric Pollution Prevention Act of 1965 (APPA). Additionally, with the introduction of improved environmental legislation, regulations such as NEMA incorporated elements of sustainable development and introduced social aspects such as the need for public involvement, co-operative governance, transparency, and mediation processes.

Furthermore, the minimum emissions standards of PM2.5, SO_2, and NO_2 can be found in part 3 of the National Environmental Management: Air Quality Act 39 of 2004 and guidelines are provided on an industrial activity basis, a partial extract of which can be found in Table 2 below.

Table 1: List of Environmental Air Regulations in South Africa (Naiker et al., 2012)

Date	Legislation/Policy
1965	Atmospheric Pollution Prevention Act (APPA)
1996	The Constitution of the Republic of South Africa
1998	The National Environmental Management Act (NEMA)
2000	The White Paper on Integrated Pollution and Waste Management for South Africa
2004	The National Environmental Management: Air Quality Act (NEMAQA)
2007	The National Framework for Air Quality Management in South Africa

Table 2: Air Emission Limits (DEA, 2010)

Air Pollutant	Unit of Measurement	Solid Fuel Combustion	Liquid Fuel Combustion	Solid Biomass Combustion	Gas Combustion
Particulate Matter	mg/m^3	50	50	50	10
Sulphur Dioxide	mg/m^3	500	500	500	400
Nitrogen Oxides	mg/m^3	750	250	750	50
Air Pollutant	**Unit of Measurement**	**Petroleum Processing**	**Coal Gasification**	**Metallurgical Processing**	
Particulate Matter	mg/m^3	50	50	50	
Sulphur Dioxide	mg/m^3	250	1000	400	
Nitrogen Oxides	mg/m^3	0.4 [kg/ton crude]	700	300	

2.4. Theoretical Framework

The following section discusses the various theoretical frameworks that feature prominently in the study and that may have an influence on the conclusions that are drawn.

2.4.1. EKC Framework

The EKC framework, as alluded to in prior sections, is highlighted by the notion of an initial, unwavering focus on economic growth followed by radical environmental redress. This is not to assume that negligible environmental mitigation is present during the growth phase, only that primary focus is directed toward growth initiatives - a balance moderated by sustainable development practices.

The framework is delineated by the theory of a quadratic relationship between economic growth and environmental degradation depicting an inverted U-shaped graphical curve. This is postulated to be a result of an initial, positive relationship between economic growth and environmental quality which, after reaching an apex of domestic income levels, assumes a negative relationship between economic growth and environmental quality due to a myriad of factors underpinned by changed behaviour, improved technology and production mechanisms, and stringent legislation, to name a few (Tenaw & Beyene, 2021). The relationship between economic growth and environmental quality is multidimensional and vests within three pillars, according to Grossman and Krueger (1991).

The first is the *scale effect* which relates the increase in economic productive activity to an increase in environmental degradation (Tsurumi & Managi, 2010). This is due to the need to achieve industrial economies of scale which, initially, often entails archaic processes and technologies, and which are renowned for hazardous air emissions and other ecological impacts. There are also anthropogenic factors related to the scale effect. Biomass combustion to meet residential energy demands has a devastating effect on the environment and human health. Reliance on fossil fuel modes of individual commuter transport, in the absence of an integrated, efficient, mass public transport system and infrastructure, has detrimental effects on air quality as well.

Secondly, is the *composition effect* which relates to the change in composition, or development, of the structure of the economy from an industrial to a services-based economy (Grether et al., 2009). This is also evident in the precursory phases of economic development from agrarian to industrial. During the first two phases, growth in income levels degrades environmental quality. In the tertiary phase, however, there is an implied diversion from energy intensive, industrial practices to technology driven, energy efficient service oriented economic activities. During this period, the increased national income levels are postulated to also improve domestic levels of income inequality and literacy (Usenata, 2018). The anticipated result, a firmer stance on environmental conservation, mitigation policies, and regulations.

Lastly, is the *technique effect* which is often observed in conjunction with the composition effect. It relates to the influence of technological, human capital and knowledge accumulation and advancement accompanied by an increase in income levels that successively result in a change from carbon intensive industrial methods to technologically efficient, benign practices (Grether et al., 2009). Simply, an improvement in the techniques, or ways, in which the economy operates may result in improved environmental quality.

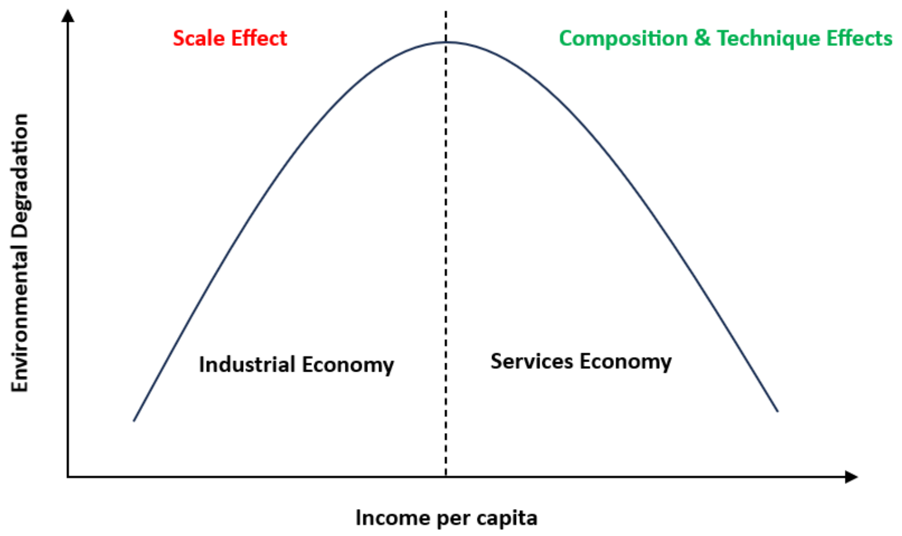

Figure 2: Economic development phases, adapted from (Grossman & Krueger, 1991)

2.4.2. Economic Growth Theories

Various economic growth theories exist which individually attempt to provide a narrative on endogenous and exogenous factors of sovereign economic activities that have an influence on growth characteristics, trajectory, and socioeconomic impacts. Criticism of economic growth indicators such as GDP, however, suggest that the indicators do not capture elements of economic growth outside of productive processes (Van den Bergh, 2011). For example, informal markets are not specifically or directly captured in the measure. Additionally, social welfare and environmental degradation is often excluded. Notwithstanding the various drawbacks, economic growth is useful as a primary indicator of the average socioeconomic state of the population (Piętak, 2014).

2.4.2.1. Lewis Growth Theory

The growth theory postulated by Arthur Lewis in 1954 serves as a precursor to the latter theories which provide the basis for the EKC framework. Lewis' theory is based on a dual economic perspective centred around developing countries which also grapple with overpopulation. This laid the groundwork for the theory in which it is suggested that the mobilisation of mass labour from low output agrarian activities to high output, capital intensive industrial sectors with the intention of attracting additional capital inputs into the economy (Gollin, 2014). In other words that capital accumulation and income distribution could be interdependent. The capital inflow will result in job creation, higher levels of income per capita and capital accumulation through savings (Lewis, 1954). The capital accumulation is hypothesised to lead to a cyclic growth environment by autonomously enabling more capital inflow. The theory, however, has its drawbacks in the firm assumptions that the economy will always be labour driven, i.e., an infinite surplus of labour, that there exists a technology barrier that will restrain the development cycle between two growth sectors – agrarian (subsistence) and industrial – that the agrarian sector has no need for and/or cannot utilise capital, and that the industrial sector has a seemingly indefinite capacity to absorb the subsistence labour force (N. Islam & Yokota, 2008). In terms of the EKC framework, Lewis' theory encompasses the early development phase of an economy between the lowest income levels and the postulated income turning point.

2.4.2.2. Kuznets Growth Theory

Following from Lewis' theory which linked capital accumulation and income distribution, Simon Kuznets developed a growth theory in 1955 which attempted to link income inequality with economic output. The theory has a similarly labour reliant foundation as with Lewis' theory, however, is premised on a substantial income differential between skilled and unskilled labour during early phases of economic development which later narrows at higher levels of economic output, forming the famed inverted U-shaped curve or Kuznets curve (Galor & Tsiddon, 1996). Kuznets observed that the shift in income distribution as national output increased was attributable to a shift of labour from agrarian to industrial sectors and, simultaneously, a shift from rural to urban dwelling. This observation is due to the composition effect in practice and provides a basis for the widening gap in the distribution of income during the initial stages of development (Korzeniewicz & Moran, 2005). Conversely, the narrowing of the income distribution gap is suggested to also be due to the composition effect, once a threshold of urbanisation is surpassed and, additionally, the effect of institutional transformation is said to also play a role. The growing citizenry in urban areas and their increasing participation in the functioning of institutions will inevitably result in growing support and political strength of the working class to support legislation that remedy the income imbalance (Kuznets, 1955).

2.4.2.3. Rostow Growth Theory

Walt Rostow postulated a combinatory theory to that of Lewis and Kuznets in 1959 wherein he suggests that economic growth is moderated by capital accumulation and traverses several stages of growth (Rostow, 1959). The first stage is referred to as *traditional society* where most of the labour is concentrated in agricultural sectors, characterised by low levels of productivity, and technological advancement is seemingly stifled. The second stage is the *preconditions for* *take-off* where advancement in agricultural output is observed and with the higher levels of productivity, agricultural export is met with import of key capital goods as enablers of additional productive efficiencies (Parr, 1998). This stage is also characterised by knowledge exchange and the establishment of functional sovereign institutions and trade. The third stage is known as *take-off* which is also emphasised by Rostow to be a crucial and often difficult stage to reach and requires a leading industrial sub-sector to spearhead domestic production to ensure sustained economic growth and a net investment of at least 10% per annum (Kesgingoz & Dilek, 2016). This stage of growth is earmarked by technological advancement and requires a formalisation of financial institutions to enable capital accumulation and investment. The fourth stage is the *drive to maturity* where the technological advancement is observed not only in the primary industrial sub-sector but in other sectors as well which also assume a leading role in driving economic growth (Khan & Marinaro, 2017). Political and legislative effects begin to play a more significant role during this stage. The fifth, and final stage according to Rostow's theory, is the *age of high mass consumption*. During this stage, the developed society can decide to venture into three possible directions, precipitated by economic surplus (Rostow, 1959). Firstly, it is possible to offer enhanced social welfare. Secondly, the mass provision of goods and services. Lastly, the exertion of political, economic and/or military dominance globally.

2.5. Review of Empirical Literature

The environmental-economic growth linkage has been widely studied since the introduction of a novel adaptation by Grossman and Krueger (1991) of Simon Kuznets' 1955 theory on economic growth and income inequality and is aptly referred to as the Environmental Kuznets Curve (EKC) hypothesis (Kuznets, 1955). A plethora of research exists which investigates the EKC hypothesis globally and in the context of South Africa, with 10 published and exclusively South African studies to the author's knowledge, however the results appear to be disparate and inconsistent, and with no apparent consensus regarding an appropriate data analysis technique. A summary of prior studies is found in Table 3, below.

The earliest period of study is 1911 which is the earliest source of environmental carbon dioxide data, according to Ben Nasr et al. (2015) and the latest period of study is 2020 indicative of the most recently available environmental data, corroborated by (Udeagha & Breitenbach, 2023; Udeagha & Muchapondwa, 2022b, 2022a; Udeagha & Ngepah, 2023). Nearly all studies of the EKC hypothesis for South Africa utilise carbon dioxide emissions as a proxy for environmental quality due to its close relationship with fossil fuel energy consumption and gross domestic product (GDP) as a proxy for income (Ben Nasr et al., 2015; Ganda, 2019; Ngarava et al., 2019; Rafindadi & Usman, 2019; Udeagha & Breitenbach, 2023; Udeagha & Muchapondwa, 2022a; Usman et al., 2020).

Ganda (2019) suggests that obtaining a detailed perspective of the type of fossil fuel energy and its relationship to carbon emissions in South Africa will allow for more detailed policy recommendations; The study revealed that a high dependency on coal for electricity has a significant and positive relationship with carbon dioxide emissions in the long run and that this can be abated by augmenting domestic energy policies to incorporate more renewable energy into the energy mix.

Numerous other studies include modified versions of the EKC hypothesis which test various sub-factors and their pertinence to the overall development process. A study by Rafindadi and Usman (2019) included a modified EKC hypothesis which found that globalisation has pollution mitigating effects in the short run. Similarly, Usman et al. (2020) studied the influence of globalisation and the extent of democratic institution integrity, which found that democratic institutional integrity has a positive, insignificant effect on environmental quality in the long and short run. Udeagha and Muchapondwa (2022a) found that economic policy uncertainty has a detrimental effect on environmental quality in the short and long run, however, the influence of technological advancement and renewable energy applications has the potential to mitigate environmental damage.

Many EKC investigations for South Africa have yielded positive outcomes in that the EKC hypothesis was valid over the period of study (Sarkodie & Adams, 2018; Udeagha & Breitenbach, 2023; Udeagha & Muchapondwa, 2022b, 2022a; Udeagha & Ngepah, 2023; Usman et al., 2020). Conversely, some EKC investigations for South Africa invalidated the EKC hypothesis for the country (Ben Nasr et al., 2015; Ngarava et al., 2019), while others produced mixed results where the EKC hypothesis was either valid only under certain conditions and/or valid only under the short/long runs (Ganda, 2019; Rafindadi & Usman, 2019). Few studies have been conducted exclusively on the linkage between economic growth and other pollutants such as carbon dioxide (CO_2), sulphur oxides (SO_2), nitrogen oxides (NO_2) and suspended particulate matter (PM2.5), in a South African context, at the time of compilation of this study and to the best of the author's knowledge.

By far, the most common methodological approach to study the EKC hypothesis in general has been the utilisation of the Autoregressive Distributed Lag (ARDL) bounds testing approach, developed by Pesaran et al. (2001), due to its robustness, statistical effectiveness with smaller samples of data and its innate ability to negate autocorrelative effects (Ganda, 2019; Ngarava et al., 2019; Saint Akadırı et al., 2021; Sarkodie & Adams, 2018; Shahbaz et al., 2016; Tenaw & Beyene, 2021). Notably, these studies produced varying results and in some cases were inconclusive. The Dynamic ARDL approach, a modified version of its namesake, has been revered by some studies due to its ability to draw more reliable conclusions from time-series data with inconsistent model coefficients, compared to its standard version (Udeagha & Breitenbach, 2023; Udeagha & Muchapondwa, 2022b; Udeagha & Ngepah, 2023). The Dynamic ARDL approach has often been associated with a valid EKC hypothesis from the array of studies considered.

Some studies have successfully used a dynamic ordinary least square (DOLS) and a fully modified ordinary least squares (FMOLS) approach where the EKC hypothesis was confirmed for the selected panel data and period for South Africa (Udeagha & Muchapondwa, 2022a). Other common approaches, used jointly, are the fixed generalised least squares regression and random effects generalised least squares regression (Baiardi, 2012; Bibi & Jamil, 2021; Fujii & Managi, 2016; Leitão et al., 2021; Sarkodie, 2018; Selden & Song, 1994). The former approach assumes that variations in observable effects are due to errors in sampling (Borenstein et al., 2010). The latter approach, while structurally similar, is credited by Laird and Ware (1982) with being able to more effectively handle unbalanced data compared with other multivariate models and, in contrast, determines a mean of a distribution of observable effects.

Table 3: Summary of EKC studies in South Africa and similar regions/scopes

No.	Country/Region	Timeframe	Technique (s)	Summarised Result	Source
1	South Africa	1980 - 2014	• Auto Regressive Distributed Lag (ARDL) • Johansen cointegration test	Mixed Results	(Ganda, 2019)
2	17 African Countries	1971 - 2013	• Westerlund Error Correction Model • U-Shape Relationship Test • Fixed and Random Effects Estimator • Bootstrap Panel Unit Root Test with Cointegration	EKC confirmed	(Sarkodie, 2018)
3	20 SSA Countries	1990 - 2015	• Common Correlated Effects Pooled Mean Group (CCE-PMG) Estimator • Panel unit root and cointegration Tests • Auto Regressive Distributed Lag (ARDL) • U-Shape Relationship Test	Mixed Results	(Tenaw & Beyene, 2021)
4	BRICS (Brazil, Russia, India, China & South Africa)	1995 - 2018	• Auto Regressive Distributed Lag (ARDL) • Pooled Mean Group (PMG) Estimator • Panel unit root and cointegration Tests	Mixed Results	(Saint Akadırı et al., 2021)
5	South Africa	1911 - 2010	• Co-summability Approach	No EKC	(Ben Nasr et al., 2015)
6	South Africa	1960 - 2020	• Dynamic Auto Regressive Distributed Lag (Dynamic ARDL)	EKC confirmed	(Udeagha & Breitenbach, 2023)
7	South Africa	1971 - 2014	• Error Correction Model (EMC) Regression • Maki Cointegration Tests • Fully Modified Ordinary Least Square (FMOLS) Regression • Canonical Cointegrating Regression (CRR) • Toda-Yamamoto causality test	Mixed Results	(Rafindadi & Usman, 2019)
8	South Africa	1971 – 2014	• Augmented Dickey-Fuller (ADF) • Phillips–Perron (PP) unit root tests • Bayer-Hanck cointegration test • Vector Error Correction Model (VECM) • Fully Modified Ordinary Least Square (FMOLS) Regression	EKC confirmed	(Usman et al., 2020)
9	South Africa	1960 - 2020	• Dynamic Auto Regressive Distributed Lag (Dynamic ARDL) • Kwiatkowski–Phillips–Schmidt–Shin (KPSS), Augmented Dickey–Fuller (ADF), Phillips–Perron (PP), and Dickey–Fuller GLS (DF-GLS) unit root tests	EKC confirmed	(Udeagha & Muchapondwa, 2022b)

10	122 countries	2000 - 2018	• Random and fixed effects model of estimation • Hausman test for panel model selection	Mixed Results	(Bibi & Jamil, 2021)
11	Southern African Customs Union; USA; UK	1981 - 1997 (USA) 1985 - 2002 (UK)	• Cole's (2004a:74) method of calculating net exports developing regions proportional to consumption for dirty goods as opposed to clean goods was applied to data on trade flows between both the USA and SACU, and the UK and SACU	No EKC	(Nahman & Antrobus, 2005)
12	10 African Countries	1997 - 2021	• Augmented mean group (AMG) model. • Mean group (MG) model • Common correlated effects mean group (CCEMG) model	EKC confirmed	(Voumik et al., 2023)
13	BRICS (Brazil, Russia, India, China & South Africa)	1990 - 2015	• Fully Modified Ordinary Least Square (FMOLS) Regression • Panel Dynamic Ordinary Least Square (DOLS) • Fixed Effects Regression • Panel Quantile Regression • Pedroni and Kao cointegration tests	EKC confirmed	(Leitão et al., 2021)
14	South Africa	1990 - 2012	• Auto Regressive Distributed Lag (ARDL) • Error Correction Model	No EKC	(Ngarava et al., 2019)
15	19 African Countries	1971 - 2012	• Auto Regressive Distributed Lag (ARDL) • Unrestricted error correction method (UECM)	Mixed Results	(Shahbaz et al., 2016)
16	Top 10 CO2 emitting countries (China, USA, India, Russia, Japan, Germany, South Korea, Canada, Mexico, and South Africa)	2000 - 2014	• Panel quantile regression Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) model • ADF Unit Root Test Augmented Dicky–Fuller unit root test	EKC confirmed	(Thio et al., 2022)
17	173 countries	1990 - 2014	• Spatial Durbin Error Model (SDEM) • Spatial Lag of X (SLX) model • Spatial Error Model (SEM)	Mixed Results	(Balado-Naves et al., 2018)
18	South Africa	1960 - 2020	• Dynamic Ordinary Least Squares (DOLS) • Fully modified ordinary least squares (FMOLS) • Canonical Cointegration Regression • Maki Cointegration Test	EKC confirmed	(Udeagha & Muchapondwa, 2022a)

19	South Africa	1971 - 2017	• Response Surface Regression Structural Break Cumulative Sum (CUSUM) • Recursive Residual • Ordinary Least Squares Residuals • Auto Regressive Distributed Lag (ARDL)	EKC confirmed	(Sarkodie & Adams, 2018)
20	South Africa	1960 - 2020	• Dynamic Auto Regressive Distributed Lag (Dynamic ARDL) • Frequency Domain Causality (FDC) • Stationarity Tests: Kwiatkowski–Phillips–Schmidt–Shin (KPSS) Augmented Dickey–Fuller (ADF) Phillips–Perron (PP) Dickey–Fuller GLS (DF-GLS)	EKC confirmed	(Udeagha & Ngepah, 2023)
21	39 Countries	1995 - 2009	• Random effect generalized least squares regression • Fixed effect generalized least squares regression	Mixed Results	(Fujii & Managi, 2016)
22	South Korea	2000 - 2012	• Hausman and Taylor model Dynamic Panel System Generalized Methods of Moments	Mixed Results	(Jung Kim et al., 2016)
23	Italy	1990 - 2005	• Random effect generalized least squares regression. • Fixed effect generalized • Two-Stage Least Squares (2SLS) • Hausman's test	EKC confirmed	(Baiardi, 2012)
24	Bangladesh	1971 - 2020	• Auto Regressive Distributed Lag (ARDL) • Impact, Population, Affluence, and Technology (IPAT) model	Mixed Results	(Chandra Voumik et al., 2022)
25	30 Countries	1973 - 1984	• Random effect generalized least squares regression. • Fixed effect generalized Hausman model	EKC confirmed	(Selden & Song, 1994)
26	42 Countries	1977 - 1988	• Random effects generalised least squares regression	EKC confirmed	(Grossman & Krueger, 1991)

Chapter 3: Methodology

3.1. Introduction

This chapter outlines the analytical methodology employed in the study. The sequence of the chapter begins with an overview of the research approach governing the study, the research design, data sampling procedure and data sources, and the analytical framework utilised in the study. The analytical framework further charts the course of the model used in the data analysis, a brief overview of the nature of the variables considered, the analytical techniques and associated considerations.

