An Essay on the Welfare and Growth Implication of the Energy Mix in the South African Economy

By

Masedi Sesele

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Prof Dambala Gelo Kutela

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Declaration

I declare that this thesis, which I hereby submit for the degree of PhD in Economics at the University of The Witwatersrand, is entirely my work and has not been submitted anywhere else for the award of a degree or otherwise.

Masedi Sesele
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Dedication

I dedicate this thesis to my mother, Pulane Martha Sesele and my sister, Mamokgosi Raboshakga. Thank you for your support.

Abstract

This study investigated the welfare and growth implications of introducing renewable energy in South Africa's energy mix. The investigation is divided into three chapters, providing a holistic analysis of climate change mitigation on developmental goals in South Africa. The first chapter determines the impact of the usage of non-renewable energy sources on selected sectors' economic output in South Africa. The second chapter determines the pass-through effect and the response of consumer prices to renewable energy share increases in South Africa while using the exchange rate as a threshold. The third chapter determines through a natural experiment the impact of renewable energy policies such as the White Paper on the Energy Policy of the Republic of South Africa (1998), the White Paper on Renewable Energy Policy (2003) and the Integrated Resource Plan (2010) on South Africa's economic growth by comparing the gross domestic product (GDP) growth path before and after the introduction of these policies.

Results from the second chapter showed that coal was the least contributing factor to production for most sectors, showing that excessive coal usage may hinder economic output within the country. Petroleum has a positive and significant effect on the transport and agriculture sectors but has less of an effect on the other sectors. Electricity is a major contributing factor to production in some sectors, except for the industry sector, which may be adversely affected by the increasing electricity costs and constant loadshedding in the country.

Results from the third chapter showed that at an exchange rate threshold value of 7.7 R/$, the share of renewable energy pass-through to consumer prices is statistically significant below and above the threshold exchange rate value. When the exchange rate is above the threshold value, the pass-through effect is negative, indicating that an increase in the share of clean energy will decrease consumer prices. These results are largely attributed to the cost of renewable energy, which has been declining significantly in periods where the exchange rate was above the threshold value and, as a result, it had a negative pass-through effect on consumer prices.

Results from the fourth chapter showed that each of the three green energy policies has a positive impact on the GDP, which shows that implementing renewable energy policies in South Africa has not only resulted in generating clean, renewable energy but also fosters economic growth within the country. Using a natural experiment, the study constructed a synthetic GDP growth path that would have been in place had there been no renewable energy intervention and compared it with the current GDP growth path post the intervention of renewable energy policy to identify the causal positive impact of green energy on economic growth.

This thesis' results encourage policymakers to further implement and improve renewable energy policies as the share of clean energy within South Africa's energy mix not only mitigates climate change by decreasing greenhouse gas emissions but also positively affects economic growth by creating a clean ecosystem, job creation, increasing innovation and capital formation and overall improving total factor productivity in South Africa and the standard of living of ordinary South Africans.

Keywords: Economic Output, Renewable Energy, Non-renewable Energy, Capital, Labour Force, Petroleum Product, Coal, Electricity, Natural Experiment, Consumer Prices, Exchange Rate, Economic Growth

JEL codes: C22, C23**,** P28, Q30, Q42**,** Q43, C24, D61, Q20, Q56

List of Acronyms

ADF	Augmented Dickey-Fuller
CPI	Consumer Price Index
CO_2	Carbon Dioxide
COP26	United Nations Climate Change Conference in Glasgow
COVID-19	Coronavirus Disease
GDP	Gross Domestic Product
IPCC	Intergovernmental Panel on Climate Change
IPS	Im, Pesaran and Shin
IRP	Integrated Electricity Resource Plan for South Africa
LCOE	Levelized Cost of Energy
LLC	Levin, Lin and Chu
MW	Megawatt
NDP	National Development Plan
OECD	Organisation for Economic Co-Operation and Development
PV	Photovoltaic
StatsSA	Statistics South Africa
TFP	Total Factor Productivity
TVAR	Threshold Vector Autoregressive
US	United States
VAR	Vector Autoregressive

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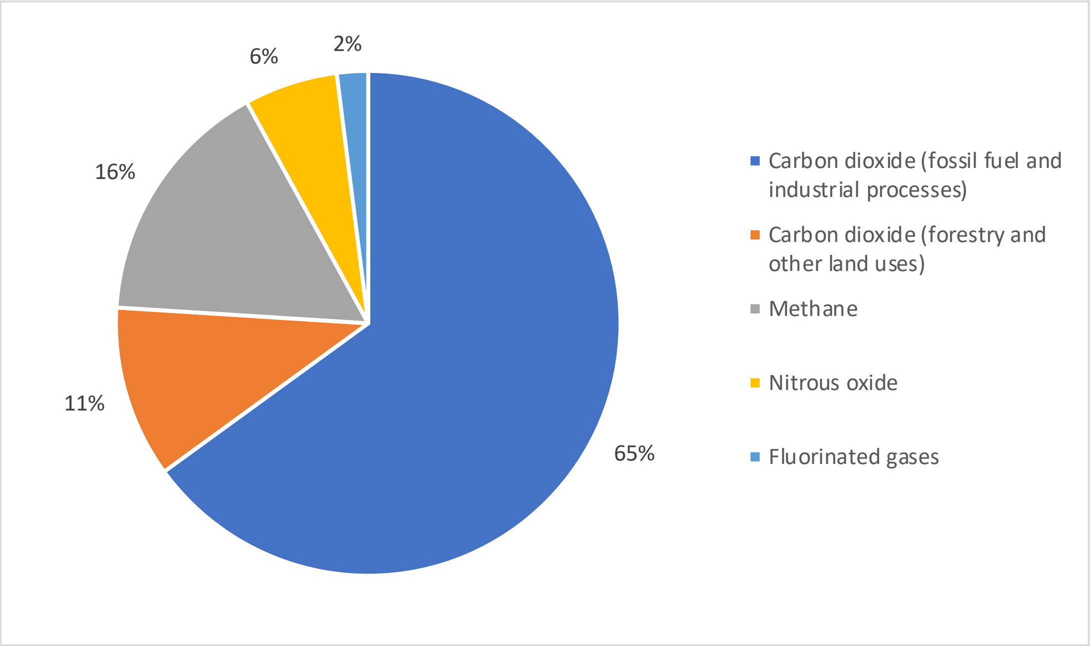
1 Chapter One: General Introduction

1.1 Introduction

With the world transitioning to a green economy to mitigate climate change, this study investigated the implications of this transition on growth and welfare in the South African context. Global warming is largely driven by greenhouse gas emissions that cause heat to be trapped in the atmosphere creating a shift in climate patterns, which is regarded as climate change. Greenhouse gases are sourced from natural systems, such as earthquakes, forest fires and volcanoes, and human systems, such as energy production, industrial activities and land use (Fawzy et al., 2020). The United States Environmental Protection Agency (2021) reported global greenhouse gas emissions composition, as seen in Figure 1.1.



<u>Figure 1.1: The composition of global greenhouse gas emissions</u>

Source: United States Environmental Protection Agency (2021)

The high concentration of these greenhouse gases in the atmosphere is a major concern for current and future generations, as the UNCC (2021) State of Climate on 2021 report has shown that the accumulated heat in the atmosphere has pushed Earth into unfamiliar terrain. The report highlights the changes in climate indicators, such as temperature, ocean acidification, precipitation, sea-level rise, sea ice melt and extreme weather conditions, due to climate change. Natural disasters, such as floods, storms, wildfires and droughts, affected 68.5 million people in 2018 and resulted in economic losses that amounted to $ 131.7 billion in the same year (Fawzy et al., 2020).

The Intergovernmental Panel on Climate Change (IPCC) investigated the impact of 1.5 to two degrees Celsius global warming on freshwater sources, human health, ecosystems, poverty, food production and food security. The report also focused on the effect of global warming on economic sectors such as energy, tourism and transportation. The analysis showed that the risks of global warming on these factors increase as the temperature increases from 1.5 to two degrees Celsius (IPCC, 2018). The IPCC concluded that emissions of greenhouse gases must be halved by 2050 to keep global warming below two degrees Celsius. A similar conclusion was reached by the Kyoto Protocol, which, through the Paris Agreement, aimed to limit global emissions and ensure that global temperatures only reach two degrees Celsius by 2100 (UNFCCC, 2020a).

Multiple global policies have come to effect to mitigate climate change since the first climate change conference held in Geneva in 1979 by the World Meteorological Organization (WMO, 1979). The United Nations Framework Convention on Climate Change has been the driving force and evaluator of climate change mitigation globally. The convention aimed to stabilise greenhouse gas concentration in the atmosphere to prevent adverse effects of climate change by establishing an international environmental treaty, which has been signed by over 160 countries (UNFCCC, 2020b).

The 2021 United Nations Climate Change Conference in Glasgow (COP26) brought together world leaders to participate in the proceedings and produced new approaches to advancing the transition towards a low-carbon global economy through implementing actions from the Paris Agreement. Amongst other agreements, the conference empathised with the acceleration of countries in terms of the transition from fossil fuels and delivering on climate finance (United Nations, 2021).

All climate change policies highlight using clean energy technologies as an approach to mitigate climate change. In South Africa, the National Development Plan (NDP) predicts that, by the year 2030, the country will be in a position whereby the energy sector will have the capacity to supply reliable and efficient energy services at competitive rates. These energy services should be environmentally friendly to reduce greenhouse gas emissions and pollution (DoE, 2019). Climate change mitigation is of utmost importance, as the 2022 KwaZulu-Natal floods have shown that South Africa is likely to experience harsh climate change events, resulting in infrastructure destruction and the displacement and loss of life of many individuals (Motsoere, 2022).

It is, therefore, in South Africa's best interest to join the global community in combating the rapidly rising climate crisis, following the nation's circumstances and development priorities. Mitigating climate change will strengthen the country's abilities and capabilities to cope with extreme weather events by ensuring the resilience of human settlements, individuals and society as a whole. As such, the South African government is a signatory to the Paris Agreement and has committed to a 42% reduction in emissions, which are the pollutants that drive climate change, against the baseline projection by the year 2025 (DoE, 2015).

Cyril Ramaphosa, the President of South Africa, announced that South Africa concluded a historic agreement to secure R 131 billion from partner countries, to finance the just transition to a low-carbon economy in the country (Ryan, 2021). The just transition declaration includes halving the country's greenhouse gas emissions to achieve net zero CO_2 (carbon dioxide) emissions by 2050. This will be achieved by decommissioning coal power stations and increasing investment into the renewable energy sector while also shifting towards producing electric vehicles. The declaration also notes that for the process of transition to be just, key members of society, such as organised labour, need to be involved and reskilling and upskilling programmes need to be implemented to create employment and provide other forms of support to ensure that workers benefit from the transition to a greener future (South African Government, 2021).

To show the country's commitment towards transitioning to a low-carbon economy, the President has established the Presidential Climate Commission, which is an independent, statutory, multistakeholder body tasked to oversee and facilitate a just and equitable transition to a green economy (PCC, 2022). The Commission's focus has been to define a vision for a just transition and methods of achieving that vision by analysing all sectoral shifts, technological innovation, employment opportunities and climate finance, as well as conducting climate change impacts on jobs and the economy. The Commission also focuses on monitoring progress towards climate change mitigation and adaptation goals and developmental objectives (PCC, 2022).

South Africa is one of the largest coal producers in the world, and coal is the largest energy fuel source in the country (IEA, 2021). This results in South Africa having a carbon-intensive economy, which can present a risk as many countries in the world have embarked on aggressive decarbonisation of their economies, and as such, South Africa's exports may be penalised, and investment in carbon-intensive sectors may decrease. As such, reducing greenhouse gas emissions and growing new green sectors is crucial to maintaining the country's economic competitiveness with the rest of the world.

Currently, South Africa has rising energy demands, which have started to overwhelm the country's existing power-generating plants. As such, the state-owned power utility, Eskom, implemented a loadshedding approach to cope with the high energy demands (Eskom, 2020). A Council for Scientific and Industrial Research study showed that loadshedding reduces economic output by about R 700 million per loadshedding stage per day. The study also reported that in 2019 alone, the economy lost between R 60 billion and R 120 billion due to loadshedding (Mahlaka, 2021). Besides, it has been reported by multiple economists that loadshedding has led to job shedding and an increased unemployment rate (Modise, 2020).

Because of the adverse impact of loadshedding on the South African economy, the country continues to develop its renewable energy sector as an alternative energy source to reduce the over-reliance on coal and to provide reliable electricity. Due to the human population and geographical location of South Africa, clean energy sources, such as wind and solar, have great potential. The move towards implementing renewable energy has added advantages and opportunities, such as the potential to make electricity cheaper and more dependable, as renewable energy technologies are relatively cheaper than non-renewable technologies. Also, the push for renewable energy creates new manufacturing and maintenance jobs, as well as new markets for the supply of clean energy minerals.

Regardless of the South African President's position regarding moving to a net zero carbon economy, the Minister of Energy, Gwede Mantashe, has pushed back on the complete exclusion of coal in South Africa's energy mix. He stated that although the government was fully committed to a move towards a green economy away from detrimental carbon emissions, the government would not desert coal in favour of renewable energy at the expense of economic growth. The minister detailed that even though the country is committed to low-carbon emissions, it would embark on this transition prioritising developmental needs; as such, all energy sources that positively contribute to economic growth, including coal, will form part of the national energy mix (Dludla, 2021).

The statement made by the Minister of Energy is of utmost importance as even though there is a major push for a transition to renewable energy and the green economy, arguably, the welfare and growth consequences of this transition have not been rigorously examined in extant literature to ascertain a fuller range of their potential benefits. The relationship between climate change policies and developmental goals remains unclear. Not much research has been conducted to determine whether the move to green energy complements or competes with the country’s developmental goals, such as economic growth, poverty alleviation and employment.

To fill this research gap, Moreno and Lopez (2008) investigated the effects of the transition towards the green economy on employment in Spain. Results showed that clean energy consumption positively impacts employment as the green energy sector is expected to create more jobs in construction and installation. This will compensate for the gradual loss of employment in the traditional mining sector. On the other hand, Thiam (2011) showed how using clean energy can improve the standard of living and alleviate poverty in rural Senegal by using a life-cycle-cost approach. Results showed that in rural areas without grid connection, photovoltaic (PV) renewables technologies provide a stable solution for delivering energy.

Studies such as Shahbaz et al. (2020), Inglesi-Lotz (2016), Fang (2011) and Tiwari (2011) all concluded that variables, such as clean and dirty energy consumption, capital and labour, positively affect gross domestic product (GDP). By contrast, Ahn et al. (2021) analysed the impact of the transition towards green energy on social welfare, showing a decrease in social welfare due to increases in the share of green energy in the energy mix. These results are similar to those of Omri and Belaïd (2021), who concluded that clean energy consumption, together with CO_2 emissions from liquid fuel consumption and CO_2 intensity, negatively affect economic growth.

Mulder and Scholtens (2013) analysed the effect of weather conditions on electricity prices and found that wind speed in Germany negatively impacts Dutch electricity prices. Correa-Quezada et al. (2022) also examined the impact of increased clean energy consumption on electricity prices in South American countries, and the results showed that the price of electricity paid by households is affected by the consumption of renewable energies. However, it was determined that energy prices in industrial, commercial and services sectors are not affected by renewable energy consumption. On the other hand, Bijnens et al. (2021) specified that high electricity prices can be attributed to implementing a carbon tax or increased investment into clean electricity generation, which can decrease labour demand and investment in sectors that mostly rely on electricity as an input factor.

Studies by van Heerden et al. (2016) and Cuervo and Gandhi (1998) concluded that carbon taxes have a net negative impact on the GDP, income distribution and international competitiveness under all exemption regimes and all revenue recycling options assessed. However, the negative effect is reduced by how the tax revenue is recycled. On the contrary, Metcalf and Stock (2020) concluded through point estimates that carbon taxes have a zero to modest positive effect on GDP growth and employment growth rates and found no robust evidence of a negative impact of the tax on employment or GDP growth.

Despite the large interest in the impact of green energy on developmental goals, such as poverty and employment, literature offers little attention to the impact of green energy on growth and employment on a sector basis. Previous analysis focuses on the effects of renewable energies on a country level, and they do not go deeper to analyse the effect on a sector-specific basis, as the growth implications of renewable energies may differ depending on each sector. As such, the current study differs from previous ones by examining the effects of non-renewable energies on different sectors to provide a more in-depth analysis.

Existing studies have also focused on the ability of clean energy to reduce environmental pollution, and, in turn, improve the GDP as a welfare function. However, there have been some inconsistent results in this regard. Therefore, the current study follows a different approach by using consumer prices as a welfare function, offering a unique and more powerful indication of how the introduction of renewable energy affects the standard of living of individuals, judging by its impact on the prices of goods and services.

With South Africa facing multiple developmental challenges, determining whether the move to green energy will benefit or disadvantage the developmental goals is of utmost importance. Thus, this study aimed to fill this research gap by providing a rigorous analysis of the relationship between climate change mitigation policies and developmental goals in the South African context. The study will provide more clarity in this regard to assist policymakers in making the right decisions regarding the just transition.

1.2 Research Objectives

This thesis was inspired by the aforementioned gaps in the literature concerning the impact of the shift towards the green economy on South Africa's developmental goals. As such, the objectives of this research were threefold. The first objective was to determine the impact of using non-renewable energy sources on selected sectors' (industry, mining, agriculture, transport and commercial) economic output in South Africa. By doing this, we can compare the sectors' dependence on dirty energy sources use for their economic production. Understanding these differences will assist policy design in promoting energy efficiency and demand-side management without compromising economic growth.

The second objective was to analyse the pass-through mechanism of the share of renewable energy to consumer prices as a welfare indicator. As opposed to many studies that used GDP as a welfare indicator to model the impact of renewable energy on economic welfare, this study followed a different approach by making use of the Consumer Price Index (CPI) as a welfare indicator. The CPI measures the change in the price of consumer goods and services over a certain period (StatsSA, 2017). It is an ideal welfare measure as it can be used as a cost-of-living index. A Vector Autoregressive (VAR) model was used to estimate this pass-through and the response of consumer prices to renewable energy share shocks in a multivariate, two-regime threshold vector autoregression.

The third objective was to evaluate the structural break analysis of the GDP growth drift due to the introduction of green energy into the national energy mix in South Africa. This was achieved by conducting a natural experiment (Regression Discontinuity in time and Synthetic Control methods) to evaluate the impact of renewable energy policies and their subsequent implementation on South Africa's economic growth. Three renewable energy policies were evaluated: the White Paper on the Energy Policy of the Republic of South Africa (1998), the White Paper on Renewable Energy Policy (2003), and the Integrated Electricity Resource Plan for South Africa (IRP) 2010. The comparative analysis determined the GDP growth before and after introducing renewable energy policies.

1.3 **Research Relevance**

South Africa is embarking on a just transition from a carbon-intensive economy to a more environmentally friendly green economy. This is a trend, not only experienced in South Africa but worldwide, to combat the effects of climate change. A study of this nature is of utmost relevance and importance, not only to the South African community but to the world at large. Debatably, not enough research has been conducted with regard to how the move away from a carbon-intensive economy to a green economy affects developmental goals, such as employment, poverty alleviation and economic growth, especially for a country like South Africa, which is heavily dependent on carbon-intensive industries for employment and economic growth.

The analysis in this research is of the utmost importance as it first analyses the impact of using dirty energy sources on economic growth in several economic sectors in South Africa. Understanding how different sectors of the South African economy rely on non-renewable energy for their economic output will assist policy design in promoting energy efficiency and demand-side management without compromising economic growth. This will also provide an analysis of how certain sectors can be harmed or benefit from climate mitigation policies, such as carbon taxes; as such, each sector will require a unique approach. A sector-based analysis of this nature is uncommon in economic literature and provides a unique analysis.

Secondly, the study will provide an analysis of how the decreasing costs of renewable energy technology can be passed on to consumer prices as a welfare function. Results from this analysis will motivate policymakers to rigorously invest in the move towards renewable energy as a factor of production. This is so because the decreasing cost of renewable energy can be passed on to consumers through lower-priced goods and services, improving the cost of living of ordinary South African.

Lastly, the natural experiment evaluated the impact of clean energy policies and their subsequent implementation on South Africa's economic growth. Much of the extant economic literature has confirmed a strong relationship between clean energy in the energy mix and economic growth. However, the literature followed either time series or panel data models, making it difficult to interpret this relation as causal rather than an association. This study followed a different approach by employing a natural experiment (Regression Discontinuity in time and Synthetic Control methods) to pinpoint the causal effects of green energy policies and the clean energy share in the energy mix on South Africa's economic growth. Analysing the impact of renewable energy policies on economic growth in South Africa is essential as it will measure the effectiveness of each policy on economic growth. This will help policymakers draft better policies that can foster economic growth based on the shortcomings of previous policies with regard to their impact on growth.

1.4 Summary of Analysis

The results from the first empirical chapter indicate that coal was the least contributing factor to the production for most sectors, showing that excessive coal usage may hinder economic output within the country. Labour, electricity and capital are major contributing factors to production, and petroleum has a positive and significant effect on the transport and agriculture sectors but has less of an effect on the other sectors.

Results from the second empirical chapter showed that by using a threshold VAR (TVAR) model, the share of renewable energy pass-through to consumer prices is statistically significant below and above the threshold exchange rate value. Due to the decreasing cost of renewable energy, increasing the share of clean energy will decrease consumer prices. Results from the third empirical chapter showed through a natural experiment that each South African green energy policy increases GDP, causing a positive GDP growth drift when comparing the GDP growth before and after the clean energy policy intervention. The investment into renewable energy infrastructure and the job creation, as a result of creating the green energy sector post-renewable energy policy implementations, positively impacts economic growth.

The research recommends that policymakers should encourage policies that increase the share of clean energies within South Africa's energy mix to reap their full benefits. The just transition to a green economy should be supported. However, climate mitigation policies, such as the carbon tax, should only be applied to economic sectors that will not suffer in economic output because of them.

1.5 Thesis Outline

Chapter Two analyses the role of non-renewable energy sources on economic output in selected South African sectors. Chapter Three examines the effects of clean energy consumption on economic welfare. Chapter Four investigates the effects of clean energy introduction on the GDP growth through evidence from a natural experiment in South Africa. Finally, Chapter Five concludes the thesis.

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2 Chapter Two: The Role of Non-renewable Energy Resources on Economic Output in Selected South African Sectors

Abstract

This study determined the impact of using non-renewable energy sources on selected sectors' (industry, mining, agriculture, transport and commercial) economic output in South Africa. Specifically, controlling for other traditional inputs, this study determined the impact of petroleum products, coal and electricity on economic output in a panel data regression framework, including the five sectors from 1992 to 2018. Results showed that electricity is a major contributing factor to production in some sectors, except for the industry sector, which may be adversely affected by the increasing electricity costs. Coal was the least contributing factor to production for most sectors, showing that excessive coal usage may hinder economic output in the country. Petroleum has a positive and significant effect on the transport and agriculture sectors but has less of an effect on the other sectors. From a policy point of view, promoting increases in the usage of an energy mix skewed towards electricity from renewable energy sources will benefit South Africa's economic output and environment. Furthermore, sector-specific climate change policies should be favoured rather than implementing such policies across all sectors, which will adversely affect some sectors while favouring others. Greenhouse gas emissions policies should also be specifically applied to non-renewable energy sources that adversely impact economic growth instead of those that foster it due to the heterogeneity between non-renewable energy sources.

Keywords: Economic Output, Renewable Energy, Non-renewable Energy, Capital, Labour Force, Petroleum Product, Coal, Electricity, Panel Data

JEL codes: C22, C23, P28, Q20, Q30, Q42, Q43, Q56

2.1 Introduction

The transition towards a global low-carbon economy to protect the environment has become an important issue for international institutions, governments and other stakeholders who have an interest in sustainable development, as the use of dirty energy sources poses a risk to human and environmental health. However, in developing countries such as South Africa, which are highly carbon intensive, the move towards renewable energies has been met with criticism as it remains unclear what impact this transition will have on economic growth and other developmental goals.

The Kyoto Protocol (1997) committed industrialised economies to largely reduce their greenhouse gas emissions, and since much of the world's growth is heavily dependent on carbon-intensive energy, it remains unclear how this reduction in the use of carbon-intensive energy can affect economic growth. As such, the objective of this study was to determine the impact of using dirty energy sources on selected sectors' (industry, mining, agriculture, transport and commercial) economic output in South Africa. By doing this, we can compare the sectors' dependence on dirty energy sources for economic production. Arguably, this is an essential exercise that has not been explored in economic literature, which has historically mainly focused on the effects of dirty energy sources on economic growth on an aggregate level. This study stands out by focusing on these effects on a sector level, which can inform sector-specific climate policies and account for heterogeneity across sectors.

The rest of this chapter is organised into five sections, the first of which is the literature review. The second is the development of the theoretical and empirical methodology. The third is the econometric methodology followed in this study. The fourth section is an analysis and discussion of the empirical results, and the fifth section presents the study's conclusion and recommendations.

2.2 Literature Review

The impact of non-renewable energy sources on economic output has been well documented; however, studies have mainly focused on this impact from an aggregated view, either analysing from a national level or across different countries, and less research has been conducted on a sector level. Therefore, this review is divided into two groups based on the different types of analysis from literature.

2.2.1 Aggregate Level Analysis Review

The study by Awodumi and Adewuyi (2020) focused on highly carbon-intensive oil-producing African countries and measured whether a move away from the use of dirty energy sources will impact the economic growth in these countries. The findings showed that changes in the consumption of dirty energy sources provided mixed results regarding their effect on economic growth amongst the top oil producers in Africa. Similarly, Baz et al. (2021) analysed the fossil fuel, clean energy and economic growth nexus using time series Pakistan data from 1980 to 2017. Results from the asymmetric causality test showed that increases in fossil fuel consumption led to an upsurge in the GDP, while in the long run, increases in the consumption of clean energy harmed GDP. A decrease in the consumption of fossil fuels also had a positive effect on GDP; as such, negative and positive shocks in fossil fuels and economic growth had a neutral effect in the asymmetric test.

On the other hand, Ivanovski et al. (2021) looked at the consumption of different energy types in OECD (Organisation for Economic Co-Operation and Development) and non-OECD countries to assess their impact on economic growth. The study concluded that dirty energy sources positively impact economic growth, while clean energy sources have little to no effect on economic growth in OECD countries. However, in non-OECD countries, both types of energy sources have positive implications for economic growth. The results for the non-OECD countries are similar to those found by Rahman and Velayutham (2020), who concluded the positive impact of both energy sources on economic growth in South Asian countries. The study further indicated that clean energy sources had a larger effect on growth than dirty energy sources. Similar results were found in the study by Asif et al. (2021), but only for upper-middle and high-income countries, while for low-income countries, the effect was negative.

Žarkovic´ et al. (2022) also investigated the relationship between renewable and non-renewable energy consumption, greenhouse gas emissions and gross GDP per capita. The results showed that a 1% increase in the consumption of non-renewable energy has a significant and negative impact on GDP per capita in the long run in old and new European Union members. On the contrary, Gyamfi et al. (2020) explored the dynamic interaction between hydroelectricity energy, renewable energy consumption and non-renewable energy consumption on economic growth over annual time-frequency data from 1990 to 2018. The empirical results showed a one-way causality relationship between economic growth and non-renewable energy. However, as economic growth increases, there is less strengthening of energy from non-renewable energy consumption.

Asiedu et al. (2020) investigated the nexus among renewable and non-renewable energy consumption, CO_2 emissions and economic growth in 26 European countries between 1990 to 2018. The Granger causality test showed a bidirectional causality between economic growth and renewable energy consumption, as well as a unidirectional causality between renewable and non-renewable energy consumption. The results also showed that non-renewable energy consumption decreases economic growth. On the other hand, Le et al. (2020) investigated the effects of renewable and non-renewable energy on economic growth and emissions in 102 countries. Empirical results showed that both renewable and non-renewable energy consumption contributes significantly to the level of income across countries. However, using non-renewable energy significantly raised the level of emissions across different income groups of countries.

Gozgor et al. (2018) empirically analysed the effects of renewable and non-renewable energy consumption on economic growth in panel data of 29 OECD countries for the period from 1990 to 2013. The results showed that both non-renewable and renewable energy consumption are positively associated with a higher rate of economic growth. Saqib (2022) also examined the relationship between non-renewable energy and economic growth from 1990 to 2020 for 63 emerging and developed economies. The results showed a positive bivariate correlation between GDP, non-renewable energy consumption and renewable energy consumption.

2.2.2 Sector-Level Analysis Review

It is evident that existing economic literature mainly focuses on the impact of non-renewable energy sources on an aggregate level, and as such, a research gap exists with regard to providing analysis on a more granular sector level. Certain literature has attempted to fill this gap but has fallen short in some aspects, such as Gazheli et al. (2016), who considered the potential trade-off between climate change mitigation and economic growth by using a sector-based approach to analyse the relationship between emissions of CO_2 per dollar of output on the growth in labour productivity and economic output. The study covered several European countries from 1995 to 2007. Despite climate policies developed by the Kyoto Protocol, the results showed that environmentally friendly sectors are not necessarily more productive than environmentally unfriendly sectors, and both types of sectors do not display higher productivity growth. The study also concluded that high-carbon-intensive sectors have grown more in absolute terms than low-carbon-intensity sectors.

On the other hand, Acemoglu et al. (2012) created a model whereby the same final goods were produced by green sectors (renewables) and brown sectors (non-renewables). The model showed that because of the long history of cost-reducing research and development in the brown sector, the goods produced in that sector were cheaper than goods produced in the green sector. The brown sector is also more productive and has a larger market share than the green sector. To reduce the productivity gap between the two sectors, environmental taxes will need to be imposed on the brown sector, and subsidies for research and development will need to be provided to the green sector. Tutak and Brodny (2022) investigated the degree of renewable energy use in selected sectors of the economy and households in the European Union countries between 2000 and 2019, including the whole economy, industry and agriculture. The results showed that renewable energy consumption positively impacts economic growth, the reduction of conventional energy consumption and the reduction of greenhouse gas emissions in all European Union countries.

Votteler and Brent (2017b) analysed the internal structure of mining firms and their operations in South Africa and investigated the feasibility of implementing renewable electricity sources and how they can perform within the mining sector. Since the electricity sources were diesel generators and the Eskom grid connection, the study showed that a hybrid version of these sources, together with onshore wind and solar PV cells, performed better than the current sources alone. Also, Ali et al. (2012) investigated the impact of sustainable energy in the agricultural sector in India. The study reviewed how solar energy, oil from plants, wind energy, waterpower, wood from sustainable sources, biomass and biogas can be harvested continuously, affording farmers an opportunity for a long-term source of income. Within the industry sector, which includes construction among other sub-sectors, there have been studies such as Yue and Zhi (2012), who analysed the structure of the construction sector and the feasibility of implementing multiple green energy sources, such as solar and geothermal energy. The study showed that a combination system of water cascade utilisation, domestic solar water, shallow geothermal energy and solar energy could decrease the sources of energy usage within the construction sector, reducing the amount of CO_2 emitted.

2.2.3 Overall Analysis

The above analysis of previous literature highlights the significance of the current study in economic literature and the global energy environment. Firstly, most of the economic studies with regard to the impact of renewable energy on economic growth are at a national level, either focusing on one country and analysing the effects of renewable energy overall or by making use of a panel of countries and comparing the effects across the countries. This provides an aggregate analysis, which could be misleading when implementing carbon mitigation policies. If the overall effect of renewable energy in a country is positive for the country's growth, a move towards renewable energies will be promoted across all sectors of the country's economy. However, sectors are heterogeneous and cannot be treated the same. Some sectors might have a positive relationship with economic growth using dirty energies; as such, climate mitigation policies will harm economic output in such sectors.

The opposite is also true; if nationally aggregated results show that non-renewable energy sources are positively related to a country's economic growth, then the policy will not recommend a move towards renewable energy. However, certain sectors could benefit from a move to more clean technologies and will suffer under a carbon-intensive environment. As such, the current study addresses this deficiency by analysing the impact of dirty energy sources on economic growth in five sectors of the South African economy, namely industry, mining, agriculture, transport and commercial. This will provide a richer analysis supporting the move towards sector-specific climate change policies.

When analysing the literature that attempts to investigate the impact of non-renewable energy sources at a sector level (Acemoglu et al., 2012; Gazheli et al., 2016), it is clear that these analyses only focus on the carbon intensity of each sector and do not analyse the individual non-renewable energy source, which is driving this carbon intensity. As such, these studies also provide an aggregate analysis of the type of non-renewable energy sources and fail to differentiate the dirty energy sources. The current study fills this gap by providing a more in-depth analysis of a selection of specific dirty energy sources and their impact on sectors' economic output. The non-renewable energy sources examined in this study are coal, petroleum and electricity, as they are the most preferred sources used by South African economic sectors. This study will not establish the relationship between clean and dirty energy sources, but it does, however, acknowledge that classifying electricity as a non-renewable energy source is not entirely accurate, as even though coal-fired stations produce most of the electricity in the country, Eskom also has gas-fired, nuclear power, hydro and pumped storage stations, as well as the recently commissioned Sere Wind Farm, which are renewable energy sources (DoE, 2018).

