The Role of Renewable Energy in the South African Energy Supply Mix and Economy

By

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DECLARATION

I, Vanessa Constance Ndlovu 16401183, hereby declare that the thesis for the degree Doctor of Philosophy in Economics (PhD) to be awarded is my own work and that it has not previously been submitted for assessment or completion of any postgraduate qualification to another University or for another qualification.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

BRICS	Brazil, Russia, India and China
CCGT	Combined Cycle Gas Turbine
CSP	Concentrated Solar Power
CTL	Coal-To-Liquids
DG	Diesel Generator
EEP	Excess Electricity Production
EKC	Environmental Kuznets Curve
ESI	Electricity Supply Industry
GDP	Gross Domestic Product
GHG	Green House Gas
INDC	Intended Nationally Determined Contribution
IPCC	Intergovernmental Panel on Climate Change
IPPs	Independent Power Producers
IRP	Integrated Resource Plan
LCOE	Levelized cost of energy
MLP	Multi-Level Perspective
MTMC	Minimum Total Mix Capacity
NRE	Non Renewable Energy
OECD	Organization for Economic Co-operation and Development
PV	Photovoltaic

QOL	Quality of Life
R&D	Research and Development
RE	Renewable Energy
REIPPP	Renewable Energy Independent Power Producer Procurement Programme
RES	Renewable Energy Supply
SDGs	Sustainable Development Goals
TPES	Total Primary Energy Supply
UNFCC	United Nations Framework Convention on Climate Change

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ABSTRACT

Globally and in most emerging economies such as South Africa, there is an urgent need to attain sustainable development goals as well as honor climate change mitigation commitments. In order to achieve this and to participate in a global transition to clean, low-carbon energy systems, it is imperative for South Africa to focus on its energy transition strategy. In South Africa, the current energy system is mainly reliant on fossil fuel, nuclear and gas energy sources. The high reliance on fossil fuels combined with an old fleet of power plants have intensified the challenges of unsustainability, poor security of supply, as well as unreliability demonstrated in frequent disruptions in the electricity supply. The South African energy supply system is in great need for transformation through the strengthening of cleaner and sustainable energy technologies.

This thesis used the international energy supply mix comparison, energy supply mix drivers causality analysis, as well as the energy supply mix system modelling to investigate and propose an optimal energy supply mix which is aligned to the current South African national policy frameworks as well as the strategic targets and plans which enable a sustainable and secure energy transition.

The overarching aim of this study was to investigate the role of renewable energy in the South African energy supply mix and economy. To do so, the specific research questions of the study were: 1) How is South Africa's planned energy supply mix relative to the rest of the world and how has it changed in recent years? ; 2) What is the relationship between renewable energy and economic growth in South Africa?; 3) What is the optimal energy supply mix that is used in South Africa in order to assist with the transition from fossil fuels to renewable energies? These questions were addressed through three research papers around which the thesis is structured.

The study's findings advance the EnergyPlan system modelling tool and methodology and its introduction in the South African context. In terms of its energy supply mix (specifically electricity supply mix), South Africa is still heavily dependent on fossil fuels and there is a need for diversification towards a cleaner and sustainable energy supply mix. As a result, it is evident that nonrenewable energy has the most impact on economic growth. There is also a need to increase R&D expenditure and energy technology development.

The key contribution of this thesis is the introduction to the South African context an energy supply mix methodology and tool that can be used to accurately determine the maximum contribution of renewable energy into the South African energy supply mix at the least cost and minimum emissions enabling the transition from a fossil fuel dominated mix to one that has more renewable energy. Also providing an evaluation of the role of renewable energies in the future optimal energy supply mix of the country and empirically evaluating and discussing the current Intergrated Resource Plan (IRP) as part of the process. In this regard, identifying the gaps in the current energy mix against likely scenarios based on the current economic climate. As well as better informing the policy makers and key stakeholders in the electricity industry on the role and effect of preferring a renewable -based energy supply mix.

Keywords:

Energy mix, Energy Transition, Renewable Energy, Non-Renewable Energy, Green Economy, EnergyPlan, GDP, R&D, BRICS, OECD.

CHAPTER 1: GENERAL INTRODUCTION

Globally and in most emerging economies such as South Africa, there is an urgent need to attain Sustainable Development Goals (SDGs) as well as to honor international climate change mitigation commitments. In order to achieve this and to participate in a global transition to clean, low-carbon energy systems, it is imperative for South Africa to focus on its energy transition strategy. The country's current energy system is mainly reliant and dominated by; fossil fuel, nuclear and gas energy sources. Coal has 59% of the primary energy supply and it is followed by renewables with 20% and crude oil with 16%. Natural gas contributed 3% and nuclear energy had 2% of the total primary supply in 2015 (DoE, 2018; (Ndlovu & Inglesi-Lotz, 2019). The high reliance on fossil fuels combined with an old fleet of power plants have intensified the challenges of unsustainability, poor security of supply, as well as the unreliability that has been demonstrated in frequent disruptions in the electricity supply. The South African energy supply system is in great need of transformation through the strengthening of cleaner and sustainable energy technologies.

It has become evident that the optimization and diversification of South Africa's energy generation mix is fundamental to meeting the various developmental goals and in enhancing the crucial security of supply. South African energy policymakers have to make critical decisions for the energy supply mix in the future. The supply mix is currently generated from fossil fuels such as coal, oil and gas which are major pollution contributors as they affect air quality. South Africa is responsible for over 50% of Africa's emissions, because of its extensive coal use and less than 40% is transformed into useful energy (Boden et al., 2011). According to the Department of Environmental Affairs (DEA, 2010), the largest contributor to greenhouse gas emissions is the energy generation sector as it accounts for more than 80% of South Africa's emissions, while the largest source of fuel emissions is the combustion of coal, gas and oil. Globally, the electricity sector has shifted from a primary reliance on fossil fuels to alternative energy solutions (Foster et al., 2017).

South Africa is evidently catching up to the trend of transitioning to alternative energy solutions with its renewable energy initiatives, including the Renewable Energy Independent Power Producer (REIPP) Procurement Programme. This was initially determined in August 2011 by the Minister of Energy through the Electricity Regulation Act Number 4 of 2006 (Government Gazette, 2006), which required that 3 725 MW of energy must be generated from renewable energy sources. According to the Minister, REIPP had to procure the 3 725 MW and contribute it towards socio-economic, sustainable growth, creating jobs and developing the country's renewable energy industry (Department of Energy (DoE), 2015). The next ministerial determination in December 2012 required a further 3 200 MW of renewable generation capacity to be procured from Independent Power Producers (IPPs). A third determination in August 2015 gave provisions for the procurement of a further 6 300 MW of renewables generation capacity from IPPs. On the 4th of April 2018, the Minister of Energy, Jeff Radebe, signed additional agreements for 27 projects to be procured under bid (Phases or so-called Windows 3.5 and 4). The Minister highlighted that:

> *'The procurement of the 27 new projects was the biggest IPP procurement by the Department of Energy to date, representing a total of R56 billion of investment and about 2300 MW of generation capacity to be added to the grid over the next 5 years. He also indicated that this investment of R56 billion injected by the private into the economy, with no contribution from Government other than support to Eskom in the event of a default by*

> *the buyer. This will have a positive impact on the economy and competition in the energy sector will certainly benefit the consumer' (DoE, 2018).*

There has been a global commitment and drive to mitigate climate change through the Paris Agreement (2015) which is all around viewed as a fundamental point in the improvement of the universal environmental change system under the United Nations Framework Convention on Climate Change (UNFCC). The agreement is an exhaustive system which will manage global endeavors to restrict emissions and to address all the difficulties presented by climate change. It flags the adjustment in pace towards the low carbon advancement from 2020 onwards through the different nations' duties that are spelt out in driven national plans called Nationally Determined Contributions. This result highlights that environmental change speaks to a pressing danger to human social orders and the planet, as it requires the most stretched out conceivable collaboration by all nations and different partners (DEA, 2016). South Africa signed the agreement on the 22nd of April 2016. According to South Africa's Intended Nationally Determined Contribution (INDC),

> *"South Africa is firmly committed to working with others to ensure temperature increases are kept well below 2°C above pre-industrial levels, which could include a further revision of the temperature goal to below 1.5°C in light of emerging science, noting that global average temperature increase of 2°C translates to up to 4°C for South Africa by the end of the century" (INDC, 2016).*

In keeping with South Africa's commitment to contribute to the global effort in order to mitigate climate change in line with the principle of common but differentiated responsibilities and respective capabilities, South Africa's mitigation component of its INDC moves from a "deviation from business-as-usual" form of commitment and takes the form of a *peak, plateau and decline* GHG emissions trajectory range. South Africa's emissions between 2025 and 2030 will be in the range between 398 and 614 Mt CO_2–eq, as defined in the national policy (INDC, 2016).