3.2. Research Approach

Traditionally, two schools of thought exist on the ideal research approach to embark on academic inquiry with diverse epistemological approaches. Epistemology is a philosophical field concerned with the study of knowledge, the extent and nature of knowledge and how it relates to the knower (Truncellito, 1995).

The first school, proponents of quantitative research, places importance on empirical investigation with the aim of verification of a hypothesised phenomenon or theory and falls under the ambit of a philosophical movement called logical positivism (Creath, 2011). The philosophy is premised on the existence of a singular truth demanding impartiality from the researcher, uses numerical or quantifiable data, and seeks to test a prevailing hypothesis and/or theory on a subject using empirical data obtained from experimentation, existing secondary data sources, scales, and tests (McGregor, 2018). This approach does not seek to add to theory but rather to test existing theoretical concepts.

The second school of thought, proponents of qualitative research, place credence on phenomenological investigation and interpretation of observation with the aim of generating hypotheses of a phenomenon and, conversely, falls under the ambit of a philosophical approach called interpretivism (Adom et al., 2016). The philosophy is premised on the existence of a multiple truths expecting a level of subjectivity from the researcher. This approach seeks to generate a view or hypothesis of a theory or phenomenon on a subject using qualitative data, data that cannot be quantified or is non-numerical, obtained from interviews, observations, and case studies (McGregor, 2018). This approach seeks to add to the body of theory and discover new or varying insights.

It has become increasingly common to find an amalgamation of the above approaches, known as mixed methods research approach. Mixed method approaches also combine the fundamental aims, data collection methods and authors attitude toward interpretation of results from the aforementioned approaches.

The following research investigates the existence of the EKC hypothesis in South Africa between economic growth measures of GDP per capita and environmental quality indicators of ambient PM2.5, CO_2, SO_2, and NO_2 concentrations, respectively. The study tests the hypothesis ringfenced by the EKC framework/theory using secondary data sources and statistical methods in an objective manner with the singular outcome of validating or invalidating the hypothesis. Additionally, authors of current EKC research in South Africa and other regions also determined a quantitative approach to be ideal to answer similar research questions (Ahmed & Long, 2013; Balado-Naves et al., 2018; Tenaw & Beyene, 2021). Considering that (1) all variables can be quantified, (2) it is possible to investigate a causal relationship between them and, (3) the aim of the study is to test theory rather than build on it, a quantitative approach is appropriate for this study.

3.3. Research Design

The following sub-section seeks to rationalise and define the appropriate design to answer the research questions posed. This is done in a systematic manner by outlining the dataset, sampling techniques, data sources and period, and analytical framework used in the investigation.

3.4. Population and sampling

The study tests the EKC hypothesis for South Africa due to the characteristic benefits that South Africa offers in terms of an integrated energy network, a diverse mining sector, a thriving industrial sector, its reliance on coal for primary energy generation and its reputation for being a key atmospheric pollution emitter in Africa. Therefore, the study utilised a single indicator of economic growth in the form of South Africa’s annual GDP per capita, and environmental air quality indicators in the form of PM2.5, CO_2, SO_2, and NO_2, which are average atmospheric concentrations measured and published annually for South Africa.

Kaika and Zervas (2013) comments on implicit assumptions of the EKC framework relating to the requirement that economic growth be normally distributed. The possibility of GDP having a nonnormal distribution exists, therefore Keller (2018) suggests that applying the Central Limit Theory - which states that for any population, the sampling distribution is approximated to be normally distributed around the sample mean for a large enough sample - negates any nonnormality for the study sample. As a guideline it is accepted that a sample size of 30 data points or more can achieve this outcome. The sampling prerequisite for this study was to obtain timeseries data of GDP per capita for South Africa for a minimum of 30 years ($n \geq 30$, where n is the sample size) historic data chronologically from the latest available measure. The period is mirrored for all variables to ensure complete datasets and support statistical integrity. Therefore, a minimum of 30 units of analysis is required for this study. The sample variables are GDP per capita, PM2.5, CO2, SO2, and NO2, respectively, and the sample selection procedure comprises 30 units of analysis or more retrospectively from the most current population dataset.

3.5. Data source and period

The World Bank Group provides an open database called the "World Development Indicators" which consists of various development related information, including GDP and GDP per capita measured in South African Rands (ZAR) and United States Dollars (USD) and total population figures measured in number of people, from 1960 to 2022 (World Bank, 2023). The availability of data spans 62 years or 62 units of analysis which exceeds the minimum requirement for the study. The World Bank Group database is reputable and utilised in several studies pertaining to the EKC framework (Bibi & Jamil, 2021; Ogundipe, 2015; Stern et al., 1996).

Complete, annualised timeseries datasets for the variables of PM2.5, CO2, SO2, and NO2 are readily available from the Emissions Database for Global Atmospheric Research (EDGAR) for South Africa from 1970 to 2018. This traverses a 48-year period which aligns to the sampling prerequisite to utilise a minimum of 30 units of analysis. EDGAR is a database comprising pollutant and greenhouse gas emission information for 220 countries globally, as an independent initiative by the European Commission for use in scientific inquiry (European Commission, 2018). Annualised emissions data for the above variables are available as total emissions measured in kilograms per capita.

The rationale for requiring population data is to ensure that the pollution variables can be regularised to a per a capita basis by dividing the total emission measures by total population figures for the corresponding years to align with GDP on a per capita basis. This approach ensures that all analysis is performed on similar degrees of magnitude which provides more dependable results and creates the opportunity for determining a turning point of GDP per capita.

Therefore, the overlap period of available data is from 1970 to 2018 which is used as the period of study, ensuring that there is 48 units of analysis or 48 years of timeseries data which meets the study sampling criteria. Additionally, the data sources are of reputable, dependable standards and have been utilised in prior scientific study.

3.6. Analytical Framework

The following sub-section seeks to expand on the analytical framework that underpins the empirical analysis between the variables considered, to establish whether relationships exist and the extent thereof, consequently enabling the research questions to be answered.

3.6.1. Model Specification

According to Ganda (2019), long run linear regression models pertaining to EKC hypothesis tests represents the explanatory (independent) variable to be factors which influence the extent of environmental degradation, in this instance economic growth and by extension the specific economic and anthropogenic activities that influence it. Therefore, the independent variable for the proposed model is economic growth and the response (dependent) variables are the specific pollution indicators - PM2.5, CO2, SO2, and NO2, respectively. However, many studies on the EKC framework include a secondary variable of economic growth squared to consider the technique effect in economic growth dynamics and to cater for non-linearity by rendering the model quadratic in structure (Ganda, 2019; Tenaw & Beyene, 2021). The model is expressed as a logarithmic transform in Equation (1), below. Al-Mulali et al. (2015) explains that the natural logarithmic transform aids in alleviating issues of non-normality in latter analytical steps.

$$\ln POL = \beta_0 + \beta_1 \ln GDP + \beta_2 \ln GDP^2 + \varepsilon \qquad (1)$$

Where, POL is the respective annual pollutant measure per capita for PM2.5, CO2, SO2, and NO2, respectively, GDP represents income per capita, GDP^2 represents the influence of the technique effect of economic growth, and ε the residual error term. A separate form of equation 1 is utilised for each environmental indicator and statistical analysis is conducted on each of the 4 models, respectively. Ganda (2019) explains that the functional form of the output can be discerned from the coefficients in equation 1 in the following manner:

$\beta_1 = \beta_2 = 0$ a horizontal relationship exists

$\beta_1 < 0\ and\ \beta_2 = 0$ a monotonically decreasing relationship exists

$\beta_1 > 0\ and\ \beta_2 = 0$ a monotonically increasing relationship exists

$\beta_1 > 0\ and\ \beta_2 > 0$ an inverted U-shaped curve is present (EKC)

$\beta_1 < 0\ and\ \beta_2 > 0$ a U-shaped curve is present

3.6.2. Variable Descriptions

3.6.2.1. Economic Growth

Economic growth can be represented by various indicators depending on the context of the discussion and/or research. Kenny and Williams (2001) outlines the challenges faced by economists and development practitioners in establishing consensus on what could constitute an accepted indicator of economic growth. Daly (1987) offers a possible definition of economic growth as a "quantitative increase in the scale of the physical dimensions of the economy". He adds that economic growth is generally limited by "biophysical" and "ethicosocial" factors which relate to the limitations imposed by the environment in terms of raw materials supply and waste absorption, and the negligible consideration of social welfare and assumed labour surplus, respectively. McKinsey and Company (2022) explains that economists rely on GDP as an approximate indicator of economic growth as it accounts for the total fiscal value of the goods produced and services rendered by a country domestically and internationally, a notion supported by other authors (Du et al., 2005; Millin & Nichola, 2005).

Studies relating to the investigation of the EKC phenomenon have generally accepted GDP per capita as an indicator of economic growth and have also utilised the square of GDP per capita to capture non-linearity of the model (Ganda, 2019; Rafindadi & Usman, 2019; Sarkodie, 2018; Sarkodie & Adams, 2018; Udeagha & Breitenbach, 2023; Udeagha & Muchapondwa, 2022a, 2022b; Usman et al., 2020). GDP per capita is the annualised GDP figures divided by the total population in the country for the year/period under consideration and is useful in capturing the effect of change in population on GDP whilst also allowing for comparative analysis between countries where disparities in population figures are present. GDP per capita for South Africa used for this study are constant 2015 local currency units (LCU) for the sample series.

3.6.2.2. Carbon Dioxide

Carbon dioxide is often utilised in EKC studies as a proxy for energy consumption and industrialisation due to its nefarious reputation as a leading greenhouse gas (Ahmed & Long, 2013). Although carbon dioxide is a naturally occurring gas, excessive emissions due to energy generation processes, combustion of biomass and other anthropogenic factors have simultaneously increased its presence in the atmosphere and reduced its physical reintegration into the natural environment through degradation of carbon sinks by activities such as deforestation (Disli et al., 2016). This has led to an unsustainable concentration of carbon dioxide which is considered a leading greenhouse gas due to its ability to absorb and trap excessive heat which inevitably results in climate change by disruptions to natural carbon cycles. EKC studies have found that economic growth has a significant and positive effect on carbon dioxide emissions and that a valid EKC presence exists between economic growth as the independent variable and carbon dioxide emissions as the dependent variable in South Africa (Disli et al., 2016; Udeagha & Muchapondwa, 2022b, 2022a; Usman et al., 2020). Ahmed & Long (2013) in their study on the impact of economic growth, trade openness, population, and energy consumption on environmental degradation (proxied by carbon dioxide) in Pakistan found that a valid EKC presence existed in the long run between all independent variables and the dependent variable. Furthermore, it is expected that GDP will have a statistically significant and positive effect on carbon dioxide emissions and GDP squared will have a statistically significant, negative effect on carbon dioxide emissions (Bilgili et al., 2016; Gokmenoglu & Taspinar, 2018; Ngarava et al., 2019). CO2 emissions for South Africa are measured in kilotons per annum for the sample series of this study.

3.6.2.3. Sulphur Dioxide

Sulphur dioxide is the one of the key pollutants emitted from power generation processes utilising fossil fuels, especially coal (El Hedi et al., 2012). Olivier et al. (2005) explains that significant emissions of sulphur dioxide are associated with commercial vehicle activity as part of national and regional supply chains, and chiefly during the refining process of crude oil where it is expelled as flue gas. Furthermore, sulphur dioxide has been identified among the leading contributing pollutants which have a substantial and adverse effect on human health (UNECE, 2023). Very few studies exist for the EKC validation of SO2 and economic growth in South Africa. Shikwambana et al. (2021) studied the effects of GDP on select pollutants, inclusive of SO2, in South Africa between 1994 and 2019, and found a positive relationship between GDP and SO2 per capita. Overall, however, the results of the study pertaining to the income-SO2 relation were inconclusive and an EKC relationship was not found. Markandya et al. (2004) studied the effects of GDP and GDP squared on SO2 emissions in selected European countries. The outcome of the study produced mixed results with the EKC being valid in few countries considered. Furthermore, it found that GDP had a positive and statistically significant effect on SO2 emissions, whereas GDP squared had a negative and statistically significant effect on SO2. Merlevede et al. (2006) conducted a similar study on various firms globally to deduce the impact of region and firm size (in addition to GDP) on SO2 emissions. The study revealed a positive and statistically significant relationship between income and SO2 emissions, both on a per capita basis. Furthermore, the study also confirmed a negative and statistically significant relationship between GDP squared and SO2 emissions per capita. SO2 emissions for South Africa are measured in kilotons per annum for the sample series of this study.

3.6.2.4. Nitrogen dioxide

Direct agricultural activity and agriculturally related industrial production are leading causes of increasing nitrogen dioxide emissions into the atmosphere. These direct activities entail soil runoff due to irresponsible farming practices, leaching of fertilizers into atmospheric cyclical systems and accumulation of animal waste (Olivier et al., 2005). Industrial activity which contributes to excessive nitrogen emissions involve the production of synthetic fertilizers, flue gas released from gas to liquid petroleum processes often involving coal as a precursor to methane production, landfill accumulation and natural gas production for energy. The above factors are anthropogenic in nature, relate to economically stimulating activity, and are prevalent economic activities in South Africa. Han et al. (2021) studied the relationship between economic growth and NO_2 emissions in China. The study found no EKC presence for the period under consideration, however established that economic growth had a positive and statistically significant effect on NO_2 emissions. Conversely, Hung & Shaw (2004) studied the EKC relationship between economic growth and NO_2 for Taiwan and establish a valid EKC hypothesis over the period of study. It was also found that economic growth had a positive and significant relationship with NO_2 emissions. NO2 emissions for South Africa are measured in kilotons per annum for the sample series of this study.

3.6.2.5. PM2.5

Suspended particulate matter (SPM) is a significantly overlooked pollutant and contributor to adverse human health effects. Unlike CO_2, SPM does not have a greenhouse gas effect on the environment and does not have detrimental effects by extension of its impact on other natural subsystems, but rather SPM directly and immediately impacts human health. The World Health Organization has reported that micro particles of 2.5 micrometres and smaller (PM2.5), have the most harmful effects on respiratory systems because the particles are small enough to embed into lung tissue and is difficult for the body's natural expulsion mechanisms to rid itself of this harmful particulate matter. Furthermore, Sepadi and Nkosi (2023) reports that in 2015 exposure to PM2.5 accounted for almost 7.6% of all premature deaths globally and ranking PM2.5 as the fifth highest international risk factor. PM2.5 is released by a number of industrial and anthropogenic activities ranging from mining activity, biomass fuelled cooking, industrial combustion and incineration processes, transport exhaust fumes, fossil fuel energy generation, earth works pertaining to construction, timber and forestry industries, and desertification caused by climate change and reduced rainfall (Gupta et al., 2022; Muyemeki et al., 2021; Zhang et al., 2021). These are prevalent economic activities in South Africa, making PM2.5 a key pollutant for this study. Numerous EKC studies have been conducted on PM2.5, mostly in Asia, and to an extent, Sub-Saharan Africa, but none for South Africa exclusively, and many have concluded a valid EKC presence in the region of study with economic growth having a positive and statistically significant effect on PM2.5 emissions (Ding et al., 2019; Koçak & Celik, 2021; Qi et al., 2023; Ssekibaala et al., 2022). PM2.5 emissions for South Africa are measured in kilotons per annum for the sample series of this study.

3.6.3. Hypothesised effect of Independent Variable

Table 4: Summary of expected effects of independent variables

Dependent Variable (below)	GDP Expected Effect	GDP squared Expected Effect	Data Source
CO2	+	-	(European Commission, 2018)
PM2.5	+	-	(European Commission, 2018)
SO2	+	-	(European Commission, 2018)
NO2	+	-	(European Commission, 2018)
Data Source	(World Bank, 2023)	(World Bank, 2023)	

3.7. Analytical Technique(s)

According to Dogan and Turkekul (2016), the first step in timeseries regression analysis is to determine the properties related to the integration of the variables under consideration. The second step is to apply an appropriate bounds testing approach to establish whether the variables are cointegrated in the long run, for non-stationery variables. Third, based on a positive outcome for the cointegration test, the short and long run coefficients are estimated and, lastly, causality is tested among the variables using an appropriate model that caters for error correction.

The overview above is simplistic and it is important to understand the characteristics of time series analysis more fully to assess the interaction between variables and within variables over a period. This enables a more coherent and useful discussion to ensue and will negate spurious conclusions from being derived.

3.7.1. Autoregression Issue

Shrestha and Bhatta (2018) explains that a characteristic feature of timeseries data is its autoregressive nature, in other words the possible dependency of a current variable value to its past value (lagged value) and an estimated constant factor. Timeseries which has a reliance on one lagged value (past value) is first order autoregressive, AR(1), and a reliance on two lagged values (two past values) is second order autoregressive, ad infinitum. The basic format of the autoregressive characteristic is shown in Equation (2), below:

$$Y_t = a + b_1 Y_{t-1} + \cdots + b_n Y_{t-n} + \varepsilon_t \tag{2}$$

Where, Y_t is the present value of the dependent variable at time t, a is a constant, Y_{t-1} is the first lagged value, b_1 is the coefficient of the first lagged value, n is the nth order lagged value, b_n is the nth order coefficient of the nth order lagged value, and ε is the error term.