This analysis is essential as non-renewable energy sources are heterogeneous and can affect economic output differently across sectors. A sector like transport may have a positive relationship between its economic output and petroleum but negatively impact the effect of coal and electricity on economic output. Thus, deeper analysis is required, not only to implement climate change policies that account for differences across economic sectors but also differences across individual non-renewable energy sources, to give the policymaker a richer in-depth analysis that can ensure that policies are critical of the sector and non-renewable energy type they are implemented in.

Certain literature, such as Ali et al. (2012), Yue and Zhi (2012) and Votteler and Brent (2017b), analysed the implementation and feasibility of renewable energy in certain sectors of the economy like mining and agriculture. However, these studies lack the critical evaluation of how non-renewable energy sources in these sectors affect their economic output and how the move towards implementing renewable energy takes away from the economic gains of non-renewable energy sources. As such, the current study can act as the first point of reference before embarking on a move towards renewable energy in certain sectors. It will be critical to conduct an analysis of such a nature as this study first to establish if the move towards renewable energy in a specific sector is justifiable, depending on the impact of the current non-renewable energy sources on that sector's economic output. Then, if the impact is negative, a move towards renewable energy will be justified.

There is also a lack of such in-depth literature in the South African context, which is currently moving towards a just transition to a low-carbon economy. Focusing on South Africa, the current study's analysis is of utmost importance as the country is currently pushing the just transition agenda and is not fully aware of the implication of this transition on specific economic sectors. South Africa faces significant developmental challenges, such as high levels of unemployment, which have been reported in the second quarter of 2021 to have increased by 1.8% to 34.4% (StatsSA, 2021). The high unemployment rate accompany the high poverty levels, as the South African poverty headcount increased from 53.2% to 55.5% from 2011 to 2015, which is over half of the population (StatsSA, 2017). As such, any move towards a low-carbon economy should be critically analysed to ensure no sector is adversely affected, further exacerbating the country's developmental challenges.

2.3 Theoretical Model

To analyse the interrelations between output growth rate and environmental quality along an economy's balanced-growth path, this study followed the proposed analytical framework by Chambers and Guo (2009), which assumes an economy where social technology exhibits increasing returns-to-scale because of externalities generated by capital inputs and the representative household lives forever while providing a fixed labour supply and deriving utility from consumption goods. The economy has a continuum of identical and competitive firms, with the total number normalised to one. The constant returns-to-scale Cobb-Douglas production function takes the following form:

$$\mathbf{Y}_t = (\mathbf{K}_t)^{\beta}(\mathbf{H}_t)^{1-\beta}(\mathbf{X}_t) \text{ and } \mathbf{0} < \beta < \mathbf{1} \tag{2.1}$$

Where $\mathbf{Y}_t$ is the output produced by each firm, $\mathbf{K}_t$ is the physical capital, $\mathbf{H}_t$ is the utilised/harvested renewable natural resources, and $\mathbf{X}_t$ is the productive externalities taken as given by an individual firm and postulated to take the following form:

$$\mathbf{X}_t = \mathbf{A}\,\mathbf{K}_t^{1-\beta} \text{ and } \mathbf{A} > \mathbf{0} \tag{2.2}$$

Where $\bar{\mathbf{K}}_t$ is the economy-wide average level of capital stock and in a symmetric equilibrium, all firms take the same actions such that $\mathbf{K}_t = \bar{\mathbf{K}}_t$. Therefore, when equation 2.2 is substituted into equation 2.1, the following social production function that shows increasing returns-to-scale is

$$\mathbf{Y}_t = \mathbf{A}(\mathbf{K}_t)(\mathbf{H}_t)^{1-\beta} \tag{2.3}$$

Under the assumption that factor markets are perfectly competitive, the first-order conditions for the firm's profit maximisation problem are given by the following form where $\mathbf{r}_t$ is the capital rental rate, and $\mathbf{p}_t$ is the real price paid to utilised natural resources:

$$\mathbf{r}_t = \beta\,\frac{\mathbf{Yt}}{\mathbf{Kt}} \tag{2.4}$$

$$\mathbf{p}_t = (\mathbf{1} - \beta)\,\frac{\mathbf{Yt}}{\mathbf{Ht}}$$

The economy is also populated by a unit measure of identical infinitely-lived households; each has perfect foresight and maximises a discounted stream of utilities over its lifetime in the following form:

$$\int_0^\infty \frac{1}{1-\sigma} (C_t^{1-\sigma} - 1) (e^{-pt})\, dt \text{ and } \sigma > 0, \sigma \neq 1 \tag{2.5}$$

Where C_t is the individual household's consumption, $p \in (0,1)$ is the subjective discount rate, and σ is the inverse of the intertemporal elasticity of substitution in consumption. The budget constraint faced by the representative household is given by the following form:

$$C_t + \check{K}_t + \delta K_t = r_t K_t + p_t H_t \text{ and } K_0 > 0 \text{ given,} \tag{2.6}$$

Where $\delta \in [0,1]$ is the capital depreciation rate. The law of motion for total renewable resources, which is a proxy for environmental quality N_t, is given by the following form:

$$\grave{N}_t = F(N_t) N_t - H_t \text{ and } N_0 > 0 \text{ given,} \tag{2.7}$$

Where $F(N_t)$ is the regeneration function that is assumed to be strictly increasing in N_t. The rate of natural regeneration is independent of the environmental state, specifically $F(N_t) = \theta > 0$. H_t is the extraction of natural resources and the disposal of waste as both activities decrease the environment's absorption capacity represented by $F(N_t)\, N_t$. The household first-order conditions for the dynamic optimisation problem are as follows: $C_t^{-\sigma} = \lambda_{Kt}$, which states that the marginal benefit of consumption equals its marginal cost, which is the marginal utility of having an additional unit of physical capital; $\lambda_{Kt}(r_t - \delta) = -\lambda_{Kt}' + p\lambda_{Kt}$ and $\theta\lambda_{Nt} = -\lambda_{Nt}' + p\lambda_{Nt}$ are standard euler equations that govern the evolution of K_t and N_t over time; $\lambda_{Kt} p_t = \lambda_{Nt}$ shows that the firm utilises natural resources to the point where the marginal value of more output is equal to the marginal cost of resource depletion; $\lim_{t\to\infty} \lambda_{Kt} K_t\, e^{-pt} = 0$ and $\lim_{t\to\infty} \lambda_{Nt} N_t\, e^{-pt} = 0$ are the transversality conditions; and λ_{Kt} and λ_{Nt} are utility values of capital stock and natural resources, respectively.

Equations 2.3 and 2.5 show that the economy exhibits sustained endogenous growth whereby output, consumption and physical capital all display a common, positive constant growth rate given by g. Equation 2.7 implies that in the long run $(\grave{N}_t = 0)$ total and utilised natural resources will reach their respective steady-state levels, N^* and H^*. This imposes a sustainable long-run environmental quality constraint where a constant level of pollution exactly matches the environment's absorption capacity.

Therefore, a balanced growth path is derived by making $X_t \equiv \frac{Ct}{Kt}$ and re-expressing the model's equilibrium conditions as the following autonomous differential equations:

$$\frac{Xt'}{Xt} = \frac{1}{\sigma}(\boldsymbol{\beta} \mathbf{A}\mathbf{H}_t^{1-\beta} - \boldsymbol{\delta} - \boldsymbol{p}) - \mathbf{A}\mathbf{H}_t^{1-\beta} + \mathbf{X}_t + \boldsymbol{\delta} \tag{2.8}$$

$$\frac{\hat{H}t}{Ht} = \frac{1}{\beta}\,[\mathbf{A}(1-\boldsymbol{\beta})\mathbf{H}_t^{1-\beta} - \mathbf{X}_t + \boldsymbol{\theta}]$$

$$\grave{\mathbf{N}}_t = \boldsymbol{\theta}\mathbf{N}_t - \mathbf{H}_t$$

Given the dynamic system equation 2.8, the balanced-growth equilibrium is characterised by a triplet of positive real numbers **(X*, H*, N*)** that satisfy the condition $\mathbf{X}_t' = \hat{\mathbf{H}}_t = \grave{\mathbf{N}}_t = \mathbf{0}$. The model economy exhibits a unique balanced-growth path along which the utilised natural resource maintains its steady-state level:

$\mathbf{H}^* = [\frac{\sigma\theta - [p-(\sigma-1)\delta]}{\beta A(\sigma-1)}]^{1/(1-\beta)}$ which leads to the expressions for X* and N* as follows:

$$\mathbf{X}^* = \mathbf{A}(1-\boldsymbol{\beta})(\mathbf{H}^*)^{1-\beta} + \boldsymbol{\theta} \text{ and } \mathbf{N}^* = \frac{H^*}{\theta} \tag{2.9}$$

It then follows that the common (positive) rate of economic growth **g** is given by the following form:

$$\mathbf{g} = \boldsymbol{\beta}\mathrm{A}(\mathbf{H}^*)^{1-\beta} - \boldsymbol{\theta} - \boldsymbol{p} \tag{2.10}$$

or

$$\mathbf{g} = \frac{\theta - p}{\sigma - 1} \text{ and } \boldsymbol{\theta} > \boldsymbol{p} \text{ when } \boldsymbol{\sigma} > \mathbf{1}$$

As a result, the balanced-growth path's growth rate ceteris paribus is positively related to the steady-state level of utilised natural resources. As such, an increased usage of services from the environment in production will increase the economy's rate of growth in output, consumption and physical capital. In addition, the quantity of utilised natural resources per unit of GDP steadily declines along the economy's balanced-growth path.

2.3.1 Empirical Model

Given that the balanced growth path's output growth rate rises with productive utilisation of natural resources $\frac{\partial g}{\partial H^*} > \mathbf{0}$ as a result, the empirical analyses is restricted to the output-growth effect of natural resource utilisation. The empirical framework follows a Cobb-Douglas production function. The current study's contribution is that it is conducted at a sectoral level and focuses mainly on non-renewable natural energy sources. The Cobb-Douglas function will take the following form (Cobb & Douglas, 1928):

$$y_{it} = \mathbf{A}\,(\mathbf{K}_{it})^{\beta 1}(\mathbf{L}_{it})^{\beta 2}(\mathbf{P}_{it})^{\beta 3}(\mathbf{E}_{it})^{\beta 4}(\mathbf{C}_{it})^{\beta 5} \qquad \mathbf{(2.11)}$$

Where y denotes the economic output of the sectors, **K** denotes the capital; **L** denotes the labour force; **P** denotes petroleum product consumption; **E** denotes electricity consumption and **C** denotes coal consumption.

The proposed linear panel model specification in this research takes the following equation:

$$y_{it} = \beta_0 + \beta_1 \ln K_{it} + \beta_2 \ln L_{it} + \beta_3 \ln P_{it} + \beta_4 \ln E_{it} + \beta_5 \ln C_{it} + \mu_{it} \qquad \mathbf{(2.12)}$$

With t representing the time frame and **i** representing each sector, the variables are in their natural logarithmic format to avoid the influence of heteroscedasticity on regression results, allowing for convenient percentage/elasticity interpretation and to mitigate problems with outliers.

2.3.2 Data Source and Descriptive Statistics

The data used in this study are derived from the South African Reserve Bank, the South African Department of Energy commodity flow and energy balances[1] (DoE, 2019) and labour data from Statistics South Africa's (StatsSA) Quarterly Labour Force Survey (StatsSA, 2021)). The sectors (**i**) are agriculture, mining, industry, transport and commercial, while the time data from the period (t) is 1992 to 2018. The period was based on the availability of data. The industry sector includes the following subsectors as per the energy balances structure: iron and steel, transport equipment, construction, chemical and petrochemical, non-Ferrous metals, non-metallic minerals, food and tobacco, machinery, paper pulp and print, wood and wood products, textile and leather and non-specified. The commerce sector compromises the financial services, retail, information technology, tourism and service industries.

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[1] The Department of Energy commodity flow and energy balances data has a number of missing data points that could not be accounted for; however, for the purpose of this study, the missing data points were replaced with the last observation carried forward method of imputing missing data in longitudinal studies.

The variables were economic output (y), which is gross value added at basic prices (constant 2010 prices); capital[2] (**K**), which is measured as fixed capital stock at constant 2010 prices; and petroleum (**P**), coal (**C**) and electricity (**E**), which are all measured in a single energy unit (TJ). The labour force (**L**) data were obtained from the South African Reserve Bank (SARB, 2020) (Index 2010 = 100), and for transport and agriculture, the labour data were obtained from StatsSA (StatsSA, 2021).

The descriptive statistics mean, median, maximum, minimum and standard deviations of the logged variables are recorded in Table 2.1. Labour force has the lowest standard deviation, meaning most data points are close to the mean, indicating less variation. Coal has the highest standard deviation, which shows that the data points are spread over a wide range of values, indicating a high variation in coal per sector.

Table 2.1: Descriptive statistics of the variables

	Mean	**Standard deviation**	**Minimum**	**Maximum**
Output	12.57	1.20	10.55	14.84
Capital	13.46	0.69	12.55	14.76
Labour force	4.7	0.62	3.53	5.79
Petroleum	10.66	1.89	4.95	13.74
Electricity	10.96	1.16	6.37	12.81
Coal	9.41	2.44	3.76	13.24

Table 2.2 shows the correlation matrix. Economic output is positively correlated with all variables, except for petroleum, which is negatively related to all variables. The correlation between labour, capital, coal and electricity is positive. However, this is not an indication of causality but rather an indication of a correlation between variables.

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[2] Plant, machinery, vehicles and equipment

Table 2.2: Pairwise correlation matrix

	Output	**Capital**	**Labour force**	**Petroleum**	**Electricity**	**Coal**
Output	1					
Capital	0.5974	1				
Labour force	0.5997	0.0014	1			
Petroleum	-0.2526	-0.2727	-0.3700	1		
Electricity	0.7901	0.3341	0.6418	-0.5060	1	
Coal	0.7833	0.3644	0.7119	-0.4360	0.7556	1

Figure A.1 (Appendix A) shows a graphical representation of the logged variables per sector, with the labour variable being on the secondary axis. As seen in the first frame, electricity and coal are highly consumed energy sources in the industry sector, while petroleum has been consumed less. Capital consumption has moderately increased over time, while consumption of labour force within the industry sector decreased sharply from 1996 to 2003 and then increased until 2008 before decreasing again for the remaining periods due to the financial crisis and large retrenchments in industry subsectors such as construction.

Figure A.2 (Appendix A) graphical represents the commercial sector. Electricity is a highly consumed energy source, while coal consumption has been decreasing in recent years. Petroleum products have low consumption during the study period. Capital consumption has moderately increased over time, while labour force consumption has increased at a higher rate than all other factors within the sector since 1992.

A graphical representation of the transport sector is shown in Figure A.3 (Appendix A). Petroleum product is the most significantly consumed energy source, while electricity consumption has decreased slightly in recent times. Coal has had periods of high consumption, but in recent years, consumption has been on a decline, except in 2018, when a spike can be observed. Capital has been increasing over time, while the consumption of the labour force within the transport sector has increased at a higher rate than all other factors of production within the sector since 1992.

The fourth frame (Figure A.4, Appendix A) shows the graphical representation of the agricultural sector. Petroleum product is a highly consumed energy source, as is electricity. Coal consumption has gradually decreased over time but has increased in recent years. Capital consumption has been increasing over time, while the labour force has been sharply declining since 2008, mainly due to the financial crisis, but has been increasing since 2011.

The last frame (Figure A.5, Appendix A) represents the mining sector. Electricity is a highly consumed energy source, while coal has been decreasing in recent years. Petroleum product has also been increasing over time and is now consumed more than coal. Capital consumption has been increasing over time while labour force consumption decreased from 1992 until 2003 before gradually increasing from 2004 while experiencing brief periods of decline through the remaining period. Output has gradually increased for all sectors except mining, which has seen a constant trend.

2.4 Econometric Method

The stated empirical model was estimated using a linear panel model specification. Firstly, unit root tests were conducted as they are essential in determining whether the variables are non-stationary and possess a unit root. The Im, Pesaran and Shin (IPS) test (Im et al., 2003) was the unit root test used in the current study. The IPS test allows for a heterogeneous coefficient on the dependent variable **(y_i, t-1)** and provides a testing approach whereby individual Augmented Dickey-Fuller (ADF) unit root test statistics are averaged. The null hypothesis is that there is a unit root in all series within the panel, whereas the alternative hypothesis is that not all the series within the panel have unit roots. The model runs separate ADF regressions for each cross-section of the form:

$$\Delta y_{it} = \Phi\, y_{i,t-1} + Z_{it}` \gamma_{it} + \varepsilon_{it} \qquad \textbf{(2.13)}$$

Where Φ is panel-specific indexed by **i**. The IPS test assumes that ε_{it} is independently normally distributed for all **i** and **t**, and they allow ε_{it} to have heterogeneous variances σ^2_i across panels. The $Z_{it}` \gamma_{it}$ term can represent panel-specific means.

For robustness purposes, the Levin, Lin and Chu (LLC) test (Levin et al., 2002) and the Breitung (2000) regression model were conducted to confirm the univariate properties of the variables. The LLC regression model is as follows:

$$\Delta y_{it} = \Phi\, y_{i,t-1} + Z_{it}` \gamma_{it} + \sum_{j=1}^{P} \Delta\, y_{i,t-j}\, \theta_{ij} + \mu_{it} \qquad \textbf{(2.14)}$$

Where $\mathbf{p}$ is the number of lags and $\boldsymbol{\mu}_{it}$ is white noise with potentially heterogeneous variance across panels. The Breitung regression model is as follows:

$$\mathbf{y}_{it} = \mathbf{Z}_{it}' \gamma_i + \mathbf{X}_{it} \tag{2.15}$$

Where $\mathbf{X}_{it} = \alpha_1 \mathbf{X}_{i,t-1} + \alpha_2 \mathbf{X}_{i,t-2} + \varepsilon_{it}$ where ε_{it} is an error term. If the results show that the variables are indeed stationary, a pooled panel linear specification was estimated; however, if the results show that the variables contain a unit root, the Kao Engle and Granger test for co-integration (Kao, 1999) was conducted. Co-integration implies that the variables are linked and move together over time to form an equilibrium relationship, which spans the long run even if there are stable non-stationary differences between them. The Kao Engle and Granger (Kao, 1999) test is an application of the ADF test for stationarity on the residual of the co-integration equation. The null hypothesis is that of no co-integration and the alternative hypothesis is that of co-integration. The regression model is:

$\mathbf{y}_{it} = \gamma_i + \mathbf{X}_{it}' \boldsymbol{\beta} + \varepsilon_{it}$ and it is assumed the same cointegrating vectors $\boldsymbol{\beta}_i = \boldsymbol{\beta}$ so that all panels share a common slope coefficient. $\boldsymbol{\Gamma}_i$ denotes panel-specific fixed effects, and $\boldsymbol{\beta}$ is the same cointegrating vector. If the results from the Kao Engle and Granger test (Kao, 1999) conclude that there is indeed co-integration amongst the variables, the Hausman test was conducted to identify which baseline estimations between pooled, fixed and random effects are preferred for the estimation.

The idea behind the Hausman test is to compare one estimate that is consistent under the null and alternative hypothesis with another estimate that is only consistent under the null hypothesis. The difference between the two was measured and a large difference leads to rejecting the null hypothesis. The null hypothesis for the Hausman test implies the exogeneity of the regressors (no misspecification), while the alternative hypothesis implies the endogeneity of regressors. Based on the Hausman test results, either random, fixed effects or pooled estimations were used to estimate the linear panel model specification.

As some reviewed literature has established causation from output growth to energy use with no evidence of feedback, a Granger causality test for panel data was conducted on the energy sources and sectoral output. The Dumitrescu–Hurlin test was used to detect causality in panel data. The underlying regression is:

$$\mathbf{y}_{i,t} = \alpha_i + \sum_{K=1}^{K} \gamma_{\,Ik}\; \mathbf{y}_{i,t-k} + I_{ik}\, \mathbf{X}_{i,\,t-k} + \varepsilon_{i,t} \tag{2.16}$$

Where $i = 1,\ldots,N$ and $t = 1,\ldots,T$ where $X_{i,t}$ and $y_{i,t}$ are the observations of two stationary variables for individual i in period t. Coefficients are allowed to differ across individuals but are assumed to be time-invariant. The lag order K is assumed to be identical for all individuals, and the panel must be balanced.

As South African economic sectors are interconnected, panel analysis ought to take into consideration issues of panel heterogeneity and cross-sectional dependency. Shocks originating in one sector may spill over onto another because of the high degree of economic integration, possibly resulting in misspecifications. A cross-sectional dependence test was conducted in the pooled, fixed or random effects model to determine whether the cross sections are independent. Friedman's test statistic (Friedman, 1937), the statistic proposed by Frees (Frees, 1995) and the cross-sectional independence test of Pesaran (Pesaran, 2004) were conducted to determine the independence of the cross sections.

As the focus of this research was to determine the impact of the independent variables on economic output in specific sectors, Swamy's Random Coefficients (Swamy, 1970) was used, in addition to fixed or random effects, as they provide cross-sectional specific slope parameters and as such provided each sector with its linear panel specification. Swamy's Random Coefficients control for slope heterogeneity by allowing each panel to have its vector of slopes randomly drawn from a distribution familiar to all panels. The slope parameters reported are a weighted average of the panel-specific ordinary least squares estimates. Swamy (1970) considers a random coefficients model of the form:

$$y_i = X_i \beta_i + \varepsilon_i \qquad \textbf{(2.17)}$$

Where $i=1\ldots P$ denotes panels, y_i is a $T_i \times 1$ vector of observations for the i th panel, X_i is a $T_i \times K$ matrix of non-stochastic covariates, and β_i is a $k \times 1$ vector of parameters specific to panel i. The error term vector ε_i is distributed with mean zero and variance $\sigma_{ii}I$. The panels do not need to be balanced and each panel-specific β_i is related to an underlying common parameter vector β: $\beta_i = \beta + v_i$ where $E\{ v_i \} = 0$.

2.5 Empirical Results

2.5.1 Unit Root Resting

As stated in the methodology, tests for the univariate characteristics of the variables were conducted, and Table A.1 (Appendix A) shows the results of the IPS and LLC test and the Breitung regression model for stationarity. For output, capital and labour force, all tests fail to reject the null hypothesis at the 5% significance level, concluding that all panels contain unit roots. For petroleum and coal, we fail to reject the null hypothesis at the 5% significance level, concluding that the panels contain unit roots for two of the three tests. For electricity, we reject the null hypothesis at the 5% significance level, concluding that the panel is stationary for two of the three tests. Based on these results, we can conclude that the variables are non-stationary and proceed to conduct the co-integration test.

2.5.2 Co-integration and Hausman Test

Table A.2 (Appendix A) shows the results obtained from the Kao Engle and Granger co-integration test, where output was the dependent variable, while capital, labour force, petroleum, electricity and coal were the independent variables. There is evidence of a co-integrated relationship at the 5% significance level, with test statistic = -3.009 (p-value = 0.0013).

As stated in the methodology, the Hausman (1978) test was conducted to identify if either random or fixed effects are preferred for the estimation. Table A.2 (Appendix A) shows the results from this test; the chi-squared test statistic with five degrees of freedom is -63.78, with a p-value of 0.000. Therefore, we reject the null hypothesis of exogeneity at the 1% significance level, indicating the presence of misspecification due to endogeneity. It was concluded that fixed effects estimation is preferred; therefore, the linear panel model specification was estimated using fixed effects estimators.

2.5.3 Baseline Estimations: Fixed and Random Effects

Baseline estimations inform prior expectations on an aggregate level and provide a form of robustness when comparing them to the actual sector-specific results, which are the crux of this study. In panel data, fixed effects regression is an estimation approach that allows for controlling time-invariant unobserved individual characteristics that may correlate with the observed independent variables. From Table 2.3, the results of the fixed effects within regression show that the coefficients of pooled variables for capital, electricity and coal are significant at the 5% significance level, while the coefficients of pooled variables for petroleum and labour force are insignificant at the 10% significance level. All coefficients are positive except for the intercept. The F-test results, testing the null hypothesis of no individual effects against the alternative hypothesis of individual effects, show that we reject the null hypothesis that all individual effects are not significantly different from zero; therefore, fixed effects are valid. We must control for sector heterogeneity and should, therefore, not pool the intercepts.

The rationale behind the random effects model, as opposed to the fixed effects model, is that it assumes the differences amongst sectors to be random and uncorrelated with the independent variables included in the model. This means that the assumption made in random effects is that the sector’s error terms are uncorrelated with the predictors, as such time-invariant variables are allowed to play a part as explanatory variables and random effects will be preferred if it is believed that variations across sectors have an impact on the dependent variable. The random effects model results are all statistically significant at the 5% significant level. The random effects model is valid. However, from Table 2.3, it was concluded that fixed effects estimation is preferred. As a result, the linear panel model specification was estimated using fixed effects estimators.

Table 2.3: Estimation results

Dependent variable	Fixed effects	Random effects
Capital	1.13	0.78
	(9.73)***	(12.06)***
Labour force	0.14	0.51
	(1.31)	(5.22)***
Petroleum	0.02	0.19
	(1.18)	(8.12)***
Electricity	0.23	0.48
	(5.23)***	(9.06)***
Coal	0.04	0.11
	(3.30)***	(3.87)***
Intercept	-6.39	-8.6
	(-4.33)***	(-7.75)***
F-test	193.56***	1158.63***
Adjusted R-squared	0.6781	0.9416

T-statistics of coefficients in brackets (); [***] denote 1% levels of statistical significance

2.5.4 Granger Causality Test

Granger causality was developed by Granger (1969) who developed a methodology for analysing the causal relationship between time series. Dumitrescu and Hurlin (2012) provide an extension designed to detect causality in panel data. The null hypothesis is the absence of causality for all individuals in the panel, and the alternative hypothesis is that there can be causality for some individuals but not necessarily for all. The Dumitrescu and Hurlin (2012) Granger non-causality test results show that sectoral output Granger-causes all variables (Appendix A, Table A.3.1). The results further show that all variables Granger-causes sectoral output except for coal, which fails to reject the null hypothesis at the 5% significance level (Appendix A, Table A.3.2). This gives insight into the possibility of reducing coal dependence without having adverse impacts on sectoral economic growth.

2.5.5 Cross-section Dependence Test

A nonparametric test based on the correlation coefficient of Spearman's rank, calculated from ranks and regarded as a regular product moment, with regards to the proportion of variability that is accounted for, was developed by Friedman (1937). Frees (1995) developed a statistic based on the sum of the squared rank correlation coefficients. The null hypothesis for these two tests and the cross-sectional independence test of Pesaran (2004) is cross-sectional independence. Table 2.4 shows that both the Frees and Friedman tests reject the null hypothesis and conclude cross-sectional dependence at the 10% significance level. The Pesaran test fails to reject the null hypothesis at the 10% significance level.

Table 2.4: Cross-section dependence test results

Variables	Test statistic		
	Pesaran	Frees	Friedman
Labour force	0.917	1.997*	30.17***
Petroleum			
Electricity			
Coal			
Capital			
Conclusion	No cross-sectional independence	Cross-sectional dependence	Cross-sectional dependence

*[***] denote 10%,1% levels of statistical significance, respectively

2.5.6 Swamy Random Coefficient Regression

As stated in the methodology, Swamy's Random Coefficients control for slope heterogeneity; as such, they were used to determine cross-sectional specific slope parameters (Table 2.5).

Table 2.5: Swamy Random Coefficient regression results

Swamy Random Coefficients						
Variables	Overall model	Sector-specific coefficients				
		Industry	Transport	Mining	Agriculture	Commercial
Capital	0.684*	1.906***	0.519***	0.102	0.779***	0.367***
	(1.94)	(8.10)	(20.35)	(1.25)	(6.51)	(4.17)
Labour force	-0.045	-0.938***	0.741***	-0.057	-0.56***	0.068
	(-0.11)	(-3.04)	(6.21)	(-0.46)	(-4.22)	(0.26)
Petroleum	0.041**	0.012	0.091***	0.014	0.06***	0.026
	(2.00)	(0.99)	(8.44)	(0.94)	(3.16)	(1.37)
Electricity	0.386*	-0.109	0.093***	0.979***	0.37***	0.611***
	(1.91)	(-0.94)	(4.30)	(7.99)	(0.82)	(3.96)
Coal	-0.063	-0.285***	0.020*	0.012	-0.053***	-0.016***
	(-1.08)	(-7.25)	(1.81)	(1.24)	(-3.39)	(-1.13)
Chi-square	4040.33 ***					
Wald chi-square	2433.41 ***					

Z-statistics of coefficients in brackets ().*(**)[***] denote 10%, 5%, 1% levels of statistical significance, respectively

The results in Table 2.5 are split into two groups, firstly, the overall Swamy Random Coefficients for the variables and secondly, the sector-specific Swamy Random Coefficients for the variables in each sector. The overall regression model results show that capital, petroleum and electricity are all positive and statistically significant at the 10% significance level. The coefficients for all other variables are statistically insignificant at the 5% significance level. This does not mean the effects being tested for these variables do not exist, but rather, the data that was observed (which, as already discussed, has missing data points that were imputed using the last observation carried forward method) does not furnish strong evidence for the existence of that effect.

The test for parameter constancy was conducted to test whether the panel-specific parameters are significantly different from each other, and the results ($\mathcal{X}^2$ = 4040.33 and p-value = 0.000) lead us to reject the null hypothesis and conclude that the parameters are not constant across different cross sections and analysing them separately (in system context) is justified. Regarding the sector-specific Swamy Random Coefficients, the analysis has shown that labour is the most contributing factor of production in the transport sector, while the coefficients are statistically insignificant in two sectors and negative in the other two. This shows that South Africa’s economy is still labour-intensive, and this result is consistent with Bhorat et al. (2016), who analysed human capital’s positive impact on economic growth in South Africa. However, the negative coefficients in the industry and agriculture sectors can be explained by the decreasing demand for labour in both sectors. In the industry sector, the construction subsector has had significant retrenchments due to construction firms facing financial losses as there is limited infrastructure investment in South Africa. The increased use of advanced machinery has also decreased the demand for workers in agriculture as machinery is more efficient than manual labour.

On the other hand, coal is the least contributing factor to production for most of the sectors, as the coefficients are statistically insignificant in one sector, negative in three sectors and only positive in the transport sector. These results are consistent with studies such as Jin and Kim (2018) and Odhiambo (2016), who concluded that economic growth Granger-causes coal consumption and not vice versa in South Africa. These results were also consistent with the Granger causality test performed in this study. In most of the sectors, coal use has gradually decreased as South Africa continues to develop its renewable energy sector. This implies that coal usage could be reduced in South Africa, without having to necessarily compromise economic growth.

Petroleum has a positive and statistically significant coefficient for the transport and agriculture sectors; however, coefficients for the other three sectors are insignificant. These results are expected as petroleum is highly consumed in both the transport and agriculture sectors. On the other hand, as per prior expectations, capital is positive and statistically significant for all sectors, except for mining, where the coefficient is surprisingly and unexpectedly statistically insignificant. Regarding the positive effect of capital on most sector’s economic output, the results of the current study are consistent with other studies, such as Coetzee and Kleynhans (2017) and Feddersen (2017), which similarly identified the positive effect of capital on South Africa’s economic growth.

Electricity is a major contributing factor to production in most sectors, with coefficients being statistically significant and positive (except for industry, which is possibly negatively affected by loadshedding and increased electricity prices). This result is encouraging as Yue and Zhi (2012) concluded that electricity usage within sectors can be realistically substituted for renewable energy. These results are consistent with those of Odhiambo (2009), who concluded that economic growth and electricity consumption in South Africa have a distinct bidirectional causality and that employment in South Africa Granger-causes economic growth. These sector-level results have given insight into the possibility of shifting electricity production from coal to renewables, as coal negatively impacts most of the economic sectors analysed.

The mining sector has seen certain unexpected results, which can be explained by StatsSA's (2016) report that highlighted the decline in platinum, iron ore, gold and coal production within the mining industry in 2015. This has decreased the overall production and resulted in multiple job losses within the sector; as such, an increase in certain factors of production will seem to have an adverse or insignificant impact on the declining overall economic output within the sector, which will seem to justify the results in Table 2.5.