Although energy transition is a global concept, it differs from country to country in terms of drivers, motivation, governance issues, challenges and opportunities. The most common motivation is securing energy supply specifically in South Africa where there is instability and lack of security of supply. As highlighted in the Intergovernmental Panel on Climate Change (IPCC) special report on renewable energy sources and climate change mitigation, there exists three major global energy challenges; (a) Ensuring sufficient energy supply to meet growing energy demand, (b) Curbing the contribution of the energy supplied to climate change, and (c) Providing everybody with access to energy services (IPCC, 2011). It is especially topical in the African context where there are several challenges such as poverty, energy access and where there are approximately 600 million people that do not have access to basic electricity. An energy transition towards renewables would be an opportunity for South Africa and Africa as a whole to leap frog legacy energy systems through technological, economical, and financial innovation in a transition to a low carbon future while ensuring that economic growth in the country does not stagnate. The other challenges in South Africa include the serious imbalances in the development path as well as the rapid speed of change. This results in issues of cost and affordability, sustainability, as well as policy and regulatory environmental issues. As was found by Bohlmann et al., (2019), the impact of a transition to an energy supply mix with less coal is sensitive to other economic and policy conditions, specifically the response of the global coal market and hence, South Africa's coal exports. In the case that surplus coal coming from lower local interest cannot be promptly traded, the economies of coal-producing regions in South Africa, for example, the Mpumalanga territory are the most seriously affected. The ensuing movements of semi-skilled labor from that area to others within the country require appropriate and timeous planning by energy policymakers and urban planners.

The global trend of staying away from carbon energy technology implies a growing base of carbon friendly technologies and cheaper renewable energies such as solar and wind are fast becoming coal's competition. The transition will be a challenging task which requires coercive and enabling regulatory frameworks. This can be achieved through existing energy policy by harnessing the opportunities of alternative energy sources such as renewables and gas. Studies have shown that a combination of gas and renewable energy provides the least cost alternative for electricity generation. Introducing alternative energy sources to the current energy mix has several benefits such as the reduction of carbon emissions since gas emits 40% less carbon dioxide and has more flexible cleaner burning than coal and it can be used in conjunction with renewable energy in order to provide a constant and reliable energy supply for South Africa. Energy transition should be aligned with the nation's development plan which enables inclusive growth and development.

South Africa is in the initial stages of an energy transition, with a 10% increase in renewable energy supply in the past 10 to 15 years. This has largely been enabled by the flexibility of deployment, as well as the decentralized nature of renewables. To date, South Africa has invested approximately R200 billion into renewables through the Renewable Energy Independent Power Producer (REIPP) Procurement Programme (Independent Power Producers Office (IPPO), 2017). This transition came with several challenges due to the hurdles posed by the monopoly of energy supply in South Africa as well as due to the grid connectivity of the renewables and the ability to deploy the renewables in a more decentralized manner resulting in regulatory issues. Renewables are also still largely seen as a competitor instead of a partnering technology (Climate Change Tracker SA, 2018). A major hindrance for the successful energy transition in South Africa is the lack of a solid and coherent energy policy. The current IRP is not necessarily an energy policy, but it is more of a model and guide on what new plants should be built, it does not address the social and economic impact. A diverse energy mix which is based on the least cost and one that is informed by an energy policy that is a catalyst and stimulus for the country's economic growth is required.

It is essential for South Africa to determine an appropriate optimal energy mix that will enable the transition to a decarbonized economy. The mix should also enable economic growth and job creation through skills transformation. The recent Integrated Resource Plan (IRP) document was released for public comments at the end of 2017 but it has not been adopted formally. The necessity of the determination of an optimal energy supply mix in the country has therefore become obvious. Taking into consideration the country's socioeconomic challenges, the concept of "optimal" takes a wider definition and it does not only refer to the technical.

1.1 Specifics of this study

1.1.1 Background

Developing and emerging economies are currently faced with a challenge in meeting the energy needs of billions of people while simultaneously participating in a global transition to clean, low-carbon energy systems. The energy industry has a significant influence over the robustness and sustainability of the entire economy, from job creation to resource efficiency. In most developing countries such as South Africa, the energy system is mainly reliant and dominated by fossil fuel, nuclear power and gas energy sources. These types of energy sources, particularly the fossil fuels, have posed many challenges such as unsustainability, poor security of supply and increased carbon emissions. These challenges have led to a need for a system transformation and the strengthening of cleaner and sustainable energy technologies.

1.1.2 South African Electricity Supply Mix Overview

South Africa has four groups of electricity generators, namely: the national public electricity utility, Eskom; municipal generators; Independent Power Producers (IPPs) in partnership with Eskom and the auto generators.

Currently, the main source of electricity generation is through coal-fired power plants which contribute 93% of the 44 134 MW generating capacity. Eskom supplies approximately 95% of South Africa's electricity and it also supplies more than 45% of Africa's electricity (Eskom, 2015). Eskom uses various technologies to generate electricity, the combination of which is called the 'plant mix'. The utility is constantly investigating other forms of generating energy and it is also in a quest to find renewable energy sources that could be used to expand its current plant mix. It has initiated various research projects that look at wind, solar, tidal, wave and biomass sources of energy. Coal-fired base load power stations make up the largest portion of Eskom's plant mix. These stations use coal as their energy source and they operate 24 hours a day in order to meet the demand for electricity. Eskom's generation division consists of 36 441 MW of coal-fired stations, 1 860 MW of nuclear power, 2 409 MW of gas-fired stations, 600 MW of hydro and 2 724 MW pumped storage stations, as well as the recently commissioned 100 MW Sere Wind Farm. The 3 MW Klipheuwel Wind Farm was impaired during 2016 as it had reached the end of its useful life. The four Ingula units, with a nominal capacity of 331 MW each were commissioned in 2016, thereby supplementing the capacity added by Unit 6 of the Medupi Power Station, commissioned in 2017 (DoE, 2018).

Africa's only nuclear station is at Koeberg, which is 30 kilometers north of Cape Town. There is modest hydro capacity on the Orange River, which is located on two dams and there are also two pumped storage schemes, one in the Drakensberg and the other on the Palmiet River in the Western Cape. Municipalities own 22 small power stations and back-up gas turbines, but these total only 4% of the national generation capacity and generally run at low load factors. Private generators comprise the remaining 1% of capacity (DoE, 2018). South Africa has reached a point where other methods of power generation are to be considered and implemented. Fossil fuels, particularly coal and oil, have major implications for pollution. South Africa is responsible for over 50% of Africa's emissions, because of its extensive coal use, of which less than 40% is transformed into useful energy. According to the Department of Environmental Affairs (DEA, 2010), the largest contributor to greenhouse gas emissions is the energy generation sector as it accounts for more than 80% of South Africa's emissions. The report also argues that the largest source of South African emissions is the combustion of coal, gas and oil. Globally, the electricity sector has shifted from a primary reliance on fossil fuels to alternate energy solutions.

In August 2018, the 2016 Draft IRP was further updated with the release of the 2018 Draft IRP which was released for public comment. The updated plan includes 25 GW of electricity generating capacity with no new nuclear, pumped storage or CSP. Instead, gas and wind power are to contribute more than half of the additional capacity. Coal-fired power generation will drop from over 80% currently to less than 50% by 2030 according to the new plan (See Table 1).

Table 1

Adjusted plan with resultant installed capacity mix for the period up to 2030

Technology	New additional capacity	Resultant installed capacity	% of total installed capacity
Coal	1000 MW	34 000 MW	46
Nuclear	–	1860 MW	2,5
Hydro	2500 MW	4696 MW	6
Pumped storage	–	2912 MW	4
PV	5670 MW	7958 MW	10
Wind	8100 MW	11 442 MW	15
CSP	–	600 MW	1
Gas	8100 MW	11 930 MW	16
Totals	25 370 MW	75 098 MW	100

Source: Adapted from Minister of Energy speech August 2018

As stated by the DoE (2018), a number of assumptions used in the Integrated Resource Plan 2010–2030 have since changed, which necessitated its review. The key assumptions that changed included the electricity demand projection that did not increase as envisaged; the existing Eskom plant performance was also way below the 80% availability factor. The additional capacity that was committed to and commissioned, as well as the technology costs that had been projected declined significantly. The update process, as was the case in the Integrated Resource Plan 2010–2030 development process, aimed to ensure the security of supply and it also intended to minimize the cost of electricity, as well as to minimize the negative environmental impact of emissions and to minimize water usage.