3.7.2. Stationarity

Furthermore, timeseries data that tends to approximate its long-run parameters of mean, variance and co-variance is said to be stationary. Macroeconomic variables such as GDP often portray non-stationary characteristics whereby the parameters vary considerably with time. Non-stationary timeseries data has the additional characteristic of possessing a unit root which, when determined via a unit root test, is useful to gauge whether a timeseries is stationary or non-stationary. A timeseries Y_t is stationary if the following holds:

$$E(Y_t) = E(Y_{t-n}) = a \text{ ; for all n>0,} \tag{3}$$

$$VAR(Y_t) = VAR(Y_{t-n}) = \sigma y^2; \tag{4}$$

$$COV(Y_t, Y_{t-n}) = \gamma_n \tag{5}$$

Where, $E(Y_t)$ is the expected value of Y at time t, VAR is the variance of Y at time t, COV is the covariance of Y_t and Y_{t-n}, and Y_{t-n} is the lag of Y at time t-n.

Structural breaks are another factor of consideration for timeseries analysis and refers to abnormalities to the series trend because of external shocks, political effects, and policy changes. The challenge arises when conducting a unit root test to ascertain stationarity, structural breaks can lead to an inadvertent conclusion by many unit root tests that the series is non-stationary, when the opposite holds true. Macroeconomic data and environmental data are highly susceptible to external shocks, political and policy implications and therefore selection of the appropriate unit root tests which can cater for structural breaks is imperative.

There are numerous avenues that can be explored for purposes of selecting the appropriate timeseries regression model, all of which is based on the result of the unit root test. The first is if the unit root test produces the result that the series is stationary. In this instance, Shrestha and Bhatta (2018) suggests that a vector autoregressive model (VAR) or an ordinary least square (OLS) can be used with a sufficient degree of accuracy and unbiasedness. In the non-stationary and mixed results cases, an autoregressive distributed lag model can be used. Finally, cointegration can be determined using a common method of the Johansen test.

3.7.3. Unit Root Testing

A common method for performing unit root tests is the Augmented Dickey Fuller (ADF) test which has been employed in numerous studies pertaining to EKC investigations, some with confirmed EKC presence (Thio et al., 2022; Udeagha & Muchapondwa, 2022a; Udeagha & Ngepah, 2023; Usman et al., 2020), and others with mixed results (Ganda, 2019; Rafindadi & Usman, 2019; Shahbaz et al., 2016).

Shrestha and Bhatta (2018) explains that a primary shortcoming of the ADF unit root test is its inability to cater for structural breaks. Additionally, another unit root test, the Phillips-Peron (PP) test, is advantageous compared with the ADF approach due to its ability to cater for autocorrelation and heteroskedasticity issues. Almost all studies that utilise the ADF unit root test, regardless of EKC outcome, and include the PP test for good measure.

According to Shrestha and Bhatta (2018), the ADF unit root test takes the form:

$$\Delta Y_t = a + \delta Y_{t-1} + \sum_{i=1}^{k} \beta_i \Delta Y_{t-i} + e_t \tag{6}$$

Where, δ = 1-b, b = coefficient of Y_{t-1}, β_i is the coefficient of ΔY_{t-1}, ΔY_t is the first difference of $Y_t - Y_{t-1}$.

The null hypothesis is when $\delta = 0$ and the alternative hypothesis is when $\delta < 0$. If the null hypothesis is rejected, then the timeseries is stationary, and if not rejected then it is non-stationary.

Similarly, Shrestha and Bhatta (2018) describes that the PP test takes the following form:

$$\Delta Y_t = \pi Y_{t-1} + \beta_i D_{t-1} + e_t \quad (7)$$

Where, all the variables from the ADF that are common in the PP have the same representation, and D_{t-1} is the deterministic trend component. The null hypothesis is when $\pi = 0$ and the alternative hypothesis is when $\pi < 0$. If the null hypothesis is rejected, then the timeseries is stationary, and if not rejected then it is non-stationary.

Dogan and Turkekul (2016) suggests that the Zivot-Andrews (ZA) unit root test be used in addition to the ADF and PP tests, as the ZA test is better able to cater for structural breaks, and that the ADF and PP tests are susceptible to sample size distortion and low robustness. For the purposes of this study, 48 units of analysis is a relatively small sample size and therefore the ADF and PP tests will be sufficient. Should this not be the case, other more robust unit root tests such as ZA can be explored.

3.7.4. Model Estimation

The traditional Autoregressive Distributive Lag (ARDL) model estimation technique, developed by Pesaran et al. (2001), has been widely used for EKC framework studies with often inconclusive results (Ngarava et al., 2019; Saint Akadırı et al., 2021; Shahbaz et al., 2016; Tenaw & Beyene, 2021). Comparatively, the ARDL model has reported benefits over other estimation methods as it is able to utilise data series with varying lengths of lags whereas other models would require uniform lag lengths (Chen et al., 2022). Furthermore, the ARDL model is elastic in that it can incorporate data which have mixed stationarity or are fully non-stationary. It is also able to be applied to data with orders of integration that are mixed (Shrestha & Bhatta, 2018). Udeagha and Ngepah (2023) add that the traditional ARDL approach is well suited to smaller data samples without autocorrelation issues and can overcome challenges with endogeneity through appropriate delay selection. This study therefore utilised the ARDL model estimation technique outlined in equation (1) for each of the pollutants, respectively.

To select the optimal lag length, an appropriate information criterion needs to be employed. Information criterion is a statistical measure to determine goodness of fit by harmonising goodness-of-fit and complexity when comparing various models and/or model scenarios.

According to Gonzalo and Pitarakis (2002), there are numerous information criterion that can be used to determine optimal model lag length for ARDL model selection, namely: Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), Hannan-Quinn Information Criterion (HQIC). The BIC and HQIC are known to provide reliable estimates regardless of stationarity, while the AIC is characterised with overfitting in some cases. Gonzalo and Pitarakis (2002) adds that in the context of cointegrated samples, the AIC and BIC provides the best determination of optimal lag order for finite samples. For this study, both the AIC and BIC are utilised to determine the optimal ARDL model lag length.

3.7.5. Cointegration

It is possible that the utilisation of certain model estimation techniques may lead to a false conclusion that two or more variables possess a significant relationship and/or correlation, where they do not. This can lead to incorrect observations and conclusions being drawn about the data series, leading to spurious results and recommendations. Therefore, it is imperative to test for cointegration between variables which are non-stationary.

Shahbaz et al. (2016) utilised the Autoregressive Distributed Lag (ARDL) bounds testing approach to determine cointegration and explains that this method has the benefit of enabling cointegration to be tested without having to test for integration initially. Sinaga et al. (2019) confirms that the model negates the need for the variables to be integrated of order 1, is more aptly suited for smaller sample sizes and is comparably easier to use than conventional methods for cointegration testing.

The general form of the ARDL bounds test for cointegration is adapted from Sinaga et al. (2019) and given for the variables of this study as:

$$\begin{aligned}\Delta \ln Y_t = \beta_0 + \sum_{i=1}^{n} \delta_1 \Delta \ln(Y)_{t-i} + \sum_{i=1}^{n} \delta_2 \Delta \ln(GDP)_{t-i} + \sum_{i=1}^{n} \delta_3 \Delta \ln(GDP^2)_{t-i} \\ + \beta_1 \ln(Y)_{t-i} + \beta_2 \ln(GDP)_{t-i} + \beta_3 \ln(GDP^2)_{t-i} + \varepsilon_t\end{aligned} \tag{8}$$

Where, Y_t is the relevant pollutant per capita, and δ_1, δ_2, δ_3 represent the short run changes, and β_1, β_2, β_3 represent the long run coefficients, Δ represents the first difference operator which is used to force stationarity, GDP is economic growth per capita, and ε_t is the residual error term.

Pesaran et al. (2001) developed the method and outlines the hypotheses for the cointegration tests. The null hypothesis $H_0 = \beta_1 = \beta_2 = \beta_3 = 0$ and the alternative hypothesis $H_1 \neq \beta_1 \neq \beta_2 \neq$

$\beta_3 \neq 0$. According to Sinaga et al. (2019), a calculated F-statistic that exceeds the upper critical value will result in the rejection of the null hypothesis (no cointegration is rejected) and therefore the variables are cointegrated. Similarly, if the F-statistic is below than the lower critical value then the null hypothesis is accepted and there is no cointegration between the variables (no cointegration is accepted). If the F-statistic falls between the critical limits, then the test is inconclusive.

Numerous EKC studies have used the ARDL bounds test for cointegration with varying results of the EKC hypothesis. Shahbaz et al. (2016), while studying the effect of economic growth, trade openness and energy consumption on carbon dioxide emissions for Pakistan, utilised the ARDL bounds test for cointegration, and found a valid EKC hypothesis for the period of study. Ali et al. (2017) studied the economic-environmental linkage within the context of the EKC framework for Malaysia and, also employing the ARDL bounds test approach, found that a valid EKC presence existed for the data sample. Other studies in the context of South Africa have also used this approach for cointegration testing with positive EKC results (Udeagha & Breitenbach, 2023; Udeagha & Ngepah, 2023). While another study by Ganda (2019), also on the EKC hypothesis in South Africa, utilising the same cointegration approach, yielded an inconclusive EKC result.

Therefore, for the purposes of this study, the ARDL bounds test for cointegration is used due to its reported ease of application, suitability for smaller data series (as is the case in this study), and its robustness which is evident from the body of studies that have utilised it successfully within the EKC framework.

3.7.6. Causality

It has been discussed that cointegration reveals the relationship between variables, however, it does not indicate the directional characteristics of the relationship. Hence, causality reveals the pattern underpinning the relationship between two variables that are cointegrated. Shrestha and Bhatta (2018) discusses a very commonly used causality test for macroeconomic variables, developed by Granger (1969), unsurprisingly called the Granger Causality test.

Some valid EKC studies for South Africa have utilised Granger Causality tests (Udeagha & Ngepah, 2023; Usman et al., 2020), and some studies which investigated EKC presence in other parts of the world with confirmed results have also utilized Granger Causality within their statistical analysis (Akram et al., 2021; Jahanger et al., 2022; Katircioğlu, 2014). Granger Causality tests are utilised in this study due to its applicability and apparent reliability in prior

EKC studies with varying data types and over various regions. Therefore, its robustness and versatility are an advantage.

The standard form and requirement of the Granger Causality test is given by Shrestha and Bhatta (2018) and adapted for this study in Equations 10, 11 and 12, below:

$$\Delta Y_t = \sum_{i=1}^{n} a_i \Delta Y_{t-i} + \sum_{j=1}^{n} b_j \Delta GDP_{t-j} + \sum_{k=1}^{n} d_k \Delta GDP_{t-k}^2 + C_1 \quad (9)$$

$$\Delta GDP_t = \sum_{i=1}^{n} x_i \Delta GDP_{t-i} + \sum_{j=1}^{n} z_j \Delta Y_{t-j} + \sum_{k=1}^{n} p_k \Delta GDP_{t-k}^2 + C_2 \quad (10)$$

$$\Delta GDP_t^2 = \sum_{i=1}^{n} q_i \Delta GDP_{t-i}^2 + \sum_{j=1}^{n} w_j \Delta Y_{t-j} + \sum_{k=1}^{n} g_k \Delta GDP_{t-k} + C_3 \quad (11)$$

Where, Y_t is the relevant pollutant per capita measure, and a, b, d, x, z, p, q, w, and g represent the model coefficients, and C_1, C_2, and C_3 represent the model intercepts, Δ represents the first difference operator, and GDP is economic growth per capita.

The null hypothesis for Equation 10 is $H_0 = b_j = d_k = 0$, and the alternative hypothesis for Equation 10 is $H_1 \neq b_j \neq d_k \neq 0$.

The null hypothesis for Equation 11 is $H_0 = z_j = p_k = 0$, and the alternative hypothesis for Equation 11 is $H_1 \neq z_j \neq p_k \neq 0$.

The null hypothesis for Equation 12 is $H_0 = w_j = g_k = 0$, and the alternative hypothesis for Equation 12 is $H_1 \neq w_j \neq g_k \neq 0$.

A calculated F-statistic that exceeds the upper critical value results in the rejection of the null hypothesis (no causality is rejected) and therefore the independent variable(s) in each equation Granger-causes the dependent variable. Similarly, if the F-statistic is below than the lower critical value then the null hypothesis is accepted and therefore the independent variable(s) in each equation do not Granger-cause the dependent variable (no causality is accepted). If the F-statistic falls between the critical limits, then the test is inconclusive.

Chapter 4: Discussion of Findings

4.1. Introduction

The following chapter discusses the analysis of the study and key findings. The study attempts to establish if an EKC relationship exists for South Africa between economic growth and environmental degradation, proxied by key air pollutants. The null hypothesis is that economic growth has no EKC relationship with CO_2, SO_2, NO_2, and PM2.5, respectively, in South Africa. The alternative hypothesis is that economic growth has an EKC relationship with CO_2, SO_2, NO_2, and PM2.5, respectively, in South Africa. It commences with an overview of the descriptive statistics, the general behaviour of the variables in the time series analysis, the stationarity, cointegration, long and short run dynamics of the model and a conclusion of the findings. The data for CO_2, SO_2, NO_2 and PM2.5 are obtained from European Commission (2018) and the data for GDP per capita at constant local currency units is obtained from World Bank (2023).

4.2. Descriptive Statistics

The sample size of the study comprises 49 data points per variable, spanning 1970 to 2018, for annual GDP per capita and annual pollutant emissions for CO_2, NO_2, SO_2 and PM2.5, measured in kilotons, over the same period. The descriptive statistics for the sample population, provided in table 5 below, indicates that the data is symmetrical due to the mean, median, minimum, and maximum being relatively close together. There is also negligible variation in the data for all variables considered, which is evident from the low standard deviation across the variable range.

The descriptive statistics of the sample population also indicates that all the variables under consideration exhibit a platykurtic distribution, emphasised by the slightly negative kurtosis. Furthermore, the data for CO_2 is slightly negatively skewed, and the remaining variables exhibit a slight positive skewness. These are considered insignificant as the Jarque-Bera probabilities for all variables under consideration are above 0.05, except for NO_2, indicating that the error terms are normally distributed. The Jarque-Bera for NO_2 is 0.047 which is sufficiently close to 0.05 to consider its error terms normally distributed. Therefore, the null hypothesis that the residuals are normally distributed is not rejected for all variables.

Table 5: Descriptive statistics

Variable	LN CO2 [kt]	LN NO2 [kt]	LN SO2 [kt]	LN PM2.5 [kt]	LN GDP	LN GDP2
Mean	12.877	7.236	7.548	6.255	(0.007)	0.013
Median	12.865	7.104	7.443	6.211	(0.014)	0.007
Minimum	12.399	6.894	6.987	5.985	(0.208)	0.000
Maximum	13.216	7.633	8.027	6.611	0.175	0.043
Standard Deviation	0.239	0.262	0.315	0.185	0.115	0.013
Sample Variance	0.057	0.069	0.099	0.034	0.013	0.000
Kurtosis	(0.961)	(1.583)	(1.246)	(1.034)	(0.972)	(0.901)
Skewness	(0.290)	0.353	0.087	0.391	0.107	0.624
Jarque-Bera (JB)	2.572	6.136	3.231	3.431	2.024	4.839
JB Probability	0.276	0.047	0.199	0.180	0.364	0.089
Standard Error	0.034	0.037	0.045	0.026	0.016	0.002
Count	*49*	*49*	*49*	*49*	*49*	*49*

(Source: Stata estimates from research data)

Notes: LN CO2 – Natural Logarithm of Carbon Dioxide emissions measured in kilotons; LN NO2 – Natural Logarithm of Nitrogen Dioxide emissions measured in kilotons; LN SO2 – Natural Logarithm of Sulphur Dioxide emissions measured in kilotons; LN PM2.5 – Natural Logarithm of Particulate Matter emissions of less than or equal to 2.5 micrometres measured in kilotons; LN GDP – Natural Logarithm of GDP per capita measured in constant 2015 local currency units; LN GDP2 – Natural Logarithm of GDP per capita squared measured in constant 2015 local currency units;

4.3. Variable Trend Analysis

4.3.1. GDP per Capita

Figure 3 depicts the centred natural logarithm data for GDP per capita for the period between 1970 and 2018. The graph indicates that South Africa experienced its lowest GDP per capita in 1993. This period of South Africa's history was marked by tumultuous socio-political events, economic sanctions, tightened economic policy aimed at curbing inflationary pressures, and meagre economic growth, all preceding the nations transition into a democratic state (Gelb, 2007). The trend also appears to be inclining between 1994 and 2008. This is attributable to comparably higher levels of economic growth to population growth during this period. The trend also tapers down post the global financial crisis in 2007-2008, compounded by the onset of electricity supply disruptions in South Africa ("loadshedding") which commenced in late 2007, leading to diminished foreign investor sentiment (Walsh et al., 2021). GDP per capita has its local minima in 1993 at ZAR 54,442 per capita (ZAR -0.21 per capita on log scale) and its local maxima in 2013 at ZAR 79,859 (ZAR 0.81 per capita on log scale).

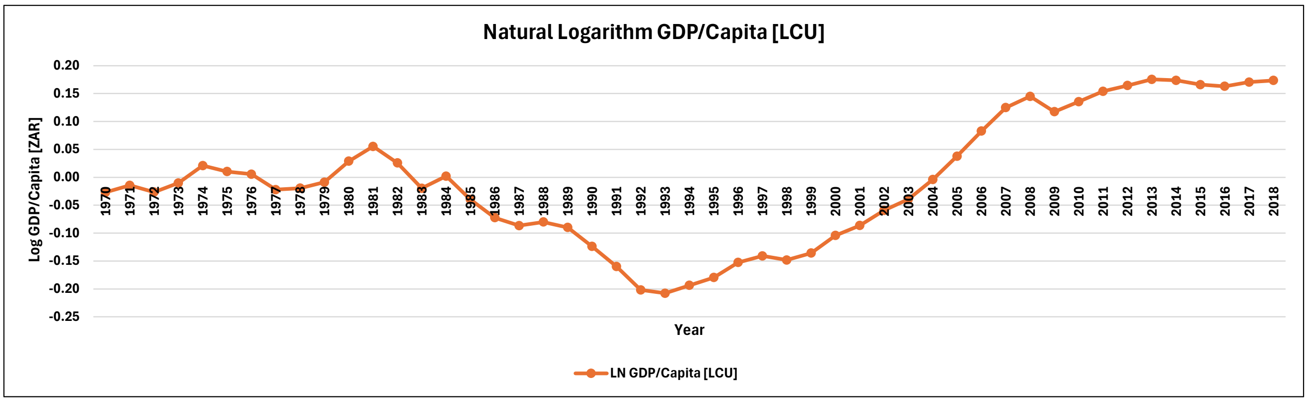

Figure 3: Natural Log of GDP per capita for South Africa between 1970 and 2018

(Source: Authors Illustration)

4.3.2. CO2

The graph of annual CO2 emissions in South Africa, Figure 4 below, appears to have a trend of moderate inclination for the period 1970 to 2018. Considering that circa 83% of South Africa's CO2 emissions are associated with energy production, this aligns with the narrative of steadily deteriorating environmental quality (Kohler, 2013). A contributory factor to the perceived flattened patter of the graph between 2008 and 2018 is the introduction of the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) in 2007 and the first round of subsequent renewable energy integration into the country's electricity generation capacity in 2011 (Baker et al., 2014). This is also influenced by the challenges experienced in maintaining energy generating assets and the resultant supply/generating unreliability. CO2 has its local minima in 1970 at 242,569 kt p.a (12.40 kt p.a on log scale) and its local maxima in 2008 at 549,348 kt p.a (13.22 kt p.a on log scale).