It is clear from the results that economic sectors and dirty energy sources are heterogeneous. The effects of the different non-renewable energy sources are different, depending on each economic sector of the South African economy. The same can also be said about the differences in the type of dirty energy sources, as even within a sector, the impact of non-renewable energy sources is different on economic growth. These findings provide new insight into how implementing climate change mitigation policies should be tailor-made per sector and per non-renewable energy sources, not just in South Africa but globally. For example, petroleum positively impacts the transport and agricultural sectors; however, it has less impact on all the other sectors. This means that a carbon tax on motor vehicle emissions will adversely impact economic output in the transport and agricultural sectors. On the contrary, carbon tax on motor vehicle emissions will have either no impact or a positive impact on economic output in the commercial, mining and industry sectors. As such, a climate change mitigation policy of this nature should only be implemented in the sectors that will benefit from its implementation (commercial, mining and industry sectors) and not in sectors that will be harmed by it (transport and agricultural sectors).

Also, the results indicate that moving away from dirty energy sources to clean energy sources in certain sectors can harm their economic output. Therefore, an analysis of this nature is required before the transition to a low-carbon sector can be implemented, as in a country like South Africa, which faces many developmental challenges, moving from non-renewable energy sources that contribute to the economic growth in that sector to renewable energy sources that hinder economic growth in these sectors will have disastrous effects on country's developmental goals. As such, policymakers must identify sectors that rely on non-renewable energy sources for economic output and only implement renewable energy sources in sectors that do not rely on dirty technologies for economic output growth.

2.6 Conclusion and Recommendation

The primary purpose of this research was to determine the impact of using non-renewable energy sources on selected sectors' (industry, mining, agriculture, transport and commercial) economic output in South Africa. This allows us to determine the sectors that rely more on non-renewable energy sources and whether these sectors can potentially substitute these non-renewable energy sources for cleaner technologies without compromising output. To do so, this study quantitatively determined the impact of petroleum products, coal, electricity, labour and capital on economic output in a panel data regression framework, including the five sectors from 1992 to 2018.

Results of the panel regression showed that labour is the most contributing factor to production in the transport and commercial sectors and the least contributing factor to production in industry and agriculture, largely due to major job losses in these sectors. Capital is positive and statistically significant for all sectors except mining, where the coefficient is surprisingly and unexpectedly statistically insignificant. This result can be explained by the decline in mining production (platinum, iron ore, gold and coal) and multiple job losses within the sector.

Coal is the least contributing factor to production for most sectors, as the coefficients are statistically insignificant in one sector (mining) and negative in the three sectors (industry, agriculture and commercial), while positive in the transport sector. This can be explained by the excessive and inefficient coal usage within those sectors. This also implies that coal usage could be reduced in South Africa without compromising economic growth. Petroleum has a positive and statistically significant coefficient for transport and agriculture; however, positive coefficients for the other three sectors are insignificant. Electricity is a major contributing factor to production amongst some sectors, with coefficients being statistically significant and positive except for the industry sector, which has a surprisingly negative insignificant coefficient but can be explained by the rising cost of electricity and loadshedding, which harms economic growth.

The findings indicate the impact each non-renewable energy source has on the economic output of each sector. This allows us to determine which sectors' economic output will be negatively or positively affected by the implementation or substitution of dirty energy sources for cleaner renewable energy sources and the impact of the implementation of climate change policies on different sectors. It is evident that capital is a major contributing factor to production for most sectors, showing that South African's economy is still capital intensive. Labour is a major contributing factor to production in only the transport sector and with the increasing unemployment rate within the country, it will be advantageous for policymakers to implement measures to increase labour employment and capital within most sectors, possibly increasing the country's economic output.

It is evident that electricity is a major contributing factor to production, which is expected in South Africa's electricity-intensive economy. The country is already proposing a gradual decrease in coal-generated electricity supply and an increase in the capacity of electricity generated from solar PV and wind energy, as per the most recently accepted IRP by the Department of Minerals and Energy (StatsSA, 2018a). As electricity is a major contributing factor to production, electricity from renewable sources will positively impact many sectors. Coal and petroleum products also impact economic growth differently depending on the sector in which they are consumed.

This study recommends that policymakers should make use of sector-specific climate change policies. As evident from the current study's results, each sector consumes non-renewable energy sources differently; as such, each experiences different impacts of dirty energy sources on economic growth. The current economic studies on the impact of dirty energy sources on economic growth have been on an aggregate national level, which is misleading as it could motivate policymakers to apply the same climate change mitigation policies across all economic sectors in the country without first determining the impact of these policies on a disaggregated sector level. This study recommends that policymakers should first make use of the current study's analysis to identify which sectors will benefit from climate change mitigation and a move to renewable energy sources without compromising economic output and which sectors rely on non-renewable energy sources for economic growth, then, only implement such policies in sectors that will benefit from them.

The study also analysed the heterogeneity between non-renewable energy sources that affect economic output differently within a sector, providing more in-depth insight. Policymakers should also analyse the dirty energy sources and only apply greenhouse gas emissions policies to non-renewable energy sources that adversely impact economic growth. For example, in agriculture, the study showed that coal usage negatively impacts economic output, while petroleum products have a positive impact on economic output. Therefore, the consumption of coal could hinder economic output in agriculture, but the consumption of petroleum fosters economic growth in the sector. Consequently, climate change policies should be non-renewable energy type-specific, and policymakers should follow this analysis to inform their approach.

Overall, transitioning to a low-carbon economy globally is a positive initiative that has been heavily promoted worldwide because of the positive impact of clean energy sources on the environment and human capital. However, for developing countries such as South Africa, it is equally important to determine if retiring dirty energy sources will adversely impact economic growth and, subsequently, the country's developmental goals. Non-renewable energy sources that foster economic growth in certain sectors should not be abandoned but encouraged in those sectors to continue the push for economic growth. On the other hand, dirty energy sources, which do not contribute to economic growth in other sectors, should be abandoned as the move towards renewable energy sources or implementing climate change policies will foster growth in these sectors.

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Appendix A

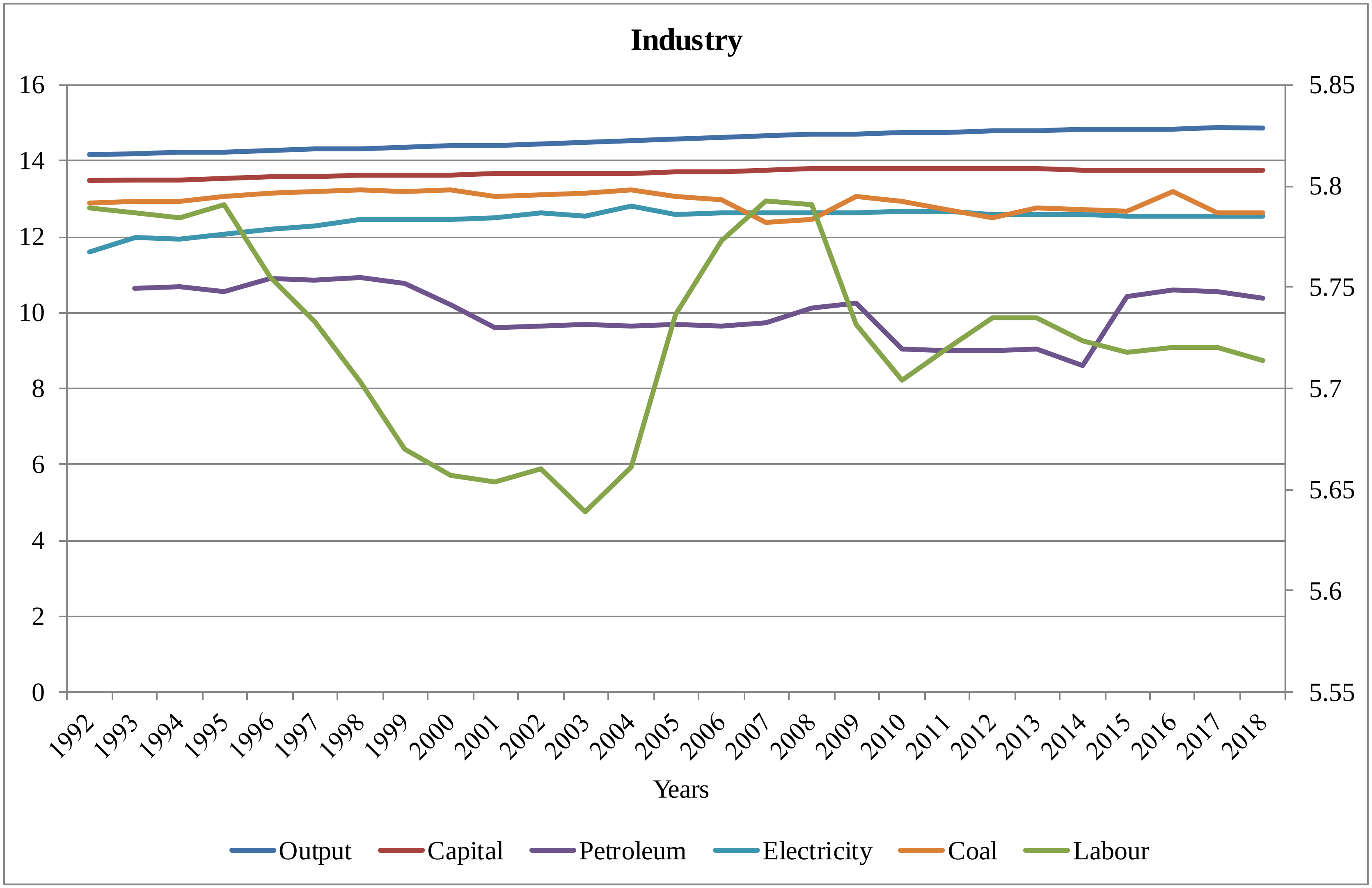

Figure A.1: Graphical representation of logged variables for the industry sector from 1992 to 2018

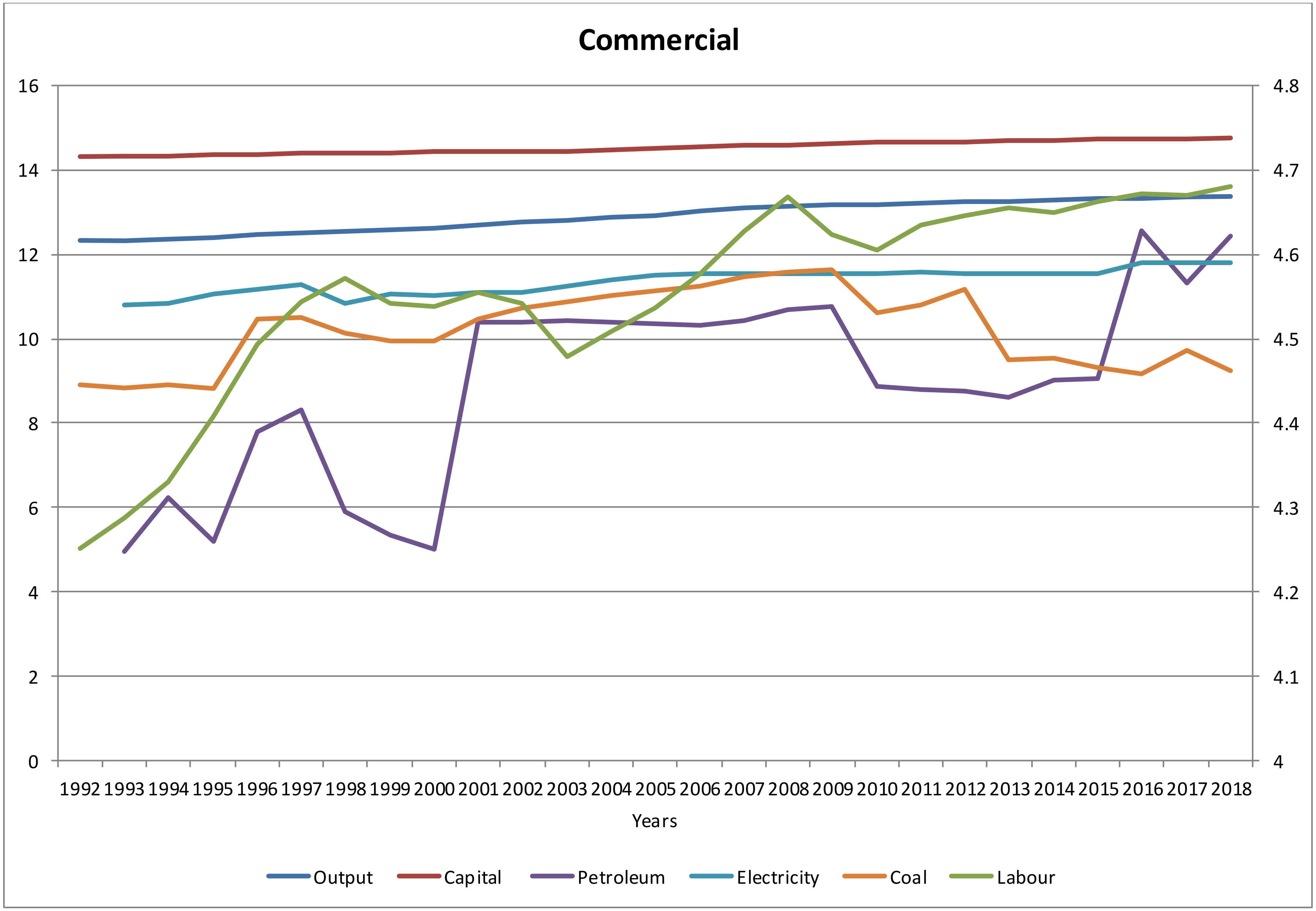

Figure A.2: Graphical representation of logged variables for the commercial sector from 1992 to 2018

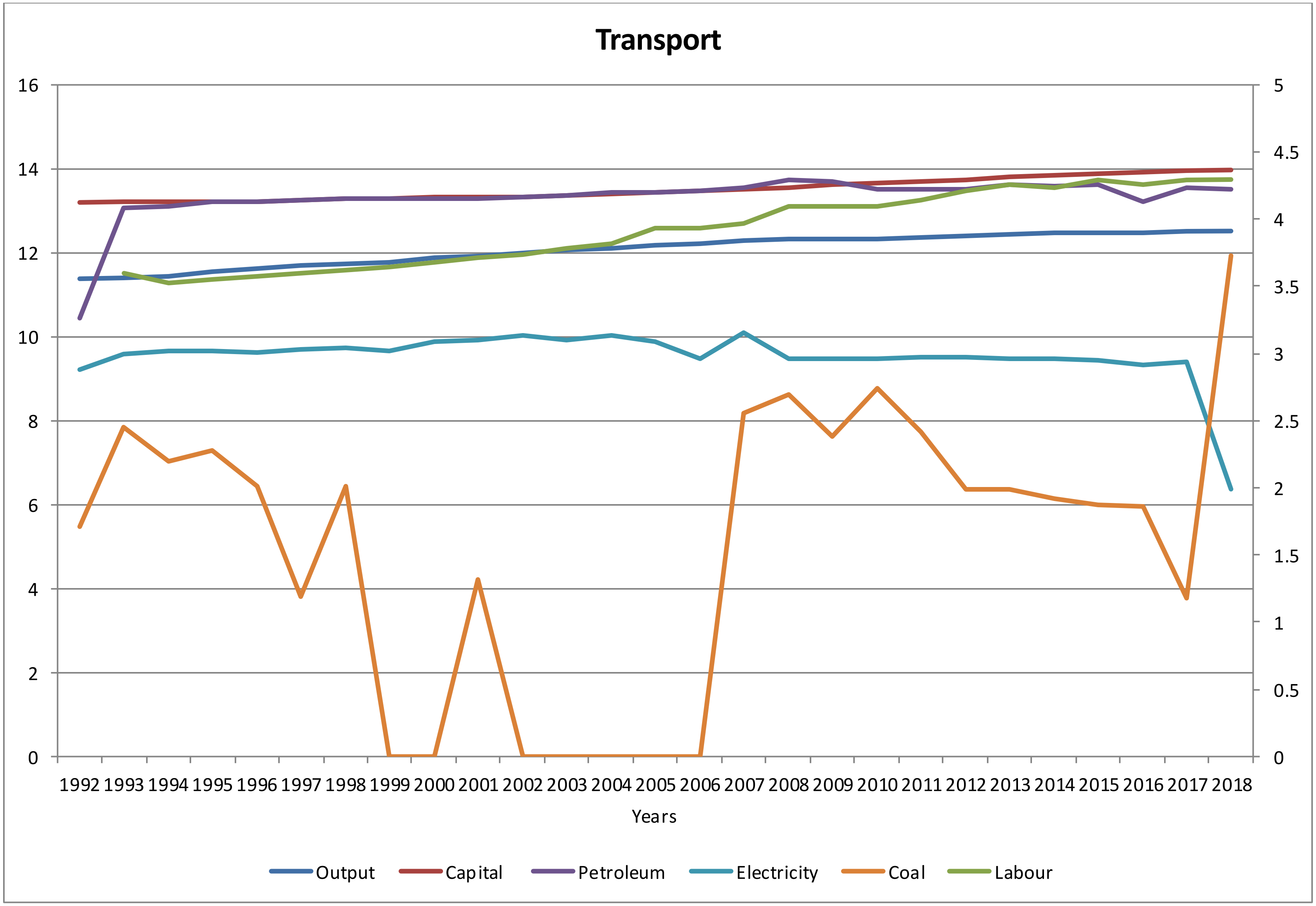

Figure A.3: Graphical representation of logged variables for the transport sector from 1992 to 2018

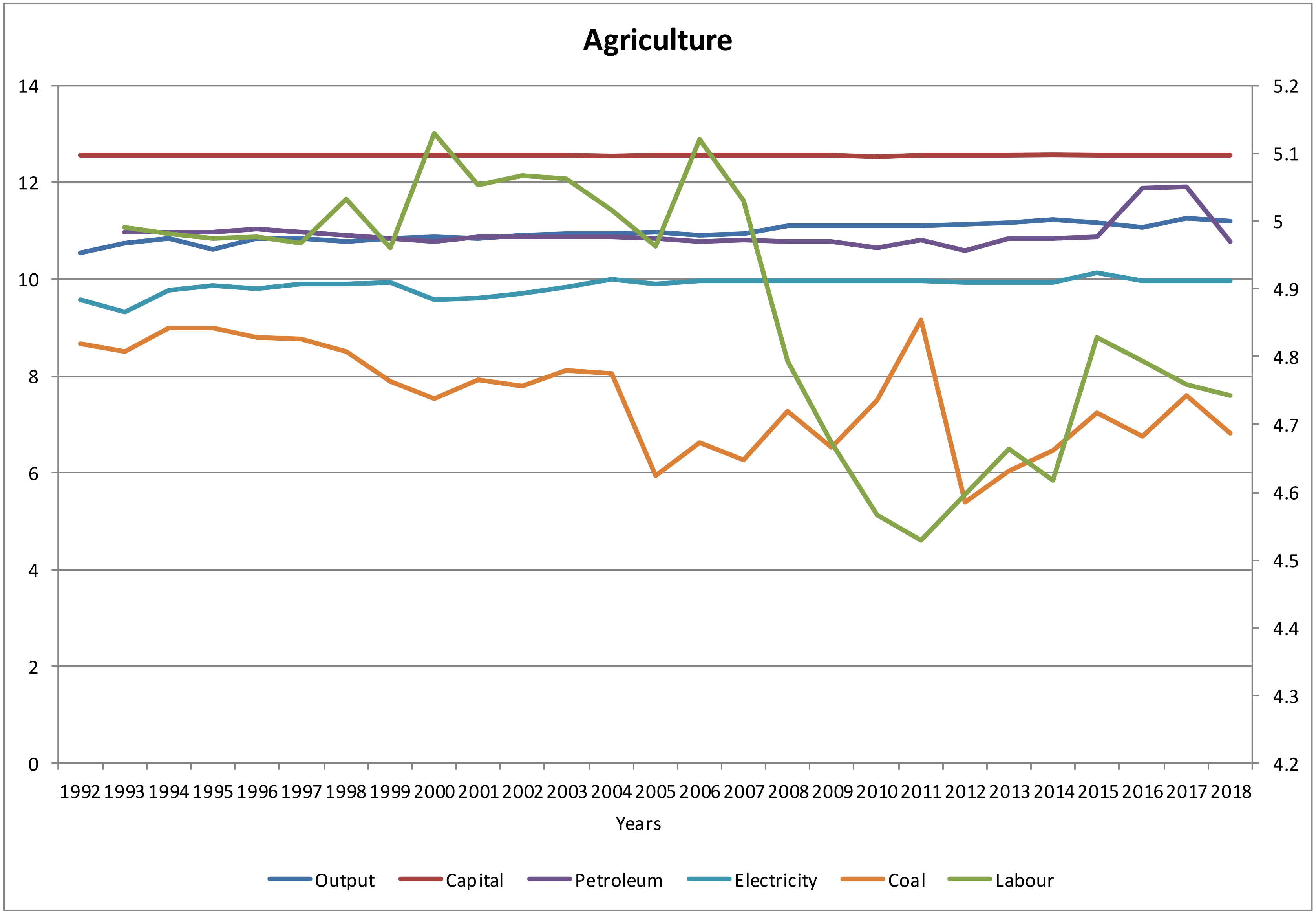

Figure A.4: Graphical representation of logged variables for the agricultural sector from 1992 to 2018

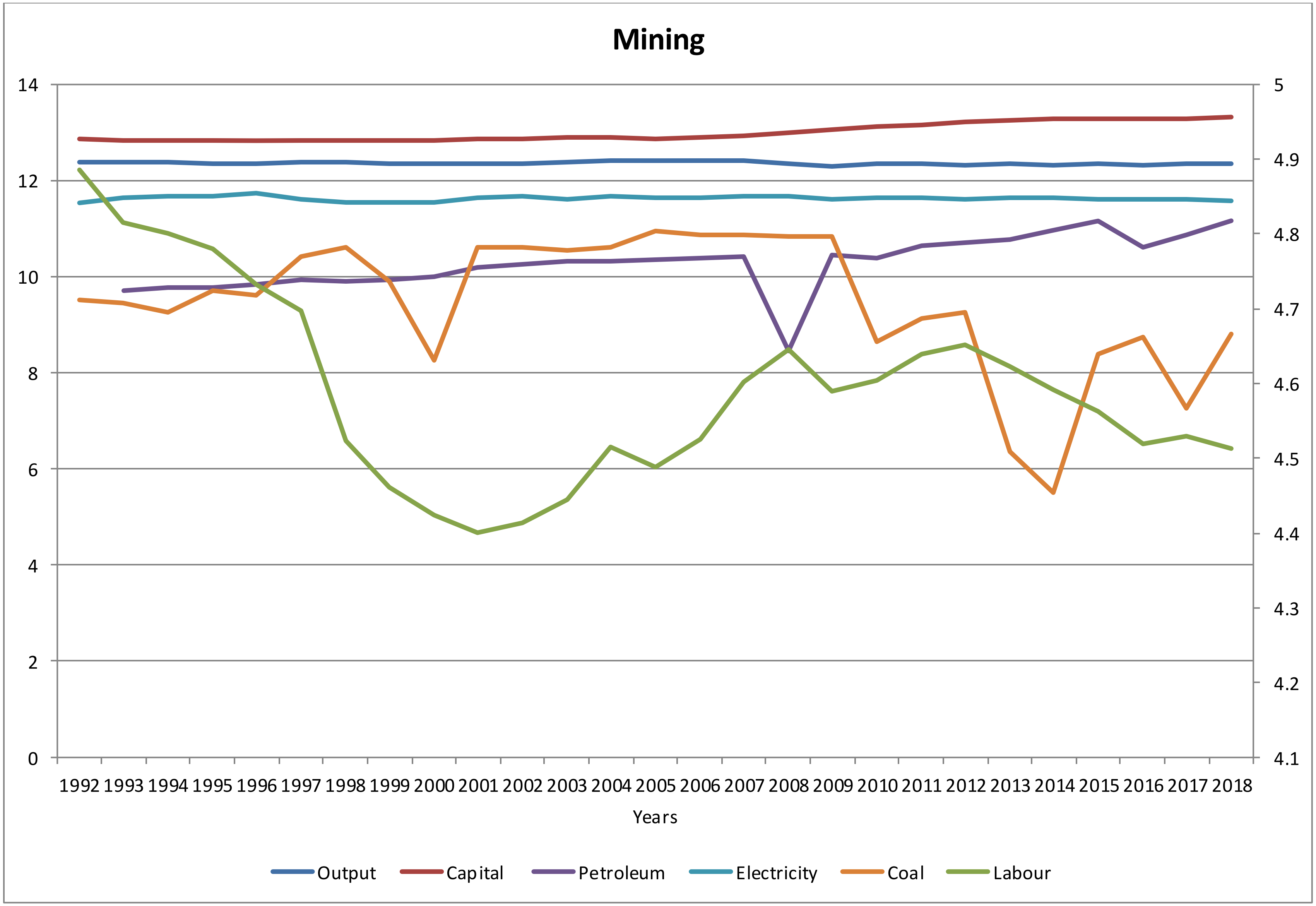

Figure A.5: Graphical representation of logged variables for the mining sector from 1992 to 2018

Table A.1: Unit root tests results

Variable	Method	Statistic	p-value	Conclusion
Output	IPS	1.289*	0.901	Non-stationary
	LLC	-1.600*	0.054	Non-stationary
	Breitung	5.982	1	Non-stationary
Capital	IPS	5.646	1	Non-stationary
	LLC	-0.677*	0.249	Non-stationary
	Breitung	6.167	1	Non-stationary
Labour force	IPS	-0.106*	0.458	Non-stationary
	LLC	-0.64*	0.261	Non-stationary
	Breitung	2.01*	0.978	Non-stationary
Petroleum	IPS	-2.41**	0.008	Stationary
	LLC	-1.014*	0.155	Non-stationary
	Breitung	-0.979*	0.164	Non-stationary
Electricity	IPS	-1.828**	0.034	Stationary
	LLC	-1.906**	0.028	Stationary
	Breitung	-0.116*	0.454	Non-stationary
Coal	IPS	-1.190*	0.117	Non-stationary
	LLC	0.245*	0.597	Non-stationary
	Breitung	-2.957**	0.001	Stationary

Null hypothesis is non-stationarity; IPS: Im, Pesaran and Shin; LLC: Levin, Lin and Chu; *(**)[***] denote 10%, 5%, 1% levels of statistical significance, respectively

Table A.2: Kao Engle and Granger's test and Hausman test results

Kao Engle and Granger's test	Test statistics		
Variables			
Dependent: Output Independent: Capital, Labour force, Petroleum, Electricity, Coal	-3.009***		
Hausman test results			
Variables	Degrees of freedom	Test statistics	Conclusion
Capital, Labour force, Petroleum, Electricity, Coal	5	-63.78***	Fixed effects

[***] denotes 1% level of statistical significance

Table A.3.1: Granger non-causality test (Causality from sectoral output to variables)

Variables	Wald statistics	p-value	Conclusion
Capital	W-bar = 11.3542		Sectoral output does Granger-cause capital for at least one panel
	Z-bar = 16.3714	0.0000	
	Z-bar tilde = 13.7635	0.0000	
Labour	W-bar = 4.0579		Sectoral output does Granger-cause labour for at least one panel
	Z-bar = 4.8350	0.0000	
	Z-bar tilde = 3.9748	0.0001	
Petroleum	W-bar = 7.6426		Sectoral output does Granger-cause petroleum for at least one panel
	Z-bar = 10.5029	0.0000	
	Z-bar tilde = 8.7840	0.0000	
Electricity	W-bar = 3.5699		Sectoral output does Granger-cause electricity for at least one panel
	Z-bar = 4.0633	0.0000	
	Z-bar tilde = 3.3200	0.0009	
Coal	W-bar = 4.0453		Sectoral output does Granger-cause coal for at least one panel
	Z-bar = 4.8150	0.0000	
	Z-bar tilde = 3.9578	0.0001	

Table A.3.2: Granger non-causality test (Causality from variables to sectoral output)

Variables	Wald statistics	p-value	Conclusion
Capital	W-bar = 4.1841 Z-bar = 5.0345 Z-bar tilde = 4.1440	 0.0000 0.0000	Capital does Granger-cause sectoral output for at least one panel
Labour	W-bar = 4.0732 Z-bar = 4.8591 Z-bar tilde = 3.9953	 0.0000 0.0001	Labour does Granger-cause sectoral output for at least one panel
Petroleum	W-bar = 3.1604 Z-bar = 3.4160 Z-bar tilde = 2.7707	 0.0006 0.0056	Petroleum does Granger-cause sectoral output for at least one panel
Electricity	W-bar = 3.6465 Z-bar = 4.1845 Z-bar tilde = 3.4229	 0.0000 0.0006	Electricity does Granger-cause sectoral output for at least one panel
Coal	W-bar = 2.3517 Z-bar = 2.1372 Z-bar tilde = 1.6857	 0.0326 0.0919	Coal does not Granger-cause sectoral output

3 Chapter Three: The Effects of Renewable Energy Consumption on Economic Welfare

Abstract

This study determined the pass-through effect and the response of consumer prices to renewable energy share increases while using the exchange rate as a threshold in South Africa. To determine this effect and response, the study used a two-regime multivariate threshold vector auto-regression model. Results show that with an exchange rate threshold value of 7.7 R/$, the share of renewable energy pass-through to consumer prices is statistically significant below and above the threshold exchange rate value. However, when the exchange rate is above the threshold value, the pass-through effect is negative, indicating that an increase in the share of renewable energy will decrease consumer prices. When the exchange rate is below the threshold value, the pass-through effect is positive, indicating that an increase in the share of clean energy will increase consumer prices. These results are largely attributed to the cost of renewable energy, which has been declining significantly in periods where the exchange rate was above the threshold value and as a result, it had a negative pass-through effect on consumer prices. As South Africa is transitioning to a low-carbon economy, this analysis encourages policymakers to implement the use of clean energy further to take advantage of their decreasing cost, which can be pass-through to consumers and improve their economic welfare.

Keywords: Renewable Energy, Threshold Vector Auto-regression, Consumer Prices, Exchange Rate, Share of Renewable Energy Pass-through

JEL codes: C24, D61, Q20

3.1 Introduction

The negative impact that climate change has imposed on the environment is a major concern in the modern world. The International Energy Agency Global Energy Review reported that in 2020, global CO_2 emissions declined by 5.8% due to the fall in oil and coal demand because of the coronavirus disease (COVID-19) pandemic and subsequent economic lockdown restrictions (IEA, 2021b). However, despite this decrease, energy-related CO_2 emissions have remained high and have contributed to a CO_2 concentration in the atmosphere of 412.5 parts per million in 2020. Global energy-related CO_2 emissions have since rebounded, growing by 4.8% in 2021 as the energy demand rebounded with the economy, and as such, the transition to renewable energy consumption has become even more imperative to mitigate global emissions (IEA, 2021b).

South Africa is one of the largest coal producers in the world, and with coal being the largest energy fuel source in the country, South Africa is among the top ten gas emitters globally (IEA, 2021a). However, the rising energy demands have started to overwhelm the country's power-generating plants; as such, the state-owned power utility, Eskom, has implemented a loadshedding approach to cope with the high energy demands (Eskom, 2020). This loadshedding approach has adversely impacted South Africa's economy. To reduce CO_2 emissions and provide stable and reliable electricity, South Africa is slowly developing its renewable energy sector as an alternative energy source to reduce the over-reliance on coal (DoE, 2017).

Due to South Africa's human population and its geographical location, renewable energy sources have good potential and the implementation of the Renewable Energy Independent Power Producer's Programme has utilised their potential within the energy supply mix. The government of South Africa had planned to launch the sixth window for bidders in the Renewable Energy Independent Power Producer's Programme by January 2022 to procure 2600 MW (megawatts) of renewable energy, including 1600 MW onshore wind and 1000 MW solar PV (Dludla, 2021). This is intended to improve the electricity supply within the country as Eskom continues to struggle with the increased demand.

Shortly after COP26, the President of South Africa announced that South Africa had concluded a historic agreement to secure R 131 billion to finance the move to a green economy (Ryan, 2021). The main aim of the conference was to achieve net zero emissions by the middle of this century by increasing the decommissioning of coal and motivating investment in renewable energy. This indicates developed countries assisting developing countries in repurposing their retired coal power plants with renewables. The funding also includes support for communities and workers who will be impacted by the move away from coal and enable the creation of clean jobs (Bega, 2021).

The development of the renewable energy sector not only has positive effects on the environment but also on the economy. In a country with a high unemployment rate, the development of renewable energy will provide job opportunities and skills development for ordinary South Africans, which could improve the economy (DoE, 2017). The cost of clean energy technology has also decreased and is currently cheaper than dirty energy, which provides a cost-saving advantage that can be channelled to improving people's general standard of living in the long run while addressing environmental concerns (DoE, 2017).

The costs of fossil fuels have been increasing over the years due to factors such as increasing extraction costs, which will continue increasing into the near future as conventional oil and gas are depleted and hard-to-extract unconventional oil and gas become a larger part of the fossil fuel supply. Post the COVID-19 pandemic, fossil fuel prices have increased due to the economic rebound from the pandemic-related recession. The sanctions imposed on Russia due to its invasion of Ukraine have also reduced the supply of gas, which has increased its price substantially. Other factors, such as extreme weather conditions, carbon pricing and low storage levels, have contributed to the increase in fossil fuel prices. Increased natural gas prices have also led to increased coal consumption in many countries, subsequently leading to increased coal prices in South Africa (Jaller-Makarewicz, 2021).