The update process consisted of four key milestones that included the development of input assumptions; the development of a credible base-case and scenario analysis; the production of a balanced plan and policy adjustment. Whereas the Integrated Resource Plan 2010–2030 covered a study period up to 2030, the Integrated Resource Plan Update study period was extended to the year 2050.

The scenarios studied included demand-growth scenarios where the impact of projected load demand on the energy mix was tested. Other key scenarios were based on varying the key input assumptions. These included; the use of carbon budget instead of peak-plateau-decline as a strategy to reduce greenhouse gas emissions in electricity, the removal of annual build limits on renewable energy (unconstrained renewables) and varying the price of gas for power (DoE, 2018).

The current South African policy, especially the IRP encourages the growth of renewable electricity creation. The announcement and the beginning of the REIPPP bidding process accelerated the extensive execution of renewable electricity creation. Nevertheless, there are still a number of obstacles. Schedules and policies must be created such that they can expedite the execution and implementation of electricity technologies. Several studies have explored the available technologies. Kusakana and Vermaak (2013) explore the probability of using and creating hydrokinetic power to provide dependable, affordable and sustainable electricity to

South Africa's rural and isolated areas where enough water is accessible. Simulations are done using the Hybrid Optimization Model for Electric Renewable (HOMER) and the results are contrasted with other supply options that include but are not limited to Standalone Photovoltaic system (PV), wind, Diesel Generator (DG) and grid extension.

In South Africa and the rest of the BRIC countries, renewable energy development has only started in recent years. The countries are also facing the challenge of lack of funding when juxtaposed to developed OECD countries. A green economy and the use of more renewable energy sources can assist to alleviate the difficulties that these developing countries are facing. However, the countries that are knowledgeable about these calculated alternatives are cautious as they are contemplating the repercussions of establishing a green economy over the overall developmental objectives. The gap between policy aspirations and implementation is substantial because of the instability of the civil services and the shortage of proper institutions and implementation agencies.

With the awareness of the many benefits of incorporating more renewable energy sources into the electricity supply system and with electricity being an important component of economic development, it is vital that the most optimal electricity supply mix for South Africa to assist with the transition from fossil fuels towards renewable energies is well understood.

1.1.3 Problem and purpose statement

South Africa heavily depends on fossil fuels and it has been plagued by insistent concerns about; the adequacy of its electricity supply system and its energy policies, the lack of planning, the chronic under investment in the South African electricity sector which led to escalating power prices and a shortage of capacity during peak demand periods leading to demand rationing.

Globally, the electricity generation sector aims at transitioning from being fully dependent on fossil fuels to alternative energy solutions and South Africa slowly but surely aims at catching up with the global trends. This is demonstrated by the Renewable Energy Independent Power Producer (IPP) Programme. Renewable energies have the potential to assist with developmental issues as well as support governmental macroeconomic policies (Apergis & Payne, 2010; Inglesi-Lotz, 2015).

The purpose of this study was to evaluate the role of renewable energies in the future optimal energy supply mix of the country and to empirically evaluate and discuss the current IRP as part of the process. In this regard, the gaps in the current energy mix were identified and likely scenarios were explored based on the current economic climate in order to better inform the policy makers and key stakeholders in the electricity industry on the role and effect of preferring a renewable -based energy supply mix.

The specific problem to be investigated in this research study concerns the diversification and dependence of the South African energy supply mix on fossil fuels and how it can transition to a more renewable inclusive sustainable supply mix. This study complements this analysis with an examination of whether and how renewable and non-renewable energies in the supply mix impacts the South African economy. The studies in the energy and environmental economics literature examining the case of South Africa had focused either on the economy-energy-environment interaction (Inglesi-Lotz (2015)) or on the other side, provided supply mix scenarios based on cost-minimizing scenarios only (Østergaard (2009)). This study is innovative in the sense that it combines the analysis of causal relationships among energy, economy and technology with an energy modelling application towards establishing optimality in the energy supply mix with renewable energies playing a major role; all these being founded on theoretically informed frameworks.

1.1.4 Research Questions

Following from the purpose statement, the following research questions were outlined in order to further guide the research process:

i. How is South Africa's planned energy supply mix relative to the rest of the world and how has it changed in recent years?

   (The above research question has been answered through a published paper titled: "Positioning South Africa's energy supply mix internationally: Comparative and policy review analysis"[1] *referred to as Paper 1)*

ii. What is the relationship between renewable energy and economic growth in South Africa?

   (The above research question has been answered through a published paper titled: "The economic impact of renewable and non-renewable energy through an R&D lens: The case of South Africa within BRICS"[2] *referred to as Paper 2)*

iii. What is the optimal energy supply mix that is used in South Africa in order to assist with the transition from fossil fuels to renewable energies?

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[1] Ndlovu, V., Inglesi-Lotz, R. 2019. "Positioning South Africa's energy supply mix internationally: Comparative and policy review analysis". Journal of Energy in Southern Africa, 30 (2), 14-27.

[2] Ndlovu, V., Inglesi-Lotz, R. 2020. "The economic impact of renewable and non-renewable energy through an R&D lens: The case of South Africa within BRICS". Energy, 199,117428.

(The above research question has been answered through a working paper titled: "Energy supply mix transition strategy from fossil fuel to renewables for South Africa" referred to as Paper 3).

1.1.5 *Objectives of the Study*

In order to achieve the aforementioned, the following broad objectives were set:

i. To examine the status quo of the country's energy supply mix and it's positioning vis-à-vis international trends for future policy recommendations and implementation.

ii. To identify the economic variables that are directly related to energy supply mix and model the relationship.

iii. To explore scenarios based on the current economic climate on the role of renewable - based energy supply mix and where the efforts and funding should be concentrated.

iv. To evaluate the role of renewable energies in the future optimal energy supply mix of the country.

Table 2: Alignment of research objectives and research activities

Research Questions →	Research Objectives →	Research Activities
• How is South Africa's planned energy supply mix relative to the rest of the world and how has it changed in recent years?	• To examine the status quo of the country's energy supply mix and it's positioning vis-à-vis international trends for future policy recommendations and implementation.	• Theory and practice review and evaluation providing a detailed description of the South African energy supply mix and its evolution in the past 25 years is presented. South Africa's current and future energy

		mixes were compared with the energy mixes from other countries such as its companions Brazil, Russia, India as well as China (BRICS) and those from the Organization for Economic Co-operation and Development (OECD).
• What is the relationship between renewable energy and economic growth in South Africa?	• To identify the economic variables that are directly related to energy supply mix and model the relationship.	• Theory and practice review and evaluation providing an in-depth understanding of the dynamics and drivers of the energy resource types of the energy supply mix, as well as the existence and direction of the causal dynamic relationship between energy (renewable and non-renewable) on GDP taking into account the role of R&D expenditure.
• What is the optimal energy supply mix that is used in South	• To explore scenarios based on the current economic climate on the role of renewable -based	• Theory and practice review and evaluation to explore technical optimality while testing

Africa in order to assist with the transition from fossil fuels to renewable energies?	energy supply mix and where the efforts and funding should be concentrated. • To evaluate the role of renewable energies in the future optimal energy supply mix of the country.	various scenarios via a Minimum Total Mix Capacity (MTMC) methodology model in order to estimate the results. • Theory and practice review and evaluation providing a pilot and develop the EnergyPlan energy system optimization model that could be applicable to the South African context.

1.1.6 Expected Contribution of the research

The key contribution of this thesis is the introduction to the South African context an energy supply mix methodology and tool that can be used to accurately determine the maximum contribution of renewable energy into the South African energy supply mix at the least cost and minimum emissions enabling the transition from a fossil fuel dominated mix to one that has more renewable energy. Also providing an evaluation of the role of renewable energies in the future optimal energy supply mix of the country and empirically evaluating and discussing the current IRP as part of the process. In this regard, identifying the gaps in the current energy mix against likely scenarios based on the current economic climate. As well as better informing the policy makers and key stakeholders in the electricity industry on the role and effect of preferring a renewable -based energy supply mix.

Providing a technical analysis of the electricity supply system using an internationally recognized methodology and model. In an aid to contribute towards the informed understanding of the current energy supply drivers. As well as recommending least cost environmentally sustainable alternatives to the current energy supply system which are aligned with our current and future global emissions mitigation commitment goals and targets.