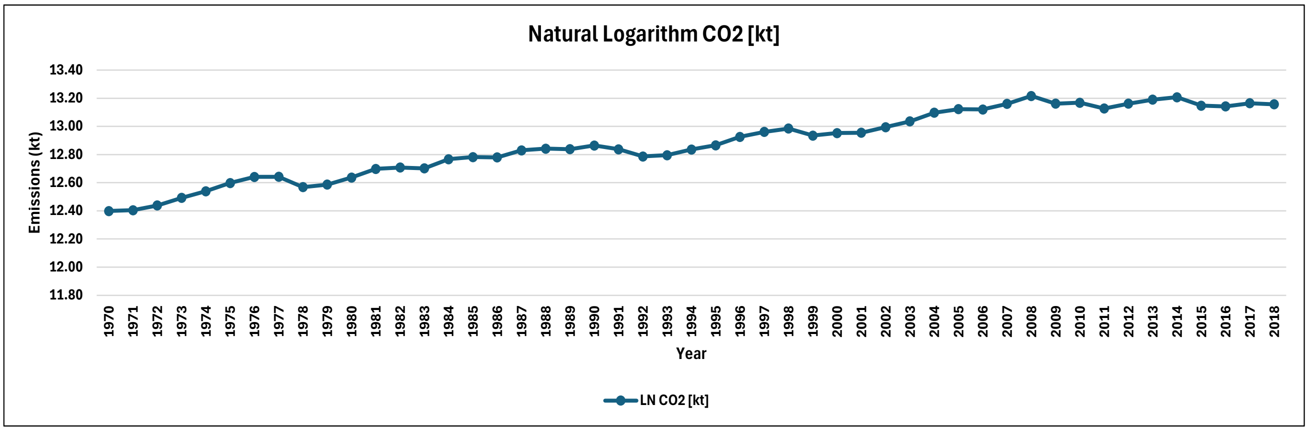

Figure 4: Natural Log of CO2 emissions for South Africa between 1970 and 2018

(Source: Authors Illustration)

4.3.3. NO2

The graph of NO2 emissions in South Africa exhibits a similar increasing trend between 1970 and 2018, shown in Figure 5 below. NO2 emissions are associated with agricultural processing and the apparent flattening of the trend could be attributed to the country's increased industrialisation and integration into manufacturing compared to its historic agricultural reliance, mentioned earlier in this study. A noticeable dip in NO2 per capita is evident between 1998 and 2000, this could be credited to the introduction of the National Environmental Management Act that was introduced into legislation in 1998 (Naiker et al., 2012). NO2 has its local minima in 1970 at 242,569 kt p.a (12.40 kt p.a on log scale) and its local maxima in 2008 at 549,348 kt p.a (13.22 kt p.a on log scale).

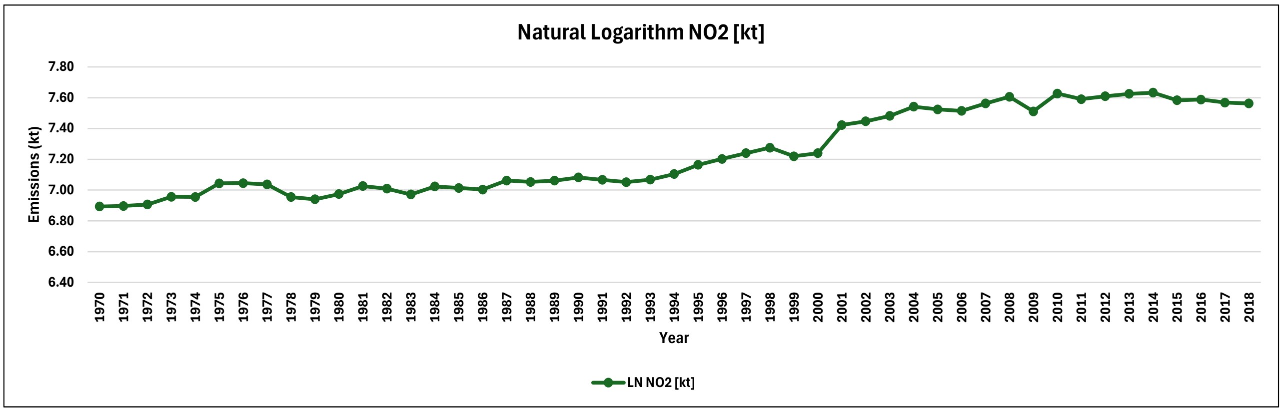

Figure 5: Natural Log of NO2 emissions for South Africa between 1970 and 2018

(Source: Authors Illustration)

4.3.4. SO2

The graph of SO2 emissions appears to have a trend of moderate inclination for the period 1970 to 2018, shown in Figure 6 below. An interesting observation is that the trend for SO2 closely resembles the trend of NO2 per capita in Figure 5, indicating a possible collinear relationship, to be discussed later in this chapter. A similar dip in SO2 emissions can be observed between 1998 and 2000, as with NO2, and as mentioned previously this could be because of the introduction of the National Environmental Management Act in 1998. Several perturbations can also be observed between 2004 and 2006, and 2008 to 2009. These fluctuations correspond with the introduction of the National Environmental Management: Air Quality Act (NEMAQA) in 2004 and the National Framework for Air Quality Management in South Africa in 2007, respectively (Naiker et al., 2012). SO2 has its local minima in 1970 at 1082 kt p.a (6.99 kt p.a on log scale) and its local maxima in 2014 at 3063 kt p.a (8.03 kt p.a on log scale).

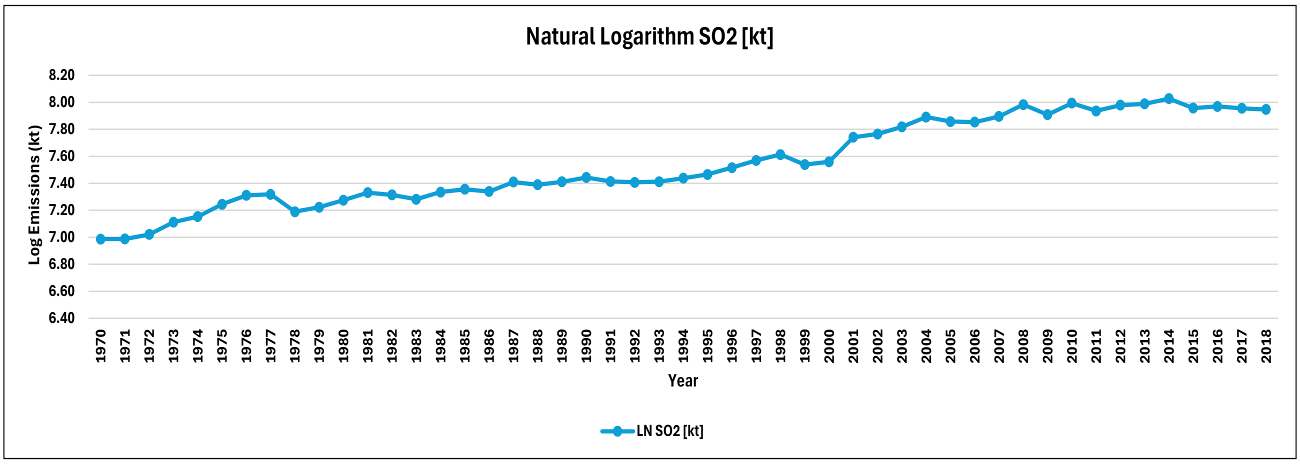

Figure 6: Natural Log of SO2 emissions for South Africa between 1970 and 2018

(Source: Authors Illustration)

4.3.5. PM2.5

The graph of PM2.5 emissions, Figure 7 below, appears to exhibit an increasing trend for the period 1970 to 2018. A noticeable dip in the trend can be observed between 2000 and 2001, which provides insight into the lack of stationarity in the data. Due to the complex nature of PM2.5 atmospheric dispersion and the plethora of sources which are possible emission factors - ranging from transport activity, mining activity, natural or anthropogenic aridity, urbanisation, population growth, increase in standards of living, real income growth, delayed influence of environmental legislation, and/or change in emission measurement methodology - it would be misleading to speculate as to the anthropogenic reason for the noticeable step change between 2000 and 2001. PM2.5 has its local minima in 1971 at 398 kt p.a (5.99 kt p.a on log scale) and its local maxima in 1998 at 743 kt p.a (6.61 kt p.a on log scale).

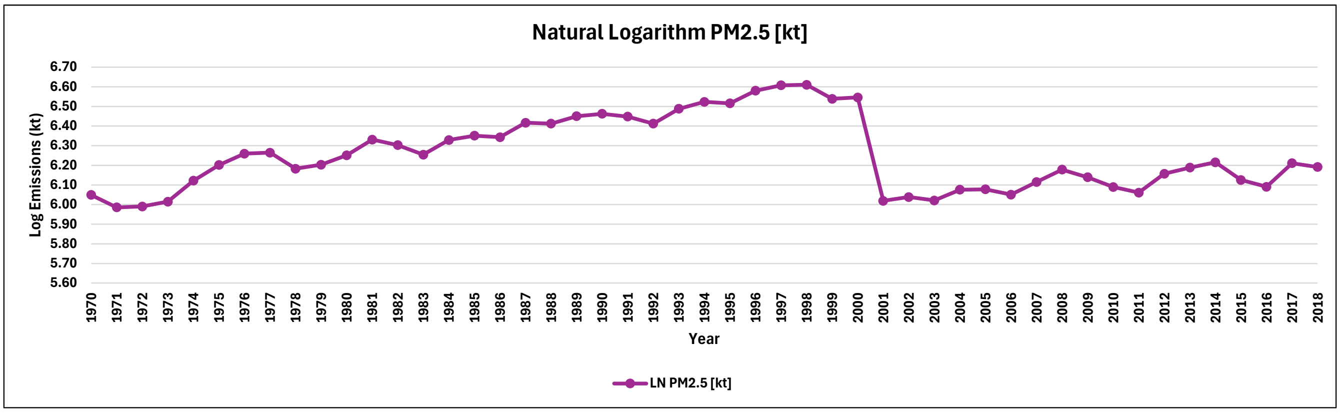

Figure 7: Natural Log of PM2.5 emissions for South Africa between 1970 and 2018

(Source: Authors Illustration)

4.4. Variable Correlation Analysis

High degrees of multicollinearity between independent variables, such as GDP/capita and GDP/capita squared, may lead to spurious conclusions on directionality and extent of relationships by introducing instability in estimated model coefficients (Wang, 2024). This occurrence originates huge standard errors among explanatory variables with larger confidence levels, resulting in a concurrent effect on estimated coefficients in the case of miniscule deviations in model parameters or data (Ardakani & Seyedaliakbar, 2019). This is especially relevant when independent variables originate from each other in the case of quadratic and/or higher order equations.

As a result, the correlation analysis of the original LN GDP/capita and its square produced a correlation factor of 1.00. There exist many methods of mitigating multicollinearity among explanatory variables such as exclusion of independent variables and to mean-centre the data points for an explanatory variable for which the multicollinearity exists (Ardakani & Seyedaliakbar, 2019). Since the EKC model requires both independent variables of GDP per capita and its square, as these represent the scale and technique effects of economic growth within the EKC theory, these variables could not be excluded. Therefore, the predictor variables were mean centred by subtracting the mean of the sample data set for GDP per capita from each data observation/point.

The resultant collinearity test in Table 6 below shows the extent of collinearity among the explanatory variables, LN GDP per capita and LN GDP per capita squared, and the respective dependent variables: LN CO2, LN NO2, LNSO2, and LNPM2.5. For avoidance of doubt, equation 1 will be used to establish 4 models for each of the above dependent variables. It is concluded that the independent variables now have an insignificant degree of multicollinearity.

While not relevant in terms of model analysis, it is observed that significant collinearity exists between the natural logarithms of CO2, NO2 and SO2, respectively.

Table 6: Collinearity Test

Variable	LN CO2	LN NO2	LN SO2	LN PM2.5	LN GDP	LN GDP2
LN CO2	**1.0000**	0.9413	0.9800	-0.0259	0.4483	0.5435
LN NO2	0.9413	**1.0000**	0.9839	-0.3133	0.6156	0.4459
LN SO2	0.9800	0.9839	**1.0000**	-0.1897	0.5588	0.4991
LN PM2.5	-0.0259	-0.3133	-0.1897	**1.0000**	-0.6487	0.3720
LN GDP	0.4483	0.6156	0.5588	-0.6487	**1.0000**	-0.0105
LN GDP2	0.5435	0.4459	0.4991	0.3720	-0.0105	**1.0000**

(Source: Stata estimates from research data)

Notes: LN CO2 – Natural Logarithm of Carbon Dioxide emissions measured in kilotons; LN NO2 – Natural Logarithm of Nitrogen Dioxide emissions measured in kilotons; LN SO2 – Natural Logarithm of Sulphur Dioxide emissions measured in kilotons; LN PM2.5 – Natural Logarithm of Particulate Matter emissions of less than or equal to 2.5 micrometres measured in kilotons; LN GDP – Natural Logarithm of GDP per capita measured in constant 2015 local currency units; LN GDP2 – Natural Logarithm of GDP per capita squared measured in constant 2015 local currency units;

4.5. Unit Root Analysis

The unit root tests using both the Augmented Dicky Fuller and the Phillips-Peron methods, respectively, were conducted, shown in Table 7. The null hypothesis for unit root tests is that the data is non-stationary, and therefore possesses a unit root, in the instances where the P-value of the test exceeds 0.05 and/or the test statistic is greater than the critical value at a particular confidence level, in this study it will be 5%. At level, all the variable data appears to meet both criteria for the existence of a unit root. Hence, the null hypothesis is accepted. The data is therefore non-stationary at level or order of integration I(0).

Both tests were re-evaluated at the first difference or first order. All the variable data appears to deviate from both criteria for the existence of a unit root. Hence, the null hypothesis is rejected. The data is therefore stationary at the first difference and is deemed to be integrated of order I(1) or first order integrated.

Table 7: Unit Root Tests

Level I(0)									
Variable	**Lag**	**ADF Test**	**PP Test**	**CV (1%)**	**CV (5%)**	**CV (10%)**	**ADF P-Value**	**PP P-Value**	**Outcome**
LN CO2	0	-1.896	-1.896	-3.594	-2.936	-2.602	0.334	0.334	Non-stationary
LN NO2	0	-0.679	-0.679	-3.594	-2.936	-2.602	0.852	0.852	Non-stationary
LN SO2	0	-1.289	-1.289	-3.594	-2.936	-2.602	0.634	0.634	Non-stationary
LN PM2.5	0	-1.923	-1.923	-3.594	-2.936	-2.602	0.321	0.321	Non-stationary
LN GDP	0	0.133	0.133	-3.594	-2.936	-2.602	0.968	0.968	Non-stationary
LN GDP2	0	-1.010	-1.010	-3.594	-2.936	-2.602	0.750	0.750	Non-stationary
First Difference I(1)									
Variable	**Lag**	**ADF Test**	**PP Test**	**CV (1%)**	**CV (5%)**	**CV (10%)**	**ADF P-Value**	**PP P-Value**	**Outcome**
LN CO2	0	-5.661	-5.661	-3.600	-2.938	-2.604	0.000	0.000	Stationary
LN NO2	0	-7.650	-7.650	-3.600	-2.938	-2.604	0.000	0.000	Stationary
LN SO2	0	-7.428	-7.428	-3.600	-2.938	-2.604	0.000	0.000	Stationary
LN PM2.5	0	-6.772	-6.772	-3.600	-2.938	-2.604	0.000	0.000	Stationary
LN GDP	0	-3.986	-3.986	-3.600	-2.938	-2.604	0.002	0.002	Stationary
LN GDP2	0	-3.719	-3.719	-3.600	-2.938	-2.604	0.004	0.004	Stationary

(Source: Stata estimates from research data)

Notes: LN CO2 – Natural Logarithm of Carbon Dioxide emissions measured in kilotons; LN NO2 – Natural Logarithm of Nitrogen Dioxide emissions measured in kilotons; LN SO2 – Natural Logarithm of Sulphur Dioxide emissions measured in kilotons; LN PM2.5 – Natural Logarithm of Particulate Matter emissions of less than or equal to 2.5 micrometres measured in kilotons; LN GDP – Natural Logarithm of GDP per capita measured in constant 2015 local currency units; LN GDP2 – Natural Logarithm of GDP per capita squared measured in constant 2015 local currency units; CV – denotes the critical value at the prevailing confidence level; ADF – Augmented Dickey Fuller unit root test; PP – Phillips Peron unit root test;

4.6. ARDL Model Estimation

An iterative method of testing model scenarios was utilised to derive an optimal model parameter lag combination and fit. The lag length for each of the dependent and independent parameters were varied to obtain an optimal lag length combination that could yield the best model fit, factoring possible inherent regression complexity. This was achieved using the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) indicators from each scenario which, according to Kripfganz and Schneider (2023), the optimal model lag scenario is the one that minimises both the AIC and BIC. Both indicators provide the basis for the same conclusions, however, the BIC is more frugal in its evaluation of complexity, and both were employed for good measure. While higher lag orders typically produce better model fits, Kripfganz and Schneider (2023) adds that lag order ranges should be selected conservatively for smaller datasets to ensure that sufficient degrees of freedom are available for precise model coefficient fit, to prevent overfitting the model, and producing spurious results.

The lag lengths for each of the dependent and independent parameters, for each model in this study were varied from zero to a selected maximum of three, due to the relatively small sample size of the study. It should be noted that the results of the study, across all models and scenarios, indicate that the increasing of regressor lag length did not necessarily yield improved model fit, therefore there is no expected benefit to increase the selected maximum lag length beyond three in this study.

The coefficient of determination, or R-squared value, of each scenario and its log-likelihood were included in the extract of results below. While both measures do not provide a basis for determining optimal parameter lag order in ARDL modelling, they provide salient indications of model fit. The AIC and BIC are functions of the log-likelihood value and are therefore interrelated. Conversely, the maximisation of log-likelihood and R-squared are preferred as this indicates optimal model fit.

It should be noted that Stata would not permit a lag order of zero for the dependent variable as this would imply that no autoregression exists, which would invalidate the intention of ARDL modelling. Consequently, scenarios for a zero-lag order of the dependent variable were not run for all models.

4.6.1. CO2 – Model 1

The optimal lag scenario for model 1, with CO2 as the dependent variable and GDP and GDP squared as the respective independent variables, is ARDL (1,0,0) with the lowest values for both the AIC and BIC, shown in table 8. Additionally, this scenario presents a comparatively high log-likelihood from all scenarios (91.933), indicating a good model fit, and a moderate R-squared value. Post review of the original model residual diagnostics, 6 outliers were omitted, which were found to negatively affect the base assumption of data normality.