Fossil fuels also have hidden costs in the form of externalities such as air and water pollution generated during the extraction process, which is harmful to local communities. Burning fuels also results in greenhouse gas emissions, which contribute to global warming and transporting fuel can also contribute towards air pollution and lead to serious accidents and spills. For example, a liquefied petroleum gas tanker exploded in Johannesburg, South Africa, claiming more than twenty lives (Aljazeera, 2022). Fossil fuel waste products are also hazardous to public health and can cause land degradation. The costs of renewable energy sources have, on the other hand, been decreasing over time and now present a significant cost advantage over fossil fuels. With fossil fuels and renewable energies being substitutes, it can be assumed that the demand for fossil fuels will decrease and the demand for cheaper alternative renewable energies will increase.

As such, the main objective of this study was to analyse the pass-through mechanism of the share of clean energy to consumer prices as a welfare indicator. As opposed to many studies that used GDP as a welfare indicator to model the impact of renewable energy on economic welfare, this study followed a different approach by using the CPI as a welfare indicator. The CPI measures changes in general price levels over time for consumer goods and services (StatsSA, 2017), and it is an ideal welfare measure as it can be used as a cost-of-living index. A VAR model was used to estimate this pass-through and the response of consumer prices to renewable energy share increases and decreases in a multivariate, two-regime TVAR.

The rest of this chapter is organised into six sections, the first of which is a literature review. The second is an analysis of renewable energy prices and what has led to their fall. The third is the theoretical framework. The fourth section develops the methodological framework for the TVAR model. The fifth section discusses the results, and the sixth section concludes the study.

3.2 Literature Review

The topic of the effects of clean energy on economic welfare has been well documented in economic literature. This review is divided based on the welfare indicators that have been more commonly used in economic literature to measure the impact of renewable energy sources.

3.2.1 Economic Growth

The study by Inglesi-Lotz (2016) used panel data techniques to determine the effect that sustainable energy consumption has on economic welfare. The results showed that economic growth is positively and significantly affected by clean energy consumption or possibly its portion of the total energy mix. These results support the previous results of Fang (2011), who used a Cobb-Douglas economic welfare function to conclude that real GDP in China is positively affected by renewable energy consumption. Similarly, Tiwari (2011) concluded that variables such as clean and dirty energy consumption, capital and labour have a positive effect on GDP. On the other hand, Omri and Belaïd (2021) concluded that clean energy consumption, together with CO_2 emissions from liquid fuel consumption and CO_2 intensity, negatively affect economic growth. Similarly, Tugcu and Topcu (2018) examined the long and short-run relationships between total, renewable and non-renewable energy consumption and economic growth in G7[3] countries using the nonlinear autoregressive distributed lag. The results of asymmetric and symmetric relationships and causality analyses were very volatile across production functions and energy proxies.

3.2.2 Income Inequality and Poverty

Topcu and Tugcu (2020) investigated the impact of renewable energy consumption on income inequality in developed countries from 1990 to 2014. The results showed that an increase in renewable energy consumption leads to decreased income inequality. On the other hand, Thiam (2011) showed how using clean energy can improve the standard of living and alleviate poverty in rural Senegal by using a life-cycle-cost approach. The results showed that in rural areas without grid connection, PV renewables technologies provide a stable solution for delivering energy.

3.2.3 Employment

Hillebrand et al. (2006) examined the expansion of renewable energies and employment effects in Germany through the expansive effect resulting from additional investment and a contractive effect resulting from an increase in the production cost of power. The first effect will dominate during the first years, leading to an increase in employment; however, the contractive effect will offset these gains, leading to a slightly negative employment balance by 2010. Böhringer et al. (2013) also analysed the employment and welfare impacts of renewable energy promotion in Germany. The results showed that the prospects for employment and welfare gains are limited and hinge crucially on the level of the subsidy rate and the financing mechanism. If renewable energy sources subsidies are financed through labour taxes, the welfare and employment effects are negative, while if the subsidies are funded by electricity tax, then there are minor benefits for small subsidy rates, which then turn negative for large subsidy rates. Moreno and Lopez (2008) investigated the effects of the transition towards the green economy on employment in Spain and showed that clean energy consumption positively impacts employment as the green energy sector is expected to create more jobs in construction and installation. This will compensate for the gradual loss of employment in the traditional mining sector. Bijnens et al. (2021), on the contrary,

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[3] G7 (Group of Seven) describes seven countries that have the largest and most advanced economies in the world: the United States, Germany, Japan, the United Kingdom, France, Italy, and Canada, along with the European Union.

specified that high electricity prices could be attributed to implementing a carbon tax or increased investment into clean electricity generation, which could decrease labour demand and investment in sectors that mostly rely on electricity as an input factor.

3.2.4 Local Sustainability

Río and Burguillo (2008) assessed the impact of renewable energy deployment on local sustainability by providing various socioeconomic and environmental benefits. The study showed other less documented benefits to renewable energy, such as income generation, which complements and diversifies the sources of income of the local population and has a positive psychological effect on isolated rural communities. Reddy et al. (2006), on the other hand, explored the interlinkages between local livelihood and environmental benefits from providing energy to remote rural households in India through small hydropower development. The results showed that the benefits from hydropower development were mostly marginally positive or neutral when looking at its impact on financial, natural, social, physical and human capital, and gender equity in the local communities.

3.2.5 Social and Economic Welfare

In their study, Amoah et al. (2020) concluded that clean energy consumption is positively affected by economic well-being, trade and business freedom. However, for economic well-being, the increase in clean energy consumption, only increases up to a certain point after which it starts to decrease. By contrast, Ahn et al. (2021) showed that social welfare is negatively affected by clean energy consumption. Ahmadpour et al. (2021) also analysed the effects of renewable energies' penetration on social welfare, which consisted of the financial profits of renewable energy production companies and the surplus welfare of subscribers. They showed that subscribers' surplus welfare increases in the long term; however, it was lower than the renewable energy production companies' profit in the short term. Ying et al. (2021) investigated the impact of renewable portfolio standards on social welfare in China's electricity market. The results showed that based on China's real economic situation, the implementation of renewable portfolio standards has achieved Pareto improvement and improved China's social welfare and promoted low-carbon energy transition.

3.2.6 Prices of Electricity and Farmlands

Blazqueza et al. (2018) provided a deeper analysis of the marginal cost of electricity generation using renewable energies. The analysis showed that renewable energies are not necessarily more cost-efficient than fossil fuels, as even though their marginal costs are low after power plants are constructed, the efficiency of the equipment degrades over time and requires maintenance, which is costly. Similarly, Lai et al. (2019) measured the impact of promoting renewable energy in Taiwan on farmland prices. The results indicated that farmlands with solar panel installation increase the prices of other farmland at different distances from 3.40% to 37.02% compared to the average farmland price, which does not benefit agriculture development in the country. Correa-Quezada et al. (2022) examined the impact of increased clean energy consumption on electricity prices in South American countries, and the results showed that the price of electricity paid by households is affected by the consumption of renewable energies. However, it was determined that energy prices in industrial, commercial and services sectors are not affected by renewable energy consumption.

In their study, Oosthuizen et al. (2019) investigated the impact of the share of green energy in the energy mix on retail electricity prices on 34 OECD countries. The impact was positive and statistically significant. However, due to the decreasing marginal costs of renewable energies, Oosthuizen et al. (2019) stated that this result should not discourage policymakers from promoting renewables as they could be more cost-effective in the long run. Miera et al. (2008) also investigated the impact of renewable electricity support schemes on power prices in Spain. They showed a decrease in the wholesale price of electricity as a result of more renewable energy sources generation being fed into the grid, which is a positive from a consumer point of view. Maciejowska (2020) assessed the impact of clean energy sources on the electricity price level and variability. Their results showed that wind and solar PV negatively impact price levels approximated by the price median, while the impact on price volatility varies depending on the energy source. On the other hand, Goodarzi et al. (2019) examined the impact of wind and solar energy forecast errors on spot electricity prices and imbalance volumes. The results showed that high spot electricity prices are due to the pass-through effect of increased absolute values of imbalance volumes because of higher wind and solar forecast errors.

3.2.7 Overall Analysis

As evidenced from these reviewed studies, the topic of the effects of clean energy on economic welfare has been well documented in economic literature. However, most of the literature only focuses on the effect of green energy on GDP, income inequality and poverty, employment, local sustainability, and social and economic welfare as their main welfare measures, and much of the research has not been conducted in the South African context. Few studies have been conducted on the impact of renewable energy consumption on price levels. However, they have mainly focused on the impact of clean energy on electricity price levels, yielding mixed results.

The current study followed a different approach by modelling the impact of the share of green energy consumption in South Africa's energy mix on the CPI as a welfare indicator, which has arguably not been explored before. With the significant cost advantage that renewable energy sources have against fossil fuels, consumer prices as an economic welfare measure provide a better analysis of the impact of the decreasing clean energy technology prices on the prices of goods and services that ordinary South Africans pay for. With South Africa embarking on a major transition to renewable energy to cope with increasing energy demands, it becomes increasingly important to analyse the impact that an increased share of clean energy will have on the cost of living of ordinary South Africans. Understanding this dynamic relationship will allow policymakers to make informed decisions regarding the procurement of clean energy and its pass-through effects on consumer prices.

3.3 Renewable Energy Prices

For the world to transition towards green energy sources, renewables must have a significant cost advantage over historically cheaper fossil fuels. However, in recent years, the costs of renewable energy technologies have drastically declined, making them more cost-effective than fossil fuels. Figures B.1 and B.2 (Appendix B) show the Levelized Cost of Energy (LCOE) for both wind and solar PV, which has consistently declined in recent years (DoE, 2017). The LCOE captures the cost of power plant construction, as well as the ongoing costs for fuel and operating the power plant over its lifespan (Lazard, 2021). As shown in Figure B.1 (Appendix B), the LCOE for solar PV declined by 85% from 2009 to 2016, while the LCOE of wind declined by 66% in the same period. This has made renewable energy significantly cheaper than fossil fuels and is one of the biggest motivations for transitioning to a green economy.

Comparing the cost of fossil fuels and renewable energy, two factors come into play. The first is the price of fuel that is burnt, and the second is the power plant's operating costs. The cost of fossil fuels depends largely on these two factors, while green energy plants are different as their operating costs are comparatively low, and no fuel is required (Roser, 2020). As such, no cost is spent on sourcing fuel, and the only costs of renewable energy are the costs of the power plant, which is the cost of renewable energy technologies. As such, to understand how the cost of renewable energy became so low, it is essential to understand how the cost of renewable energy technology became so low.

For solar energy, the initial prices of solar modules were very high; however, there was a demand for solar energy to supply electricity for a satellite, the Vanguard I, launched in 1958 (Roser, 2020). Thus, the price of solar modules began to decline as the demand increased and more modules were produced. The increased production of solar modules provided an opportunity to improve the production process through the learning-by-doing technique, and because of that increased supply, prices fell. Figure 3.1 shows that to meet the growing demand for solar modules, the deployment of the modules increases, leading to a fall in prices. Because of the low prices, the technology becomes cost-effective, causing increased demand and competition in the market. This results in a positive feedback loop.

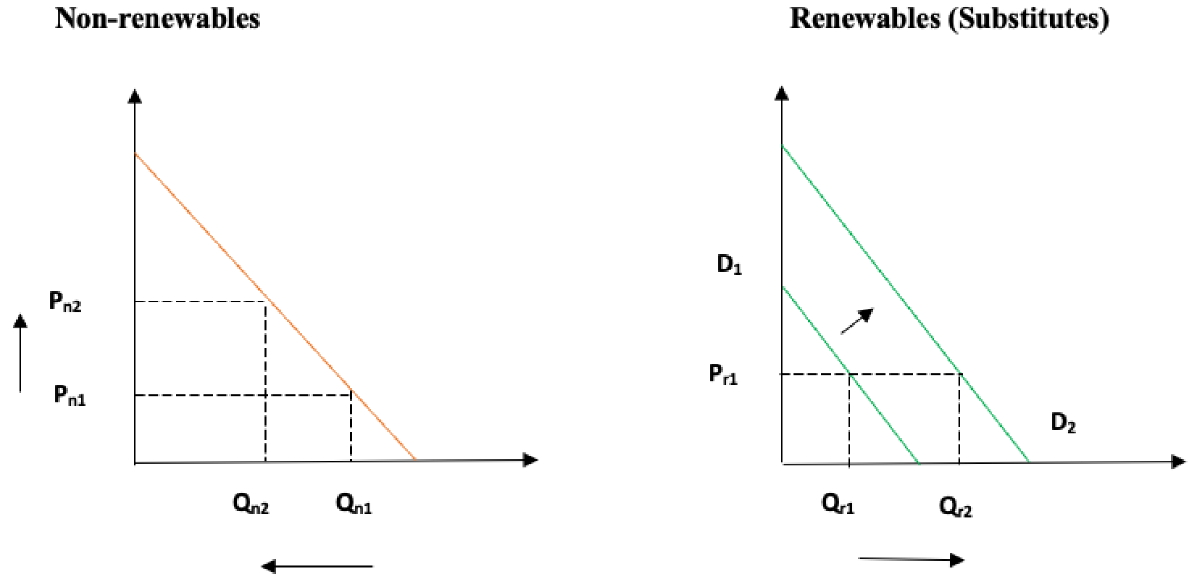
Figure 3.1: Technologies that become cheaper with increasing production enter a virtuous cycle

Source: Roser (2020)

Kavlak et al. (2018) determined that the decrease in costs of solar PV modules is due to increased module efficiency, economies of scale, learning-by-doing, and government-funded and private research and development. Larger and more efficient plants produce the modules, enabling economies of scale to reduce costs. Technological and engineering advances have improved panel efficiencies and the processes of silicon ingots and wafers. The operational experience accumulates, and modules have become more durable and have a longer lifespan. With the increased competition in the market, profits are low and capital costs for production decline. The cost of wind power has also benefitted from the learning-by-doing approach, and as such, it has decreased over the years, albeit not as sharply as solar power.

3.4 Theoretical Framework

Following research conducted by Atems et al. (2023), which assessed the impact of non-renewable energy prices on renewable energy consumption, it was determined that non-renewable and renewable energy are substitutes. As such, shocks to non-renewable energy prices positively and statistically significantly impact renewable energy consumption. Based on economic theory, Figure 3.2 shows that an increase in non-renewable energy prices from $\mathbf{P_{n1}}$ to $\mathbf{P_{n2}}$ decreases the consumption of non-renewable energy from $\mathbf{Q_{n1}}$ to $\mathbf{Q_{n2}}$. At the same time, the demand for renewable energy sources rises from $\mathbf{Q_{r1}}$ to $\mathbf{Q_{r2}}$ even though the price of renewables remains unchanged at $\mathbf{P_{r1}}$. The demand shifts from $\mathbf{D_1}$ to $\mathbf{D_2}$. Therefore, households and businesses respond to higher prices of factors of production by cutting consumption and switching to cheaper alternative energy sources. The decrease in the prices of renewable energy sources incentivises households and businesses to switch to them, increasing their demand.



<u>Figure 3.2: The theoretical relationship between non-renewable and renewable energy markets</u>

Source: Author’s own

The rationale behind using the pass-through mechanism lies in the cost pass-through theory, which describes what happens when a business changes the price of the products or services it sells following a change in the cost of producing them and was developed by RBB Economics (2014). In the current study, the cost pass-through theory was applied to the use of renewable energy sources as factors of production to determine how the decrease in the cost of renewable energy results in a decrease in the cost of production and how business changes the price of products or service in response to the change in costs of producing them.

This can be analysed either industry-wide or firm-specific pass-through. Industry-wide cost pass-through refers to a situation where all firms in an industry are affected by a common cost change. Firm-specific cost pass-through, on the other hand, refers to a situation where cost changes only affect one firm (RBB Economics, 2014). In the context of the current study, industry-wide cost pass-through refers to a situation where an industry is completely using renewable energy, such as wind or solar, in their goods and services production. As such, a decrease in the price of these renewable energies will change the price consumers pay for the produced goods and services. Firm-wide cost pass-through refers to a single firm using renewable energy sources in production and how a decrease in the cost of these energies affects the costs of the produced goods and services.

With the country-wide push to move to renewable energy and the green economy, this study is more inclined towards looking at an industry-wide perspective of the share of renewable energy in the energy mix as a factor of production and its impact on consumer prices. The measure of cost pass-through in this study lies in the pass-through elasticity, which gives a percentage increase or decrease in price arising from a 1% increase or decrease in cost (hence using the VAR model). The intuition for the cost pass-through lies in the role played by the shape of demand in determining pass-through rates. As seen in Figure 3.3, in a perfect competition setting, the price sensitivity of demand and supply has an important bearing on pass-through. The demand is downward sloping, in the sense that as price decreases, so quantity demanded increases.

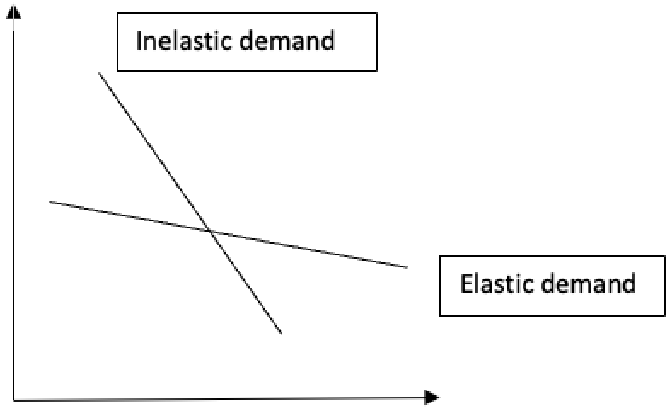
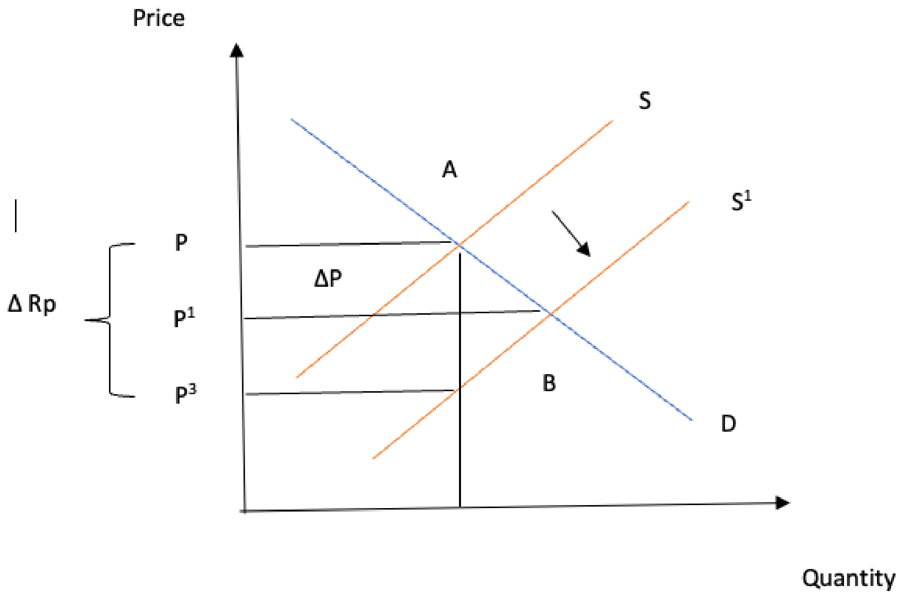


Figure 3.3:Elastic and inelastic demand

Source: Author’s own

The slope of the ‘inverse’ demand curve, however, may take different values, depending on how sensitive consumers are to price changes. A steep, falling slope implies that a price decrease would lead to a small increase in sales (inelastic demand). A flat slope implies a large increase in quantity demanded in response to a given price decrease (elastic). Figure 3.4 graphically shows the decrease in prices of renewable energies as factors of production and pass-through. The decrease in the cost of renewable energy (which are inputs in production) causes the supply curve to shift vertically by an amount **ΔRp** for **S** to **S^1**. As a result, the market equilibrium adjusts from **A** to **B**, with the equilibrium market price decreasing from **P** to **P^1**, and the quality bought (and sold) increasing commensurately. As can be seen, only a fraction of the total decrease in the prices of renewable energies is passed through to consumer prices, the change in price **ΔP**, which is less than the full decrease amount of **ΔRp.** It is then clear that the degree to which the decrease in the costs of renewable energies will be passed through to consumers is sensitive to slopes of demand and supply. As such the pass-through equation can be given as follows:

$$\textbf{Pass-through} = \frac{\textit{Price sensitivity of supply}}{\textit{price sensitivity of supply} + \textit{price sensitivity of demand}} \qquad \textbf{(3.1)}$$



<u>Figure 3.4:Decrease in renewable energy prices and pass-through</u>

Source: Author's own

3.5 Methodological Framework

This study aimed to estimate the share of renewable energy pass-through to consumer prices in South Africa. A multivariate, two-regime TVAR model was used to estimate this pass-through and the response of consumer prices to renewable energy share increases and decreases. The theoretical framework follows the one proposed by Knotek and Zaman (2021), who employed a TVAR model to model asymmetric responses of consumer spending to energy price shocks.

The TVAR methodology measures the simultaneous relationship between the share of renewable energy and other variables. Given the presence of nonlinearities in the share of renewable energy pass-through, coefficients from linear modelling methods could give imprecise results. As such a more realistic approach is required to recognise that the exchange rate environment also has an impact on the responses of economic agents to renewable energy shock.

The TVAR model consists of a set of variables that determine the renewable energy share pass-through to consumer prices. The threshold variable separating the two regimes is based on movements in exchange rate averaged over a certain amount of time. Generalised impulse responses from the TVAR model were estimated to show consumer price responses to positive and negative shocks to renewable energy share.

As a baseline, the current study used multivariate VARs where the vector $\mathbf{Y_t}$ contains the share of renewable energy, CPI, exchange rate and cost of renewable energy technology.

A general representation of the linear VAR (P) model is:

$$\mathbf{Y_t = B_c + B_1\, Y_{t-1} + \ldots + B_p\, Y_{t-p} + \mu_t} \tag{3.2}$$

Where $\mathbf{B_1,\ldots,B_p}$ denote matrices of coefficients $\mathbf{t=1,\ldots,T}$; $\mathbf{B_c}$ denotes a vector of constants; $\boldsymbol{\mu_t}$ denotes the error vector that is normally distributed with mean zero and variance-covariance matrix $\mathbf{\Sigma = E\, \mu_t\, \mu_t}$.

The nonlinear TVAR for two regimes will take the following model:

$$\boldsymbol{Y_t} = \begin{cases} \boldsymbol{Bc,1 + B1,1\; Yt-1 + \cdots + Bp,1\; Yt-p + \mu t,1 \; if\; Y^{*}t-k \leq \Upsilon} \\ \boldsymbol{Bc,2 + B1,2\; Yt-1 + \cdots + Bp,2\; Yt-p + \mu t,2 \; if\; Y^{*}t-k > \Upsilon} \end{cases} \tag{3.3}$$

A compact form of the two-regime TVAR (p) model is as follows:

$$\mathbf{Y_t = [\, B_{c,1} + B_{1,1}\, Y_{t-1} + \cdots + B_{p,1}\, Y_{t-p} + \mu_{t,1}\,]\, K_t + [B_{c,2} + B_{1,2}\, Y_{t-1} + \cdots + B_{p,2}\, Y_{t-p} + \mu_{t,2}\,]\,(1-K_t\,)} \tag{3.4}$$

The $\mathbf{K_t}$ term is defined by:

$$\boldsymbol{K_t} = \begin{cases} \mathbf{1} & \boldsymbol{if\ Y^{*}t-k\ \leq\ \Upsilon} \\ \mathbf{0} & \boldsymbol{if\ Y^{*}t-k\ >\ \Upsilon} \end{cases} \qquad \textbf{(3.5)}$$

Where $\boldsymbol{\gamma}$ denotes the unobserved threshold value; $\mathbf{Y^{*}t-k}$ denotes the threshold variable; $\mathbf{K_t}$ denotes a binary term, which determines the regimes in the TVAR model. When $\mathbf{Y^{*}_{t-k}} \leq \boldsymbol{\gamma}$, the VAR model is determined in a regime that is different from when $\mathbf{Y^{*}_{t-k}} > \boldsymbol{\gamma}$, and as such, will have a different set of coefficients and shock variances. The error terms $\mathbf{u_{t,1}}$ and $\mathbf{u_{t,2}}$ have variance-covariance matrices $\mathbf{\Sigma_1}$ and $\mathbf{\Sigma_2}$.

The stated model was estimated using a TVAR model, with the exchange rate being the threshold variable. Firstly, unit root tests were conducted as they are essential in determining whether the variables are non-stationary and possess a unit root. The ADF test was used to determine the null hypothesis that the series contains a unit root (non-stationary) against the alternative hypothesis that the series is stationary. The characteristics of the time series being analysed determined the specification of the ADF functional form. The ADF versions with intercept and the ADF version with trend and intercept were applied to the variables in level and first difference.

If the results showed that the variables contain a unit root at the level form and are stationary at the first difference, the Johansen test for co-integration was conducted. Co-integration implies that the variables are linked and move together over time to form an equilibrium relationship that spans the long run; even if they are non-stationary, differences between them are stable. The null hypothesis is that of no co-integration and the alternative hypothesis is that of co-integration. To choose the optimal lags, the following information criteria were used: Akaike Information Criterion, Final Prediction Error, Schwarz's Bayesian Information Criterion and Hannan-Quinn Information Criterion.

As the current study estimated a TVAR model, a nonlinearity test for a TVAR model against a linear VAR model was conducted by using the exchange rate as a threshold variable. The linearity test was derived from Hansen (1999) and Lo and Zivot (2001). The null hypothesis is linearity, which means only one regime and will therefore model a simple VAR model. The alternative hypothesis is nonlinearity, which means two regimes and will therefore model a TVAR model. The covariance matrix of each model was used in the test. The exchange rate below the threshold level indicates an appreciation regime while an exchange rate above the threshold level indicates a depreciation regime. Therefore, the threshold value is the turning point between the two regimes.

As this research focused on determining the pass-through effect of the share of renewable energy on consumer prices, the TVAR model was estimated with the exchange rate as the threshold variable. Generalised impulse responses from the TVAR model were estimated to show consumer price responses to positive and negative shocks to renewable energy share. Using exchange rate as the threshold variable was motivated by the relationship between renewable energy and exchange rates. Deka et al. (2023) examined the effect of renewable energy on exchange rates in emerging economies. This relationship is crucial considering the short-term costs of renewable energy and countries that import material to harness renewable energy, such as solar PV, due to poor technology in such countries.

Another study by Deka et al. (2022) investigated the relationship between using renewable energy, the rate of currency exchange and the rate of inflation. Their results showed a bidirectional association between exchange rate and renewable energy exists in Brazil. This shows that the rate of currency exchange affects the use of renewable energy, and the use of renewable energy affects the rate of currency exchange. Renewable energy use has a significant negative effect on the rate of currency exchange, showing that increased use of renewable energy significantly causes the exchange rate to appreciate. Therefore, renewable energy use facilitates an improvement in the currency's value.

3.6 Data Source and Descriptive Statistics

The data used in the current study are derived from the South African Reserve Bank, the South African Department of Energy commodity flow and energy balances, the International Monetary Fund International Financial Statistics and the International Renewable Energy Agency. The data are from 1992 to 2018, and the period was selected based on data availability. The variables were the CPI (total consumer price (all urban areas)), the share of renewable energy as a percentage of total primary energy supply, the average South African exchange rate per United States (US) dollar and the global average price of solar PV modules, measured in 2019 US$ per Watt, as a proxy for the cost of renewable energy. The variables were in their natural logarithmic format to avoid the influence of heteroscedasticity on regression results, allowing for convenient percentage/elasticity interpretation and mitigating problems with outliers.

The descriptive statistics mean, median, maximum, minimum and standard deviations of the variables are recorded in Table 3.1. The average exchange rate is 7.7 R/$, which was used as the threshold value for the threshold variable exchange rate in the VAR model. Exchange rates above 7.7 R/$ were regarded as depreciation regimes and exchange rates below 7.7 R/$ were regarded as appreciation regimes. The CPI has the highest standard deviation, which shows that the data points are spread out over a wide range of values, indicating high variation. The cost of renewable energy has the lowest standard deviation, meaning most of the data points are close to the mean, indicating less variation (Table 3.1).

Table 3.1: Descriptive statistics of variables

Variables	**Mean**	**Standard deviation**	**Minimum**	**Maximum**
Consumer prices	57.49	25.72	22.2	107.8
Share of renewable energy	11.21	3.96	5.66	20.88
Exchange rate	7.71	3.23	2.85	14.71
Cost of renewable energy	3.63	2.27	0.41	7.21

Table 3.2 shows the correlation matrix. The CPI is negatively correlated with all variables except for the exchange rate. The share of clean energy is negatively correlated with all variables. The exchange rate and the cost of renewable energy are negatively correlated. This is, however, not an indication of causality but rather an indication of a correlation between variables.

Table 3.2: Pairwise correlation matrix

	Consumer prices	**Share of renewable energy**	**Exchange rate**	**Cost of renewable energy**
Consumer prices	1			
Share of renewable energy	-0.1493	1		
Exchange rate	0.9158	-0.3030	1	
Cost of renewable energy	-0.9147	-0.1715	-0.8221	1

Figure B.3 (Appendix B) shows the graphical representation of the CPI, and an upward trend can be observed. The highest inflation rate was between 2007 and 2009 due to the financial crisis, as well as between 1993 and 1997 due to the political uncertainty in South Africa. Periods of low inflation were between 2004 to 2006 and 2010 to 2011.

The graphical representation of the share of clean energy in Figure B.4 (Appendix B) shows that the share of clean energy sharply decreasing from 1992 to 2001 due to an increase in the usage of coal in the energy mix. From there, the share of renewable energy gradually increasing from 2002 to 2018, as renewable energy policies, such as the White Paper on Renewable Energy Policy (2003), came into effect and the push for renewable energy become more evident. In 2017, the share of renewable energy reached a high of around 20%, which was due to a fall in usage of all other energy sources within the energy mix.

The exchange rate per US dollar versus the threshold value of the exchange rate is shown in Figure B.5 (Appendix B). The exchange rate was below the threshold rate between 1992 to 2000; however, it was consistently increasing. The exchange rate was then below the threshold between 2003 and 2007 and between 2010 and 2011. The exchange rate was above the threshold between 2001 and 2002 and between 2008 and 2009. Then, from 2012 to 2018, the exchange rate was above the threshold, with 2016 experiencing the highest exchange rate.

Figure B.6 (Appendix B) represents the cost of renewable energy, and a downward trend can be observed from 2007 to 2018. The cost of renewable energies have been consistently decreasing mainly due to increased competition, innovation and economies of scale.

3.7 Results and Discussion

3.7.1 Unit Root Testing

As stated in the methodology, tests for the univariate characteristics of the variables were conducted, and Table 3.3 shows the results of the ADF test for stationarity. All variables are non-stationary in level form as all tests fail to reject the null hypothesis at the 5% significance level. However, for the share of renewable energy, for the ADF version with trend and intercept, we reject the null hypothesis at the 10% significance level. All variables are stationary in the first difference, as all tests reject the null hypothesis at the 10% significance level. Based on these results, all the variables are of the same order of integration, contain a unit root at the level form and are stationary at first difference. As such, the co-integration test was conducted.

Table 3.3: Unit root testing

Variable	**Method**	**Level**	**First difference**
Consumer Price Index		T_T T_μ	T_T T_μ
	T_T	-2.523	-3.022**
	T_μ	-3.052	-3.167*
Share of renewable energy		T_T T_μ	T_T T_μ
	T_T	-2.592*	-6.270***
	T_μ	-2.443	-6.887***
Exchange rate		T_T T_μ	T_T T_μ
	T_T	-1.571	-3.554***
	T_μ	-1.981	-3.512**
Cost of renewable energy		T_T T_μ	T_T T_μ
	T_T	1.467	-3.120**
	T_μ	-1.045	-3.360*

Null hypothesis is non-stationarity; *(**)[***] denote 10%, 5%, 1% levels of statistical significance, respectively; T_T: intercept; T_μ: trend and intercept

3.7.2 Co-integration

Table 3.4 shows the results obtained from the Johansen test for co-integration. There is no evidence of a co-integrated relationship at the 5% level of significance as the trace statistic is less than the critical value (trace statistics = 41.74 < critical value = 47.21) at maximum rank 0. As such, the variables are not linked and do not move together over time to form an equilibrium relationship that spans the long run; even if they are non-stationary, the differences between them are not stable. Thus, only an unrestricted VAR model was estimated.