The research will:

- Contribute to the growing body of literature aimed at providing greater insight into the South African energy supply mix.
- Contribute to the growing body of literature on the energy supply mix drivers and determinants; and
- Thus provide a valuable, objective research source for the South African energy policy makers, providing them with some basis for evaluating their present and future strategies.
- Provide a methodology and tool for application and integration of more renewable energy into future energy supply mixes.
- In the literature there is a gap or minimum theory and practice written on the appropriate and accurate determination of energy supply mix and transition to more renewable and sustainable energy supply.

1.1.7 Organization of the Study

The thesis is structured in five chapters as illustrated in Figure 1.1. This figure shows a flow diagram of the thesis, which is designed to illustrate the flow of the knowledge stream, as well as the contributions of each chapter to fulfilling the research objectives. The following is also a description of the way in which the research study develops:

Chapter 1 gives an overview of the research and the thesis. It includes an introduction and the broad objectives of the research. It focuses on the problem definition and identifies the research objectives that are addressed in this research study. The research methodology is also discussed, particularly with reference to the procedure in relation to achieving the research objectives.

Chapter 2 systematically reviews past researches in order to understand how the research questions outlined in this study have been answered. The chapter also presents an analysis for each of the research questions that are discussed above. Chapter 3 gives a detailed description of the methodologies and the data that was used in the study as informed by the literature review in order to address the research questions. The results derived from the empirical analysis are outlined in Chapter 4 and lastly chapter 5 discusses the research findings and recommendations.

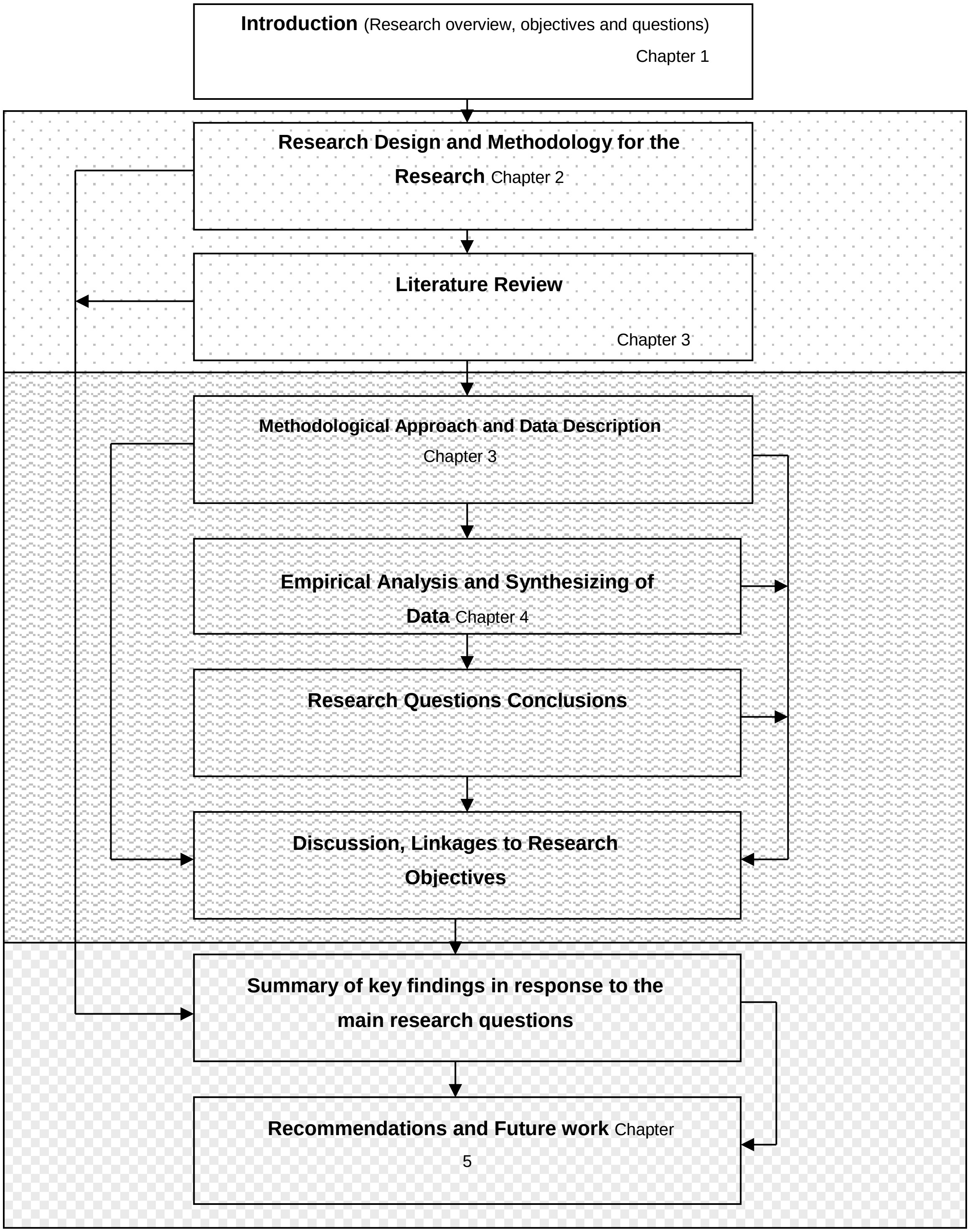


Figure 1 Systematic outline of the research chapters

CHAPTER 2: LITERATURE REVIEW

In the previous section, the problem statement and the research questions were outlined, in this section, the synthesis of relevant literature is done and this enables the researcher to answer the questions raised in this study. The chapter is divided into three sub-chapters that are aligned with the study's three research questions.

2.1 Positioning South Africa's energy supply mix internationally

Many developing countries are experiencing energy deficiencies resulting from the shortages in supply and poor infrastructure which affect their economies (Ateba & Prinsloo, 2019; Pollet et al., 2015). This challenge is exacerbated by the increasing demand in the future. Most industrial sectors, such as the manufacturing sector in India, have been negatively affected and exports have decreased (Allcott et al., 2016). The primary energy supplies are also experiencing a decline because of the notable increases in the cost of fossil fuels. Fuel imports, particularly oil, are a burden on most economies (International Energy Agency (IEA), 2016). Most developing countries such as South Africa intend to increase local energy supplies and the renewable energy sector has been recognized as a fundamental target area. It is important for a country to generate a multiple energy strategy and expand the share of sustainable and local energy resources, given that energy is an important element for sustainable development and prosperity.

Establishing an optimal energy supply mix when transitioning from a fossil fuel-dominated mix to renewable energy is important when creating greener low-carbon energy systems with enough load-following capabilities. Several studies have been conducted in determining the optimal combination of fossil fuels as well as renewable energy sources in determining a sustainable and optimal energy supply mix (Amer & Daim, 2011; Cararo et al., 2014; Vidal-Amaro et al., 2015).

Vidal-Amaro et al., (2015) proposed the use of a 'Minimum Total Mix Capacity (MTMC) method to evaluate several scenarios of Renewable Energy Supply (RES) incorporation in the Mexican electricity system in order to obtain capacity mixes of RES and fossil fuels', so as to generate an electricity system by considering the hourly values of RES production and electricity demand. The Mexican Congress announced that fossil fuel-based electricity generation must be limited to 65% by 2024, to 60% by 2035 and to 50% by 2050 (Vidal Amaro et al., 2015). The minimum complementary fossil fuel capacity that is required for the demand without electricity imports is checked to ascertain the total mix capacity for the transition system. When using the MTMC methodology, biomass, wind and solar power mergers acquire at least 35% RES electricity production and only one merger can result in the minimum overall capacity, which makes the optimal mix (Vidal Amaro et al., 2015).

Amer and Daim (2011) investigated Pakistan's renewable energy electricity generation alternatives. The analytic hierarchy process was first used in that country's energy sector in order to choose and prioritize multiple renewable energy technologies for generating electricity. A model composed of the goal, criteria, sub-criteria and alternatives was formulated. It consisted of wind energy, solar Photovoltaic (PV), solar thermal and biomass energy variants. The outcomes of the proposed decision model can be utilized for developing a long-term renewable energy policy.

As stated by the IEA (2014), renewables may improve energy security through reducing reliance on imported fuels and fossil fuels; thereby helping to diversify the power mix. Renewables can be positioned in a decentralized manner, which allows them to be more quickly deployed than centralized power plants. They can create employment for locals through their deployment and maintenance activities. Renewables are also important as they help to provide energy access to remote communities. This IEA outlook also indicated that the share of renewables in total capacity is set to 44% by 2040.