Table 8: Model 1 Summary - CO2

Scenario	**Lag Order** (LN CO2, LN GDP, LN GDP2)	**LL**	**R-Squared**	**AIC**	**BIC**
CO2 lag variation with all other regressor lags constant					
1	**(1,0,0)**	91.933	0.709	**-175.866***	**-169.532***
2	(2,0,0)	77.413	0.632	-144.827	-137.657
3	(3,0,0)	65.663	0.684	-119.326	-111.777
GDP lag variation with all other regressor lags constant					
4	(1,1,0)	91.940	0.709	-173.880	-165.962
5	(1,2,0)	91.940	0.709	-173.880	-165.962
6	(1,3,0)	87.628	0.733	-161.257	-150.572
GDP2 lag variation with all other regressor lags constant					
7	(1,0,1)	91.961	0.710	-173.923	-166.005
8	(1,0,2)	89.743	0.720	-167.487	-158.155
9	(1,0,3)	87.105	0.725	-160.210	-149.526
Other permutations of regressor lag order					
10	(1,1,1)	**91.965****	0.710	-171.929	-162.428
11	(1,2,1)	89.310	0.713	-164.620	-153.732
12	(1,3,1)	87.708	0.734	-159.416	-147.205
13	(1,1,2)	89.783	0.720	-165.566	-154.679
14	(1,1,3)	87.106	0.725	-158.212	-146.001
15	(1,2,2)	89.783	0.720	-163.566	-151.124
16	(1,2,3)	87.113	0.725	-156.227	-142.489
17	(1,3,2)	88.006	0.739	-158.012	-144.275
18	(1,3,3)	88.575	**0.748*****	-157.150	-141.886

(Source: Stata estimates from research data)

Notes: LN CO2 – Natural Logarithm of Carbon Dioxide emissions measured in kilotons; LN GDP – Natural Logarithm of GDP per capita measured in constant 2015 local currency units; LN GDP2 – Natural Logarithm of GDP per capita squared measured in constant 2015 local currency units; LL – denotes the log likelihood of the model scenario; AIC – Akaike Information Criterion; BIC – Bayesian Information Criterion; * denotes the scenario with the lowest AIC and BIC values, respectively; ** denotes the scenario with the highest log likelihood value; *** denotes the scenario with the highest R-squared/coefficient of determination value.

4.6.2. NO2 – Model 2

The optimal lag scenario for model 2, with NO2 as the dependent variable and GDP and GDP squared as the respective independent variables, is ARDL (1,0,1) with the lowest values for both the AIC and BIC, shown in table 9. Additionally, this scenario presents a comparatively high log-likelihood from all scenarios (86.449), indicating a good model fit, and a moderate R-squared value. Post review of the original model residual diagnostics, 1 outlier was omitted, which was found to adversely affect the base assumption of data normality.

Table 9: Model 2 Summary - NO2

Scenario	**Lag Order** (LN NO2, LN GDP, LN GDP2)	**LL**	**R-Squared**	**AIC**	**BIC**
NO2 lag variation with all other regressor lags constant					
1	(1,0,0)	84.612	0.668	-161.225	-153.998
2	(2,0,0)	80.078	0.671	-150.156	-141.350
3	(3,0,0)	76.425	0.683	-140.850	-130.568
GDP lag variation with all other regressor lags constant					
4	(1,1,0)	84.690	0.669	-159.381	-150.347
5	(1,2,0)	82.339	0.669	-152.678	-141.973
6	(1,3,0)	80.738	0.678	-147.476	-135.148
GDP2 lag variation with all other regressor lags constant					
7	**(1,0,1)**	86.449	0.694	**-162.899***	**-153.865***
8	(1,0,2)	84.856	0.705	-157.711	-147.006
9	(1,0,3)	83.834	0.721	-153.668	-141.339
Other permutations of regressor lag order					
10	(1,1,1)	**86.464****	0.694	-160.929	-150.089
11	(1,2,1)	84.132	0.695	-154.264	-141.775
12	(1,3,1)	82.695	0.706	-149.390	-135.300
13	(1,1,2)	84.868	0.705	-155.736	-143.247
14	(1,1,3)	84.077	0.724	-152.154	-138.064
15	(1,2,2)	84.924	0.706	-153.848	-139.575
16	(1,2,3)	84.121	0.725	-150.242	-134.391
17	(1,3,2)	83.470	0.716	-148.941	-133.090
18	(1,3,3)	84.344	**0.728*****	-148.688	-131.076

(Source: Stata estimates from research data)

Notes: LN NO2 – Natural Logarithm of Nitrogen Dioxide emissions measured in kilotons; LN GDP – Natural Logarithm of GDP per capita measured in constant 2015 local currency units; LN GDP2 – Natural Logarithm of GDP per capita squared measured in constant 2015 local currency units; LL – denotes the log likelihood of the model scenario; AIC – Akaike Information Criterion; BIC – Bayesian Information Criterion; * denotes the scenario with the lowest AIC and BIC values, respectively; ** denotes the scenario with the highest log likelihood value; *** denotes the scenario with the highest R-squared/coefficient of determination value.

4.6.3. SO2 – Model 3

The optimal lag scenario for model 3, with SO2 as the dependent variable and GDP and GDP squared as the respective independent variables, is ARDL (1,0,1) with the lowest values for both the AIC and BIC, shown in table 10. Additionally, this scenario presents a comparatively high log-likelihood, albeit suboptimal (75.764), indicating a good model fit, and a moderate R-squared value.

Table 10: Model 3 Summary - SO2

Scenario	Lag Order (LN SO2, LN GDP, LN GDP2)	LL	R-Squared	AIC	BIC
SO2 lag variation with all other regressor lags constant					
1	(1,0,0)	73.561	0.588	-139.122	-131.721
2	(2,0,0)	71.706	0.590	-133.412	-124.268
3	(3,0,0)	70.728	0.604	-129.456	-118.616
GDP lag variation with all other regressor lags constant					
4	(1,1,0)	74.500	0.604	-138.999	-129.748
5	(1,2,0)	72.452	0.603	-132.904	-121.932
6	(1,3,0)	71.766	0.622	-129.533	-116.886
GDP2 lag variation with all other regressor lags constant					
7	**(1,0,1)**	75.764	0.625	**-141.529***	**-132.278***
8	(1,0,2)	74.019	0.629	-136.039	-125.067
9	(1,0,3)	73.028	0.643	-132.057	-119.410
Other permutations of regressor lag order					
10	(1,1,1)	**76.488****	0.636	-140.975	-129.874
11	(1,2,1)	74.413	0.636	-134.827	-122.026
12	(1,3,1)	73.949	0.657	-131.898	-117.445
13	(1,1,2)	74.738	0.641	-135.476	-122.675
14	(1,1,3)	74.292	0.662	-132.584	-118.131
15	(1,2,2)	74.768	0.641	-133.535	-118.906
16	(1,2,3)	74.354	0.663	-130.709	-114.449
17	(1,3,2)	74.336	0.663	-130.672	-114.412
18	(1,3,3)	74.449	**0.665*****	-128.899	-110.832

(Source: Stata estimates from research data)

Notes: LN SO2 – Natural Logarithm of Sulphur Dioxide emissions measured in kilotons; LN GDP – Natural Logarithm of GDP per capita measured in constant 2015 local currency units; LN GDP2 – Natural Logarithm of GDP per capita squared measured in constant 2015 local currency units; LL – denotes the log likelihood of the model scenario; AIC – Akaike Information Criterion; BIC – Bayesian Information Criterion; * denotes the scenario with the lowest AIC and BIC values, respectively; ** denotes the scenario with the highest log likelihood value; *** denotes the scenario with the highest R-squared/coefficient of determination value.

4.6.4. PM2.5 – Model 4

The optimal lag scenario for model 4, with PM2.5 as the dependent variable and GDP and GDP squared as the respective independent variables, is ARDL (1,0,0) with the lowest values for both the AIC and BIC, shown in table 11. Additionally, this scenario presents a comparatively high log-likelihood across all scenarios (73.421), indicating a good model fit, and a moderate R-squared value. Post review of the original model residual diagnostics, 1 outlier was omitted, which was found to significantly affect the base assumption of data normality.

Table 11: Model 4 Summary - PM2.5

Scenario	Lag Order (LN PM2.5, LN GDP, LN GDP2)	LL	R-Squared	AIC	BIC
PM2.5 lag variation with all other regressor lags constant					
1	**(1,0,0)**	73.421	0.556	**-138.843***	**-131.616***
2	(2,0,0)	71.721	0.595	-133.442	-124.636
3	(3,0,0)	68.855	**0.613*****	-125.711	-115.429
GDP lag variation with all other regressor lags constant					
4	(1,1,0)	73.462	0.557	-136.925	-127.892
5	(1,2,0)	72.631	0.574	-133.261	-122.556
6	(1,3,0)	71.117	0.585	-128.233	-115.905
GDP2 lag variation with all other regressor lags constant					
7	(1,0,1)	74.052	0.569	-138.105	-129.072
8	(1,0,2)	71.970	0.561	-131.940	-121.234
9	(1,0,3)	69.847	0.560	-125.694	-113.366
Other permutations of regressor lag order					
10	(1,1,1)	**74.135****	0.570	-136.271	-125.431
11	(1,2,1)	73.091	0.583	-132.181	-119.692
12	(1,3,1)	71.545	0.593	-127.091	-113.001
13	(1,1,2)	72.018	0.562	-130.037	-117.548
14	(1,1,3)	69.893	0.561	-123.786	-109.696
15	(1,2,2)	73.128	0.583	-130.257	-115.983
16	(1,2,3)	71.055	0.584	-124.110	-108.259
17	(1,3,2)	71.605	0.595	-125.210	-109.360
18	(1,3,3)	71.688	0.596	-123.376	-105.764

(Source: Stata estimates from research data)

Notes: LN PM2.5 – Natural Logarithm of Particulate Matter emissions of less than or equal to 2.5 micrometres measured in kilotons; LN GDP – Natural Logarithm of GDP per capita measured in constant 2015 local currency units; LN GDP2 – Natural Logarithm of GDP per capita squared measured in constant 2015 local currency units; LL – denotes the log likelihood of the model scenario; AIC – Akaike Information Criterion; BIC – Bayesian Information Criterion; * denotes the scenario with the lowest AIC and BIC values, respectively; ** denotes the scenario with the highest log likelihood value; *** denotes the scenario with the highest R-squared/coefficient of determination value.

4.7. ARDL Bounds Test (Cointegration)

The ARDL bounds test for cointegration, developed by Pesaran et al. (2001), is useful in determining if long run relationships exist among variables. The approach utilises a lower bound, I(0), and an upper bound, I(1), in its evaluation. The null hypothesis for the test is that there is no level relationship between the response and predictor variables and therefore no long run relationship exists between the variables. A test statistic that exceeds the upper bound value will result in a rejection of the null hypothesis implying that a long run relationship exists. If the test statistic value lies between the lower and upper bound values then the test is inconclusive (Kripfganz & Schneider, 2023). Two test statistics were computed, namely the F-statistic and the t-statistic, with the former being of primary significance. The ARDL bounds test for cointegration was applied to the four models at their optimal lag positions, respectively, with each model centred on an indicator of environmental degradation as its dependent variable. The ARDL bounds test results are shown in table 12, below.

The F-statistic for all models under consideration is observed to greater than the upper bound value at all significance levels, and particularly at the 5% significance level. Similarly, the t-statistic for all models under consideration is greater than the upper bound at all significance levels. Therefore, the null hypothesis that no there is no relationship between the response and predictor variables, for all models under consideration, is rejected. It can be concluded that long run relationships exist among the dependent and independent variables for all models and, consequently, cointegration is present (Katircioglu, 2009).

Table 12: ARDL Bounds Test Results

Model	Test Statistic	Value	10% significance		5% significance		1% significance	
			I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
No.1 (CO2)	F-Statistic	26.005	3.375	4.401	4.154	5.309	5.992	7.423
	T-Statistic	-8.083	-2.591	-3.247	-2.930	-3.621	-3.619	-4.369
No.2 (NO2)	F-Statistic	25.686	3.308	4.328	4.047	5.185	5.765	7.146
	T-Statistics	-8.443	-2.575	-3.236	-2.906	-3.598	-3.569	-4.310
No.3 (SO2)	F-Statistic	20.369	3.299	4.314	4.032	5.162	5.728	7.093
	T-Statistic	-7.608	-2.575	-3.236	-2.903	-3.594	-3.561	-4.299
No.4 (PM2.5)	F-Statistic	17.142	3.321	4.320	4.058	5.170	5.769	7.106
	T-Statistics	-6.2	-2.584	-3.245	-2.912	-3.603	-3.569	-4.307

(Source: Stata estimates from research data)

Notes: CO2 – Carbon Dioxide; NO2 – Nitrogen Dioxide; SO2 – Sulphur Dioxide; PM2.5 – Particulate Matter smaller than 2.5 micro-meters; I(0) – Lower Bound; I(1) – Upper Bound.

4.8. Long Run Results

The long run results in for the various models is presented in table 13, below.

Table 13: Long Run Modelling Results

	Model 1 - CO2	Model 2 - NO2	Model 3 - SO2	Model 4 - PM2.5
LN GDP				
Coefficient	0.526	0.474	0.475	0.767
Standard Error	0.161	0.209	0.303	0.388
t-statistic	3.260	2.270	1.570	1.980
P >|t|	0.003	0.029	0.125	0.055
LN GDP2				
Coefficient	-2.308	-0.479	-1.729	1.517
Standard Error	0.865	1.276	1.817	1.902
t-statistic	-2.670	-0.380	-0.950	0.800
P >|t|	0.012	0.710	0.347	0.430

(Source: Stata estimates from research data)

Notes: CO2 – Natural logarithm of Carbon Dioxide (response variable in model 1); NO2 – Natural logarithm of Nitrogen Dioxide (response variable in model 2); SO2 – Natural logarithm of Sulphur Dioxide (response variable in model 3); PM2.5 – Natural logarithm of Particulate Matter smaller than 2.5 micro-meters (response variable in model 4); LN GDP – Natural logarithm of GDP (predictor variable 1); LN GDP2 - Natural logarithm of GDP squared (predictor variable 2).

CO2 – Model 1

An evident positive long run relationship exists between GDP and CO2. This long run relationship is statistically significant with a p-value of 0.003. This result agrees with the findings of prior studies in the context of South Africa (Ganda, 2019; Sarkodie & Adams, 2018; Udeagha & Breitenbach, 2023) and in the context of other regional countries (Disli et al., 2016; Udeagha & Muchapondwa, 2022b, 2022a; Usman et al., 2020).

A negative long run relationship is found to exist between CO2 and GDP2, the independent variable representing the technique effect of industrialised economic growth, and the relationship is statistically significant since its p-value is less than 0.05. This result concurs with the findings of similar, prior studies (Bilgili et al., 2016; Gokmenoglu & Taspinar, 2018; Ngarava et al., 2019). This result confirms that an EKC relationship is likely to exist between CO2 and economic growth in South Africa in the long run with a turning point at ZAR 75,099.00 per capita at constant 2015 levels.

This result is expected for South Africa considering its coal dominant energy sector and its abundance of secondary, carbon-intensive mineral processing facilities due to its rich resource endowment. It is also unsurprising that the GDP2 to CO2 long run relationship, representing the technique effect of economic growth, would be statistically significant as South Africa's energy sector has not portrayed noteworthy shifts in implementation of alternative and/or novel energy generation technology, away from its conventional coal fired power plants. Though the EKC relation for CO2 in South Africa may suggest that we are at or have exceeded the turning point of economic growth such that incremental growth will produce CO2 emission reductions, this is not a given and prudence is still required in management of CO2 emissions. (Ganda, 2019) offers key policy insights for South Africa by recommending that the country consider energy diversification to abate fossil fuel carbon emissions. Furthermore, it is proposed that preferential rebate initiatives and punitive tax regimes be considered to simultaneously promote energy utilisation efficiency, reduced energy dependency, and limit negligent emission contributors.

NO2 – Model 2

The long run results for NO2 as the response variable (model 2) indicates that a positive long run relationship exists between GDP and NO2. Additionally, this relationship is found to be statistically significant with a p-value of 0.029. It is noted that, to the authors knowledge, no current studies are available which specifically study the EKC phenomenon for NO2 in South Africa. This long run result supports the findings of Hung and Shaw (2004) in their EKC study of nitrous oxides in Taiwan. It also supports the findings of Han et al. (2021) in their study of the EKC phenomenon in China where GDP was found to have a positive and significant effect on NO2 in the long run. This result indicates that the scale effect of economic growth influences the degree of NO2 emissions.

Additionally, a negative and statistically insignificant long run relationship is found to exist between NO2 and GDP2, with a p-value of 0.710. While no current studies are available which specifically study the EKC phenomenon for NO2 in South Africa, this result aligns with the expected outcome from European Commission (2018).

Since the GDP2 coefficient is statistically insignificant, while possessing the appropriate sign for the EKC hypothesis, there is insufficient evidence to conclude that the EKC hypothesis is valid for NO2 in South Africa and that incremental economic growth will assuredly yield a turning point to an eventual decrease in NO2 emissions in the long run. Therefore, the result is inconclusive. However, the results can confirm that NO2 emissions has a linear and significant relationship with economic growth in South Africa, and that incremental economic growth will yield incremental NO2 emissions. Han et al. (2021) suggests that NO2 emissions can be curtailed by implementing technological adaptation to existing processes and commercial designs. These may include nitrogen scrubbers in the effluent processing of smelting and cement manufacturing processes, key industries in South Africa. Promotion of electric and/or hybrid vehicles into existing transport systems, introducing added efficiency into current transport system designs, reducing the prevalence of older vehicles in the market through higher fees and taxes are all policy considerations that can be used to manage NO2 emissions.

SO2 – Model 3

The results for SO2 as the response variable and GDP as the predictor variable reveals a positive relationship in the long run. However, this relationship is deemed to be statistically insignificant with a p-value of 0.125, as shown in table 13 above. This aligns with the outcome of a study by Shikwambana et al. (2021) on the effects of GDP on select pollutants, inclusive of SO2, in South Africa between 1994 and 2019. Further afield it also agrees with the result of the panel study conducted by Markandya et al. (2004) on select European countries.

The long run results between SO2 and GDP2 reveals a negative and statistically insignificant relationship for South Africa, over the period of study. It supports the results of similar, prior studies (Markandya et al., 2004; Merlevede et al., 2006). This also supports the existence of an inverted U-shaped relation for SO2 and economic growth in South Africa. Since both GDP and GDP2 coefficients are statistically insignificant, while possessing the appropriate signs for the EKC hypothesis, there is insufficient evidence to conclude that an EKC relationship exists for SO2 in South Africa.

SO2 emissions rarely occur in isolation and accompany other airborne environmental pollutants as amalgamated effluent from industrial activities. Therefore, policy recommendations pertaining to CO2 and NO2 would equally be effective in curtailing sulphur emissions. Furthermore, effectively reducing and/or eliminating the sulphur content entirely in the production of fossil fuels such as diesel and in metallurgical processes such as copper refining will contribute to reducing SO2 emissions.

PM2.5 – Model 4

A positive long run relationship exists between PM2.5 and GDP, which is considered to also be statistically insignificant with a p-value of 0.055, although this insignificance is marginal. While no current studies are available which exclusively investigates the relationship between GDP and PM2.5 for South Africa, this result partly agrees with similar studies conducted in Asia and sub-Saharan Africa whereby a positive relationship was found between economic growth and PM2.5, albeit statistically significant (Ding et al., 2019; Koçak & Celik, 2021; Qi et al., 2023; Ssekibaala et al., 2022).

Furthermore, a positive and statistically insignificant long run relationship was found to exist between PM2.5 and GDP2, with a p-value of 0.430. However, this result further emphasises that an EKC relationship does not exist between PM2.5 emissions and economic growth in South Africa.