Table 3.4: Johansen test for co-integration

Variables	Maximum rank	Trace statistic	5% critical value
Consumer Price Index	0	41.74*	47.21
Share of renewable energy	1	20.31	29.68
Exchange rate	2	10.20	15.41
Cost of renewable energy	3	0.1627	3.76

*denotes 10% level of statistical significance

The widely used information criteria are the Akaike Information Criterion, Final Prediction Error, Schwarz's Bayesian information Criterion and Hannan-Quinn Information Criterion. These were used to determine the optimal lag order before testing for thresholds in the VAR representation of the data. From these criteria and based on Akaike's final prediction error, 2 was selected as the optimal lag for the TVAR.

3.7.3 Nonlinearity

The nonlinearity test for a TVAR model against a linear VAR model was conducted using the exchange rate as a threshold variable. The results in Table 3.5 show that at the 5% significance level, we reject the null hypothesis of linearity (one regime) against the alternative hypothesis of nonlinearity (two regimes). As such, the results show that the 2 regime TVAR model sufficiently describes the simultaneous variables. This justifies using the 2 regime TVAR model based on exchange rate as a threshold variable. As per Deka et al. (2022), a bidirectional association between exchange rate and renewable energy use exists; appreciation in the exchange rate increases the use of renewable energy, and depreciation in the exchange rate decreases the use of renewable energy. Similarly, increased use of renewable energy significantly causes the exchange rate to appreciate and a fall in the use of renewable energy significantly causes the exchange rate to depreciate.

Table 3.5: Nonlinearity test results

Likelihood-ratio test	**Likelihood-ratio statistics**
For linearity against two regimes	979.17***
Estimated threshold	
7.7 R/$	

*** denotes 1% level of statistical significance

3.7.4 Threshold Vector Autoregression

As stated in the methodology, the TVAR model was estimated with the exchange rate as the threshold variable, and the results are shown in Table 3.6.

Table 3.6: Threshold Vector Autoregression

Variables	**Regime 1:** **Exchange rate ≤ 7.7 R/$**	**Regime 2:** **Exchange rate > 7.7 R/$**
Consumer Price Index (-1)	1.34	0.12
	(12.77)***	(0.58)
Consumer Price Index (-2)	-0.32	0.86
	(-3.46)***	(3.96)***
Share of renewable energy (-1)	0.02	-0.08
	(2.09)**	(-3.65)***
Share of renewable energy (-2)	0.04	-0.35
	(3.31)***	(-5.37)***
Exchange rate (-1)	0.18	-0.09
	(6.46)***	(-1.50)
Exchange rate (-2)	-0.12	0.11
	(-9.94)***	(1.82)*
Cost of renewable energy (-1)	0.08	-0.05
	(4.41)***	(-2.38)**
Cost of renewable energy (-2)	-0.11	0.01
	(-5.49)***	(0.63)
Constant	-0.13	1.23
	(-0.89)	(3.64)***

Z-statistics of coefficients in brackets ();*(**)[***] denote 10%, 5%, 1% levels of statistical significance, respectively

From Table 3.6, the share of renewable energy pass-through to consumer prices is statistically significant in the first and second regimes. However, below the threshold value of the exchange rate, the share of green energy pass-through is positive, which means that below the threshold, an increase in the clean energy share within the energy mix results in an increase in consumer price. However, above the threshold value of the exchange rate, the share of renewable energy is negative, which means that above the threshold, an increase in the share of green energy results in a decrease in consumer prices.

These results can be interpreted as an indication that within an appreciation regime, the share of clean energy pass-through is positive, and within a depreciation regime, the share of renewable energy pass-through is negative. These are very interesting results as different significant results are found under different regimes. This is also consistent with Deka et al. (2022), who concluded that different exchange rate regimes (appreciation or depreciation) affect renewable energy use differently. However, in the current study, the differences in the pass-through can be explained by the cost of renewable energy, as coincidentally, from 2008 to 2018, the exchange rate was mostly above the threshold level (depreciation regime), and from 2007 to 2018, the cost of renewable energy experienced the biggest fall. As such, during that period of a depreciating exchange rate and low cost of renewable energy, the pass-through of the share of clean energy to consumer prices was negative; therefore, decreasing in prices of renewable energies as factors of production pass-through to consumers in the form of low prices of goods and services.

On the other hand, before 2008, the exchange rate was mostly below the threshold level (appreciation regime), and the cost of renewable energy was not consistently decreasing, as there were years when it was increasing (1996 to 1997, 2004 to 2006). As such, during that period of appreciation and mixed cost of renewable energy, the pass-through of the share of clean energy to consumer prices was positive. This means that periods when the exchange rate was appreciating were also associated with periods when the prices of renewable energies were increasing. Therefore, the increases in renewable energies resulted in increased factors of production, which pass-through to consumers in the form of higher prices for goods and services.

Both results support the cost pass-through theory discussed. Increases and decreases in renewable energy prices will pass-through to consumers. The decreasing costs of renewable energy will motivate firms to switch from fossil fuels to renewable energies for production. This reduced cost of production will then be passed through to consumers. The pass-through rate will then be determined by the elasticity of demand. This renewable energy pass-through holds for an individual firm using renewable energy as its factors of production or many firms within an industry substituting fossil fuels for renewables due to their cost savings advantage.

3.7.5 Impulse Response Function

Figure 3.5 depicts the accumulated impulse response of consumer prices to a positive one-unit share of renewable energy shock in regime 1. As seen in Figure 3.5, a one-unit shock leads to an increase in consumer prices. However, this positive effect decreases over time until it flattens out towards the end of the course. Figure 3.6 depicts the accumulated impulse response of consumer prices to a positive one-unit share of clean energy shock in regime 2. As seen in Figure 3.6, a one-unit exchange rate shock leads to decreased consumer prices. However, this negative effect decreases over time until it curves out towards the end of the course.

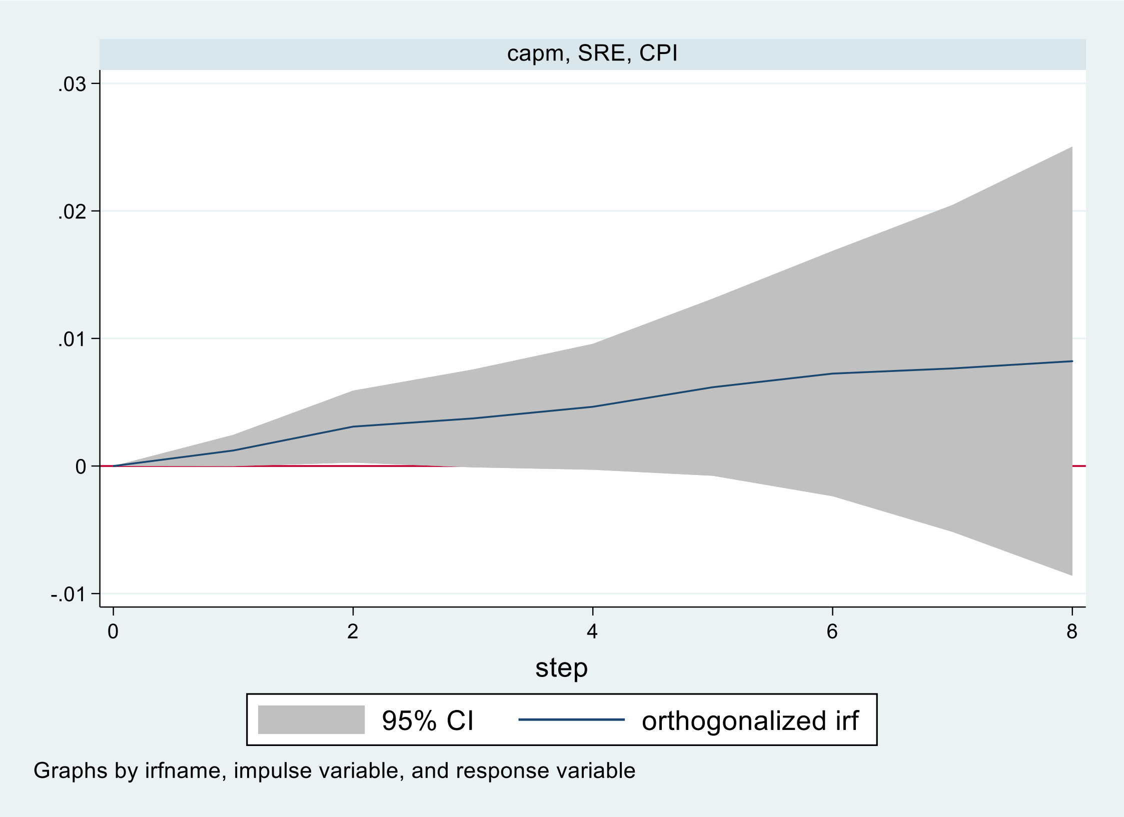


Figure 3.5: Response of Consumer Price Index to shocks in the share of renewable energy in regime 1

In a perfect competition scenario, during regime 1, the cost of renewable energy technology is increasing; therefore, a 1% increase in the share of renewable energy will result in an initial increase consumer goods and services prices. This is because the costs of the factors of production, which is renewable energy, are increasing in the appreciation regime, resulting in an upward shift in the supply curve, which increases prices. Average total, variable and marginal costs will also shift upwards. Firms will start experiencing economic losses as the increase in prices is less than the increase in cost. In the long run, firms will exit the industry until economic losses are zero.

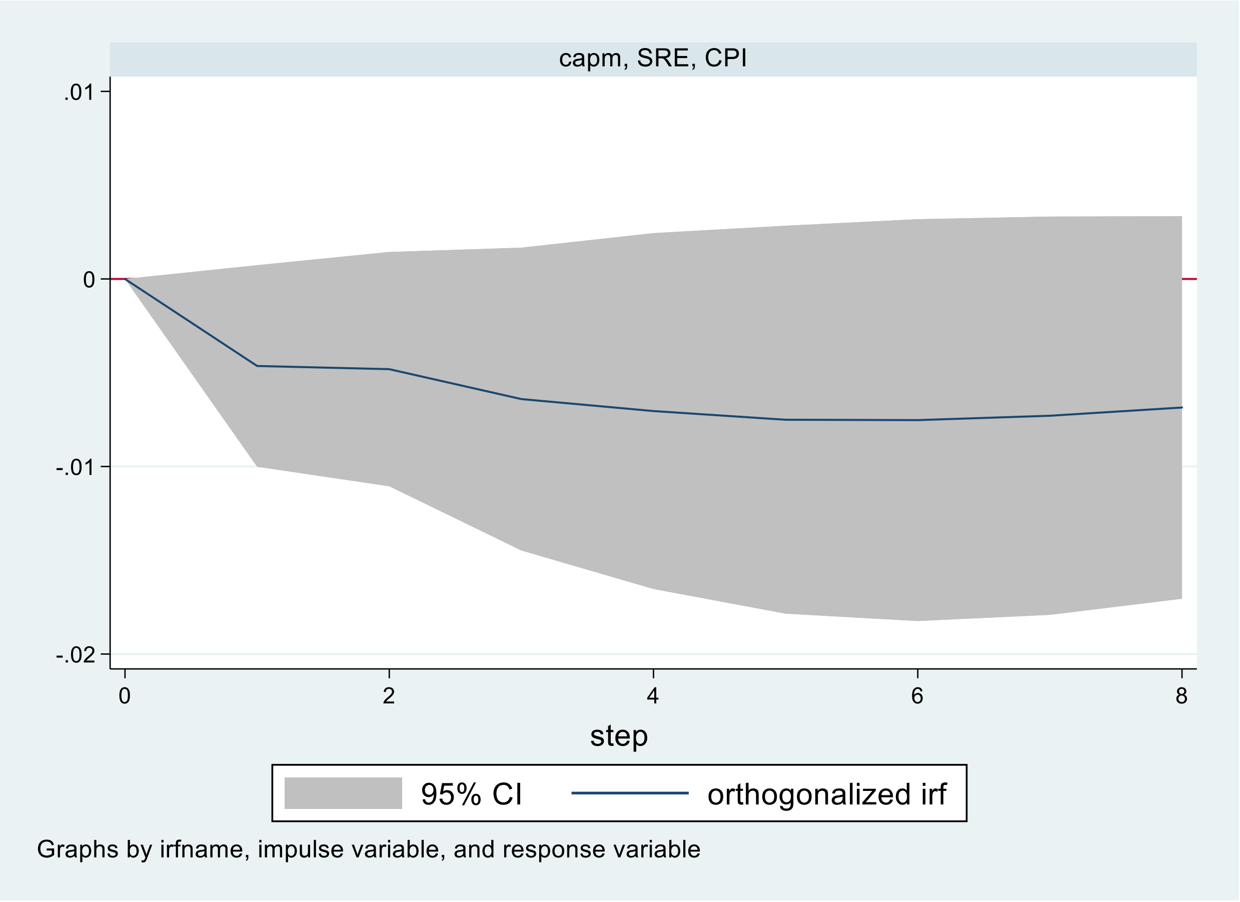


__Figure 3.6: Response of Consumer Price Index to shocks in the share of renewable energy in regime 2__

In a perfect competition scenario, during regime 2, the cost of renewable energy technology is decreasing; therefore, a 1% increase in the share of renewable energy will result in an initial decrease in consumer goods and services prices. This is because the costs of the factors of production, which is renewable energy, are decreasing in the depreciation regime. This will result in a downward shift in supply, decreasing prices. Average total, variable and marginal costs will also shift downwards. Firms will start to make an economic profit, as the decrease in prices is less than the decrease in costs. The profits will attract firm entry into the industry until economic profits are zero in the long run.

3.8 Conclusion and Policy Implications

Due to technological improvements, economies of scale and increased competition, renewable energy technology has become more accessible and affordable. Therefore, the purpose of this research was to determine the pass-through and response of consumer prices to renewable energy share increases using the exchange rate as a threshold in South Africa. The TVAR model was used to determine the pass-through effect and response using a threshold exchange rate value of 7.7 R/$. This means that a depreciation regime is when the exchange rate is greater than or equal to 7.7 R/$, and an appreciation regime is when the exchange rate is less than 7.7 R/$. The exchange rate was used as a threshold variable due to the documented bidirectional relationship between renewable energy use and exchange rate.

As fossil fuels prices continue to increase and South Africa is transitioning to a green economy, which has the potential to be more cost-efficient, policymakers must understand the impact that an increasing share of clean energy in the energy mix will have on the cost of living of ordinary South Africans as a welfare indicator. The results of the TVAR model showed that the share of renewable energy pass-through to consumer prices is statistically significant in both exchange rate regimes. However, the pass-through effect is different in both regimes.

In the appreciation regime below the threshold value of the exchange rate, the share of renewable energy pass-through is positive, which means that below the threshold, an increase in the clean energy share within the energy mix results in an increase in consumer price. While in the depreciation regime above the threshold value of the exchange rate, the share of renewable energy is negative, which means that above the threshold, an increase in the share of green energy results in a decrease in consumer prices. This dynamic is largely explained by the cost of renewable energy, as coincidentally, from 2008 to 2018, the exchange rate was mostly above the threshold level (depreciation regime), and from 2007 to 2018, the cost of renewable energy experienced the biggest fall. This decline in the cost of renewable energy was passed through to consumer prices during that period.

On the other hand, before 2008, the exchange rate was mostly below the threshold level (appreciation regime), and the cost of renewable energy was not consistently decreasing, as there were years when it was increasing (1996 to 1997, 2004 to 2006). As such, during that period of appreciation and mixed cost of renewable energy, the pass-through of the share of green energy to consumer prices was positive. This increase in the cost of renewable energy was passed through to consumer prices during that period.

Results from the impulse response function also showed that a one-unit increase in the share of clean energy led to a positive and negative temporary shock to consumer prices in each respective regime. In a perfect competition scenario, during regime 1, the cost of renewable energy technology is increasing; therefore, a 1% increase in the share of renewable energy will increase the prices of consumer goods and services. In a perfect competition scenario, during regime 2, the cost of renewable energy technology is decreasing; therefore, a 1% increase in the share of renewable energy will decrease the prices of consumer goods and services.

Based on the cost pass-through theory, both regimes represent different phases of renewable energy costs. The first regime represents a phase where renewable energy prices were high and, as a result, an increase in the share of renewable energy usage increased consumer prices. Firms passed through the increased costs of production to consumers. On the other hand, the second regime represents a phase where renewable energy prices were low, and as a result, an increase in the share of renewable energy usage decreased consumer prices. Firms passed through the decreasing costs of production to consumers.

These results show that policymakers should promote using green energy as the technology is significantly cheaper than fossil fuels, and the use of renewables will decrease total costs of production, which will then be passed through to decreased consumer prices. The decrease in costs of production will also result in increased savings and investments, which can be channelled to other sectors of the economy to further stimulate economic growth in South Africa and other countries in the world.

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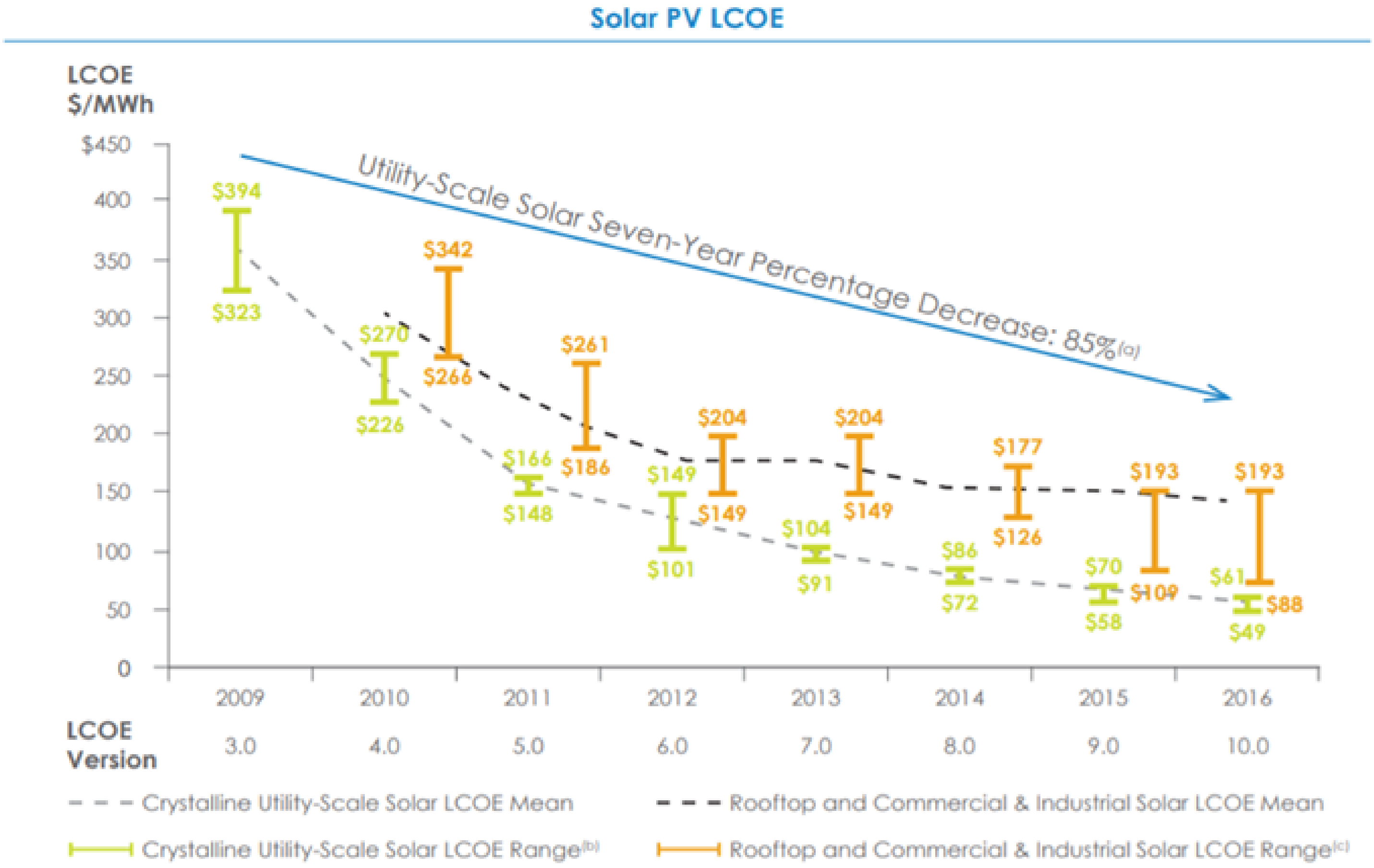
Appendix B



<u>Figure B.1: Technology price trends for solar – Levelized Cost of Energy (LCOE) in US Dollars per megawatt hour (MWh)</u>

Source: DoE, 2017; Lazard, 2021

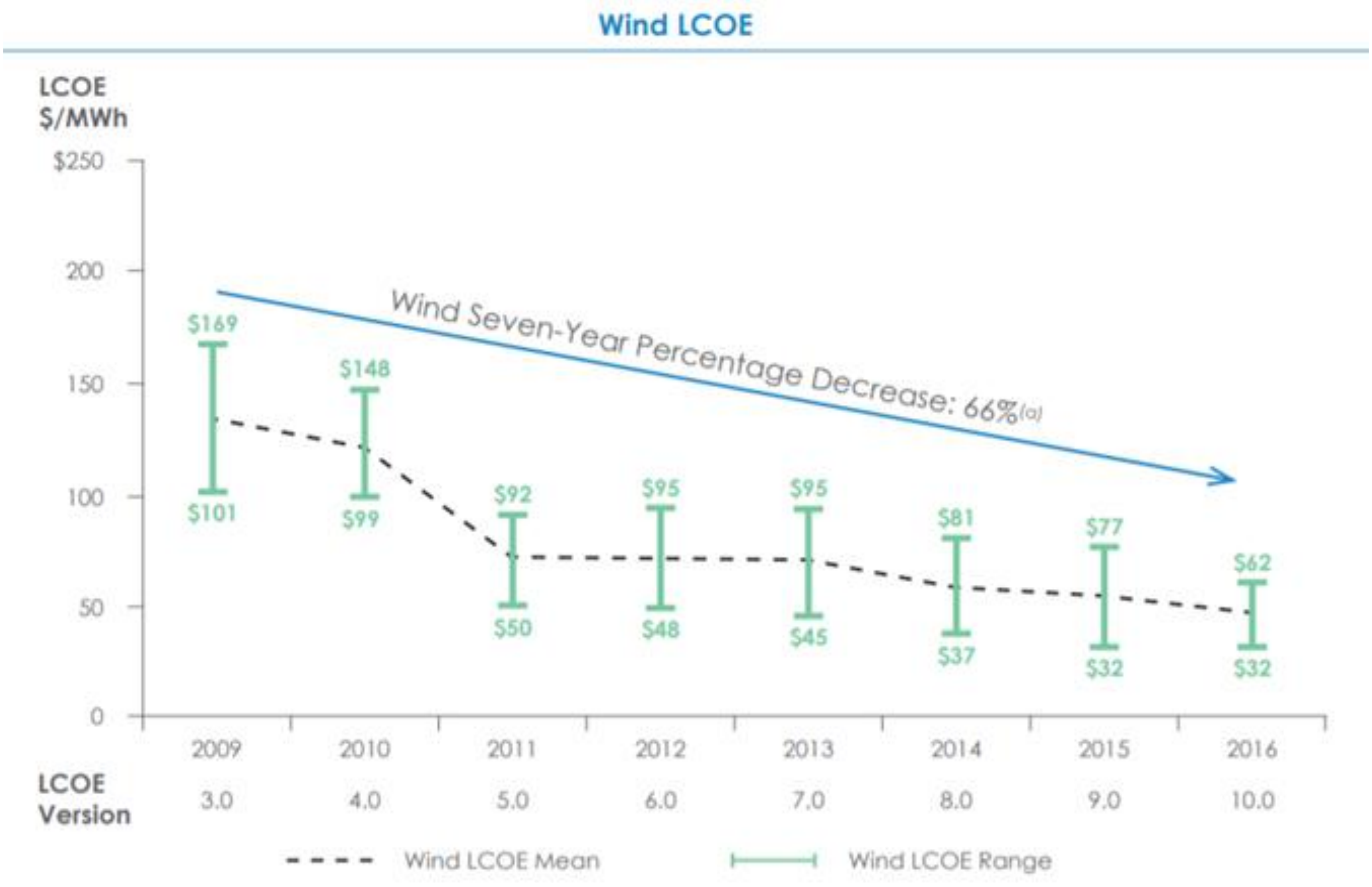


__Figure B.2: Technology price trends for wind – Levelized Cost of Energy (LCOE) in US Dollars per megawatt hour (MWh)__

Source: DoE, 2017; Lazard, 2021

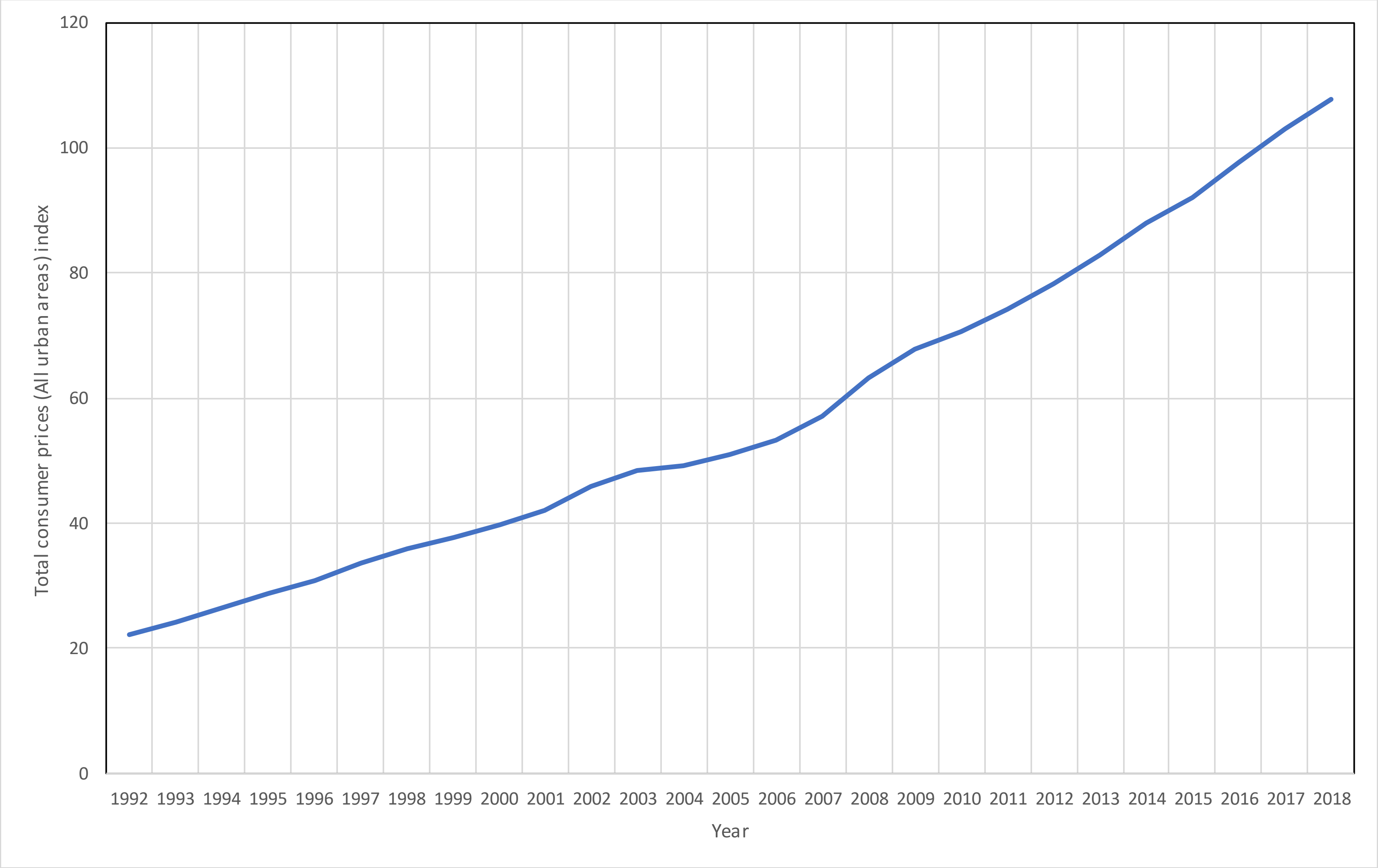


Figure B.3: Graphical representation of Consumer Price Index from 1992 to 2018

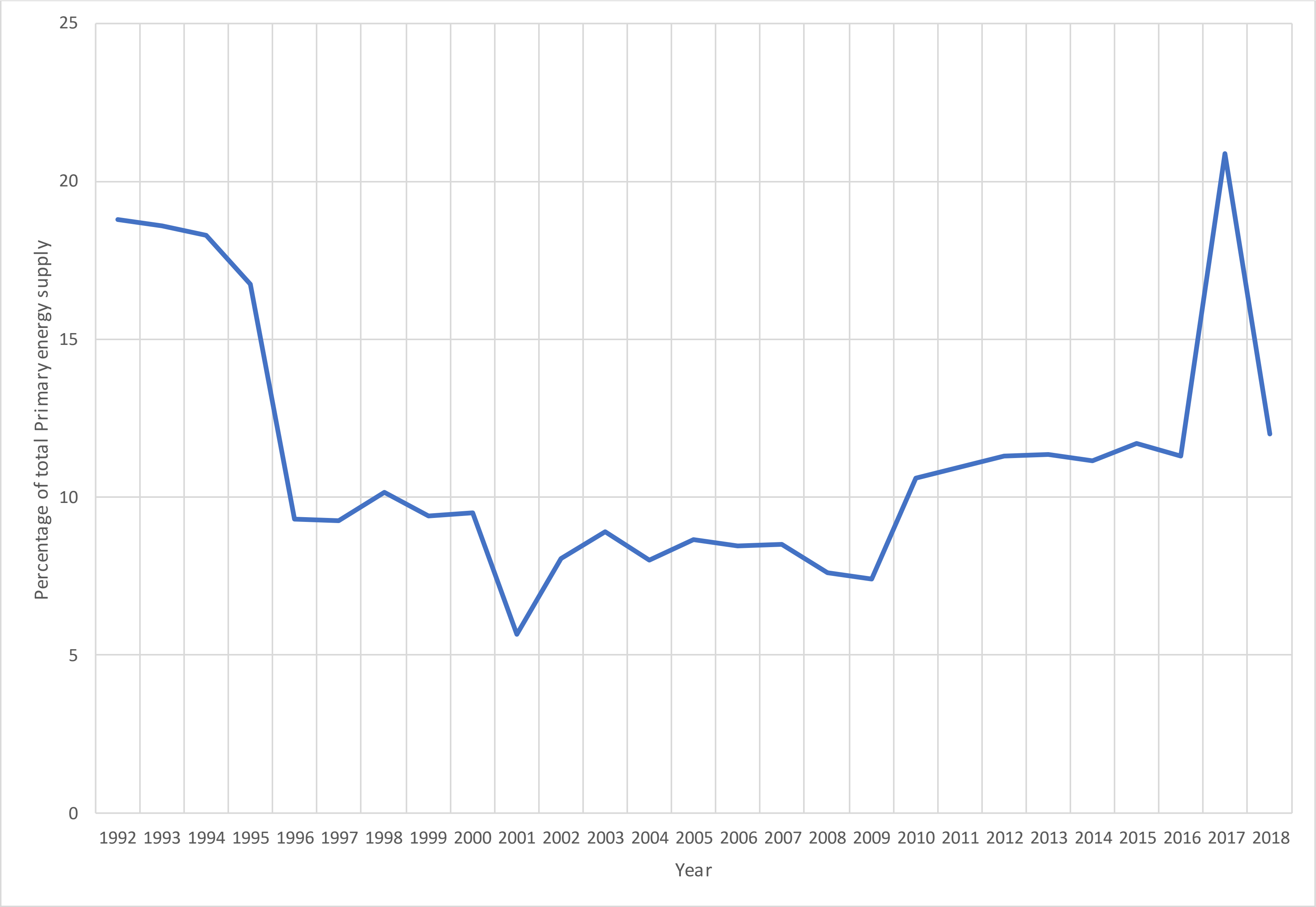


Figure B.4: Graphical representation of the share of renewable energy from 1992 to 2018