Other studies indicated and highlighted the importance of incorporating renewable energy into a country's energy mix (Apergis & Payne, 2010; Inglesi-Lotz, 2015). As reported in Apergis and Payne (2010), renewable energy will not only solve the problems that are linked to the present energy consumption patterns and it will not only provide modernization of the energy sector, but it will also advance sustainable development objectives. Inglesi-Lotz (2015) also highlighted that there is an advantage in government policies that promote renewable energy by initiating renewable energy markets and portfolio standards, not only to improve environmental conditions, but also from a macroeconomic point of view.

Literature also showed that there are deficiencies in the strategic management and policy implementation of the South African energy supply system, which has been a major contributor to the energy crisis. Ateba and Prinsloo (2019) evidenced this in a study which focused on the effective strategic management of electricity in South Africa. It was found that, 'various strategic management failures and the lack of an integrated approach have been a major stumbling block to energy supply sustainability in the country'; and it was suggested that an integrated strategic management framework would be an effective approach to achieving electricity supply sustainability in South Africa. A similar sentiment was expressed by Pollet et al., (2015), who highlight that, even though South Africa has been seen as the 'powerhouse of Africa', it faces an electricity supply crisis and it has failed to supply enough electricity for its economy for the past 40 years. This study stated that government energy and efficiency initiatives should be emphasized on oil and gas exploration; and it recommended that off-grid renewables and hydrogen energy could be considered as potential generation alternatives.

As stated in the 2010 Integrated Resource Plan (IRP) (DoE, 2011), the South African government intends to expand its independent power creation. This will be done by measures that include, but not limited to, ensuring that there is renewable energy generation, self-generation and co-generation. The IRP also stated that the involvement of IPPs will include important benefits such as the relative speed at which they can be brought to accomplishment, the lessening of Eskom's resource burden on financing, new facilities and the improvement of South Africa's renewable energy profile (DoE, 2011).

According to Montmasson-Clair and Ryan (2014), 'National electricity planning, as part of energy policy, has emerged internationally as the most effective and efficient framework to shape the development of the Electricity Supply Industry (ESI)'. The paper states that internationally, numerous administrations have ingrained electricity planning into the IRP. The IRP meets the estimated demand in a set period and does so affordably as well as efficiently. It also takes into cognizance equity issues, environmental protection, reliability as well as other country-specific goals. The IRP should minimize the present and future costs of meeting energy demand, by recognizing the impacts on utilities, government, the environment and society.

According to the South African Department of Energy, the IRP is synchronized for generation expansion and demand-side intervention programmes because of the multiple criteria to meet electricity demand (DoE, 2011). It is described in the Electricity Regulation Act Number 4 of 2006 (Government Gazette, 2006) to cover the period 2010–2030. The IRP supports private generation and power supply acquisitions from regional projects. The programme regulates the timing and project mix and states how the National Energy Regulator will license such projects. The IRP does not advise or consider the ownership of the project construction or their location. The IRP plans for both capacity additions and operating regimes of these capacities.

The 2010–2030 IRP noted the favored generation technology that is needed to meet the anticipated demand growth up to 2030. A policy-adjusted IRP update draft was released in November 2016 for consultation and included several government objectives such as affordable electricity, carbon mitigation, decreased water use, localization and regional growth, making a balanced strategy in varied electricity generation sources, as well as the gradual decarbonisation of the South African electricity sector. Progress has been identified since the promulgation of the IRP. Ministerial determinations that include renewable energy, nuclear, coal and gas have been issued. The IRP is the government's plan for new generation capacity and it will be replaced by an updated plan in the future. Several assumptions have changed and these include:

- The changed electricity demand and the link with economic growth in the past three years;
- New local and global technology and fuel developments;
- Carbon mitigation blueprints and the influence on electricity supply up to 2050; and
- Electricity affordability and its impact on demand and supply.

Key assumptions that have changed include technology costs, electricity demand projection, fuel costs, and Eskom's existing fleet performance (DoE, 2016). Gauché et al., (2012) argue that the IRP 2010 recommended energy mix is excessively dependent on unsustainable resources that are also at risk in the short-to-medium term. Coal and other conventional resources may be limited, and if this assumption is correct, action needs to be taken rapidly. The Concentrated Solar Panel (CSP) is the only maintainable and dispatchable energy technology that can supply a significant portion of South Africa's electricity needs (Ateba & Prinsloo, 2019). A proportional mix of PV, wind and CSP can provide South Africa with an energy supply, but there is a need to take advantage of the localization potential and excellent sustainable energy resources.

Several options can be used to check the alternatives that are available to South Africa between now and 2050 as per the 2016 IRP update projections. The list includes resource size, demand matching and cost; learning rate; technology risk; resource availability risk; national security risk; environmental risk; localization potential; local participation; industrialization; and export potential. These options should be examined in detail as they present an analysis of resource size, localization potential and demand matching.

The substitutes to base load and peaking fit in the shrinking substitute group with some dependence on hydro imports, with the current focus of the IRP being on risk avoidance. This implies that the risk mitigation is paradoxical if the discussed forecasts were accurate. Studies such as those by Fluri (2009); Viebahn et al., (2011) as well as Craig et al., (2017) have observed that CSP seems to be the ultimate solution. Although this technology may be ideal for post-fossil energy supply, cost and maturity are found to be limitations. As also found in Gauché et al., (2012), a system of CSP plants would be expensive despite its ability to provide all energy needs. A similar energy system with the same certainty would presumably consist of all three renewable types in the same proportion. The conclusion was that assuming that the storage potential offered by CSP will remain the most efficient and economical storage for utility scale power generation, an optimal mix of CSP with other renewables will be essential.

In evaluating energy policy and incentives, Musango (2011) highlights that the South African policy status and the incentives that affect replaceable electricity generation, electricity generation initiatives and their challenges. The policy implications and recommendations in support of future renewable electricity generation include, organizing a coordinating agency, generating public awareness, providing financial support guarantees, capacity building, and the development of skills. The conclusion was that the potential for developing wind, solar, biomass and small-scale hydro renewable electricity in South Africa is acknowledged.

The current South African policy, especially the IRP, encourages the growth of renewable electricity creation. The announcement and the beginning of the REIPPP bidding process accelerated the extensive execution of renewable electricity creation. There are, nevertheless, still several obstacles, schedules and policies must be created such that they can expedite the execution and implementation of electricity technologies. The proposed strategies in the present study include the creation of an organizing committee; increasing public awareness; investment assurances; and the need for capacity as well as skills development.

2.2 The causal relationship between energy and economic growth through Research and Development (R&D)

Economic development for the BRICS countries excluding Brazil has been expedited by principles that prefer economic expansion. In the last 20 years, China, India and the Russian Federation are still amongst the biggest greenhouse gas emitters globally. BRICS countries have ensured that energy is affordable in order to encourage competition in the industry. In China, the expansion of industries has been the main driving force behind energy demand as the industries are responsible for approximately half of the country's energy consumption. The strategies have, however, been associated with the impairment of environmental sustainability, which is linked to the energy systems (World Economic Forum, 2014).

BRICS countries have been dependent on fossil fuels for their energy production and exports. "The BRICS countries together contributed about 38 percent of global carbon emissions in 2014. By far the biggest share is China's as it is more than 24 percent of the global total, far ahead of the next biggest emitter in the group – India" (Greenpeace, 2015). Many predict that coal will influence the attainment of meeting the countries' growing energy demands. However, the impact on the environment has forced these countries to search for alternative and more efficient fossil fuel technologies. Fiscal and financial disincentives for fossil fuel usage can lead to the creation of an environment for the configuration of low-carbon power generation. The BRICS countries intend to expand their portion of energy from renewable and low-carbon energy sources. Although installed renewable capacity has increased, cost effectiveness with fossil fuels, dependency on subsidies and incentives are still a major problem, this implies that a lot still needs to be done in order to tackle the renewables' expense and market structures. Renewable energy, however, might not fill the base-load gap if the coal supply and the share are low (World Economic Forum, 2014).