The linear, positive relationship established by the GDP and PM2.5 relationship indicates that incremental economic growth may only exacerbate PM2.5 emissions and its ancillary impact on society in South Africa. PM2.5 emissions are commonly associated with carbon-based fuel combustion (for national energy production and domestic household use), soil degradation, and deforestation. Koçak and Celik (2021) suggests that effective policies be implemented to address matters of human development such as employment, education, and healthcare to reduce inequality and limit household reliance on combustible energy sources for essential activities. ul-Haq et al. (2023) recommends that pollution control schemes be introduced to enable firmer control on agricultural practices and reforestation initiatives.

4.9. Short Run Results

The short run results are presented in table 14, below. The results revealed CO2 was found to have a positive and significant short run relationship with GDP. Furthermore, CO2 has a negative and significant relationship with GDP2. The result represents the optimal lag length for the model at ARDL (1,0,0) and it can be deduced that CO2 has a valid EKC relationship with economic growth in South Africa over the short run.

NO2 portrays a positive and statistically significant short run relationship with GDP at the D1 level, with a p-value of 0.024. Furthermore, a positive and statistically insignificant relationship exists between NO2 and GDP2 at the D1 level. This coincides with the optimal lag length for model 2 at ARDL (1,0,1). It can be deduced that NO2 has a positive, parabolic relationship with economic growth in the short run and, therefore, an EKC relationship does not exist. As GDP increases, environmental degradation associated with NO2 emissions will increase at an accelerated rate over the short run. A 1% increase in GDP will result in a 0.56% increase in NO2 emissions.

SO2 depicts a positive and statistically insignificant short run relationship with GDP and GDP2 at the D1 level, with a p-value of 0.116 and 0.286, respectively. This result emanates from the optimal lag length for model 3 at ARDL (1,0,1). The relationship between economic growth and SO2 reveals a positive, parabolic relationship, however there is no evidence of an EKC relationship. Additionally, an increase in GDP will result in an increase in environmental degradation associated with SO2 emissions for South Africa in the short run. A 1% increase in GDP will result in a 0.52% increase in SO2 emissions over the short run.

PM2.5 was found to have a positive and significant short run relationship with GDP. Furthermore, *PM2.5* has a *positive* and *in*significant relationship with GDP2. The result represents the optimal lag length for the model at ARDL (1,0,0). It can be deduced that PM2.5 has a positive, parabolic relationship with economic growth in the short run and ,therefore, an EKC relationship does not exist. As GDP increases, environmental degradation associated with PM2.5 emissions will increase at an enhanced rate over the short run. A 1% increase in GDP will result in a 0.70% increase in PM2.5 emissions. It further indicates that the effects of economic growth on 2.5-micrometer particulate matter emissions are primarily perceived over the long term.

Table 14: Short Run Modelling Results

	Model 1 - CO2	Model 2 - NO2	Model 3 - SO2	Model 4 - PM2.5
LN GDP | D1				
Coefficient	0.478	0.560	0.517	0.702
Standard Error	0.137	0.238	0.322	0.316
t-statistic	3.500	2.350	1.610	2.220
P >|t|	0.001	0.024	0.116	0.032
LN GDP2 | D1				
Coefficient	-2.100	2.236	2.160	1.388
Standard Error	0.812	1.479	2.000	1.696
t-statistic	-2.590	1.510	1.080	0.820
P >|t|	0.014	0.138	0.286	0.418
Constant				
Coefficient	0.026	0.011	0.021	0.011
Standard Error	0.004	0.006	0.008	0.008
t-statistic	5.720	1.810	2.550	1.390
P >|t|	0.000	0.078	0.015	0.173

(Source: Stata estimates from research data)

Notes: CO2 – Natural logarithm of Carbon Dioxide (response variable in model 1); NO2 – Natural logarithm of Nitrogen Dioxide (response variable in model 2); SO2 – Natural logarithm of Sulphur Dioxide (response variable in model 3); PM2.5 – Natural logarithm of Particulate Matter smaller than 2.5 micro-meters (response variable in model 4); LN GDP2 - Natural logarithm of GDP squared (predictor variable 2).

4.10. Residual Diagnostics

The ARDL models for CO2, NO2, SO2, and PM2.5 were subjected to residual diagnostic assessments to verify robustness, stability and model fitness, the results of which are presented in table 15. The tests employed encompassed the Breusch-Godfrey LM Test for serial correlation, Breusch-Pagan/Cook-Weisberg test for heteroscedasticity, Ramsey RESET test for functional form and omitted variables, and Jarque-Bera test for normality, and are supported by other studies for their aptness in ARDL model diagnostics (Majumder & Donghui, 2016; Okafor & Shaibu, 2016; Sarkodie & Owusu, 2020).

The null hypothesis for the Breusch-Godfrey LM Test for serial correlation is that no serial correlation exists in the model residuals. The p-value for all models considered was assessed to be greater than the 0.05 (5%) significance level. Therefore, there is insufficient evidence to reject the null hypothesis, and the model residuals are free of any serial correlation.

Furthermore, under the Breusch-Pagan/Cook-Weisberg test for heteroscedasticity, the null hypothesis for the test is that no heteroscedasticity exists in the model residuals, implying that the residuals exhibit constant variance. The p-value for all models considered was evaluated to be greater than the 0.05 (5%) significance level. Therefore, there is insufficient evidence to reject the null hypothesis, and the model residuals are free of heteroskedasticity.

Additionally, it is important to verify that the model is well specified in terms of its functional form and that no variables are omitted to ensure that the model adequately captures the dynamics of the data. To this end, the Ramsey Regression Equation Specification Error Test (RESET) assessment was used to verify an element of robustness of the models. The null hypothesis for the test is that the model is correctly specified. The p-value for all models considered was evaluated to be greater than the 0.05 (5%) significance level. Therefore, there is insufficient evidence to reject the null hypothesis, and the models are appropriately specified in functional form and adequacy of necessary variables.

Finally, the model residuals were subjected to the Jarque-Bera test for normality, as this is an underlying criterion for the application of the ARDL modelling technique. The null hypothesis for the test is that the model residuals follow a normal distribution. The p-value for all models considered was evaluated to be greater than the 0.05 (5%) significance level. Therefore, there is insufficient evidence to reject the null hypothesis, and the models' residuals are considered to have a minimal deviation from a normal distribution. This is further supported by the kurtosis (asymmetry) and skewedness (tail) results which minimally deviate from that expected from a normal distribution. It should be noted that model 3 for SO2, while statistically indicative of having normally distributed residuals, does depict slight semblance of deviation from normality.

Table 15: Residual Diagnostic Results

Diagnostic Tests	CO2	NO2	SO2	PM2.5
Serial Correlation (Breusch-Godfrey LM Test)				
Degrees of Freedom	1	1	1	1
Chi Squared	0.010	0.456	0.070	0.004
P-Value	0.922	0.499	0.791	0.948
Heteroskedasticity (Breusch-Pagan/Cook-Weisberg test)				
Chi Squared	0.190	0.320	0.160	1.510
P-Value	0.663	0.571	0.688	0.220
Functional Form (Ramsey RESET test)				
F-statistic	0.140	2.140	0.240	0.690
P-Value	0.937	0.111	0.866	0.563
Normality Test (Jarque-Bera)				
Kurtosis	0.643	0.610	0.056	0.683
Skewness	0.784	0.486	0.392	0.751
Chi Squared (Jarque-Bera test statistic)	0.290	0.770	4.460	0.270
P-Value	0.865	0.680	0.108	0.875

(Source: Stata estimates from research data)

Notes: CO2 – Natural logarithm of Carbon Dioxide (response variable in model 1); NO2 – Natural logarithm of Nitrogen Dioxide (response variable in model 2); SO2 – Natural logarithm of Sulphur Dioxide (response variable in model 3); PM2.5 – Natural logarithm of Particulate Matter smaller than 2.5 micro-meters (response variable in model 4).

4.11. Granger Causality

Granger Causality tests were performed on the models for CO2, NO2, SO2, and PM2.5 to determine the directional characteristics of the variable relationships and the results thereof are presented in table 16, below. The test revealed that for Model 1, there was insufficient evidence to reject the null hypothesis with a P-value below the 5% significance level. Therefore, it can be concluded that LN CO2 Granger causes LN GDP.

Similarly, the Granger Causality test for Model 2 revealed that there was insufficient evidence to reject the null hypothesis for LN NO2 singularly, and LN NO2 and LN GDP2 combined. Therefore, it was concluded that LN NO2 Granger causes LN GDP. Additionally, LN NO2 and LN GDP2 collectively Granger causes LN GDP.

For Model 3, however, it was revealed that only the combined scenario of LN GDP and LN GDP2 Granger causes LN SO2, where there was insufficient evidence to reject the null hypothesis in this scenario due to the P-value being less than 0.05.

Finally, the Granger Causality test for Model 4 revealed that there was insufficient evidence to reject the null hypothesis for LN PM2.5 independently, and LN PM2.5 and LN GDP2 combined. Therefore, it was concluded that LN PM2.5 Granger causes LN GDP. Additionally, LN PM2.5 and LN GDP2 collectively Granger causes LN GDP.

Table 16: Granger Causality Results

Equation	Excluded	Chi Squared	df	P-value
Model 1 - CO2				
LN GDP	LN CO2	7.399	2	0.025
Model 2 - NO2				
LN GDP	LN NO2	7.740	2	0.021
LN GDP	LN NO2 & LN GDP2	9.631	4	0.047
Model 3 - SO2				
LN SO2	LN GDP & LN GDP2	9.869	4	0.043
Model 4 - PM2.5				
LN GDP	LN PM2.5	7.740	2	0.021
LN GDP	LN PM2.5 & LN GDP2	9.631	4	0.047

(Source: Stata estimates from research data)

Notes: CO2 – Natural logarithm of Carbon Dioxide (response variable in model 1); NO2 – Natural logarithm of Nitrogen Dioxide (response variable in model 2); SO2 – Natural logarithm of Sulphur Dioxide (response variable in model 3); PM2.5 – Natural logarithm of Particulate Matter smaller than 2.5 micro-meters (response variable in model 4); LN GDP – Natural logarithm of GDP (predictor variable 1); LN GDP2 - Natural logarithm of GDP squared (predictor variable 2).

4.12. Model Stability Diagnostics

The stability of the long run and short run coefficients for all models were evaluated using the cumulative sum of recursive residuals (CUSUM) and cumulative sum of squares of recursive residuals (CUSUM SQ) techniques developed by Brown et al. (1975).

The CUSUM plot for the CO2, NO2, SO2, and PM2.5 models, respectively, are shown in figure 8 below. It is observed that the model coefficients exhibit stable relationships over the long and short runs for all models considered and remain within the 5% confidence interval.

Furthermore, the CUSUM SQ plot for the CO2, NO2, SO2, and PM2.5 models, respectively, are shown in figure 9 below. All the model coefficients, except for PM2.5, exhibit stable relationships over the long and short runs for all models considered and remain within the 5% confidence interval. PM2.5 remains stable, however, demonstrates slight instability between 1990 and 2000.

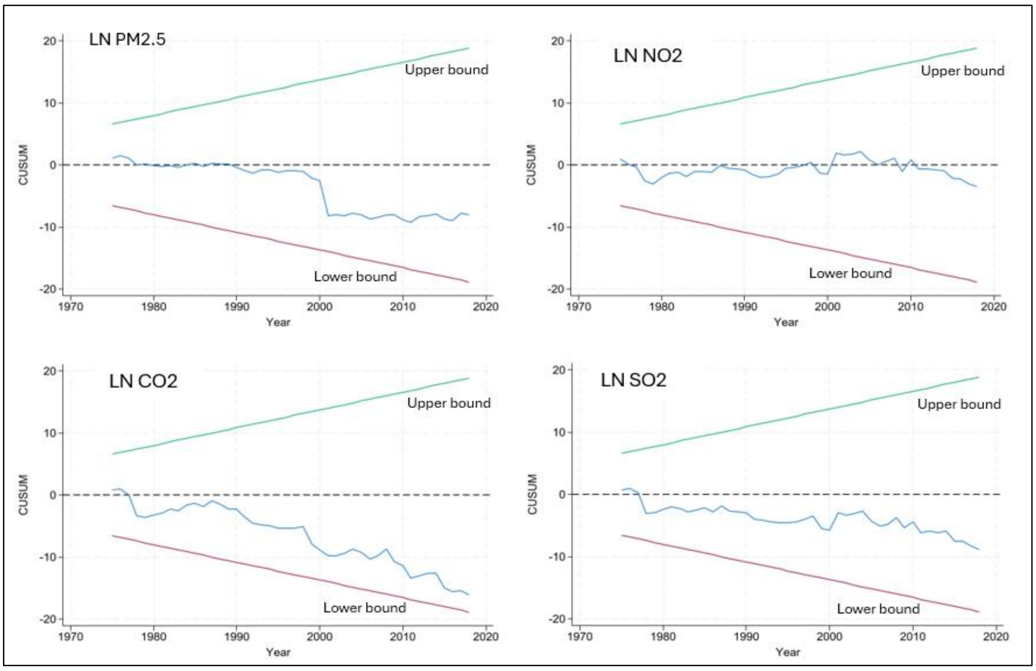

Figure 8: CUSUM Plots

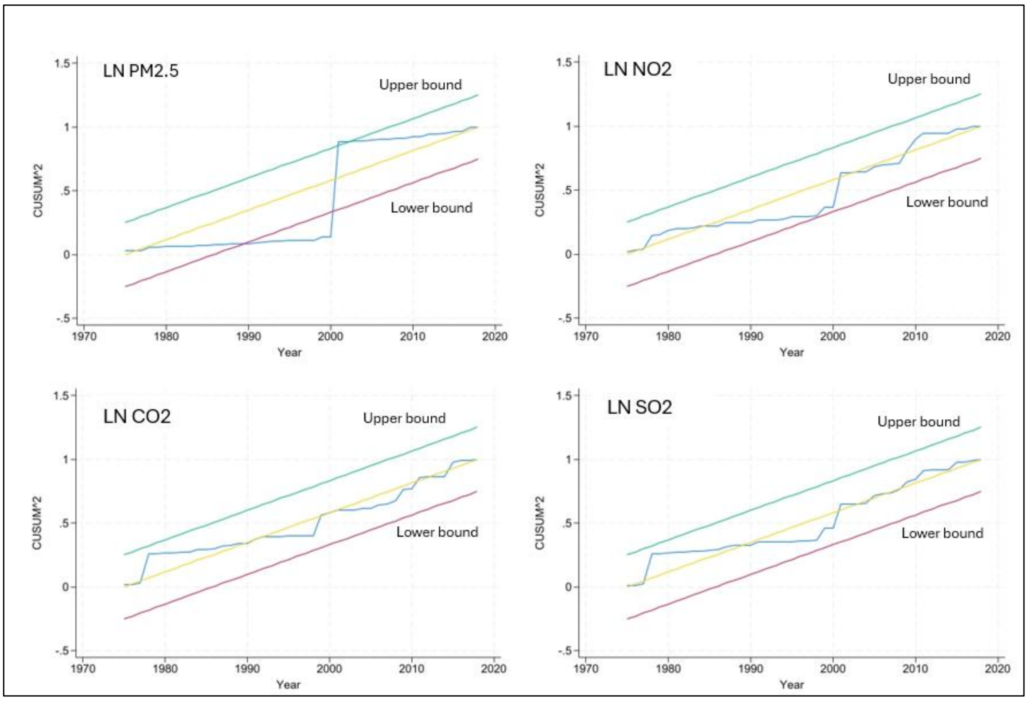

Figure 9: CUSUM SQ plots

(Source: Stata estimates from research data)

Notes: CO2 – Natural logarithm of Carbon Dioxide (response variable in model 1); NO2 – Natural logarithm of Nitrogen Dioxide (response variable in model 2); SO2 – Natural logarithm of Sulphur Dioxide (response variable in model 3); PM2.5 – Natural logarithm of Particulate Matter smaller than 2.5 micro-meters (response variable in model 4); Upper bound – Upper bound of the 95% confidence interval; Lower bound - Lower bound of the 95% confidence interval.

Chapter 5: Conclusions and Recommendations

5.1. Introduction

The following section presents a summary of the study and key insights derived from the analysis. It also provides recommendations emanating from the insights and possible areas of further research for which this study could form a basis.

5.2. Summary and conclusions

This study sought to investigate the existence of EKC relationships between CO_2, NO_2, SO_2, and PM2.5 emissions and economic growth, respectively, in South Africa. Annual emission data spanning 48 years from 1970 to 2018 was obtained for each of the abovementioned pollutants, as indicators of environmental degradation, for South Africa which was obtained from the Emissions Database for Global Atmospheric Research (EDGAR). The study also utilised GDP per capita data for South Africa, sourced from The World Bank World Development Indicators database over the same period 1970 to 2018.

The Autoregressive Distributive Lag (ARDL) modelling technique was employed using Stata statistical software to ascertain if an EKC relationship exists between the respective indicators of environmental degradation and economic growth in South Africa. This modelling technique was found to be best suited to evaluating the EKC hypothesis due to its versatility in handling structural breaks and data with varying degrees of stationarity, according to numerous similar studies. It is also the technique most associated with valid EKC results in other published studies. 4 ARDL models were evaluated with CO_2, NO_2, SO_2, and PM2.5 being the dependent variable in each respective model, and GDP and GDP squared (GDP2) being the independent variables in each model, forming a quadratic equation according to equation 1 for the EKC relationship. Additionally, the data was subjected to a natural logarithmic transformation in accordance with the EKC standard form equation. The ARDL model lags are denoted as ARDL (pollutant lag length, GDP lag length, GDP2 lag length).

Descriptive statistics established that the raw data exhibited small degrees of variation and standard errors were found to be normally distributed. Initial correlation tests revealed high degrees of correlation between the independent variables, which is expected since one is the square of the other, and a technique of mean centring of the independent variables addressed the issue, resulting in negligible collinearity. The Augmented Dicky Fuller and the Phillips-Peron unit root tests were employed and both determined that the data was stationary at the first difference and first order integrated. ARDL optimal lag lengths were determined iteratively for each model 1 to 4, representing CO2, NO2, SO2, and PM2.5, respectively. The optimal lags are model 1 – ARDL(1,0,0), model 2 – ARDL (1,0,1), model 3 – ARDL(1,0,1), and model 4 – ARDL(1,0,0). The ARDL bounds testing approach was used to establish if each of the model variables were cointegrated, and to prove if long run relationships exist between the variables in each model. It was established that cointegration was present in all models, respectively.

Furthermore, CO2, NO2, and PM2.5 were found to have positive and statistically significant relationships with GDP in the long run. SO2 was found to have a positive and statistically insignificant relationship with GDP in the long run. Thus far, all signs are congruent with the expectation of the EKC hypothesis, except for SO2 due to the insignificant relationship. CO2, NO2, and SO2 were found to have negative relationships with GDP2, as is expected under the EKC hypothesis, however, only the relationship between CO2 and GDP2 was statistically significant. PM2.5 has a positive and insignificant relationship with GDP2. Therefore, there is sufficient evidence to reject the null hypothesis of this study for CO2 and thereby concluding that an EKC relationship exists for CO2 and economic growth in South Africa in the long run. There is insufficient evidence to reject the null hypothesis for NO2, SO2, and PM2.5 in the long run. The validated EKC relationship for CO2 and economic growth in the long run is expected for South Africa considering its coal dominated energy sector as the powerhouse of its economy and the integral association between CO2 emissions and fossil fuel combustion .

CO2 had a positive and statistically significant relationship with GDP, and a negative and statistically significant relationship with GDP2 in the short run. NO2 and PM2.5 had positive and statistically significant relationships with GDP in the short run, however, their positive and statistically insignificant relationship with GDP2 in the short run does not meet the expected criteria for the EKC hypothesis. SO2 was found to have positive and statistically insignificant relationships with GDP and GDP2 in the short run. Therefore, there is sufficient evidence to reject the null hypothesis for CO2 in the short run, and consequently an EKC relationship exists between CO2 and economic growth in the short run, in South Africa. There is insufficient evidence to reject the null hypothesis for NO2, SO2, and PM2.5 in the short run, and consequently an EKC relationship does not exists for these indicators of environmental quality in the short run, in South Africa.