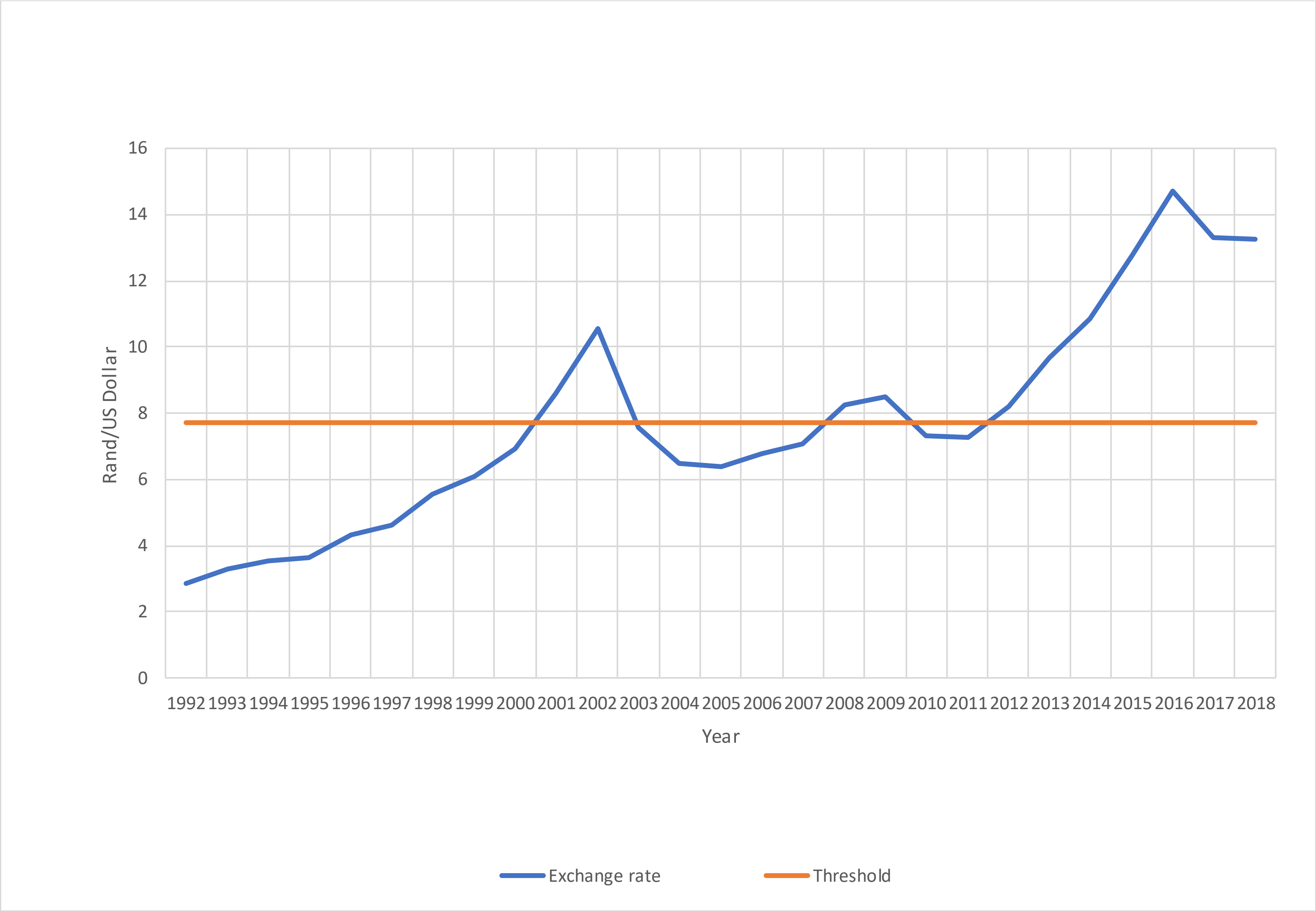


Figure B.5: Graphical representation of exchange rate from 1992 to 2018

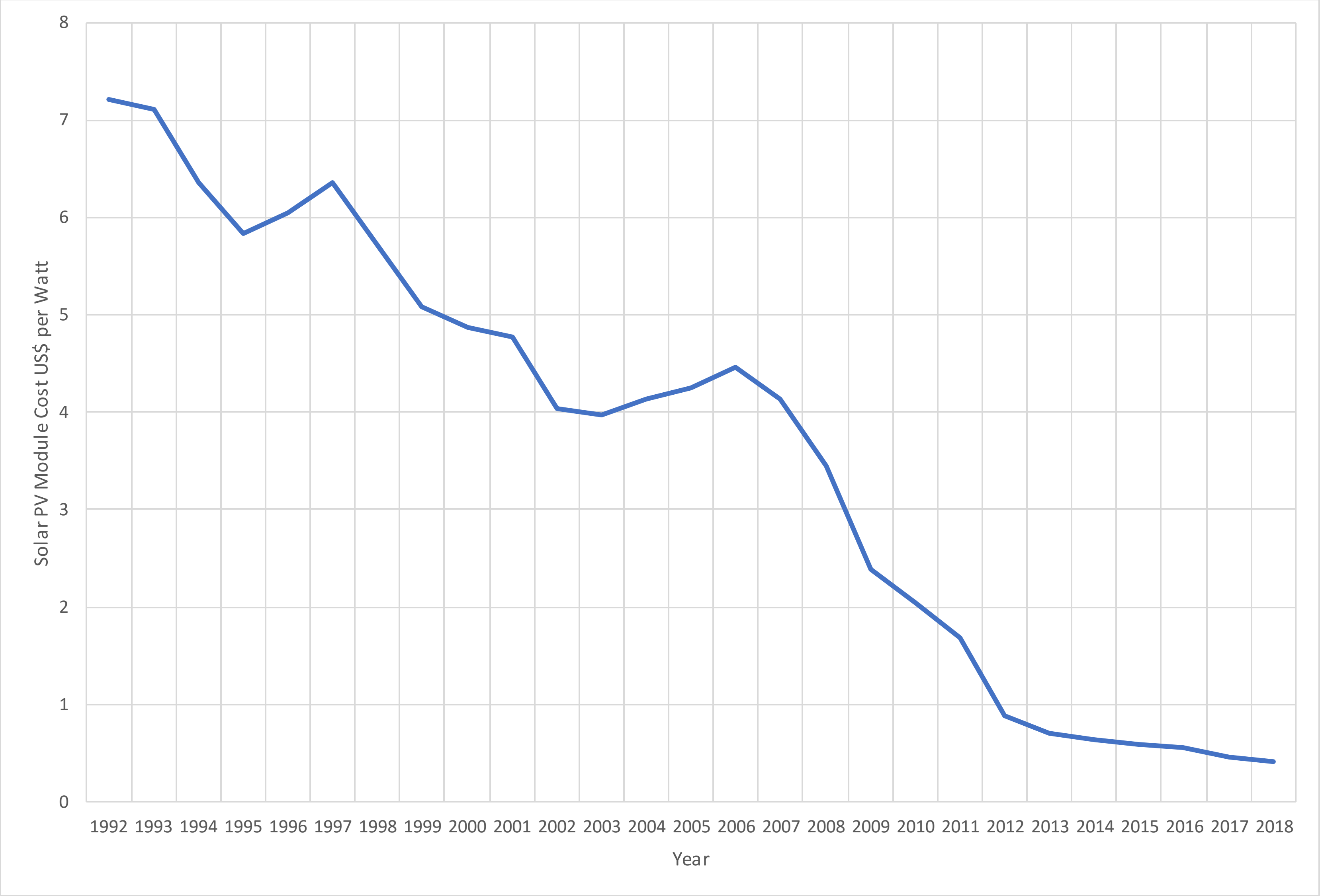


Figure B.6: Graphical representation of the cost of renewable energy from 1992 to 2018

4 Chapter Four: The Effects of Renewable Energy Introduction on Gross Domestic Product Growth: Evidence from a Natural Experiment in South Africa

Abstract

This study determined the impact of renewable energy policies, such as the White Paper on the Energy Policy of the Republic of South Africa (1998), the White Paper on Renewable Energy Policy (2003) and the Integrated Resource Plan (2010), on economic growth in South Africa. To measure this impact, a natural experiment approach was conducted, which included using Regression Discontinuity in time and Synthetic Control using Bayesian Structural Time-Series models. The Regression Discontinuity results showed that each renewable energy policy caused a positive gross domestic product (GDP) growth drift. The results from the Bayesian posterior estimate and graph distribution also showed the positive impact of the introduction of the green energy policy on economic growth by comparing the growth of GDP before and after the introduction of renewable energy through constructing a Synthetic Control, which was GDP growth had no renewable energy intervention taken place. The results from this analysis encourage policymakers to implement further and improve renewable energy policies, as the share of clean energy within South Africa's energy mix not only mitigates climate change by decreasing greenhouse gas emissions but also positively affects economic growth by creating a clean ecosystem, job creation, increasing innovation and capital formation and overall improving total factor productivity in South Africa.

Keywords: Renewable Energy, Natural Experiment, Regression Discontinuity, Bayesian Structural Time-Series, Economic Growth

JEL codes: C22, P28, Q20, Q56

4.1 Introduction

The use and production of energy are crucial for attaining and maintaining economic growth and prosperity long term. However, the consumption and production of energy have also resulted in extensive environmental concerns, as the use of dirty energy sources such as coal, gas and petroleum has led to the creation of greenhouse gases, which significantly contribute to global warming and climate change (Sahlian et al., 2021). Global energy-related CO_2 emissions were 20.5 gigatons in 1990 and increased to 33.4 gigatons in 2019, which is largely attributed to the global consumption of fossil fuels (IEA, 2021). The consumption of dirty energy sources also tends to increase the cost of energy over time, creating a situation in many parts of the world where energy deficiencies have created economic problems and contributed to the growing poverty levels (Fu et al., 2021).

To reduce greenhouse gas emissions, policies in the environment and energy field have been globally promoted to rectify the ecological imbalances caused by consuming dirty energy sources, promoting the use of green energy sources. This includes policies such as the Kyoto Protocol, which promotes the transition towards green energy and the reduction of greenhouse gas emissions (UNCC, 1997). The transition towards green energy is motivated not only by the positive impact it has on the environment but also by the reduced costs of renewable energy technologies, which gives them a significant cost advantage over fossil fuels (Vaona, 2016).

In South Africa, energy is critical to achieving economic and social development. However, providing an affordable, stable and reliable energy supply to most South Africans remains a significant challenge. The increasing energy demand has overwhelmed the country's existing power-generating capacity, resulting in loadshedding being implemented in most parts of the country, which has disrupted the country's productive capacity. With South Africa being a signatory of the Paris Agreement on Climate Change and the increasing energy deficiencies, the country has gradually developed a renewable energy sector to mitigate climate change and improve the overall energy supply (DoE, 2019). In developing the renewable energy sector, the South African government has developed several renewable energy policies, leading to the country's transition from being heavily reliant on fossil fuel for energy supply to introducing renewable energy within the energy mix.

This leads to the current study's main objective to evaluate the structural break analysis of the GDP growth drift due to introducing green energy into South Africa's national energy mix. This was achieved by conducting a natural experiment to evaluate the impact of green energy policies and their subsequent implementation on South Africa's economic growth. Three renewable energy policies were evaluated: the White Paper on the Energy Policy of the Republic of South Africa (DoE, 1998), the White Paper on Renewable Energy Policy (DoE, 2003) and the IRP 2010 (DoE, 2010).

The White Paper on the Energy Policy of the Republic of South Africa (1998) is regarded as the country's first formalised renewable energy policy (DoE, 1998). In this policy, published on the 1st of December 1998, the government believed that renewable energy implementation has a significant advantage in providing electricity in remote areas where grid electricity supply is impractical. The government aimed to manage the production and maintenance of non-grid electrification systems. This included developing solar power, particularly in homes, schools and clinics for cookers, pump water supply and heating, as well as the development of hybrid electrification and wind power. The renewable energy policy was implemented by the government to ensure enough resources are invested in renewables, given their enormous potential compared to other energy supply options. The policy also ensures that economically feasible and practical technologies and applications are implemented in the country and prioritises renewable industry development.

A few years after the introduction of the White Paper on the Energy Policy for the Republic of South Africa (1998), the White Paper on Renewable Energy Policy (2003) was introduced and implemented. This policy, published on the 1st of November 2003, provided a ten-year target of how renewable energy sources can diversify South Africa's energy mix and provide cleaner and stable energy (DoE, 2003). The policy aimed to ensure the development of the renewable energy sector by implementing renewable energy technologies and encouraging investment within the sector.

Due to the national commitment to transition to a green economy, the IRP 2010 was introduced and implemented (DoE, 2010). Following the two white papers, this IRP, published on the 22nd of October 2010, highlighted the long-term electricity demand and detailed how that demand should be met. The plan envisaged that by 2030, 17 800 MW of electricity would be produced by renewable energies, with 6 422 MW being produced by renewables in 2017; the plan seems to be on track to meet its targets. Using bidding windows, 6 422 MW were procured from 112 renewable energy independent power producers (DoE, 2020).

The rest of this chapter is organised into six sections, the first of which is a literature review. The second section discusses the implementation of green energy policies. The third section provides the natural experiment framework. The fourth section outlines the methodology that was used to model the impact that green energy policies have on economic growth. The fifth section is a discussion of the results and falsification tests, and the sixth section concludes the study.

4.2 Literature Review

4.2.1 Green Growth Theory Review

The mechanism through which renewable energy consumption can increase the GDP has been attributed to the impact of green energy consumption on total factor productivity. Rath et al. (2019) examined whether the types of energy use impacted the total factor productivity (TFP) growth by using a 36-country panel. The results showed that TFP is negatively affected by the consumption of dirty energy and positively affected by the consumption of clean energy. Another study by Sohag et al. (2021) concluded that renewable energy consumption positively affects TFP through technological innovation and energy efficiency. The study also noted that TFP could be promoted through the decline of a country’s current account caused by the endogenous production of renewable energy. On the other hand, the International Renewable Energy Agency (IRENA, 2016) published a report highlighting the economic benefits of clean energy. One of the benefits of clean energy, which can increase GDP, is job creation. Because of the labour-intensive and highly distributive nature of renewable energy, employment in the renewable energy sector (both direct and indirect) could reach 24.4 million people in 2030 (IRENA, 2016).

To achieve green growth, it is important to invest in sustaining environmental wealth while maintaining short-term developmental goals of growth and poverty alleviation (Smulders et al., 2014). Climate change mitigation policies that promote renewable energies to protect natural resources and the environment from degradation have the potential to maintain a sustainable environment without largely sacrificing economic growth. Economic growth theories, such as the neoclassical growth theory, have shown that these policies may help stimulate growth as the development of the renewable energy sector requires capital accumulation and technical change, which drive growth. In turn, capital accumulation and technical change are driven by the rewards of innovation and investment (Smulders et al., 2014).

A green growth model developed by Chambers and Guo (2009) has an economy where social technology exhibits increasing returns-to-scale and the representative household lives forever while providing a fixed labour supply and deriving utility from consumption goods. The economy has a continuum of identical and competitive firms with the total number normalised to one and can take the following form:

$$\mathbf{Y}_t = (\mathbf{K_t})^{\beta}(\mathbf{H_t})^{1-\beta}(\mathbf{X_t}) \text{ and } \mathbf{0 < \beta < 1} \tag{4.1}$$

Where $\mathbf{Y}_t$ is the output produced by each firm, $\mathbf{K_t}$ is the physical capital, $\mathbf{H_t}$ is the utilised/harvested renewable natural resources, and $\mathbf{X_t}$ is productive externalities taken as given by an individual firm and postulated to take the following form:

$$\mathbf{X_t} = \mathbf{A\ K_t}^{1-\beta} \text{ and } \mathbf{A > 0} \tag{4.2}$$

Where $\bar{\mathbf{K}}_\mathbf{t}$ is the economy-wide average level of capital stock and in a symmetric equilibrium, all firms take the same actions such that $\mathbf{K_t} = \bar{\mathbf{K}}_\mathbf{t}$. Therefore, when equation 4.2 is substituted into equation 4.1, the following social production function that shows increasing returns-to-scale is obtained:

$$\mathbf{Y}_t = \mathbf{A}(\mathbf{K_t})(\mathbf{H_t})^{1-\beta} \tag{4.3}$$

Under the assumption that factor markets are perfectly competitive, the first-order conditions for the firm's profit maximisation problem are given by the following form where $\mathbf{r_t}$ is the capital rental rate and $\mathbf{p_t}$ is the real price paid to utilised natural resources:

$$\mathbf{r_t} = \beta\,\frac{\mathbf{Yt}}{\mathbf{Kt}} \tag{4.4}$$

$$\mathbf{p_t} = (1-\beta)\,\frac{\mathbf{Yt}}{\mathbf{Ht}}$$

The economy is also populated by a unit measure of identical infinitely-lived households, each has perfect foresight and maximises a discounted stream of utilities over its lifetime in the following form:

$$\int_0^{\infty} \frac{1}{1-\sigma} (C_t^{1-\sigma} - 1)(e^{-pt})\, dt \text{ and } \sigma > 0, \sigma \neq 1 \tag{4.5}$$

Where C_t is the individual household's consumption, $p \in (0,1)$ is the subjective discount rate, and σ is the inverse of the intertemporal elasticity of substitution in consumption. The budget constraint faced by the representative household is given by the following form:

$$C_t + \check{K}_t + \delta K_t = r_t K_t + p_t H_t \text{ and } K_0 > 0 \text{ given} \tag{4.6}$$

Where $\delta \in [0,1]$ is the capital depreciation rate. The law of motion for total renewable resources, which is a proxy for environmental quality N_t, is given by the following form:

$$\dot{N}_t = F(N_t)\, N_t - H_t \text{ and } N_o > 0 \text{ given} \tag{4.7}$$

Where $F(N_t)$ is the regeneration function that is assumed to be strictly increasing in N_t. The rate of natural regeneration is independent of the environmental state, specifically $F(N_t) = \theta > 0$. H_t is the extraction of natural resources and the disposal of waste as both activities decrease the environment's absorption capacity represented by $F(N_t)\, N_t$. The household first-order conditions for the dynamic optimisation problem are as follows:

$$C_t^{-\sigma} = \lambda Kt \tag{4.8}$$

Which states that marginal benefit of consumption equals its marginal cost, which is the marginal utility of having an additional unit of physical capital. $\lambda_{Kt}(r_t - \delta) = -\lambda_{Kt}' + p\lambda_{Kt}$ and $\theta\lambda_{Nt} = -\lambda_{Nt}' + p\lambda_{Nt}$ are standard euler equations that govern the evolution of K_t and N_t over time. $\lambda_{Kt} p_t = \lambda_{Nt}$ shows that the firm utilises natural resources to the point where the marginal value of more output is equal to the marginal cost of resource depletion. $\lim_{t\to\infty} \lambda_{Kt} K_t\, e^{-pt} = 0$ and $\lim_{t\to\infty} \lambda_{Nt} N_t\, e^{-pt} = 0$ are the transversality conditions, and λ_{Kt} and λ_{Nt} are utility values of capital stock and natural resources, respectively.

Equations 4.3 and 4.4 show that the economy exhibits sustained endogenous growth whereby output, consumption and physical capital all display a common, positive constant growth rate given by g. Equation 4.7 implies that in the long run ($\dot{N}_t = 0$), total and utilised natural resources will reach their respective steady-state levels, N^* and H^*. This imposes a sustainable long-run environmental quality constraint where a constant level of pollution exactly matches the environment's absorption capacity.

Therefore, a balanced growth path is derived by making $\mathbf{X_t \equiv \frac{Ct}{Kt}}$ and re-expressing the model's equilibrium conditions as the following autonomous differential equations:

$$\frac{Xt'}{Xt} = \frac{1}{\sigma}\left(\beta A H_t^{1-\beta} - \delta - p\right) - A H_t^{1-\beta} + X_t + \delta \tag{4.9}$$

$$\frac{\hat{H}t}{Ht} = \frac{1}{\beta}\left[A(1-\beta)H_t^{1-\beta} - X_t + \theta\right]$$

$$\grave{N}_t = \theta N_t - H_t$$

Given the dynamic system equation 4.9, the balanced-growth equilibrium is characterised by a triplet of positive real numbers **(X*,H*,N*)** that satisfy the condition $\mathbf{X_t' = \hat{H}_t = \grave{N}_t = 0}$**.** The model economy exhibits a unique balanced-growth path along which the utilised natural resource maintains its steady-state level:

$$H^* = \left[\frac{\sigma\theta - [p - (\sigma-1)\delta]}{\beta A(\sigma-1)}\right]^{1/(1-\beta)} \tag{4.10}$$

Which leads to the expressions for X* and N* as follows:

$$X^* = A(1-\beta)(H^*)^{1-\beta} + \theta \text{ and } N^* = \frac{H*}{\theta} \tag{4.11}$$

It then follows that the common (positive) rate of economic growth **g** is given by the following form:

$$g = \beta A(H^*)^{1-\beta} - \theta - p \tag{4.12}$$

or

$$g = \frac{\theta - p}{\sigma - 1} \text{ and } \theta > p \text{ when } \sigma > 1 \tag{4.13}$$

As a result, the balanced-growth path's growth rate ceteris paribus is positively related to the steady-state level of utilised natural resources. As such, increased usage of services from the environment in production will increase the economy's rate of growth in output, consumption and physical capital. In addition, the quantity of utilised natural resources per unit of GDP steadily declines along the economy's balanced-growth path (Chambers and Guo, 2009). Using clean energy sources has a good impact on the environment and, as such, has the potential to improve ecosystem services and productivity, increasing productivity in economic sectors that rely on the ecosystem (Smulders et al., 2014). These long-term productivity benefits will offset the economic cost of reduced production following the transition from dirty to clean energy consumption (Smulders et al., 2014). The shift towards using renewable resources will also reduce greenhouse gas emissions, which will come at a direct mitigation cost, but the lower concentration of pollutants in the atmosphere, water bodies or even soil will generate longer-term productivity effects. Using renewable resources can also have health effects, as with less pollution, workers will be healthier and more productive. The general environment will be much cleaner, and less money will be spent on expenses such as water treatment (Smulders et al., 2014).

4.2.2 Empirical Review

Research with regard to the effects of renewable energy sources on economic growth has been well documented in economic literature; however, results and methodologies have varied greatly. Tugcu et al. (2012) used a classical and augmented production function to explain their effects on economic growth, and the results showed that clean energy is a contributing factor to economic growth. The study was consistent with Amri (2017) and Khobai et al. (2017), who both concluded a positive relationship between sustainable energy consumption and economic growth. Similarly, by using the long-run causality tests, Apergis and Danuletiu (2014) empirically explored the effect of clean energy on economic growth in several countries. Evidence showed that clean energy has a strong positive long-term relationship with real GDP for the full study and across countries. Causality existence supports the implementation of government policies that foster growth in the green energy industry.

Furthermore, Fu et al. (2021) and Shahbaz et al. (2020) concluded the positive bidirectional relationship between green energy consumption and economic growth. Kahia et al. (2016) included both clean and dirty energy consumption in their Cobb-Douglas production function, along with capital and labour factors, to determine the effect of dirty and clean energy consumption on MENA Net Oil Exporting Countries' economic growth. They used a panel co-integration approach, and the results were in line with the previously reviewed literature (causality between green energy and economic growth). Ntanos et al.(2018) followed a similar approach by including renewable energy sources in their error-corrected log-linear specification model and found similar results.

Armeanu et al. (2017) explored the influence and causal relationship between renewable energy and sustainable economic growth of 28 European Union countries. By estimating panel data fixed effects regression models, they showed that renewable energy overall and by type (biomass, hydropower, geothermal, wind and solar) positively impact GDP per capita. Similar results were found by Chang et al. (2015), who used causality methodology to investigate the bidirectional causal relationship between renewable energy consumption and economic growth in G7 countries.

Soava et al. (2018) also investigated the causal relationship between economic growth and renewable energy consumption using panel data techniques. The empirical results showed a positive impact of renewable energy consumption on economic growth and justified the political decision of the European Union concerning the necessity of increasing renewable energy consumption. Similarly, Chen et al. (2022) investigated the association between various sources of renewable energy and economic growth by using a heterogeneous approach for panel data and econometrics techniques that allowed for cross-sectional reliance and slope heterogeneity. They showed a positive impact of renewable energy sources, such as hydroelectric, solar PV, wind, geothermal and biomass power, on economic growth.

Rafindadi and Ozturk (2017) used various tests (Clemente-Montanes-Reyes detrended structural break test, the Bayer-Hanck combined co-integration test and the autoregressive distributed lag bounds testing approach to co-integration) to investigate the impact of renewable energy consumption on German economic growth. The results showed that a 1% increase in renewable energy consumption increases German economic growth by 0.2194%. Similarly, Alper and Oguz (2016) used an asymmetric causality test and autoregressive distributed lag approach to investigate the causality among economic growth, renewable energy consumption, capital and labour in European Union countries. They showed that renewable energy consumption positively impacts economic growth for all investigated countries.

Qudrat-Ullah and Nevo (2021) investigated the impact of renewable energy consumption on economic growth in African countries. The results from the Generalized Method of Moments estimation technique showed that renewable energy adoption and development increase economic growth in Africa. Similarly, Vural (2020) explored the effects of renewable energy on output for six Sub-Saharan African countries using panel estimation techniques, and the results showed that a 1% increase in the use of renewable energy increases output by 0.083%. Sahlian et al. (2021)

also used a panel analysis to analyse if an increase in clean energy consumption promotes economic growth. They showed that clean energy can decrease or neutralise the negative impact of greenhouse gases while maintaining economic growth.

The reviewed literature has shown, through various panel and time series techniques, that renewable energy sources generally positively impact economic growth. However, some studies found different results, such as İnal et al. (2022), who investigated the nexus between renewable energy and economic growth in oil-producing African countries. The study used a bootstrap panel co-integration technique, and the results showed no significant effect of renewable energy on economic growth, confirming the neutrality hypothesis. Similarly, Maji et al. (2019) estimated the impact of renewable energy on economic growth in West African countries using panel dynamic ordinary least squares. The results showed that renewable energy consumption decreases economic growth in these countries due to the nature and source of renewable energy use in West Africa, which is mainly wood biomass. This shows that using renewable energy can slow economic growth by lowering productivity when unclean and inefficient sources are used. These results are similar to those of Omri and Belaïd (2021), who concluded that clean energy consumption, together with CO_2 emissions from liquid fuel consumption and CO_2 intensity, negatively affect economic growth.

Regarding policy analysis, Inglesi-Lotz and Weideman (2016) used the Bai and Perron break test to understand whether the policies followed by the South African government between 1990 and 2010 impacted the behaviour of consumers and producers of renewable energy. They showed that while the government has made considerable commitments to renewable energy, these had not yet led to a structural break in the renewable energy market.

A growing body of extant literature is confirming a strong relationship between clean energy in the energy mix and economic growth. However, much of the literature has followed time series or panel data models, making it difficult to interpret this relation as causal rather than an association. Limited research has assessed the impact of specific green energy policies on economic growth. Unlike the extant literature, the current study followed a different approach by employing natural experiment approaches (Regression Discontinuity in time and Synthetic Control methods) to pin down the causal effects of green energy policies and the clean energy share in the energy mix on economic growth in South Africa. This was achieved by rigorously examining the impact of green energy policy shifts on economic growth, which has not been a common theme in existing economic literature. Causal inference in nonexperimental studies usually requires a strong, untestable assumption that no unobserved factor confounds the relationship between the exposure and the outcome. Violations of this assumption will lead to a biased estimation of causal effects; however, this assumption is not required for causal inference in natural experiments, which is a strong motivation for natural experiments.

A research gap exists regarding analysing the effectiveness of green energy policies on economic growth, and the current study aimed to fill this gap by conducting a natural experiment on three different renewable energy policies in South Africa to understand their causal effect on economic growth better. Results from this research will be significant, as they can be used by policymakers in South Africa when developing new renewable energy policies by understanding how previous policies have affected the country's economic growth.

4.3 Implementation of Renewable Energy Policies

4.3.1 White Paper on the Energy Policy of the Republic of South Africa (1998)

Following the White Paper on the Energy Policy of the Republic of South Africa (1998), implementation of renewable energy took place in Klipheuwel in the Western Cape, where Eskom demonstrated a wind farm for bulk electricity generation. Klipheuwel Wind Farm's first unit started generating in 2002, and at the time, it was expected to generate at a load factor of 20 to 30%. The wind farm had a total capacity of 3.2 MW and was made up of three units, which were turbines of 660 kW, 1 kW and 750 kW, and the blades spanned 47, 66 and 48 metres, respectively. The wind speed was between 11 and 50 kilometres per hour, and full power was reached at 50 kilometres per hour (DoE, 2020).

The Hluleka hybrid mini-grid system in the Eastern Cape Hluleka nature reserve on the wild coast is another renewable energy implementation post the White Paper on the Energy Policy of the Republic of South Africa (1998), which has been operational since June 2002. The grid consists of three-shell solar PV module arrays fitted with 56 100-watt PV modules wired in series and 2.5 kW wind generators. Another hybrid system serves 220 Lucingweni dwellings; it consists of 36 kW wind generators and 50 kW solar PV panels (DoE, 2020). The Darling Wind Farm, with four wind turbines that produce 5.2 MW of electricity each, was commissioned in 2008 to produce electricity commercially. The turbines were erected below Moedmaag Hill; the structure was 50m high, and the blades have a 31m span (DoE, 2020; Segar, 2008).

These renewable energy implementations resulted from the White Paper on the Energy Policy of the Republic of South Africa (1998), which highlighted the importance of using wind energy to produce electricity in a clean manner to increase South Africa's energy capacity. The policy was established in 1998, with implementations commissioned a few years later. However, before the start date of the operation of the wind farms, there was already economic activity leading up to the operation of the wind farms, including national savings and investments in renewable energy technologies and capital formation, as well as employment of workers to construct the farms, which all contribute to economic growth. Hence, this study looked at the effects of this policy on economic growth from 1998, as even before the start date of electricity generation, there was already economic activity due to the policy. Once the wind farms are operational, there is also an effect of renewables on economic growth, together with the jobs created to maintain operations.

4.3.2 White Paper on Renewable Energy Policy (2003)

Following the White Paper on Renewable Energy Policy (DoE, 2003), multiple renewable energy projects took place. One such project was the Bethlehem Hydro Sol Plaatjie Power Station, which utilises the river flow from the Lesotho Highlands Water Scheme and generates 3 MW of output. The hydropower station started operating in 2009, and its transmission lines connect to the national grid. The intake is next to the Sol Plaatje dam wall, with a powerhouse downstream. The water flowing over the dam walls is diverted to the power plant to generate power and then returned to the river (Eigenbau, 2009).

The Mariannhill Landfill Gas-to-Electricity project is another renewable energy implementation that followed the White Paper on Renewable Energy Policy (2003). This project started in 2004 in Durban, KwaZulu-Natal, a solid waste project whereby collected gas was used to generate renewable energy, feeds to the municipal grid to replace electricity supplied by dirty energy consumption. This Durban Municipal solid waste project was one of the first registered under the clean development mechanism in Africa. The electricity produced from the landfill gas is sold to the eThekwini Municipality electricity department (World Bank, 2015). Another KwaZulu-Natal landfill gas-to-electricity project that also started in 2004 is the Bisasar Road Landfill Gas-to-Electricity project.

4.3.3 Integrated Resource Plan 2010

The implementation of the IRP 2010 was carried out through ministerial determinations, which were regulated by the Electricity Regulation Act No. 4 of 2006 on new generation capacity. The Department of Mineral Resources and Energy has reported that since the implementation of the IRP 2010, 6 422 MW of electricity was procured from renewable energy sources by 2019 (DoE, 2019).

The Dassiesklip wind energy project is one of the many green energy projects implemented post the IRP 2010. The wind farm was built in the Western Cape and includes nine 3 MW turbines with a total capacity of 27 MW (Barradas, 2013). Another wind farm implemented was the Van Stadens Wind Farm in Port Elizabeth, which started in 2012. The Hopefield wind farm was also commissioned in 2013 and is in the Western Cape, with a total capacity of 65.4 MW. The wind farm comprises 37 vestas V100 1.8 MW wind turbines, and the farm spans about 900 hectares (Azari, 2013).

Following the IRP 2010, the KaXu Solar One concentrated solar power plant, which has a capacity of 100 MW, was commissioned in 2015. The Northern Cape plant supplies green energy to approximately 80 000 homes while offsetting 315 000 tonnes of CO_2 emissions annually (Power Technology, 2015). The Kalkbult Solar PV plant, which has a 75 MW capacity, was also commissioned in 2013 and supplies electricity to Eskom. The plant is in Northern Cape and supplies electricity to 33 000 households (Scatec, 2014). The Rustmo1 Solar Farm, established in the North West province, commenced operations in 2013. The solar plant has a capacity of 7 MW and supplies electricity to Eskom (Hulisani, 2019).

4.4 Natural Experiments Theoretical Framework

4.4.1 Regression Discontinuity Framework

Causal inference in nonexperimental studies usually requires a strong, untestable assumption that no unobserved factor confounds the relationship between the exposure and the outcome. Violations of this assumption will lead to a biased estimation of causal effects. In their study, Bor et al. (2014)

stated that the Regression Discontinuity design is one important quasi-experimental study design in which this assumption is not required for causal inference. Regression Discontinuity designs can be implemented when the exposure of interest is assigned by the value of a continuously measured random variable and whether that variable lies above (or below) some threshold value. Provided that subjects cannot precisely manipulate the value of this variable, assigning the exposure is as good as random for observations close to the threshold, and valid causal effects can be identified.