The current South African energy-mix is dominated by cheap domestic coal usage and as a result, the majority of South Africa's Green House Gas (GHG) emissions arise from energy supply and use (~80%), with the electricity sector being responsible for 45%. Coal-To-Liquids (CTL) technology for liquid fuel production in the transportation sector is another major contributor to GHG emissions (National Planning Commision (NPC), 2018). According to the NPC Energy Paper 2018, "South Africa is a relatively energy-secure country with most domestic energy needs being met by domestic coal…" Domestic primary energy production is mainly coal-based (> 85%) and has historically been the driving force behind the South African economy". Biomass/waste, nuclear and hydro sources account for (≈15%) of South African energy. Oil and liquid fuels energy imports dominate (≈85%) and ≈ 15% comes from natural gas, electricity and coal. South Africa imports almost all of its oil and liquid fuel (≈ 99%) (Pao, et al., 2014). South Africa has domestic solar and wind resources and these could be utilized to drive a future sustainable economy. Supportive technologies and services should be incentivized in order to enable future energy economy and to support economic growth (Pao & Tsai, 2010).

The relationship between energy use and economic growth has been the subject of extensive academic research. Most researchers have studied the connection between the use of renewable and non-renewable energy and economic growth using panel data. Multivariate cointegration techniques and VECM are the most used techniques to study this subject (Hsiao-Tien Pao, 2014). It is far more insightful to investigate disaggregated energy sources as it enables the examination of the short run and the long run relationships and causality as a direct result of renewable energy or non-renewable energy and if there is a difference between the two. In addition, as stated by Dogan (2016), this variety in the energy expansion sector's research is important as management can then create other blueprints for different energy bases in order for them to get maintainable growth rates. Pao et al. (2014) state that there are dual goals for checking the connection between the separation of the use of clean and dirty energy and economic expansion; one is confirming if clean energy can be replaced with the use of non-clean energy and the other goal is the use of the proposed disaggregated analysis in order to get a global green economy.

There are varied views and findings that either support or oppose the benefits of the use of either of the energy sources. Apergis and Payne (2011a) note a two-way short-and long-run causality connecting renewable and non-renewable energy usage and economic growth. They found a negative one direction short-run causality from renewable energy usage to non-replaceable energy usage with positive results for dual panels of 25 developed countries and 55 developing countries. This shows the significance of replaceable and non-replaceable energy sources for maintainable economic growth.

Apergis and Payne (2011b) also highlight that there exists a one directional short-run causality from economic expansion to replaceable electricity usage with bidirectional long-run causality, and a bidirectional short-and long-run causality between non-renewable electricity usage and the economic expansion for a panel of 16 growing markets. This shows that as the economy expands, there will be an increase in capital, which will stimulate the expansion of the replaceable energy industry thereby making the emerging markets to rely on non-replaceable energy.

Non-renewable energy sources such as coal and gas have a positive impact on economic growth. Lei et al. (2014) state that the consumption of coal has an impact on the economic growth of countries such as Germany, Russia and Japan. The authors found that an increase in the consumption of coal indicates the increase of the production activity that leads to the increase of economic growth. Xu et al. (2016), also found that the increase of coal consumption promotes economic growth in China. Solarin and Shahbaz (2015) identified that the consumption of natural gas has a positive effect on the economic growth in Malaysia. On the other hand, Destek (2016) found that the consumption of natural gas has a positive impact on the GDP growth in OECD countries. More recently, Dogan (2016) analyses Turkey's estimates and the causality connection between economic growth, renewable and non-renewable energy consumption in a multivariate model that includes capital and labor. The findings show that renewable energy usage has an insignificant impact on economic growth while non-renewable energy consumption has a significant positive effect. There is also evidence to support the conservation hypothesis and the feedback hypothesis both in the short and long runs.

Apergis and Payne (2010) analyse the connection between the use of renewable energy, GDP, capital and labor for 13 Eurasian countries through the application of the panel ADF unit root test, the Pedroni panel cointegration test, the Fully Modified Ordinary Least Squares estimation (FMOLS) and the panel causality test to the panel data from 1992 to 2007. Their conclusion is that the use of renewable energy, capital, and labor has positive effects on economic growth, and there is feedback hypothesis between renewable energy and real GDP. The long run estimation results highlight statistically notable and constructive coefficients on the use of renewable energy, greenhouse gas releases and employment whereas the ultimate use of energy has a coefficient of zero. The neutrality hypothesis is valid between the use of renewable energy and economic growth.

In line with Menegaki (2011) who finds the same when evaluating the case of 27 European countries by applying the ARDL approach to cointegration with structural break and the VECM causality test to the data from 1997 to 2007,.the author finds that the long run estimation results suggest statistically significant and positive coefficients on renewable energy consumption, greenhouse gas emissions and employment whereas the final energy consumption has a statistically significant coefficient of zero. Salim et al. (2014), analyse the link between the real GDP, the use of renewable energy, non-renewable energy use, capital and labor for 29 OECD countries as from 1980-2011 through the employment of a number of panel unit root tests. They conclude that all the explanatory variables have positive and numerically notable coefficients on the economy's growth. The panel Granger causality test results highlight that the feedback hypothesis is reinforced between the growth of the economy and the use of non-renewable energy while growth hypothesis is valid between the use of renewable energy and the growth of the economy in the short run and bidirectional causality is found between the use of renewable energy, non-renewable energy usage and the actual output in the long run.

Tugcu et al. (2012) acknowledge that the energy source is more supreme for the growth of the economy in G7 countries. The authors utilize the ARDL approach to cointegration and the Hatemi-J causality test (Hatemi, 2012) in a production function framework for the countries from 1980 to 2009. Additionally, physical capital, labor, Research and Development (R&D), and human capital are utilized as control variables. The results highlight that, the bi-directional causality between renewable energy and the growth of the economy is prevalent in all the countries. The authors' conclusion is that both the use of renewable and non-renewable energy has a notable responsibility in augmenting economic growth. More recent efforts, such as those of Khan et al. (2019a) and Khan et al. (2019b) also employed the ARDL modelling approach to examine the energy – environment – economic growth nexus and its interlinkages with other factors such as globalization, financial development, foreign direct investment, urbanization and innovation for the case of Pakistan. Khan et al. (2019a) proxied innovation and technological progress as the number of trademark applications, a measurement of an output innovation indicator, and conclude that innovations have a negative effect on carbon dioxide emissions.

Other studies have chosen R&D expenditure as a proxy for technological progress. It is assumed that increased R&D expenditure towards the exploration of renewable or non-renewable energy source innovation and production process can be regarded as a means to enhance and increase economic activity. This includes, enabling the substitution and transitioning between the energy sources in order to ensure sustained and consistent energy generation and supply. The overall assumption is that R&D expenditure has a positive impact on economic growth. With this impact being stronger either in expenditure on renewable energy or non- renewable energy sources.

In past studies such as those of Apergis and Sorros (2014), it has been found that there is a strong relationship between R&D expenses and profitability for energy sector firms that sell renewable energy rather than in firms that sell fossil energy. This can be an indication of the importance of renewable energy and the money spent on R&D. They also state that, “this is also due to fossil energy firms’ technological innovations being slow to play a substantial role in the profitability, given the pressure on maintaining a clean environment” (Apergis & Sorros, 2014). In agreement with this view, this study also expects to find a strong impact on economic growth through R&D expenditure towards renewable energy rather than non-renewable energy sources. This is due to the global drive for ardent policies that promote the transition to cleaner and sustainable energy sources through technology innovation.

As can been seen in the literature review above, extensive work on the nexus of energy usage and the growth of the economy has been done. However, very few studies have been conducted specifically on the BRICS countries as a block since the inclusion of South Africa in 2010. Many have argued the similarities of the BRICS countries if any especially the inclusion of South Africa with its much smaller population and economic growth standing when compared to the other countries in the group. Even though South Africa is also Africa's largest economy, but as number 31 in global GDP it is far behind its counterparts (Graceffo, 2011). According to Amorim (2010) and Camioto (2016), the BRICS, countries in addition to rapid economic growth, hold significant land mass, natural resources and considerable amounts and diversity of energy and technological advances. The BRICS countries are an alliance covering four continents and all members are emerging economies, with actions that go beyond pure diplomacy. The five countries that form the block are generally grouped by their similarities. However, individually, they have different economic, social, political and cultural characteristics, as well as differences in history, religion, geographies and climates. Energy is one of the essential components for social and economic development of a nation and must be closely linked to sustainable, efficient and safe use of energy from ecological and more economically viable approaches for future short and long-term partnerships (Tugcu, et al., 2012).