Granger causality tests on the various models revealed that CO2, NO2 and PM2.5 Granger-causes GDP. In the case of Model 3 (SO2), both GDP and GDP2 Granger-causes SO2. For

Model 2 (NO_2) and 4 (PM2.5), it was revealed that both the environmental pollutant and GDP2 collectively Granger-cause GDP.

The models were subjected to residual diagnostic tests and the model residuals were found to be absent of serial correlation and heteroskedasticity, for all models. Additionally, all models were established to be well specified in terms of its functional form, and it was concluded that no variables were omitted. Finally, the residuals of all models were found to be normally distributed, although model 3 (SO_2) presented evidence of being close to the cusp of normality. Finally, all models were evaluated using the CUSUM and CUSUM SQ tests for recursive residual stability and CO_2, SO_2, and NO_2 were found to be stable within the 5% bounds. PM2.5 depicted slight instability over a marginal period but overall remained within the 5% bounds.

5.3. Policy recommendations

Key policy recommendations that emanated from the study are the implementation of preferential rebate initiatives to promote efficient energy utilization and the imposition of punitive tax regimes to limit negligent and/or major emission contributors. Additionally, strategies should be considered to promote the advancement of technologies to enable existing industrial processes and commercial designs to be adapted to treat effluent gas and remove high concentrations of key pollutants. Improved transport technologies and systems should be integrated into the South African basic infrastructure such as electric vehicles and imposing levies or fines on utilisation of older vehicles. Focusing on human development is also considered to be a key policy objective to reduce inequality, improve access to healthcare, education, and employment, which are all impacted by exacerbated environmental degradation. Finally, South Africa needs to diversify its energy sources to enable a transition to cleaner fuels, ensuring that incremental economic growth can be achieved without the resultant impact on its environment.

5.4. Avenues for future research

It would be insightful to extend this study in its current form to a wider range of sub-Saharan African countries to ascertain if similar conclusions could be derived. This can provide useful information on the possible implications and benefits of future regional trade policy and agreements. Additionally, an inclusion of democratisation indicators would lend itself to useful conclusions on the effects of political-economic policy impacts on domestic environmental quality. The inclusion of the effects of sovereign credit rating in the EKC study would be a valuable addition.

References

Adom, D., Yeboah, A., & Ankrah, A. K. (2016). Constructivism philosophical paradigm: implication for research, teaching and learning. In *Global Journal of Arts Humanities and Social Sciences* (Vol. 4, Issue 10). www.eajournals.org

AfDB. (2022). *Africa Industrialisation Index 2022*. https://www.afdb.org/en/documents/africa-industrialization-index-2022

AfDB. (2023). *Industrialise Africa*.

Ahmed, K., & Long, W. (2013). An empirical analysis of CO2 emission in Pakistan using EKC hypothesis. *Journal of International Trade Law and Policy*, *12*(2), 188–200. https://doi.org/10.1108/JITLP-10-2012-0015

Akram, R., Fareed, Z., Xiaoli, G., & Zullqar, B. (2021). *Investigating the existence of asymmetric Environment Kuznets Curve and Pollution-Haven Hypothesis in China: Fresh evidence from QARDL and Quantile Granger Causality*. https://doi.org/10.21203/rs.3.rs-710446/v1

Ali, W., Abdullah, A., & Azam, M. (2017). Re-visiting the environmental Kuznets curve hypothesis for Malaysia: Fresh evidence from ARDL bounds testing approach. In *Renewable and Sustainable Energy Reviews* (Vol. 77, pp. 990–1000). Elsevier Ltd. https://doi.org/10.1016/j.rser.2016.11.236

Al-Mulali, U., Solarin, S. A., & Ozturk, I. (2015). Investigating the presence of the environmental Kuznets curve (EKC) hypothesis in Kenya: an autoregressive distributed lag (ARDL) approach. *Natural Hazards*, *80*, 1729–1747. https://doi.org/10.1007/s11069-015-2050-x

Altieri, K., & Keen, S. (2016). *The cost of air pollution in South Africa IGC*. http://www.theigc.org/blog/thecostofairpollutioninsouthafrica/1/3

Ardakani, M. K., & Seyedaliakbar, S. M. (2019). Impact of energy consumption and economic growth on CO 2 multivariate regression . *Energy Strategy Reviews*, *26*(1), 1–13. https://doi.org/https://doi.org/10.1016/j.esr.2019.100428

Asche, H., & Grimm, M. (2017). *Industrialisation in Africa: Challenges and Opportunities*. https://www.econstor.eu/bitstream/10419/156240/1/882016881.pdf

AU. (n.d.). *Multilateral Environmental Agreements (MEAs)*. The African Union Commission. Retrieved July 19, 2023, from https://au.int/en/meas

Baiardi, D. (2012). *Innovation and the environmental Kuznets curve: the case of CO, NMVOCs and SOx in the Italian regions Standard-Nutzungsbedingungen*. http://hdl.handle.net/10419/95279

Baker, L., Newell, P., & Phillips, J. (2014). The Political Economy of Energy Transitions: The Case of South Africa. *New Political Economy*, *19*(6), 791–818. https://doi.org/https://doi.org/10.1080/13563467.2013.849674

Balado-Naves, R., Baños-Pino, J. F., & Mayor, M. (2018). Do countries influence neighbouring pollution? A spatial analysis of the EKC for CO2 emissions. *Energy Policy*, *123*, 266–279. https://doi.org/10.1016/j.enpol.2018.08.059

Barbier, E. B. (1987). The Concept of Sustainable Economic Development. In *Conservation* (Vol. 14, Issue 2). https://about.jstor.org/terms

Bell, T., & Farrell, G. (1997). The minerals-energy complex and South African industrialisation. *Development Southern Africa*, *14*(4), 591–613. https://doi.org/10.1080/03768359708439989

Ben Nasr, A., Gupta, R., & Sato, J. R. (2015). Is there an Environmental Kuznets Curve for South Africa? A co-summability approach using a century of data. *Energy Economics*, *52*, 136–141. https://doi.org/10.1016/j.eneco.2015.10.005

Bhattacharya, M., Paramati, S. R., Ozturk, I., & Bhattacharya, S. (2016). The effect of renewable energy consumption on economic growth: Evidence from top 38 countries. *Applied Energy*, *162*, 733–741. https://doi.org/10.1016/j.apenergy.2015.10.104

Bibi, F., & Jamil, M. (2021). Testing environment Kuznets curve (EKC) hypothesis in different regions. *Environmental Science and Pollution Research*, *28*, 13581–13594. https://doi.org/10.1007/s11356-020-11516-2/Published

Bilgili, F., Koçak, E., & Bulut, Ü. (2016). The dynamic impact of renewable energy consumption on CO2 emissions: A revisited Environmental Kuznets Curve approach. In *Renewable and Sustainable Energy Reviews* (Vol. 54, pp. 838–845). Elsevier Ltd. https://doi.org/10.1016/j.rser.2015.10.080

Borenstein, M., Hedges, L. V., Higgins, J. P. T., & Rothstein, H. R. (2010). A basic introduction to fixed-effect and random-effects models for meta-analysis. *Research Synthesis Methods*, *1*(2), 97–111. https://doi.org/10.1002/jrsm.12

Brown, R. L., Durbin, J., & Evans, J. M. (1975). Techniques for Testing the Constancy of Regression Relationships over Time. *Journal of the Royal Statistical Society. Series B (Methodological)*, *37*(2), 149–192. https://hhstokes.people.uic.edu/ftp/e535/Brown_Durbin_evans_1975.pdf

Chambers, W. B. (2008). *Interlinkages and the effectiveness of multilateral environmental agreements*.

Chandra Voumik, L., Rahman, M. H., & Hossain, M. S. (2022). Investigating the subsistence of Environmental Kuznets Curve in the midst of economic development, population, and energy consumption in Bangladesh: imminent of ARDL model. *Heliyon*, *8*(8). https://doi.org/10.1016/j.heliyon.2022.e10357

Chen, H., Rehman, M. A., Luo, J., & Ali, M. (2022). Dynamic influence of natural resources, financial integration and eco-innovation on ecological sustainability in EKC framework: Fresh insights from China. *Resources Policy*, *79*. https://doi.org/10.1016/j.resourpol.2022.103043

Creath, R. (2011). *Logical Empiricism*. Stanford Encyclopedia of Philosophy.

Daly, H. E. (1987). The Economic Growth Debate: What Some Economists Have Learned But Many Have Not. *Journal of Environmental Economics and Management*, *14*, 323–336.

De Koning,’, H. W., Smith, K. R., & Last3, J. M. (1985). Scientist, Environmental Hazards and Food Protection, Division of Environmental Health. In *Bulletin ofthe World Health Organization* (Vol. 63, Issue 1). World Health Organization.

Ding, Y., Zhang, M., Chen, S., Wang, W., & Nie, R. (2019). The environmental Kuznets curve for PM 2.5 pollution in Beijing-Tianjin-Hebei region of China: A spatial panel data approach. *Journal of Cleaner Production*, *220*, 984–994. https://doi.org/10.1016/j.jclepro.2019.02.229

Disli, M., Ng, A., & Askari, H. (2016). Culture, income, and CO2 emission. In *Renewable and Sustainable Energy Reviews* (Vol. 62, pp. 418–428). Elsevier Ltd. https://doi.org/10.1016/j.rser.2016.04.053

Dogan, E., & Turkekul, B. (2016). CO2 emissions, real output, energy consumption, trade, urbanization and financial development: testing the EKC hypothesis for the USA. *Environmental Science and Pollution Research*, *23*(2), 1203–1213. https://doi.org/10.1007/s11356-015-5323-8

Du, S., Smit, B., & Plessis, S. Du. (2005). *Economic Growth in South Africa since 1994 Stellenbosch Economic Working Papers : 1 / 2006*.

El Hedi, M., Youssef, B., El Hedi Arouri, M., Ben Youssef, A., & Rault, C. (2012). *Empirical Analysis of The EKC Hypothesis for Sulfur Dioxide Emissions in Selected Middle East and North African Countries Empirical Analysis of an EKC for SO2 Emissions in Selected Middle East and North African Countries*.

Elfaki, K. E., Handoyo, R. D., & Ibrahim, K. H. (2021). The impact of industrialization, trade openness, financial development, and energy consumption on economic growth in Indonesia. *Economies*, *9*(4). https://doi.org/10.3390/economies9040174

Elliot, J. A. (2013). What is Sustainable Development? In *An Introduction to Sustainable Development* (4th ed., pp. 8–56). Routledge.

Eskom. (2022). *Eskom 2022 Integrated Report*. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.eskom.co.za/wp-content/uploads/2022/12/2022_integrated_report.pdf

European Commission. (2018, July 20). *EDGAR - Emissions Database for Global Atmospheric Research*. European Commission. https://edgar.jrc.ec.europa.eu/

Fujii, H., & Managi, S. (2016). Economic development and multiple air pollutant emissions from the industrial sector. *Environmental Science and Pollution Research*, *23*(3), 2802–2812. https://doi.org/10.1007/s11356-015-5523-2

Galor, O., & Tsiddon, D. (1996). Income Distribution and Growth: The Kuznets Hypothesis Revisited. *Economica*, *63*(250), S103. https://doi.org/10.2307/2554811

Ganda, F. (2019). Carbon emissions, diverse energy usage and economic growth in south africa: Investigating existence of the environmental kuznets curve (EKC). *Environmental Progress and Sustainable Energy*, *38*(1), 30–46. https://doi.org/10.1002/ep.13049

Gelb, S. (2007). Macroeconomic policy in South Africa. From RDP through GEAR to ASGISA . In G. Gunnarsen, P. Mac Manus, M. Nielsen, & H. E. Stolten (Eds.), *At the end of the rainbow? Social identity and welfare state in the new South Africa* (1st ed., pp. 17–18). Africa Contact (formerly Southern Africa Contact).

Gokmenoglu, K. K., & Taspinar, N. (2018). Testing the agriculture-induced EKC hypothesis: the case of Pakistan. *Environmental Science and Pollution Research*, *25*(23), 22829–22841. https://doi.org/10.1007/s11356-018-2330-6

Gollin, D. (2014). The Lewis model: A 60-year retrospective. *Journal of Economic Perspectives*, *28*(3), 71–88. https://doi.org/10.1257/jep.28.3.71

Gonzalo, J., & Pitarakis, J.-Y. (2002). Lag length estimation in large dimensional systems. *Journal of Time-Series Analysis*, *23*(4), 401–423. https://doi.org/https://doi.org/10.1111/1467-9892.00270

Government of South Africa. (2023, July 18). *South Africa at a glance*. South African Government.

Granger, C. W. J. (1969). Investigating Causal Relations by Econometric Models and Cross-spectral Methods. *Econometrica*, *37*(3), 424–438.

Green, P. (2009). *Industrialisation in South Africa: The impact of globalisation*.

Grether, J. M., Mathys, N. A., & De Melo, J. (2009). Scale, technique and composition effects in manufacturing SO2 emissions. *Environmental and Resource Economics*, *43*(2), 257–274. https://doi.org/10.1007/s10640-008-9237-5

Grossman, G., & Krueger, A. (1991). *Environmental impacts of a north American free trade agreement* (3914; NBER Working Papers).

Gupta, M., Saini, S., & Sahoo, M. (2022). Determinants of ecological footprint and PM2.5: Role of urbanization, natural resources and technological innovation. *Environmental Challenges*, *7*. https://doi.org/10.1016/j.envc.2022.100467

Han, C., Gu, Z., & Yang, H. (2021). Ekc test of the relationship between nitrogen dioxide pollution and economic growth—a spatial econometric analysis based on chinese city data. *International Journal of Environmental Research and Public Health*, *18*(18). https://doi.org/10.3390/ijerph18189697

Hassan, A. S. (2023). Coal mining and environmental sustainability in South Africa: do institutions matter? *Environmental Science and Pollution Research*, *30*(8), 20431–20449. https://doi.org/10.1007/s11356-022-23585-6

Hung, M.-F., & Shaw, D. (2004). *Economic Growth and the Environmental Kuznets Curve in Taiwan: A Simultaneity Model Analysis*. https://www.researchgate.net/publication/255587948

IEA. (2019). *Africa Energy Outlook 2019*.

IEA. (2024, July). *Africa: Energy system of Africa*. International Energy Agency. https://www.iea.org/regions/africa

Islam, N., & Yokota, K. (2008). Lewis Growth Model and China's Industrialization. In *Asian Development Working Paper Series*.

Islam, S. M. N., Munasinghe, M., & Clarke, M. (2003). Making long-term economic growth more sustainable: Evaluating the costs and benefits. *Ecological Economics*, *47*(2–3), 149–166. https://doi.org/10.1016/S0921-8009(03)00162-9

Jabareen, Y. (2008). A new conceptual framework for sustainable development. *Environment, Development and Sustainability*, *10*(2), 179–192. https://doi.org/10.1007/s10668-006-9058-z

Jahanger, A., Yu, Y., Awan, A., Chishti, M. Z., Radulescu, M., & Balsalobre-Lorente, D. (2022). The Impact of Hydropower Energy in Malaysia Under the EKC Hypothesis: Evidence From Quantile ARDL Approach. *SAGE Open*, *12*(3). https://doi.org/10.1177/21582440221109580

Jung Kim, S., Yong Jung, T., Jin Kang, S., author, F., & author, C. (2016). Regional Environmental Kuznets Curves and Their Turning Points for Air Pollutants in Korea *. In *Korea and the World Economy* (Vol. 17, Issue 3).

Kaika, D., & Zervas, E. (2013). The environmental Kuznets curve (EKC) theory. Part B: Critical issues. *Energy Policy*, *62*, 1403–1411. https://doi.org/10.1016/j.enpol.2013.07.130

Katircioglu, S. T. (2009). Revisiting the tourism-led-growth hypothesis for Turkey using the bounds test and Johansen approach for cointegration. *Tourism Management*, *30*, 17–20. https://doi.org/doi:10.1016/j.tourman.2008.04.004

Katircioğlu, S. T. (2014). Testing the tourism-induced EKC hypothesis: The case of Singapore. *Economic Modelling*, *41*, 383–391. https://doi.org/10.1016/j.econmod.2014.05.028

Keller, G. (2018). Statistics for management and economics. In *Statistics for management and economics* (Vol. 11, pp. 631–732).

Kenny, C., & Williams, D. (2001). What do we know about economic growth? Or, why don't we know very much? *World Development*, *29*(1).

Kesgingoz, H., & Dilek, S. (2016). Investigation of Tr82 Region According to the Growth Stages of Rostow. *Asian Journal of Economic Modelling*, *4*(4), 180–189. https://doi.org/10.18488/journal.8/2016.4.4/8.4.180.189

Khan, Z., & Marinaro, S. (2017). *International journal of social science and economic research summarizing the miscellaneous criticism on Rostow's model of economic growth: an overview*. www.ijsser.org

Koçak, E., & Celik, B. (2021). The Nexus between Access to Energy, Poverty Reduction and Pm2.5 in Sub-Saharan Africa: New Evidence from the Generalized Method of Moments Estimators. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3990873

Kohler, M. (2013). *CO2 Emissions, Energy Consumption, Income and Foreign Trade: A South African Perspective* (356; ERSA Working Paper). https://econrsa.org/wp-content/uploads/2022/06/working_paper_356.pdf

Korzeniewicz, R. P., & Moran, T. P. (2005). Theorizing the Relationship between Inequality and Economic. In *Source: Theory and Society* (Vol. 34, Issue 3).

Kripfganz, S., & Schneider, D. C. (2023). ardl: Estimating autoregressive distributed lag and equilibrium correction models. *The Stata Journal*, *23*(4), 983–1019. https://doi.org/10.1177/1536867X231212434

Kuznets, S. (1955). *Economic Growth and Income Inequality* (Vol. 45, Issue 1).

Kuznets, S. (1973). *Modern Economic Growth: Findings and Reflections* (Vol. 63, Issue 3).

Laird, N. M., & Ware, J. H. (1982). *Random-Effects Models for Longitudinal Data* (Vol. 38, Issue 4). https://www.jstor.org/stable/2529876

Leitão, N. C., Balsalobre-Lorente, D., & Cantos-Cantos, J. M. (2021). The impact of renewable energy and economic complexity on carbon emissions in brics countries under the ekc scheme. *Energies*, *14*(16). https://doi.org/10.3390/en14164908

Lewis, W. A. (1954). *"Economic Development with Unlimited Supplies of Labour."* https://la.utexas.edu/users/hcleaver/368/368lewistable.pdf

List of Activities Which Result in Atmospheric Emissions, Pub. L. No. 248, Department of Environmental Affairs (2010).

Longa, F. D., & van der Zwaan, B. (2021). Heart of light: an assessment of enhanced electricity access in Africa. *Renewable and Sustainable Energy Reviews*, *136*, 1–18. https://doi.org/https://doi.org/10.1016/j.rser.2020.110399.

Majumder, S. C., & Donghui, Z. (2016). Relationship between Remittance and Economic Growth in Bangladesh: an Autoregressive Distributed Lag Model (ARDL). *European Researcher*, *104*(3), 156–167. https://doi.org/10.13187/er.2016.104.156

Markandya, A. ;, Pedroso, S. ;, & Golub, A. (2004). *Empirical Analysis of National Income and So2 Emissions in Selected European Countries*. http://hdl.handle.net/10419/117880

McGregor, S. L. T. (2018). Overview of Research Design and MethodsMc. In *Understanding and Evaluating Research: A Critical Guide*. SAGE Publications, Inc.