By definition, causal inference requires comparing outcomes for the same unit of analysis in two states of the world: if treated, $\mathbf{Y_i\,(1)}$ and if not treated, $\mathbf{Y_i\,(0)}$. In this study, the unit of analysis was South Africa's GDP $\mathbf{(Y_i)}$ before the implementation of renewable energy policies $\mathbf{(Yi\,(1))}$. Analysis was also conducted to compare outcomes from different renewable energy policies, particularly looking at the current or newly implemented renewable energy policies $\mathbf{(Y_i\,(1))}$ and previous (old) implemented renewable energy policies $\mathbf{(Yi\,(0))}$.

Only one of these potential outcomes is ever observed: $\mathbf{Y_i = Y_i\,(1)}$ **if** $\mathbf{RE_i = 1}$ or $\mathbf{Y_i = Y_i\,(0)}$ if $\mathbf{RE_i = 0}$ where $\mathbf{RE_i = \{0,\ 1\}}$ is a binary variable for the implementation of renewable energy policies. The challenge of nonexperimental studies is that if there are unobserved confounders of the relationship between $\mathbf{T_i}$ and $\mathbf{Y_i}$, the potential outcomes will be correlated with treatment assignment, and effect estimates will be biased. Regression Discontinuity designs are feasible when the probability of treatment assignment changes discontinuously at some threshold value, $\mathbf{C}$, of a continuous assignment variable.

$$\mathbf{Z_i : lim_{Z \downarrow C}\, Pr\,(RE_i = 1 \mid Z_i = z\,) \neq lim_{Z \uparrow C}\, Pr\,(RE_i = 1 \mid Z_i = z\,)} \tag{4.14}$$

Where $\mathbf{C}$ is the $\mathbf{date_{it}}$ of the implementation of the renewable energy policy.

If the probability of treatment assignment changes from 0 to 1 at the threshold, then treatment assignment is a deterministic function of $\mathbf{Z_i : RE_i = 1[Z_i < C]}$ **where** $\mathbf{1[.]}$ is the indicator function, and this is known as sharp Regression Discontinuity. Therefore, when measuring the causal impact of renewable energy policy implementation on GDP, the probability of the renewable energy implementation changes from **0** (no renewable energy policy implementation) to **1** (renewable energy policy implementation). A motivation for Regression Discontinuity is that in a small neighbourhood around **C**, as the range goes toward **0**, treatment assignment (renewable energy implementation) is ignorable, that is, independent of the potential outcomes, just as in randomised experiments: $\lim_{\mathcal{E}\to 0} Y_i(0), Y_i(1) \perp RE_i \mid C = -\mathcal{E} <= Z_i < C + \mathcal{E}$. This follows from the assumption that Z_i is continuous at C and the relationship between Z_i and the potential outcomes $Y_i(0), Y_i(1)$ are continuous at C.

Under these assumptions, the conditional distribution $F(Y_i(0)) \mid Z_i)$ and $F(Y_i(1)) \mid Z_i)$ are identical as Z_i approaches C from above and below. The average causal effect is then given by estimating the differences in the means at the threshold $E[Y_i(1) \mid Z_i = C] - E[Y_i(0) \mid Z_i = C]$. Because this is a sharp discontinuity, before and on the **date** that the renewable energy policy is implemented $Z_i \leq C$, then $E[Y_i \mid Z_i] = E[Y_i(0) \mid Z_i]$ and after the implementation of renewable energy policy $Z_i > C$, then $E[Y_i \mid Z_i] = E[Y_i(1) \mid Z_i]$.

Figure 4.1 shows the continuous conditional expectation functions for the potential outcomes, $E[Y_i(0) \mid Z_i = z]$ and $E[Y_i(1) \mid Z_i = z]$. The solid lines show the observed data, $E[Y_i \mid Z_i]$ and the dotted lines show the regions of the potential outcome conditional expectation functions that are not observed. At the threshold, both $E[Y_i(0) \mid Z_i = z]$ and $E[Y_i(1) \mid Z_i = z]$ are identified by limits in the observed data. Thus, the sharp Regression Discontinuity design identifies the average causal effect at the threshold:

$$\text{Average Causal Effect} = \lim_{Z \uparrow C} E[Y_i \mid Z_i = z] - \lim_{Z \downarrow C} E[Y_i \mid Z_i = z] \tag{4.15}$$

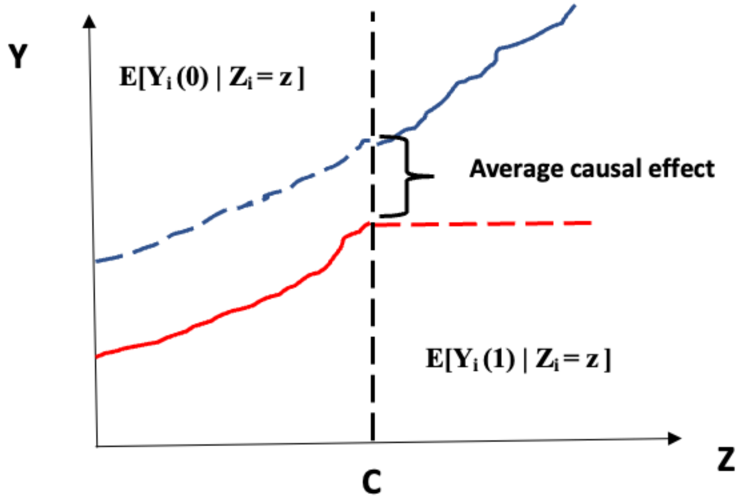


Figure 4.1: Sharp Regression Discontinuity design

4.4.2 Bayesian Structural Time-Series Framework

Inferring causal impact using Bayesian Structural Time-Series models infer causal impact based on a diffusion-regression state-space model that predicts the counterfactual response in a Synthetic Control that would have occurred had no intervention taken place. Leaning on the study by Brodersen et al. (2015), Bayesian Structural Time-Series models generalise the widely used difference-in-difference technique to a time-series setting by explicitly modelling the counterfactual of a time series observed both before and after the intervention. It provides a fully Bayesian time-series estimate for the effect and uses model averaging to construct appropriate synthetic controls for counterfactual modelling.

The current study focused on measuring the impact of the first renewable energy policy implementation on GDP in South Africa. The causal impact of a treatment (renewable energy policy implementation) is the difference between the observed response variable time series (actual GDP) and the unobserved time series (counterfactual GDP) that would have been obtained had there been no treatment (no renewable energy policy implementation). The construction of the counterfactual is based on the Synthetic Control approach, which requires three sources of information. The first is the time-series behaviour of the response itself prior to the intervention. The second is the behaviour of other time series that were predictive of the target series prior to the intervention, and lastly, the available prior knowledge about the model parameters, as elicited.

The three sources are combined using a state-space time-series model where one component of state is a linear regression on the contemporaneous predictors. The model framework allows choice from a set of potential controls by placing a spike and slab prior on the set of regression coefficients and by allowing the model to average over the set of controls (Brodersen et al., 2015). The posterior distribution of the counterfactual time series is then computed given the value of the target series in the pre-intervention period, along with the values of the controls in the post-intervention period. Subtracting the predicted from the observed response during the post-intervention period gives a semiparametric Bayesian posterior distribution for the causal effect.

State-space models differentiate between observation equations that specify how a given system state translates into measurements and state equations that explore the transition of a set of latent variables from one time point to the next. The approach by Brodersen et al. (2015) uses characteristics from the state-space paradigm, such as the ability to flexibly assist different kinds of assumptions about the latent state and emission processes underlying the observed data, including local trends and seasonality. There is also flexibility regarding summarising posterior inferences due to the full Bayesian approach and a regression component that precludes rigid commitment to the set of controls. Space models for time-series data proposed by Brodersen et al. (2015) can be defined in the following two equations:

$$\mathbf{y_t = Z_t{}^T \alpha_t + \varepsilon_t} \tag{4.16}$$

$$\mathbf{\alpha_{t+1} = T_t\, \alpha_t + R_t\, \eta_t} \tag{4.17}$$

Where $\boldsymbol{\varepsilon_t \sim N(0, \sigma^2{}_t)}$ and $\boldsymbol{\eta_t \sim N(0, Q_t)}$ are independent of all other unknowns. Equation 4.16 is the observation equation that links the observed data $\mathbf{y_t}$ to a latent *d*-dimensional state vector $\boldsymbol{\alpha_t}$. Equation 4.17 is the state equation that governs the evolution of the state vector $\boldsymbol{\alpha_t}$ through time. $\mathbf{y_t}$ is a scalar observation, $\mathbf{Z_t}$ is a *d*-dimensional output vector, $\mathbf{T_t}$ is a $\boldsymbol{d \times d}$ transition matrix, $\mathbf{R_t}$ is a $\boldsymbol{d \times q}$ control matrix, $\boldsymbol{\varepsilon_t}$ is a scalar observation error with noise variance $\boldsymbol{\sigma_t}$, and $\boldsymbol{\eta_t}$ is a *q*-dimensional system error with a $\boldsymbol{q \times q}$ state-diffusion matrix $\mathbf{Q_t}$, where $\mathbf{q \leq d}$**.** The components of state include the local linear trend, which is defined by the following two equations:

$$\boldsymbol{\mu_{t+1} = \mu_t + \delta_t + \eta_{\mu,t}} \tag{4.18}$$

$$\boldsymbol{\delta_{t+1} = \delta_t + \eta_{\delta,,t}} \tag{4.19}$$

Where $\boldsymbol{\eta_{\mu,t} \sim N(0, \sigma^2{}_\mu)}$ and $\boldsymbol{\eta_{\delta,,t} \sim N(0, \sigma^2{}_\delta)}$**.** The $\boldsymbol{\mu_t}$ component is the value of the trend at time $\mathbf{t}$. The $\boldsymbol{\delta_t}$ component is the expected increase in $\boldsymbol{\mu}$ between times $\mathbf{t}$ and $\mathbf{t + 1}$, so it can be thought of as the slope at time $\mathbf{t}$. The components of state also include seasonality, which has the following model in the time domain:

$$\boldsymbol{\tau_{t+1} = -\sum_{s=0}^{S-2} \tau_{t-s} + \eta_{\tau,t}} \tag{4.20}$$

Where $\boldsymbol{s}$ represents the number of seasons, and $\boldsymbol{\tau_t}$ denotes their joint contribution to the observed response $\mathbf{y_t}$. The state in this model consists of the $\boldsymbol{S} - 1$ most recent seasonal effects, but the error term is a scalar, so the evolution equation for this state model is less than full rank. The mean $\boldsymbol{\tau_{t+1}}$ is such that the total seasonal effect is zero when summed over $\boldsymbol{S}$ seasons. The part of the transition matrix $\mathbf{T_t}$ representing the seasonal model is a $\boldsymbol{S-1} \times \boldsymbol{S-1}$ matrix with −1s along the top row, 1s along the sub-diagonal and 0s elsewhere.

The components of state also include contemporaneous covariates with static coefficients. Control time series that received no treatment are important to the method for obtaining accurate counterfactual predictions since they account for variance components that are shared by the series, including the effects of other unobserved causes otherwise unaccounted for by the model. Control series are included in the model through linear regression, and its coefficient can be static or time-varying. A static regression can be written in state-space form by setting $\mathbf{Z_t} = \boldsymbol{\beta}^{\mathbf{T}}\mathbf{X_t}$ and $\boldsymbol{\alpha}_{\mathbf{t}} = \mathbf{1}$. The two natural experiments were used to prove or disprove the green growth theory regarding the impact of renewable energy policy implementation on economic growth in South Africa.

4.5 Methodology

This section provides the methodology used to measure the impact the green energy policies' introduction has had on the economic growth in South Africa by analysing the GDP growth drift. The date of the green energy policy will be regarded as the date of the implementation of the policy, as there was an informal share of clean energy in South Africa's energy mix before each policy. However, the policies formalised the introduction of clean energy into the energy mix and provided achievable targets. The first natural experiment was the Regression Discontinuity in time, which measured the economic growth drift due to the introduction of three green energy policies. The second natural experiment was a Synthetic Control using Bayesian Structural Time-Series models to analyse the GDP growth drift due to the introduction of the White Paper on the Energy Policy of the Republic of South Africa (1998). A description of the data and its sources follows.

4.5.1 Data Source and Descriptive Statistics

The quarterly GDP at market price data used in this study are derived from the South African Reserve Bank from the first quarter of 1980 to the third quarter of 2020. This period was based on the availability of data. The gross fixed capital formation data used in this study are derived from the South African Reserve Bank from the first quarter of 1993 to the third quarter of 2020. The gross fixed capital formation data from the first quarter of 1981 to the fourth quarter of 1992 were estimated using a forecast and extrapolation technique, while data from the first quarter of 1980 to the fourth quarter of 1980 was estimated using the last observation carried forward technique. Both techniques were used to handle the missing gross fixed capital formation data. Figure C.1 (Appendix C) illustrates the GDP and gross fixed capital formation.

Figure C.2 (Appendix C) shows the quarterly GDP and the point of introduction of the three renewable energy policies in 1998, 2003 and 2010. Each policy's impact on the GDP growth rate was investigated to determine any growth drift in GDP. Figure C.3 (Appendix C) is the aggregated historical energy balances reported by the Department of Minerals and Energy, which shows the indigenous primary energy production of the listed energy sources in South Africa, excluding coal production. The indigenous primary energy production of biomass and waste has been consistently high and continues to increase. The primary energy production of solar and wind energy gradually increased over the years as South Africa continues to develop the renewable energy sector gradually.

4.5.2 Regression Discontinuity Estimates

The Regression Discontinuity design to estimate the effects of introducing renewable energy in the energy mix on South Africa's economic growth takes the following specification:

$$\boldsymbol{Y_{it} = \alpha + \beta RE_{it} + f(date_{it}) + \varepsilon_{it}} \tag{4.21}$$

Where $\mathbf{Y_{it}}$ denotes GDP **i** during quarter **t**; $\mathbf{RE_{it}}$ denotes a binary variable, which is equal to one after the introduction of renewable energy and zero otherwise; $\mathbf{date_{it}}$ denotes the date measured in quarters from the start of the study. The function **F (.)** eliminates the endogenous relationship between $\boldsymbol{\varepsilon_{it}}$ and the **date,** which should not change discontinuously on or near the date of the start of the policy intervention. The Regression Discontinuity is sharp as the running variable $\mathbf{date_{it}}$ determines the introduction of renewable energy policies.

To estimate this model, the Imbens and Lemieux (2008) approach will be followed, and the estimated local linear regression will take the following form:

$$\mathbf{Y_{it} = \boldsymbol{\alpha} + \boldsymbol{\beta}_1\, RE_{it} + \boldsymbol{\beta}_2\, date_{it} + \boldsymbol{\beta}_3\, RE_{it} \cdot date_{it} + \boldsymbol{\varepsilon}_{it}} \tag{4.22}$$

Where the variable $\mathbf{date_{it}}$ is normalised to zero on the day the policy begins, and the function $\mathbf{F(date_{it})}$ is specified as $\boldsymbol{\beta}_2\, \mathbf{date_{it}} + \boldsymbol{\beta}_3\, \mathbf{RE_{it} \cdot date_{it}}$ whereby both $\mathbf{date_{it}}$ and $\mathbf{RE_{it}}$ only vary by date. For the days that are close to the day the renewable energy policy was implemented, the variables $\mathbf{date_{it}}$ and $\mathbf{date_{it} \cdot RE_{it}}$ absorb any smooth relationship between the **date** and $\boldsymbol{\varepsilon_{it}}$. When $\boldsymbol{\varepsilon_{it}}$ does not change discontinuously when the renewable energy policy begins, the estimated coefficient **β** will be unbiased and the Regression Discontinuity will be valid. A single group interrupted time-series analysis (Linden & Arbor, 2015) will be used to indicate the immediate effect **(β_1)** and the long-term effect **(β_3)** of the three renewable energy policies.

4.5.3 Synthetic Control using Bayesian Structural Time-Series Models

The essence of this exercise was to estimate the impact of green energy policies and inclusion in the energy mix on economic growth. In this part of the study, the causal impact of the green energy policy on economic growth was inferred using the diffusion-regression state-space model, which can predict a counterfactual economic growth response in a Synthetic Control that would have occurred had no green energy policy taken place. This allows for a generalisation of the difference-in-difference approach to time series by modelling the counterfactual economic growth observed before and after the renewable energy policy's introduction.

The state-space model differs from the classical difference-in-difference as it incorporates empirical priors on the parameters in a fully Bayesian treatment, allowing it to infer the temporal evolution of attributable impact. The model accommodates sources of variation, such as seasonality, local trends and the time-varying influence of contemporaneous covariates (Brodersen et al., 2015). Examining causal impact using Bayesian Structural Time-Series models improved existing methods by using model averaging to construct synthetic controls, making it possible to model counterfactuals and provide a fully Bayesian time series estimate for causal effect (Brodersen et al., 2015). In this study, the causal effect is the difference between the observed economic growth series and the counterfactual economic growth series that would have been observed had there been no renewable energy policy intervention.

Three sources of information were required to construct the Synthetic Control for GDP. The first source is the time-series behaviour of GDP before the renewable energy policy intervention. The second source is the behaviour of gross fixed capital formation in South Africa, which is predictive of the country's economic growth prior to the green energy policy intervention. In a Bayesian framework, the third source of information is the available prior knowledge about the model parameters. All three sources of information were combined using a state-space time-series model, where one component of the state is a linear regression on the contemporaneous predictors (Brodersen et al., 2015).

4.5.4 Bayesian Structural Time-Series Models

To examine the potential causal impact of the White Paper on the Energy Policy of the Republic of South Africa (1998), which is regarded as the first formalised introduction of green energy into the energy mix, on the GDP in South Africa, the state-space Bayesian Structural Time-Series models for time series data were employed.

The Bayesian Structural Time-Series model can be defined as:

$$y_t = \mu_t + \tau_t + \beta K_t + \varepsilon_t \tag{4.22}$$

$$\mu_{t+1} = \mu_t + w_t \tag{4.23}$$

$$\tau_{t+1} = -\sum_{s=0}^{S-2} \tau_{t-s} + v_t \tag{4.24}$$

The response variable $\mathbf{y_t}$ is the GDP at a time (quarter) **t**. Equation 4.22 includes all the components that explain the behaviour of economic growth ($\mathbf{y_t}$). The first component, $\boldsymbol{\mu_t}$, is the value of the trend at time **t**. A local linear trend is assumed in which the expected increase in $\boldsymbol{\mu}$ between **t** and **t+1**, presents a random walk pattern (Brodersen et al., 2015). $\boldsymbol{\tau}_t$ is the seasonal component, with S being the number of seasons. The vector $\mathbf{K_t}$ is the control series gross fixed capital formation to be predictive of the response variable GDP and parameter $\boldsymbol{\beta}$. $\boldsymbol{\varepsilon_t \sim N(0, \sigma^2_\varepsilon)}$, $\mathbf{w_t \sim N(0, \boldsymbol{\sigma}^2_w)}$, and $\mathbf{v_t \sim N(0, \boldsymbol{\sigma}^2_v)}$ are independent and identically distributed normal errors. The numerical results for the causal impacts were obtained using the CausalImpact package in R software.

4.6 Results and Discussion

4.6.1 Regression Discontinuity

Table 4.1 shows the results from the Regression Discontinuity at three different points of renewable energy intervention. The first is the White Paper on the Energy Policy of the Republic of South Africa (1998), where the intervention was modelled to have begun in the 4th quarter of 1998 (December 1998). In the first quarter of the introduction of the formalised renewable energy paper within the energy mix, there appears to be a significant increase in GDP of 2.7%. This is regarded as the short-term effect of the renewable energy policy intervention. The long-term effect of the policy intervention has resulted in a 0.5% significant quarterly increase in the GDP trend. Overall, the post-intervention trend increased quarterly by 0.8%.

The second intervention is that of the White Paper on Renewable Energy Policy (2003), where the intervention was modelled to have begun in the 4th quarter of 2003 (November 2003). Comparing the second intervention with the first intervention, the immediate short-term effect of the second intervention significantly increased GDP growth by 2.6%. This can be attributed to an improvement in the new renewable energy policy, as the White Paper on Renewable Energy Policy (2003) is more elaborative and clearly outlines the country's renewable energy goals and targets. The long-term effect of the policy is statistically insignificant, as such, there is no evidence of a long-term treatment effect.

The third intervention is that of the IRP 2010, which was modelled to have begun in the 4th quarter of 2010 (October 2010). The results in Table 4.1 show that there is no evidence of a short-term effect of the IRP on economic growth, as the coefficient is statistically insignificant. This means that the observed data does not show strong evidence for the existence of the effect and not necessarily that the effect does not exist. The long-term effect of the plan on economic growth is negative and statistically significant. This could be considered consistent with some studies that found that renewable energy's impact negatively affects GDP (Maji et al., 2019; Omri & Belaïd, 2021) due to the use of unsafe wood biomass, which has been largely used in South Africa post 2010 (Figure C.3, Appendix C). However, since the economic growth data used in this study contains effects of the COVID-19 pandemic on GDP, and as the data goes up to the third quarter of 2020, the decline can also be attributed to the pandemic and not necessarily to inefficient implementation of the IRP. The economic growth also appears to have increased quarterly by 0.3% before introducing the first intervention. Overall, economic growth increased by 0.9% quarterly after the second intervention and 0.2% quarterly after the third intervention. Figure 4.2 provides a visual display of these results.

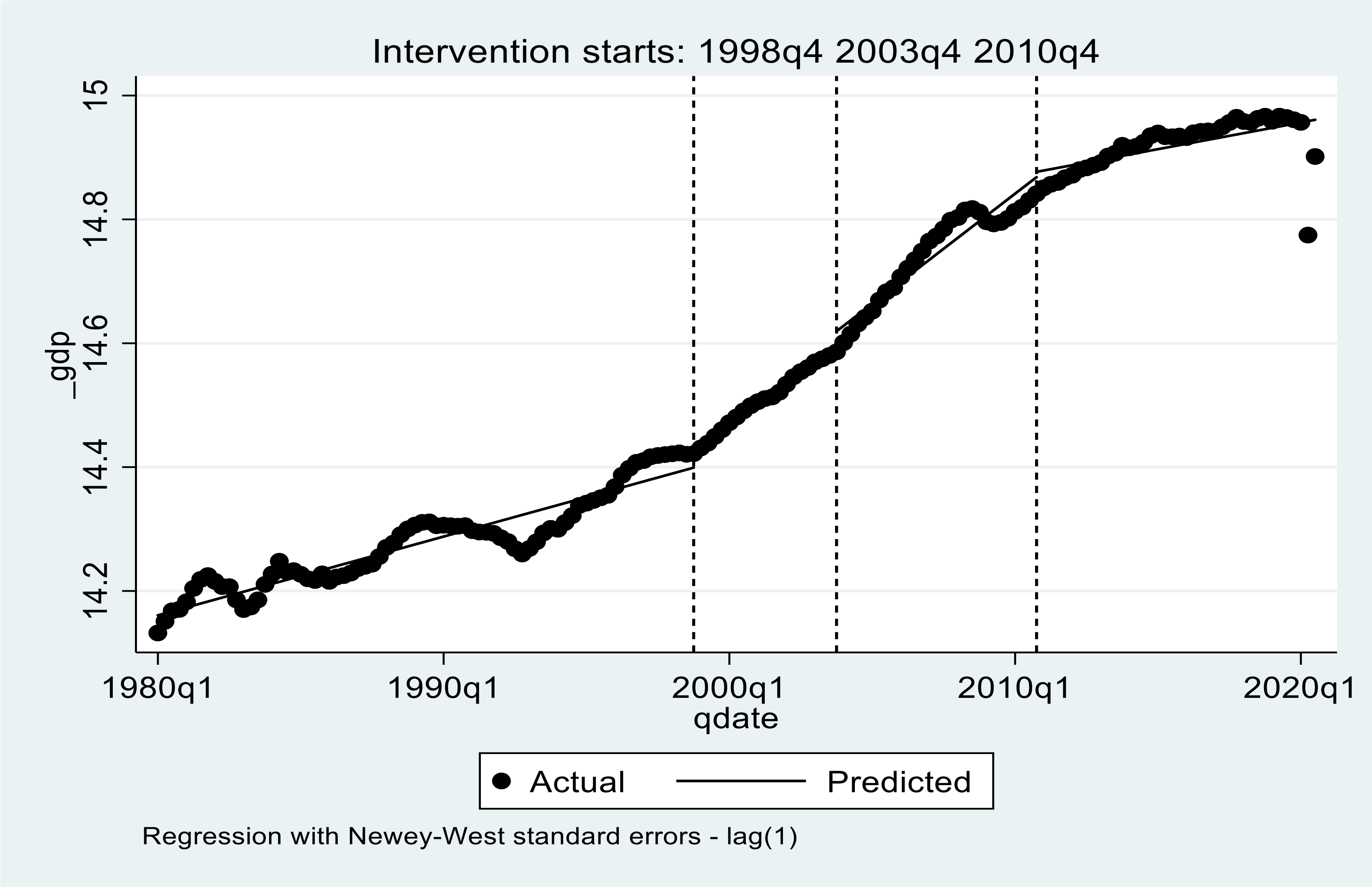
These results are expected as the reviewed literature has shown a strong, mostly positive relationship between renewable energy consumption and economic growth. Each renewable energy policy has increased capital accumulation and technology for the construction of renewable energy power plants. This has also resulted in increased employment for workers in the construction, maintenance and operations of the renewable energy power plants. The reduced greenhouse emissions due to this transition to green technologies also has ecological impacts that positively affect TFP. This results in an overall positive impact of renewable energy policy intervention on economic growth in South Africa.

Using Regression Discontinuity to pinpoint causality provides a more powerful design in determining the impact of renewable energy consumption on economic growth compared to extant literature that made use of nonexperimental designs where the relationship between economic growth and renewable energy can be assessed to be more of an association than causation. This analysis is arguably a first of its kind and the results are able to determine the effectiveness of each policy intervention with regards to its impact on economic growth.

Table 4.1: Regression Discontinuity results

	Regression with Newey-West standard errors		
	1998	2003	**2010**
Date	0.003***	0.003***	**0.003*** **
	(16.14)	(16.14)	**(16.14)**
Renewable energy policy	0.027***	0.026**	**0.009**
	(2.70)	(2.37)	**(0.44)**
Renewable energy policy * date	0.005***	0.0005	**-0.007*** **
	(20.15)	(0.61)	**(-5.66)**
Intercept	14.16***	14.16***	**14.16*** **
	(2002.1)	(2002.1)	**(2002.1)**
Post-intervention linear trend	0.008***	0.009***	**0.002*** **
	(48.81)	(11.01)	**(2.52)**
F-test	**2080.07*** **		

T-statistics of coefficients in brackets ();*(**) [***] denote 10%, 5%, 1% levels of statistical significance, respectively


Intervention starts: 1998q4 2003q4 2010q4

Regression with Newey-West standard errors - lag(1)

<u>Figure 4.2: Gross domestic product (GDP) from quarter 1 (q1) 1980 to q1 2020 showing points of intervention of renewable energy in the energy mix</u>

4.6.2 Bayesian Posterior Estimates

The results for the posterior estimates of the effect of the introduction of green energy policies into the energy mix on South Africa's economic growth are in Table 4.2. The average values for the actual data and forecasted (predicted) data are shown, as well as the absolute and relative effects of introducing green energy into the energy mix. During the post-renewable energy policy intervention, the GDP had an average value of about R2.64 million.

However, had renewable energy policy introduction not occurred, the average value would have been R2.04 million with a 25541 standard deviation and a 95% confidence interval of this counterfactual prediction being [R1.99 million, R2.09 million]. To estimate the causal effect of renewable energy introduction into the energy mix on economic growth, the predicted average value was subtracted from the actual observed value. In absolute terms, this effect is R0.60 million with a 95% confidence interval of [R0.55 million, R0.65 million]. In relative terms, the GDP in South Africa showed an increase of about 30% with the 95% confidence interval of this percentage being [27%, 32%]. This means that the positive effect observed after the formalised introduction of renewable energy is statistically significant at a 5% significance level.

The posterior tail-area probability value of 0.003 indicates that there is only a 0.3% chance that renewable energy introduction would have a negative effect on GDP in South Africa, which reinforces the above findings that the positive causal effect is statistically significant. The cumulative column in Table 4.2 represents the summing of individual data points after the introduction of renewable energy. The GDP has an overall value of R229.50 million and by contrast, had renewable energy intervention not taken place, the sum was expected to be R177.09 million. The 95% confidence interval of this prediction is [R172.97 million, R181.56 million].

Table 4.2: Results of posterior estimates (inference)

	Average **(R million)**	**Cumulative** **(R million)**
Actual	2.64 m	229.50 m
Prediction	2.04 m (25541) [1.99 m, 2.09 m]	177.09 m (2222075) [172.97 m, 181.56 m]
Absolute effect	0.60 m (25541) [0.55 m, 0.65 m]	52.0 m (2222075) [48.0 m, 57.0 m]
Relative effect	30% ** (1.3%) [27%, 32%]	p = 0.003

The values in square brackets show a 95 % confidence interval while those in round brackets are standard deviations; ** represents a 5% significance level; p stands for Posterior tail-area probability; m represents million ZAR rands.

4.6.3 Bayesian Posterior Distribution Graphs

This section considers the impact of introducing renewable energy policies on economic growth by analysing posterior distribution graphs. The study assessed the time path of the effect of renewable energy on economic growth. In Figure 4.3, the blue-dotted lines denote the time path of the predicted values, whereas the black line denotes the time path of the actual values. The difference between the blue-dotted and black lines (the original panel) measures the average effect of the green energy policy on economic growth (the pointwise panel). The cumulative panel measures the cumulative impact, and the blue areas denote 95 % confidence intervals.

From Figure 4.3 and using the pointwise and cumulative panels, the positive impact of introducing renewable energy into the energy mix on economic growth is statistically significant. This is because the blue line within the 95 % confidence level is above zero after the introduction of the White Paper on the Energy Policy of the Republic of South Africa (1998), confirming the quantitative results discussed above. Based on these results, it can be said that introducing renewable energy positively impacts South Africa's economic growth.

The Bayesian posterior estimates and distribution graphs approach to determine the causal impact of White Paper on the Energy Policy of the Republic of South Africa (1998) on South Africa's economic growth is arguably a first of its kind. The results are similar to those found in the Regression Discontinuity approach in terms of reinforcing the positive impact that renewable energy has on the country's economic growth. The results are also similar to those of reviewed literature in terms of the positive impact of renewable energy on economic growth; however, the natural experiment design using Bayesian Structural Time-Series models allowed for a more powerful assessment of causality by establishing a Synthetic Control unobserved GDP that was compared with actual observed GDP to quantify and visualise the causal impact of the first renewable energy policy in South Africa on economic growth.