With their fast paced economic growth and industrialization, the BRICS countries are also fast becoming the world's biggest pollution emitters due to their reliance and utilization of mostly fossil fuels in their energy mixes. According to the 2015 UNEP Emission Gap Report, it is highlighted that China; Russia and India are among the six largest emitters of carbon dioxide (CO2) in the world with the largest culprit being China (UNEP, 2015). This imposes a threat for these countries in their endeavor to attain sustainable development. There is global and national pressure to decarbonize and this need for the transition of energy sources has led to the increased interest in this topic and there have been various studies that have been conducted to find solutions and inform policies.

Pao and Tsai (2010) investigate the dynamic causal relationships between pollutant emissions, energy consumption and output for a panel of BRIC countries over the period of 1971–2005, except for Russia which was investigated between 1990–2005. They find that in the long-run, equilibrium energy consumption has a positive and statistically significant impact on emissions, while real output displays the inverted U-shape pattern that is associated with the Environmental Kuznets Curve (EKC) hypothesis with the threshold income of 5.393 (in logarithms). They suggest that in the short term, changes in emissions are driven mostly by the error correction term and short-term energy consumption shocks. In addition, the panel causality results indicate that there are; energy consumption emissions, bidirectional strong causality and energy consumption output, bidirectional long-run causality, strong and short-run causalities from emissions and energy consumption, respectively, when compared to output. Increasing energy supply investment and energy efficiency as well as stepping up energy conservation policies in order to reduce the unnecessary waste of energy can be done for energy-dependent BRIC countries if they are to reduce emissions.

Subsequent to this, Pao and Tsai (2011) examined the impact of the economy and financial growth on environmental degradation for BRIC countries utilizing a panel cointegration technique from 1980 and 2007. Russia was, however, investigated for the period from 1992 to 2007. Their results highlight that there is bidirectional causality between emissions and FDI as well as unidirectional causality from output to FDI. Therefore, in attracting FDI, developing countries should check the foreign investment qualifications or they should encourage environmental protection. There exists strong output-releases and output-energy usage bidirectional causality, while there is unidirectional strong causality between energy usages to emissions. In conclusion, managing both energy demand and FDI as well as increasing investment in the energy supply and energy efficiency in order to reduce CO_2 emissions can be adopted by energy-dependent BRIC countries.

Cowan et al. (2014) re-examined the causal link between the use of electricity, the growth of the economy and CO_2 releases in the BRICS countries from 1990 to 2010, using a panel causality analysis. They found that with the electricity–GDP nexus, their empirical results are in line with Russia's feedback hypothesis as well as South Africa's conservation hypothesis. However, they found that Brazil, India and China have a neutrality hypothesis. With regard to the GDP– CO_2 emissions nexus, the authors highlight that there exists a feedback hypothesis for Russia, a one-way Granger causality running from GDP to CO_2 emissions in South Africa and a reverse relationship from CO_2 emissions to GDP in Brazil. There is no evidence of Granger causality between GDP and CO_2 releases in India and China. Additionally, electricity usage is found to

Granger cause CO2 emissions in India, while there is no Granger causality between electricity usage and CO2 releases in Brazil, Russia, China and South Africa.

Zhang et al. (2011) investigate the renewable energy policy evolution of the BRICs countries based on the Bai and Perron's structure breaks test. Their results highlight that there are no time series breaks for renewable energy production in Russia, while the series of renewable production and usage are characterized as segmented trend stationary processes around one or two structural breaks in Brazil, India and China. The results indicate that Brazil and China's renewable policies have long-term positive effects on renewable energy production and usage. In addition, they found that the Russian renewable policies are not working as they are decreasing renewable energy usage growth in the long-run. This shows that policy implications in China should; command the promotion of renewable energy, develop biomass energy on the base of comparative advantage and improve the renewable energy industry chain integration.

Similarly, Sebri and Ben-Salha (2014) analyzed the causal relationship between economic growth and renewable energy consumption in the BRICS countries over the period between 1971–2010 within a multivariate framework. They examined the long-run and causal relationships between economic growth, renewable energy consumption, trade openness and carbon dioxide emissions. They found that there exists a long-run equilibrium relationship among the competing variables. Based on the VECM results, it was noted that there was a bi-directional Granger causality between the growth of the economy and renewable energy usage. Recently, in studies pertaining to the investigation of the nexus between energy and the growth of the economy, there has been interest in the development of new and renewable energy technology. Funding is being invested in creating new and renewable energy technologies in order to decrease the dependence on fossil fuels (Lee & Lee, 2013).

Encouragingly, according to the 2014/15 National Survey of Research and Experimental Development (R&D survey), South African investment in R&D has shown an improved positive outlook. In addition, certain industries such as the electricity, gas, water supply, transport, storage and communication that have for the past three surveys reported declines are now showing an improved increase in R&D expenditure (Mail and Guardian, 2017). South Africa follows global trends for recovering R&D spending. R&D trends around the globe indicate that there is renewed interest in investing in R&D after the 2008-2010 economic crisis. Within BRICS, China has shown the highest growth in such investments. To insure enhanced global competitiveness, it is essential for countries to promote and support high level expenditure on R&D. Investment towards R&D is an essential contribution towards achieving the country's key developmental objectives. R&D undertakings are an eminent mechanism for knowledge production and the creation of new ideas. R&D also plays a critical role in innovation and economic development.

These economic outputs contribute to and can be accounted for as part of the economic output of a country through the national accounting system which uses GDP as an indicator of economic size. The significance of R&D expenditure and the prospects for these investments to enhance development projections have concurred with or directed the growth in the number and range of countries that are dedicated to science and technology policy and technology-led growth strategies. Formerly, high levels of investment towards R&D were mainly associated with developed countries as has been found in the study by Bointner (2014) where the author states that, "nearly all energy R&D is performed in the world's richest nations, he is also supported by Breyer et al (2010) who find that 85-90% of global energy R&D is performed in OECD countries". Conversely, it has been seen in the last two decades that developing countries such as

Brazil, India and China have also increased their national investment in R&D significantly (Mail and Guardian, 2017).

Inglesi-Lotz (2017) estimated that the social rate of return of R&D on a number of energy applications and technologies for the G7 countries. The results highlight that R&D investment on energy efficiency technologies as well as nuclear power get high social benefits and the opposite is true for fossil fuels. Johnstone et al. (2010) investigate the effect of environmental policies on technological revolution in renewable energy. The findings indicate that tradable energy certificates can influence transformation in technologies that are in competition with fossil fuels. Similarly, Garrone and Grilli (2010) examine the causality connections that relate R&D to carbon intensity, carbon factor and energy intensity in OECD economies from 1980 to 2004 through the use of a dynamic panel. The findings show that there is a positive link between public expenditures in energy R&D and energy efficiency.

Pfeiffer and Mulder (2013) inspect the diffusion of Non-Hydro Renewable Energy (NHRE) technologies for electricity generation across 108 developing countries from 1980 to 2010. They use two-stage estimation methods to identify the determinants of whether or not to adopt NHRE. The results indicate that various energy mixes increase the chances of NHRE adoption. (Wong, et al., 2013), investigate the causal connection between fossil fuel R&D, renewable energy R&D and real output for 20 OECD countries between 1980 and 2010. Fully-Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) were used for this investigation. The results indicate that there is some R&D energy that is inputted to the growth of the economy thereby indicating that output is also reliant on energy R&D.

For the case of China, Li and Lin (2016) investigate the effects of R&D investment activities, economic growth, and energy price on energy technology patents in 30 provinces of China over the period between 1999 to 2013. Their results highlight that R&D investment activities and economic growth have a good impact on energy technology patents. However, the panel error correction models show that the cointegration relationship promotes the growth of the economy, but it reduces R&D investment and energy price in the short term. Similarly, Guo et al. (2016) examined the elements that may prompt the transition of a coal resource-based economy by categorizing them into four types: Innovation policy, innovation input, innovation ability and innovation organization. They collected data from 314 Chinese energy firms. The results indicate that the four proposed factors are crucial in transforming the coal resource-based economy.

Noaillya and Shestalova (2016) investigate the relevance of knowledge flows within the same specific technological field (intra-technology spill overs), to other technologies in the field of power generation (inter-technology spill overs), and to technologies that are not connected to power-generation (external-technology spill overs). They used citation data of patents in renewable technologies filed at 18 European patent offices from 1978 to 2006. The results indicate that there are notable differences in numerous technologies. Nicolli and Vona (2016) investigate the impact of market regulation and renewable energy policies on change activity in different renewable energy technologies. Their results show that reducing entry barriers is a more notable driver of renewable energy innovation. However, its effect is different across technologies.