McKinsey & Company. (2022, August 17). *What is economic growth?* McKinsey & Company.

Merlevede, B., Verbeke, T., & De Clercq, M. (2006). The EKC for SO2: Does firm size matter? *Ecological Economics*, *59*(4), 451–461. https://doi.org/10.1016/j.ecolecon.2005.11.010

Millin, M., & Nichola, T. (2005). Explaining economic growth in South Africa: a Kaldorian approach. *International Journal of Technology Management & Sustainable Development*, *4*(1), 47–62. https://doi.org/10.1386/ijtm.4.1.47/1

Mitchell, R. (2003a). International environmental agreements: A survey of their features, formation, and effects. *Annual Review of Environment and Resources*, *28*, 429–461. https://doi.org/10.1146/annurev.energy.28.050302.105603

Mitchell, R. (2003b, July 19). *International Environmental Agreements (IEA) Database Project*. University of Oregon. https://iea.uoregon.edu/base-agreement-list

Monash University. (2023). *What Is Sustainable Development?* Monash University .

Muyemeki, L., Burger, R., Piketh, S. J., Language, B., Beukes, J. P., & van Zyl, P. G. (2021). Source apportionment of ambient PM10−2.5 and PM2.5 for the Vaal Triangle, South Africa. *South African Journal of Science*, *117*(5). https://doi.org/10.17159/SAJS.2021/8617

Nahman, A., & Antrobus, G. (2005). Trade and the environmental Kuznets curve: Is Southern Africa a pollution haven? *South African Journal of Economics*, *73*(4), 803–814. https://doi.org/10.1111/j.1813-6982.2005.00055.x

Naiker, Y., Diab, R. D., Zunckel, M., & Hayes, E. T. (2012). Introduction of local Air Quality Management in South Africa: Overview and challenges. *Environmental Science and Policy*, *17*, 62–71. https://doi.org/10.1016/j.envsci.2011.11.009

Ngarava, S., Zhou, L., Ayuk, J., & Tatsvarei, S. (2019). Achieving food security in a climate change environment: Considerations for environmental kuznets curve use in the South African agricultural sector. *Climate*, *7*(9). https://doi.org/10.3390/cli7090108

Noe, C., Sulle, E., & Brockington, D. (2017). *Tanzania's partnership landscape: Convergence and divergence in the wildlife sector*. www.cbs.dk/dbp

Obaidullah, M., Bram, S., Verma, V. K., & De Ruyck, J. (2012). *A Review on Particle Emissions from Small Scale Biomass Combustion* (Vol. 2, Issue 1).

Ogundipe, A. (2015). *An Empirical Examination of Environmental Kuznets Curve (EKC) in West Africa Sources of Business Cycle Fluctuation in Emerging Africa Economies View project Developing an Entrepreneurial Ecosystem View project*. http://www.absronline.org/journals

Okafor, C., & Shaibu, I. (2016). Modelling Economic Growth Function in Nigeria: An ARDL Approach. *Asian Journal of Economics and Empirical Research* , *3*(1), 84–93. https://doi.org/10.20448/journal.501/2016.3.1/501.1.84.93

Olivier, J. G. J., Van Aardenne, J. A., Dentener, F. J., Pagliari, V., Ganzeveld, L. N., & Peters, J. A. H. W. (2005). Recent trends in global greenhouse gas emissions:regional trends 1970–2000 and spatial distributionof key sources in 2000. *Environmental Sciences*, *2*(2–3), 81–99. https://doi.org/10.1080/15693430500400345

Olufemi, A. C., Bello, P. O., & Mji, A. (2018). *Conflict implications of coal mining and environmental pollution in South Africa: Lessons from Niger Delta, Nigeria*.

Parr, J. B. (1998). *On the regional dimensions of growth*.

Pesaran, M. H., Shin, Y., & Smith, R. J. (2001). Bounds testing approaches to the analysis of level relationships. *Journal of Applied Econometrics*, *16*(3), 289–326. https://doi.org/10.1002/jae.616

Piętak, Ł. (2014). Review Of Theories And Models Of Economic Growth. *Comparative Economic Research. Central and Eastern Europe*, *17*(1), 45–60. https://doi.org/10.2478/cer-2014-0003

Qi, G., Wei, W., Wang, Z., Wang, Z., & Wei, L. (2023). The spatial-temporal evolution mechanism of PM2.5 concentration based on China's climate zoning. *Journal of Environmental Management*, *325*. https://doi.org/10.1016/j.jenvman.2022.116671

Rafindadi, A. A., & Usman, O. (2019). Globalization, energy use, and environmental degradation in South Africa: Startling empirical evidence from the Maki-cointegration test. *Journal of Environmental Management*, *244*, 265–275. https://doi.org/10.1016/j.jenvman.2019.05.048

Rostow, W. W. (1959). The Stages of Economic Growth. *The Economic History Review*.

Saint Akadırı, S., Adewale Alola, A., & Usman, O. (2021). Energy mix outlook and the EKC hypothesis in BRICS countries: a perspective of economic freedom vs. economic growth. *Environmental Science and Pollution Research* , *28*, 8922–8926. https://doi.org/10.1007/s11356-020-11964-w/Published

Sarkodie, S. A. (2018). The invisible hand and EKC hypothesis: what are the drivers of environmental degradation and pollution in Africa? *Environmental Science and Pollution Research*, *25*(22), 21993–22022. https://doi.org/10.1007/s11356-018-2347-x

Sarkodie, S. A., & Adams, S. (2018). Renewable energy, nuclear energy, and environmental pollution: Accounting for political institutional quality in South Africa. *Science of the Total Environment*, *643*, 1590–1601. https://doi.org/10.1016/j.scitotenv.2018.06.320

Sarkodie, S. A., & Owusu, P. A. (2020). How to apply the novel dynamic ARDL simulations (dynardl) and Kernel-based regularized least squares (krls). *MethodsX*, *7*, 1–11. https://doi.org/https://doi.org/10.1016/j.mex.2020.101160

Selden, T. M., & Song, D. (1994). Environmental Quality and Development: Is there a Kuznets curve for air pollution emissions? *Journal of Environmental Economics and Management*, *27*, 147–162.

Sepadi, M. M., & Nkosi, V. (2023). Personal PM2.5 Exposure Monitoring of Informal Cooking Vendors at Indoor and Outdoor Markets in Johannesburg, South Africa. *International Journal of Environmental Research and Public Health*, *20*(3). https://doi.org/10.3390/ijerph20032465

Shahbaz, M., Solarin, S. A., & Ozturk, I. (2016). Environmental Kuznets Curve hypothesis and the role of globalization in selected African countries. *Ecological Indicators*, *67*, 623–636. https://doi.org/10.1016/j.ecolind.2016.03.024

Shikwambana, L., Mhangara, P., & Kganyago, M. (2021). Assessing the relationship between economic growth and emissions levels in south africa between 1994 and 2019. *Sustainability (Switzerland)*, *13*(5), 1–15. https://doi.org/10.3390/su13052645

Shrestha, M. B., & Bhatta, G. R. (2018). Selecting appropriate methodological framework for time series data analysis. *Journal of Finance and Data Science*, *4*(2), 71–89. https://doi.org/10.1016/j.jfds.2017.11.001

Signe, L. (2018). *The potential of manufacturing and industrialization in Africa*. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.brookings.edu/wp-content/uploads/2018/09/Manufacturing-and-Industrialization-in-Africa-Signe-20180921.pdf

Sinaga, O., Haizam, M., & Saudi, M. (2019). Environmental Impact of Biomass Energy Consumption on Sustainable Development: Evidence from ARDL Bound Testing Approach Intellectual Property Right As An Indicator of Business Success During A Pandemic View project green supply chain practices View project. *Ekoloji*, *28*(107). https://www.researchgate.net/publication/331502873

Ssekibaala, D. S., Ariffin, M. I., & Duasa, J. (2022). Economic growth, international trade, and environmental degradation in Sub-Saharan Africa. *Journal of Economics and Development*, *24*(4), 293–308. https://doi.org/10.1108/jed-05-2021-0072

Stats SA. (2023). *Statistical Release: Gross domestic product*.

Stern, D. I., Common, M. S., & Barbier, E. B. (1996). Economic Growth and Environmental Degradation: The Environmental Kuznets Curve and Sustainable Development. In *World Development* (Vol. 24, Issue 7).

Szirmai, A. (2012). Industrialisation as an engine of growth in developing countries, 1950-2005. *Structural Change and Economic Dynamics*, *23*(4), 406–420. https://doi.org/10.1016/j.strueco.2011.01.005

Szirmai, A., & Verspagen, B. (2015). Manufacturing and economic growth in developing countries, 1950-2005. *Structural Change and Economic Dynamics*, *34*, 46–59. https://doi.org/10.1016/j.strueco.2015.06.002

Tenaw, D., & Beyene, A. D. (2021). Environmental sustainability and economic development in sub-Saharan Africa: A modified EKC hypothesis. *Renewable and Sustainable Energy Reviews*, *143*. https://doi.org/10.1016/j.rser.2021.110897

The Global Economy. (2025). *Manufacturing value added - Country rankings*. The Global Economy. https://www.theglobaleconomy.com/rankings/manufacturing_value_added/Africa/

Thio, E., Tan, M. X., Li, L., Salman, M., Long, X., Sun, H., & Zhu, B. (2022). The estimation of influencing factors for carbon emissions based on EKC hypothesis and STIRPAT model: Evidence from top 10 countries. *Environment, Development and Sustainability, 24*(9), 11226–11259. https://doi.org/10.1007/s10668-021-01905-z

Truncellito, D. (1995). *Epistemology*. Internet Encyclopedia of Philosophy .

Tsurumi, T., & Managi, S. (2010). Decomposition of the environmental Kuznets curve: Scale, technique, and composition effects. *Environmental Economics and Policy Studies*, *11*(1), 19–36. https://doi.org/10.1007/s10018-009-0159-4

Udeagha, M. C., & Breitenbach, M. C. (2023). The Role of Financial Development in Climate Change Mitigation: Fresh Policy Insights from South Africa. *Biophysical Economics and Sustainability*, *8*(1). https://doi.org/10.1007/s41247-023-00110-y

Udeagha, M. C., & Muchapondwa, E. (2022a). Environmental sustainability in South Africa: Understanding the criticality of economic policy uncertainty, fiscal decentralization, and green innovation. *Sustainable Development*. https://doi.org/10.1002/sd.2473

Udeagha, M. C., & Muchapondwa, E. (2022b). Investigating the moderating role of economic policy uncertainty in environmental Kuznets curve for South Africa: Evidence from the novel dynamic ARDL simulations approach. *Environmental Science and Pollution Research*, *29*(51), 77199–77237. https://doi.org/10.1007/s11356-022-21107-y

Udeagha, M. C., & Ngepah, N. (2023). Can public–private partnership investment in energy (PPPI) mitigate CO2 emissions in South Africa? Fresh evidence from the novel dynamic ARDL simulations approach. *Frontiers in Environmental Science*, *10*. https://doi.org/10.3389/fenvs.2022.1044605

ul-Haq, Z., Mehmood, U., Tariq, S., & Mariam, A. (2023). Defning the role of renewable energy, economic growth, globalization, energy consumption, and population growth on PM2.5 concentration: evidence from South Asian countries. *Environmental Science and Pollution Research, 30,* 40008–40017. https://doi.org/https://doi.org/10.1007/s11356-022-25046-6

UNCC. (2023a, July 19). *The Paris Agreement*. United Nations Climate Change.

UNCC. (2023b, July 19). *What is the United Nations Framework Convention on Climate Change?* United Nations Climate Change.

UNDP. (2023, June 25). *The SDGs in action*. United Nations Development Programme. https://www.undp.org/sustainable-development-goals#:~:text=What%20are%20the%20Sustainable%20Development,people%20enjoy%20peace%20and%20prosperity.

UNECE. (2023, June 27). *Air pollution and health*. United Nations Economic Commission for Europe. https://unece.org/air-pollution-and-health#:~:text=Air%20pollution%20is%20now%20considered,around%20the%20world%20every%20year.

UNEP. (2023, July 19). *The Maputo Convention on the Conservation of Nature and Natural Resources: Conference of Heads of State and Government of the African Union - Note*. United Nations Environment Programme.

UNWECD. (1987). *United Nations World Commission on Environment and Development*.

USDOS. (2023, July 19). *The Montreal Protocol on Substances That Deplete the Ozone Layer*. United States Department of State.

Usenata, N. (2018). *Munich Personal RePEc Archive Environmental Kuznets Curve (EKC): A Review of Theoretical and Empirical literature*.

Usman, O., Olanipekun, I. O., Iorember, P. T., & Abu-Goodman, M. (2020). Modelling environmental degradation in South Africa: the effects of energy consumption, democracy, and globalization using innovation accounting tests. *Environmental Science and Pollution Research*, *27*(8), 8334–8349. https://doi.org/10.1007/s11356-019-06687-6

Van den Bergh, J. C. J. M. (2011). Environment versus growth - A criticism of "degrowth" and a plea for "a-growth." *Ecological Economics*, *70*(5), 881–890. https://doi.org/10.1016/j.ecolecon.2010.09.035

Voumik, L. C., Rahman, M. H., Nafi, S. M., Hossain, M. A., Ridzuan, A. R., & Mohamed Yusoff, N. Y. (2023). Modelling Sustainable Non-Renewable and Renewable Energy Based on the EKC Hypothesis for Africa's Ten Most Popular Tourist Destinations. *Sustainability (Switzerland)*, *15*(5). https://doi.org/10.3390/su15054029

Walsh, K., Theron, R., & Reeders, C. (2021). Estimating the Economic Cost of Load Shedding in South Africa. *Paper Submission to Biennial Conference of the Economic Society of South Africa (ESSA)* , *22*. https://cms.novaeconomics.co.za/wp-content/uploads/2023/01/ESSA_The-economic-cost-of-load-shedding_edit2.pdf

Wang, Y. (2024). Study on the Relationship between Economic Growth and Environmental Pollution in Shanxi Province Based on EKC . *Applied Mathematics and Nonlinear Sciences*, *9*(1), 1–19. https://doi.org/https://doi.org/10.2478/amns-2024-1579

WHO. (2023, July 1). *Air quality and health*. World Health Organisation.

World Bank. (2023, July 21). *World Development Indicators*. World Bank Group. https://databank.worldbank.org/source/world-development-indicators

Zalk, N. (2014). Industrial policy in a harsh climate: The case of South Africa. In J. M. Salazar-Xirinachs & I. Nübler (Eds.), *Transforming Economies: Making industrial policy work for growth, jobs and development* (pp. 327–354). nternational Labour Review.

Zarenda, H. (1989). The rationale underlying the policy of inward industrialisation in South Africa. *Development Southern Africa*, *6*(4), 409–420. https://doi.org/10.1080/03768358908439484

Zhang, D., Du, L., Wang, W., Zhu, Q., Bi, J., Scovronick, N., Naidoo, M., Garland, R. M., & Liu, Y. (2021). A machine learning model to estimate ambient PM2.5 concentrations in industrialized highveld region of South Africa. *Remote Sensing of Environment*, *266*. https://doi.org/10.1016/j.rse.2021.112713

Appendix 1: Research Data

Year	LN CO2 [kt]	LN NO2 [kt]	LN SO2 [kt]	LN PM2.5 [kt]	LN GDP/Capita [LCU]	LN GDP2/Capita [LCU]
1970	12.3990	6.8936	6.9866	6.0493	-0.0270	0.0007
1971	12.4051	6.8966	6.9873	5.9855	-0.0144	0.0002
1972	12.4383	6.9065	7.0209	5.9901	-0.0265	0.0007
1973	12.4921	6.9565	7.1126	6.0147	-0.0102	0.0001
1974	12.5394	6.9552	7.1536	6.1220	0.0210	0.0004
1975	12.5979	7.0437	7.2442	6.2017	0.0102	0.0001
1976	12.6412	7.0452	7.3109	6.2596	0.0056	0.0000
1977	12.6423	7.0369	7.3182	6.2643	-0.0221	0.0005
1978	12.5688	6.9544	7.1893	6.1827	-0.0194	0.0004
1979	12.5866	6.9406	7.2230	6.2033	-0.0088	0.0001
1980	12.6371	6.9743	7.2750	6.2512	0.0289	0.0008
1981	12.6981	7.0263	7.3307	6.3312	0.0554	0.0031
1982	12.7083	7.0097	7.3137	6.3030	0.0257	0.0007
1983	12.7019	6.9714	7.2816	6.2542	-0.0197	0.0004
1984	12.7670	7.0238	7.3351	6.3291	0.0021	0.0000
1985	12.7825	7.0141	7.3564	6.3507	-0.0397	0.0016
1986	12.7799	7.0039	7.3392	6.3435	-0.0723	0.0052
1987	12.8300	7.0620	7.4093	6.4169	-0.0865	0.0075
1988	12.8422	7.0531	7.3891	6.4125	-0.0800	0.0064
1989	12.8387	7.0617	7.4115	6.4502	-0.0899	0.0081
1990	12.8647	7.0825	7.4431	6.4627	-0.1239	0.0153
1991	12.8374	7.0668	7.4139	6.4481	-0.1597	0.0255
1992	12.7867	7.0518	7.4067	6.4125	-0.2018	0.0407
1993	12.7956	7.0679	7.4118	6.4882	-0.2077	0.0431
1994	12.8364	7.1043	7.4383	6.5235	-0.1935	0.0375
1995	12.8660	7.1646	7.4657	6.5159	-0.1795	0.0322
1996	12.9260	7.2029	7.5162	6.5803	-0.1526	0.0233
1997	12.9616	7.2398	7.5698	6.6077	-0.1408	0.0198
1998	12.9852	7.2755	7.6126	6.6105	-0.1483	0.0220
1999	12.9350	7.2200	7.5382	6.5389	-0.1357	0.0184
2000	12.9531	7.2397	7.5593	6.5458	-0.1041	0.0108
2001	12.9552	7.4229	7.7413	6.0187	-0.0864	0.0075
2002	12.9952	7.4467	7.7657	6.0384	-0.0591	0.0035
2003	13.0362	7.4822	7.8185	6.0212	-0.0393	0.0015
2004	13.0976	7.5419	7.8911	6.0756	-0.0041	0.0000
2005	13.1234	7.5241	7.8575	6.0779	0.0379	0.0014
2006	13.1208	7.5149	7.8528	6.0508	0.0827	0.0068
2007	13.1605	7.5631	7.8953	6.1151	0.1248	0.0156
2008	13.2165	7.6062	7.9833	6.1780	0.1449	0.0210
2009	13.1621	7.5112	7.9086	6.1394	0.1175	0.0138
2010	13.1690	7.6273	7.9935	6.0895	0.1355	0.0184
2011	13.1278	7.5908	7.9363	6.0609	0.1541	0.0237
2012	13.1623	7.6099	7.9791	6.1571	0.1645	0.0271
2013	13.1903	7.6254	7.9887	6.1881	0.1754	0.0308
2014	13.2078	7.6331	8.0270	6.2154	0.1737	0.0302
2015	13.1477	7.5839	7.9574	6.1254	0.1661	0.0276
2016	13.1429	7.5884	7.9695	6.0905	0.1630	0.0266
2017	13.1651	7.5687	7.9553	6.2110	0.1706	0.0291
2018	13.1578	7.5626	7.9467	6.1913	0.1735	0.0301