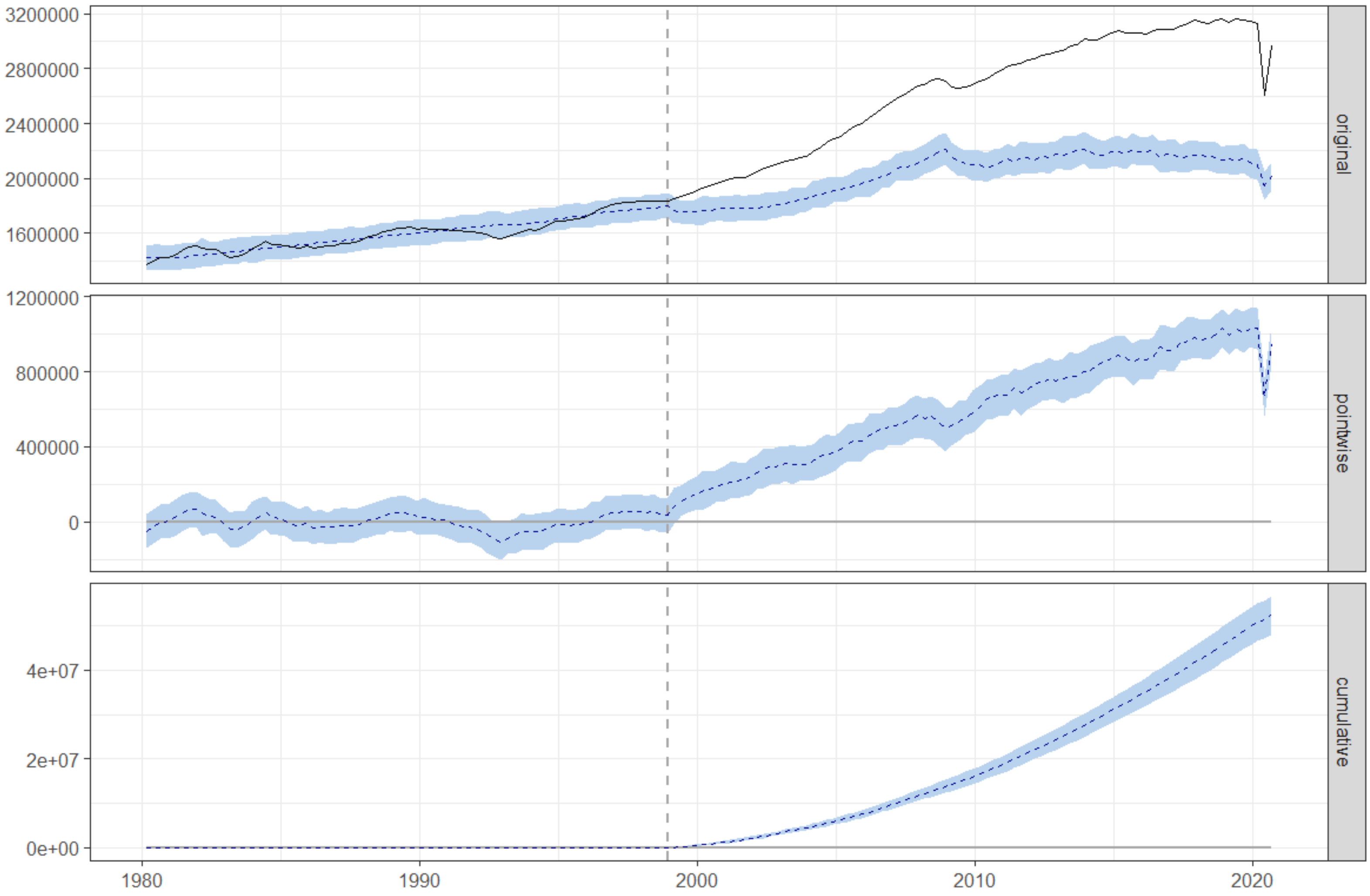


Figure 4.3: Bayesian posterior distribution graphs

Blue-dotted lines: time path of the predicted values; black line: time path of the actual values

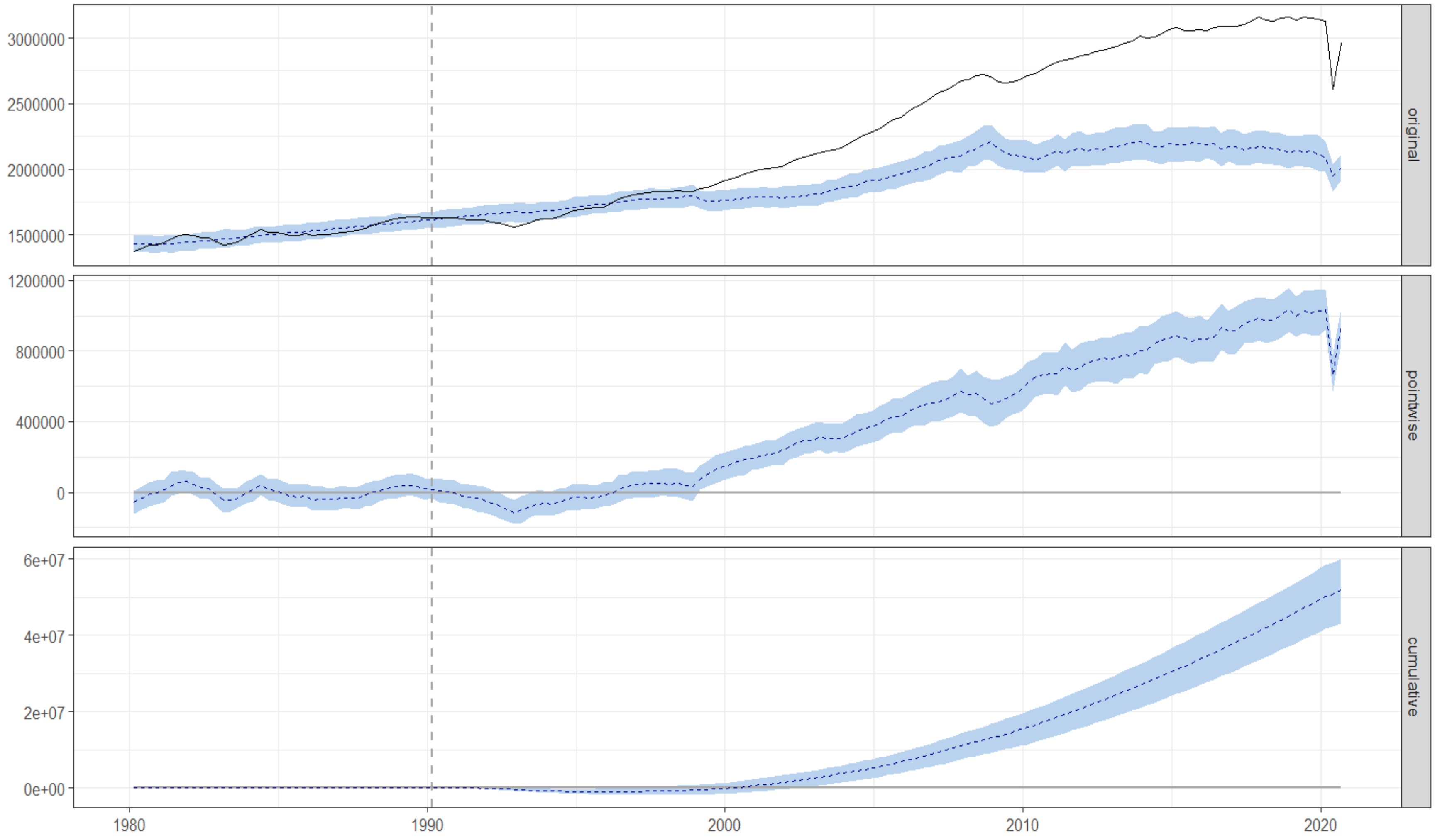
4.7 Falsification Tests

4.7.1 Placebo Tests

It can be argued that the pointwise panel is above zero due to the inability of the state-space model to predict the counterfactual economic growth. As such, a placebo tests using fictitious dates of the renewable energy policy introduction was used as a falsification strategy to address this concern. The results from the placebo tests shed insight into whether the reported impact of renewable energy on economic growth is due to the inability of the model to replicate the outcome in the absence of the renewable energy intervention. From thereon, if the counterfactual was unable to replicate the observed performance for placebo treatment, the test succeeded in falsifying the claim that the pointwise gap is driven by the intervention. However, if it replicated the observed performance in response to the fictitious dates, the higher confidence was attached to the results.

Since the White Paper on the Energy Policy of the Republic of South Africa was introduced in 1998 in South Africa, no formalised renewable energy policy was introduced and implemented before 1998. As such, years prior to 1998 were used to conduct a falsification test of the results. If the Bayesian posterior estimates in this study are correct, estimating the impact of introducing renewable energy on economic growth before the 1998 White Paper would result in no substantive departure between the actual data and the predicted data. To test for these concerns, the study applied a placebo introduction of renewable energy in the first quarter of 1990 and the fourth quarter of 1985, which are earlier than the actual introduction of renewable energy in South Africa.

Figure 4.4(a) and (b) show no significant divergence between the actual and the predicted data in response to the fictitious introduction of renewable energy in 1990 and 1985. The counterfactual unit correctly predicts the economic growth in both instances. Since there is no significant difference between the actual the predicted data in both placebo examples, the observed pointwise gap between the actual and the predicted economic growth as of 1998 cannot be attributed to the method’s failure to reproduce the counterfactual. As such, we can be confident that the positive pointwise is due to the introduction of clean energy into the energy mix.



<u>Figure 4.4a: Bayesian posterior distribution graphs (placebo): Placebo 1: Fictitious introduction of renewable energy 1990 first quarter</u>

Blue-dotted lines: time path of the predicted values; black line: time path of the actual values

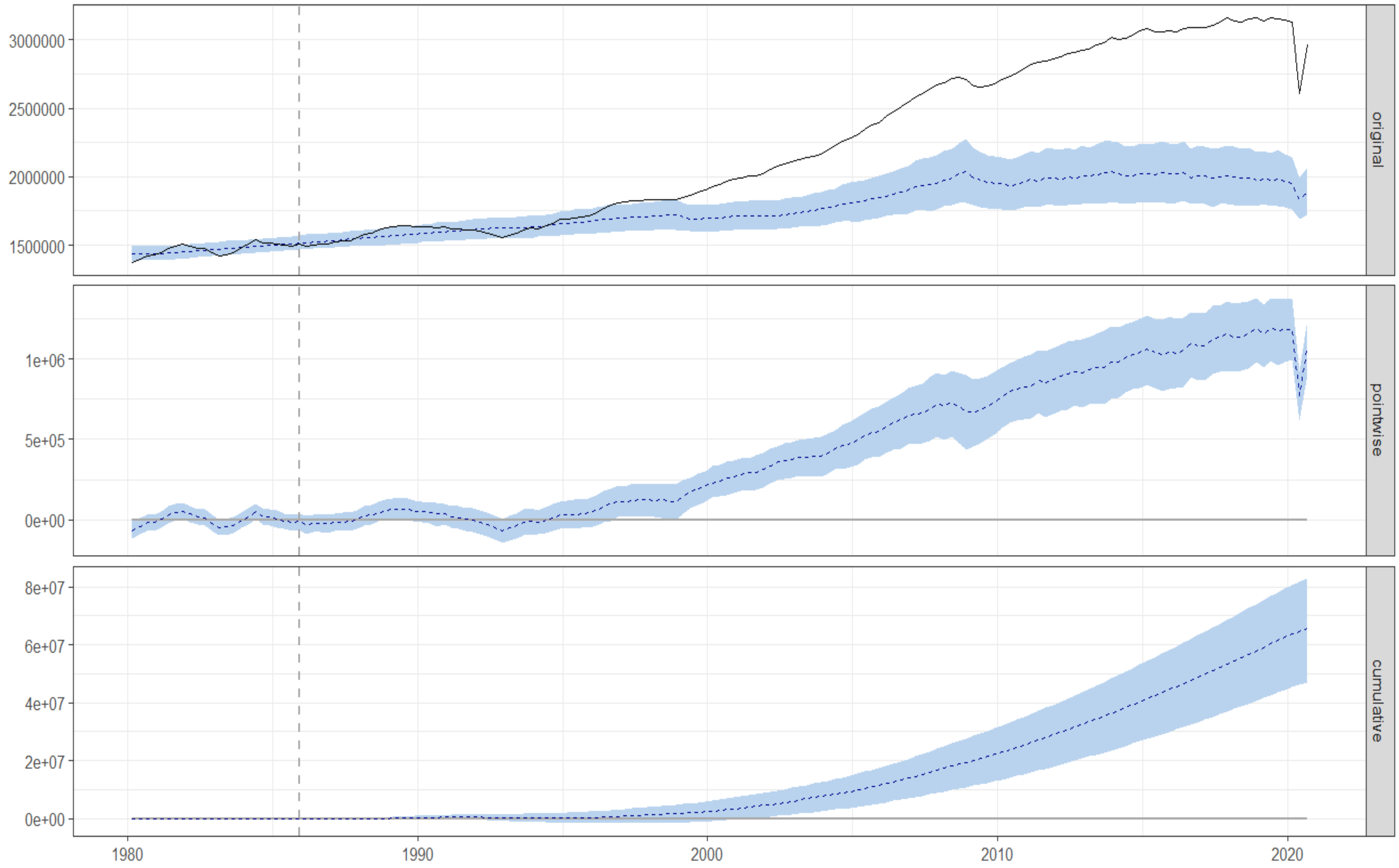


Figure 4.4b: Bayesian posterior distribution graphs (placebo): Placebo 1: Fictitious introduction of renewable energy 1985 fourth quarter

Blue-dotted lines: time path of the predicted values; black line: time path of the actual values

4.7.2 Robustness Checks

A robustness check for the analysis above was conducted to examine the potential dynamic causal impacts of renewable energy on economic growth. This was done by augmenting equation 4.22 to exclude gross fixed capital formation as a determinant of economic growth.

Specifically, the following equation is estimated:

$$y_t = \mu_t + \tau_t + \varepsilon_t \qquad (4.25)$$

$$\mu_{t+1} = \mu_t + w_t \qquad (4.26)$$

$$\tau_{t+1} = -\sum_{s=0}^{S-2} \tau_{t-s} + v_t \qquad (4.27)$$

Table 4.3 shows the results from estimating equations 4.25 to 4.27. The absolute and relative impact of introducing green energy on economic growth is similar to the ones analysed in Table 4.2, confirming the robustness of the results. However, in relative terms, the GDP in South Africa showed an increase of about 44% with the 95% confidence interval of this percentage being [35%, 51%]. This means that the positive effect observed after the formalised introduction of renewable energy is statistically significant at a 5% significance level. The effect here is higher than in Table 4.2.

Table 4.3: Results of posterior estimates (inference)

	Average	**Cumulative**
Actual	2.64 m	229.50 m
Prediction	1.83 m (71677) [1.70 m, 1.99 m]	159.38 m (6235867) [147.91 m, 173.19 m]
Absolute effect	0.81 m (71677) [0.65 m, 0.94 m]	70 m (6235867) [56 m, 82 m]
Relative effect	44% ** (3.9%) [35%, 51%]	p = 0.002

The values in square brackets show a 95 % confidence interval while those in round brackets are standard deviations; ** represent 5% significance level; p stands for Posterior tail-area probability; m represents million ZAR rands

4.8 Conclusion and Policy Implications

The purpose of this research was to determine the impact of introducing clean energy policies on economic growth in South Africa as green growth theory and the reviewed literature have confirmed the positive impact that clean energy has had on economic growth. This study analysed the effectiveness of each of the three renewable energy policies in promoting economic growth. The three policies were the White Paper on the Energy Policy of the Republic of South Africa (1998), the White Paper on Renewable Energy Policy (2003) and the IRP of 2010. To measure this impact, a natural experiment approach was conducted, which included Regression Discontinuity in time and Synthetic Control using Bayesian Structural Time-Series models. Causal inference in nonexperimental studies usually requires a strong, untestable assumption that no unobserved factor confounds the relationship between the exposure and the outcome. Violations of this assumption will lead to a biased estimation of causal effects; however, with natural experiments, this assumption is not required for causal inference.

This is a strong motivation for using natural experiments, as extant literature has largely used time series and panel data techniques to model the effect of renewable energy consumption on economic growth, resulting in more of an association than causation. Therefore, using a natural experiment provides are more powerful analysis of the causal impact of renewable energy policies and consumption on economic growth, which has arguably not been presented in economic literature.

The Regression Discontinuity results showed that each green energy policy has caused a positive GDP growth drift. This result is consistent with the reviewed studies on the effects of green energy on economic growth, as the coefficients from this approach show a positive relationship between the introduction of each renewable energy policy and economic growth. The results from the Bayesian posterior estimate and graph distribution also showed the positive impact of the introduction of the green energy policy on economic growth by comparing the growth of GDP before and after the introduction of renewable energy by constructing a Synthetic Control that would have been the GDP growth had no renewable energy intervention taken place. It was observed that the actual GDP data are much higher than the predicted GDP data, which would have been if no renewable energy intervention had taken place. This further reinforced the results from the Regression Discontinuity analysis.

The unique natural experiment approach used in this study goes further to provide a richer analysis of the impact of using clean energy on economic growth. Constructing a GDP growth path had there been no renewable energy intervention and comparing it with the current GDP growth path post the intervention of the renewable energy policy gives a powerful analysis that quantifies the impact of green energy on economic growth, both numerically and graphically.

Renewable energy policies have resulted in increased capital accumulation and technology for constructing renewable energy power plants. This has also resulted in increased employment for workers in the construction, maintenance and operations of the renewable energy power plants. Reduced greenhouse emissions due to this transition to green technologies has ecological impacts that positively affected TFP. This results in an overall positive impact of renewable energy policy intervention on South Africa's economic growth.

The results from this analysis encourage policymakers to further implement and improve renewable energy policies, as the share of clean energy within South Africa's energy mix not only mitigates climate change by decreasing greenhouse gas emissions, but the share of clean energy also has a positive effect on economic growth through creating a clean ecosystem, job creation, increasing innovation and capital formation and improving TFP in South Africa overall.

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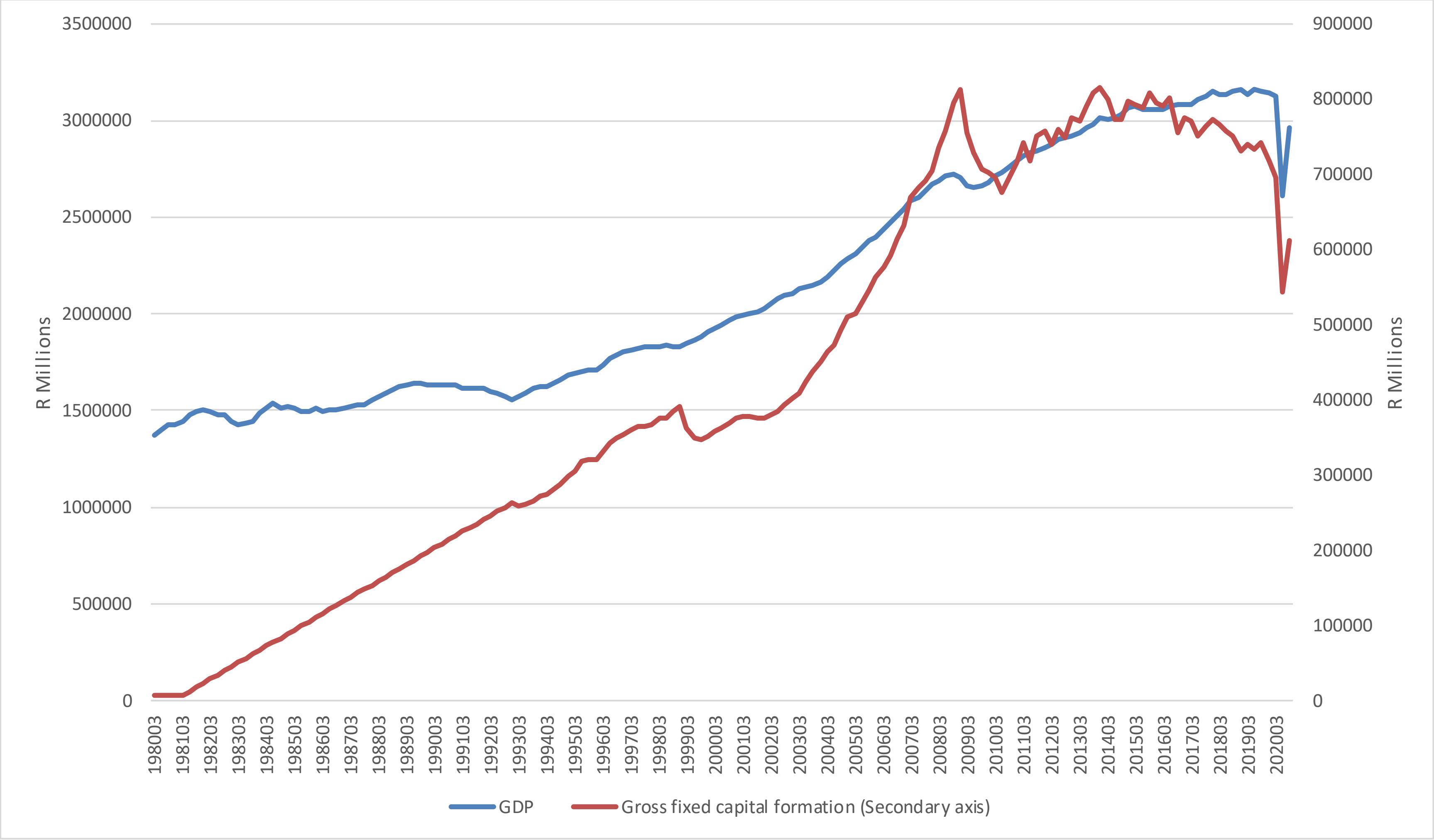
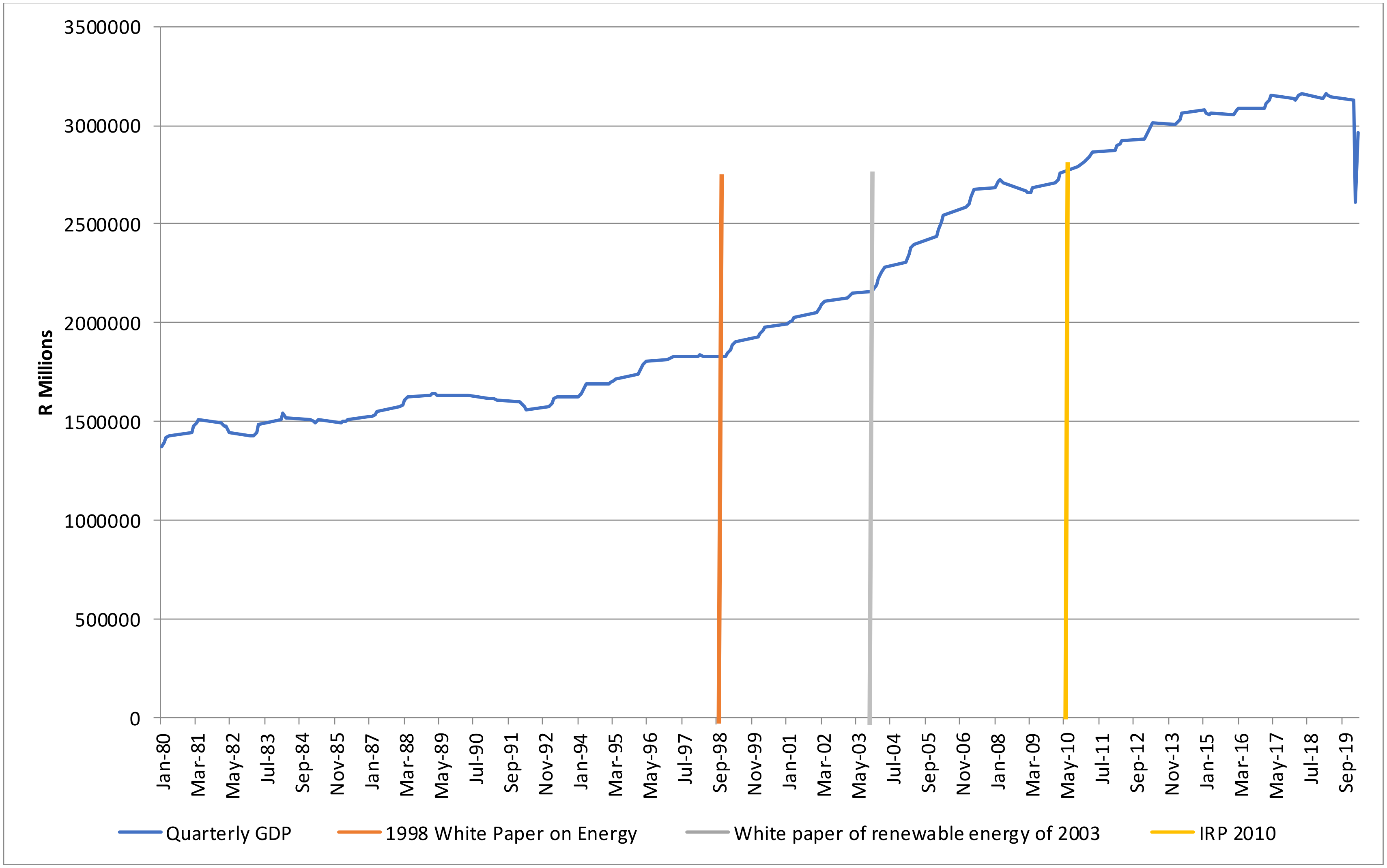
Appendix C



<u>Figure C.1: Gross domestic product and gross fixed capital formation in South African rands (R)</u>

Source: South African Reserve Bank, 2020



<u>Figure C.2: South Africa's quarterly gross domestic product in South African rands (R) showing renewable energy policy introduction</u>

Source: South African Reserve Bank, 2020

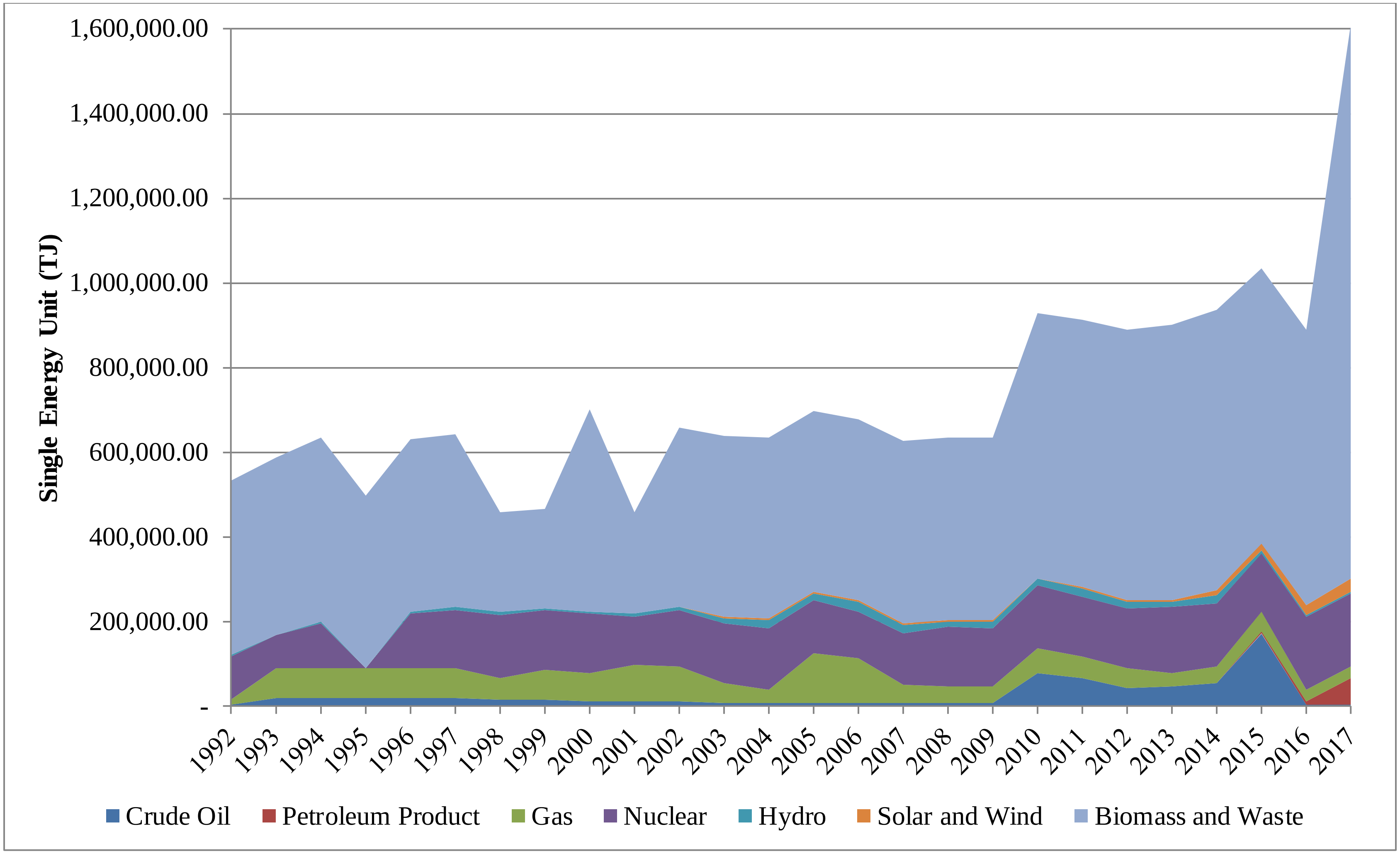


Figure C.3: Indigenous primary energy production

Source: Department of Mineral Resources and Energy Energy Balances, 2019

5 Chapter Five: General Conclusion

The primary purpose of this research was to analyse the welfare and growth implication of introducing green energy in the South African energy mix. This analysis adds to the growing body of literature regarding green energy and its impact on economic growth. However, this research follows a unique approach, which offers more clarity with regard to how the transition to a green economy affects South Africa's developmental goals. The research has been divided into three empirical chapters (Chapters Two, Three and Four), each offering a holistic approach to this investigation and encouraging the use of clean energy, not only for climate change mitigation but also for economic growth and opportunities in South Africa.

Chapter Two determined the impact of using non-renewable energy sources on selected sectors' (industry, mining, agriculture, transport and commercial) economic output in South Africa. This allowed us to determine which sectors rely more on non-renewable energy sources and whether these sectors can potentially substitute these non-renewable energy sources for cleaner technologies without compromising output. The study quantitatively determined the impact of petroleum products, coal, electricity, labour and capital on economic output in a panel data regression framework, including the five sectors from 1992 to 2018. The findings from this analysis indicate the impact each non-renewable energy source has on the economic output of each sector. This allowed us to determine which sector's economic output will be negatively or positively affected by substituting dirty energy sources for clean energy sources or implementing clean energy sources and climate mitigation policies.

The panel regression results showed that labour is the most contributing factor to production in transport and the commercial sector. Capital is positive and statistically significant for all sectors except for mining, where the coefficient is surprisingly and unexpectedly statistically insignificant due to declining mining productivity and job losses in the sector. Coal is the least contributing factor to production for most sectors, as the coefficients are statistically insignificant in mining and negative in the other three sectors while positive in the transport sector. Petroleum has a positive and statistically significant coefficient for transport and agriculture; however, positive coefficients for the other three sectors are insignificant. Electricity is a major contributing factor to production in some sectors, with coefficients being statistically significant and positive, except for the industry sector.

Chapter Three determined the pass-through and the response of consumer prices to renewable energy share increases while using the exchange rate as a threshold in South Africa. The TVAR model was used to determine the pass-through effect and response using a threshold exchange rate value of 7.7 R/$. This means that a depreciation regime is when the exchange rate is greater than or equal to 7.7 R/$, and an appreciation regime is when the exchange rate is less than 7.7 R/$.

The TVAR model results showed that the share of renewable energy pass-through to consumer prices is statistically significant in both exchange rate regimes. However, the pass-through effect is different in both regimes. In the appreciation regime, the share of renewable energy pass-through is positive, which means that below the threshold, an increase in the renewable energy share within the energy mix results in an increase in consumer price. While in the depreciation regime, the share of renewable energy is negative, which means that above the threshold, an increase in the share of clean energy results in a decrease in consumer prices.

This dynamic is largely explained by the cost of renewable energy, as coincidentally, from 2008 to 2018, the exchange rate was mostly above the threshold level (depreciation regime), and from 2007 to 2018, the cost of renewable energy experienced the biggest fall. This decline was passed through to consumer prices during that period. These results show that policymakers should promote the use of renewable energy, as the technology is significantly cheaper than fossil fuels, and using renewables will decrease total production costs, which will be passed through to decreased consumer prices.

Chapter Four determined the impact of introducing green energy policies on South Africa's economic growth. The three policies were the White Paper on the Energy Policy of the Republic of South Africa (1998), the White Paper on Renewable Energy Policy (2003) and the IRP 2010. To measure this impact, a natural experiment approach was conducted, which included the use of Regression Discontinuity in time and Synthetic Control using Bayesian Structural Time-Series models. The Regression Discontinuity results showed that each renewable energy policy positively impacted GDP growth. This result is consistent with previous studies on the effects of renewable energy on economic growth, as the coefficients from this approach show a positive relationship between the introduction of each renewable energy policy and economic growth.

The results from the Bayesian posterior estimate and graph distribution also showed the positive impact of the introduction of the green energy policy on economic growth by comparing the growth of GDP before and after its introduction by constructing a Synthetic Control that would have been the GDP growth had no renewable energy intervention taken place. The results from this analysis encourage policymakers to implement further and improve renewable energy policies, as the share of renewable energy within South Africa's energy mix not only mitigates climate change by decreasing greenhouse gas emissions but the share of clean energy positively affects economic growth.

Overall, a study of this nature is very important, and the results determined in each chapter are very powerful and crucial to develop a better, more in-depth analysis of the impact of the move towards renewable energy and the green economy on South Africa's developmental goals. The results from this study can be used by policymakers and global leaders in two approaches. Firstly, the results could be used to encourage the implementation of renewable energy in South Africa and globally, as the results have supported the positive impact that renewables have on economic growth.

The move towards renewable and retiring coal power plants has also been discouraged in some developing countries. As such, a second approach that policymakers could use the results from this study is to support the establishment of sector-specific climate change mitigation policies. This is crucial, as economic sectors are heterogeneous, and certain climate change mitigation policies can harm developmental goals in certain sectors that rely heavily on non-renewables for economic growth. As such, they should be applied to sectors that benefit from them in terms of their developmental goals and not those that are harmed by them.