In contribution, this study will close the gap pertaining to the investigation fixated explicitly on R&D for BRICS countries. Secondly, this study identifies whether trivariate causality exists between Renewable Energy (RE); Non Renewable Energy (NRE) and economic growth taking into consideration R&D expenditure for the developing BRICS countries. The outcome of this study will enable and direct policy intervention and also inform policy decision in the investment towards R&D expenditure for RE and NRE which will be beneficial to promoting economic growth.

2.3 Energy supply mix transition strategy from fossil fuel to renewables for South Africa

In the previous section, there was an evaluation of the identified economic variables that are directly related to the energy supply mix and modeling the relationship as well as exploring scenarios based on the current economic climate on the role of renewable -based energy supply mix. In this section, the literature on energy supply mix transition strategy for fossil fuel to renewable for South Africa is evaluated.

Historically, South Africa has been plagued by insistent concerns about the adequacy of both its electricity supply system and its energy policies, which resulted in the 2007–2008 energy crisis and in the ensuing shortages in the following decade. Bellos (2018) observes that the 2007/2008 electricity "load shedding" in South Africa was inadequately prepared for. It is also highlighted by Pollet et al (2015) that South Africa failed to supply enough electricity for its economy due to the chronic under investment in the South African electricity sector which led to escalating power prices and a shortage of capacity during peak demand periods leading to demand rationing.

The determination of an optimal electricity supply mix to transition from a fossil fuel dominated mix, to a more renewable energy one is imperative to enable a greener low-carbon energy system with adequate supply capabilities. In theory, any optimization problem relies on the formulation of the objective function and the constraints imposed on it. The main objectives of transitioning and establishing an optimal energy mix should include competitively priced energy, energy security, supply stability, minimal environmental impact, employment creation, and a positive transformative impact on the overall economy.

Numerous studies have been conducted in order to determine the optimal combination of fossil fuels as well as renewable energy sources when determining a sustainable and optimal electricity supply mix. Østergaard (2009) highlights that the energy mix optimization methodology can be categorized into two groups namely: Methodologies appropriate to the economic objectives and methodology directed to the techno-operational objectives. It was mainly found in the literature by Lund (2006), Østergaard (2009), as well as Tafarte, Das, Eichhorn and Thrän (2014) that when optimizing renewable energy systems from a techno-operational perspective, the optimization criteria used were reserve capacity, import and export dependence, primary energy consumption and fuel saving, the share of renewable energy, carbon dioxide emissions (CO_2) and the excess electricity production. The criteria used for the economic optimization were: societal costs or cost-benefit data, utility costs, the impact of exchange rates, the Levelized Cost of Energy (LCOE) or levelized unit electricity costs, the total resources spent by consumers, energy companies and government bodies, as well as marginal costs (Østergaard, 2009).

Østergaard (2009) further explains that varying optimization methodologies generated different results. He concludes that no unequivocal answer can be found to the topic of how to plan an ideal optimal energy system. However, he further infers that the examination demonstrates that, when references are being made to explicit renewable energy source targets or to urban communities or territories with policy aspirations of changing to renewable energy source or getting to be carbon neutral, the optimization criteria should be clearly defined. It is evident that as far as techno-operational needs are concerned, economic optimization alone may not be sufficient in fulfilling the requirements; rather it leans towards a more commercial perspective on the feasibility of a project. A typical example would be that of the intermittency issues found in renewable energy sources. It is found that optimization over a longer time frame based on the lowest cost or LCOE may not capture the balancing issues. However, the factors surrounding the problem statement that necessitates optimization may influence the choice of methodology.

In demonstrating the economic objective methodology point of view, Monga et al (2006) conducted a study on the rural differential and aggregate resource potentials for renewable resources in India and defined the important characteristics affecting the fuel mix in rural areas. The rural constraints on renewable supply were evaluated and their potential effects on local, regional and global environmental attributes were discussed. They also proposed a model for studying energy mix alternatives for rural areas. Their model emphasized social needs rather than economic goals. They analyzed the renewable energy outlook in India and also took into consideration the potentials and infra structures required for renewable energy. They categorized rural India in the different system scenarios of the model. The basic algorithm used the Quality Of Life (QOL) as indicators and proposed a methodology which would enable the policymakers to estimate the additional energy demands that are needed to ascend the QOL ladder.

On the other hand, from the techno-operational objective point of view, Lund (2006) utilized an electrical power minimization methodology to estimate the level of renewables integration for an optimal combination of solar Photovoltaic (PV), wind and wave power. They found that although this approach addresses the important problem of Excess Electricity Production (EEP), it does not demonstrate the integration of the complementary power that is needed to satisfy the demand.

As stated in the Africa Energy Outlook (IEA, 2014), renewables potentially improve energy security by reducing the reliance on imported fuels as well as fossil fuels and they help to diversify the power mix. Renewables can be deployed in a decentralized manner which may enable them to be deployed faster than centralized power plants and this can provide local employment for deployment and maintenance. Renewables are also critical technologies that help to provide access to remote communities. The outlook also indicates that the share of renewables in total capacity is set to more than double to 44% by 2040. Several academic studies have been conducted which indicate and highlight the importance of incorporating renewable energy into a country's energy mix. As found in Apergis and Payne (2010), renewable energy will not only address the limitations associated with the current energy consumption patterns and provide much needed modernization of the energy sector, but it will also promote sustainable development objectives. Inglesi –Lotz (2015) also highlights that there is an advantage in supporting the government policies as this promotes the use of renewable energy by establishing renewable energy markets. Renewable energy portfolio standards do not only improve the environmental conditions, but they are also an advantage from a macroeconomic point of view.

Mendes and Soares (2014) investigated the effects of well-developed renewable energy sources such as wind power on the generation capacity mix of a competitive market, such as in the Iberian wholesale electricity market. The aim of their study was to provide the necessary tools for understanding the relationship between renewable energy sources and the optimal generation capacity mix in a liberalized, competitive market. The methodology they used was from reviewed literature that focused on the impact of wind power on the generation capacity mix. They followed an article developed by Milstein and Tishler (2009) which was applied to the Israeli market which has been subject to extensive reforms in order to deregulate the electricity market since it was dominated by state-owned vertically integrated electric utility which is what is currently in South Africa. Given that underinvestment is one of the major concerns to policymakers in deregulated electricity markets, that article offered a formal model of endogenous capacity with uncertain demand to aid the regulatory body in understanding that underinvestment is due to the rational behavior of profit-seeking producers.

Later, Milstein and Tishler (2011) applied the base model to the same market in order to aid the regulatory body in realizing the relationship between renewable energy, the optimal generation mix and electricity price level as well as volatility. Therefore, in order to explore the connection between renewable energy sources and the optimal generation capacity mix in a competitive wholesale electricity market, the Mendes and Soares (2014) study applied and solved this theoretical model to the Iberian Electricity Market. They presented a two-stage game of endogenous investments and operations in a competitive electricity market with wind and Combined Cycle Gas Turbine (CCGT) technologies under the uncertainties of supply and demand. In the first-stage of the game, each producer decides on their capacity investment in order to maximize expected profits. In the second-stage of the game, the producer selects the daily electricity production subject to capacity availability and equilibrium prices are determined. The game is developed under the Cournot Framework and solved using the MATLAB software. They concluded that, when the producers can operate both technologies, the introduction of wind power replaces the choice of investments in; conventional power (CCGT), in the MIBEL and in each country that constitutes it.

This conclusion showed that the investment in new renewable capacity would be the most efficient choice. An analogous result was obtained regarding optimal industry production. Just as the majority of investment in installed capacity was in wind power, so too the share of wind power in the total of optimal industry production was greater than the share of CCGT power. This result was valid for the Iberian Electricity Market (MIBEL) and its constituting countries, Portugal and Spain.

For Japan, Saeko et al., (2010) developed an optimal power generation mix model in an attempt to explore the operational effect on the optimal power supply mix of large renewable energy source deployment. They employed a sensitivity analysis nuclear capacity, capable of electricity inter exchange among utility companies and carbon dioxide emissions regulation. They found that the model, under various assumptions, sought to minimize total power generation cost, mainly consisting of facility cost and fuel cost. Utilizing a linear programming method, their study stated that, in future power generation mix, solar and wind power were expected to become the center of renewable power supply sources. Furthermore, they confirmed that wind power generation when effectively adopted will lead to the reduction of carbon dioxide.

De Jonghe et al., (2011) analyze the impact of a high level of wind power penetration on the optimal future power technology mix. Their model is based on the screening curve methodology to include wind energy, using a static linear programming investment model to determine the optimal technology mix by determining the mix of technologies operating as base, intermediate and peak loads that are capable of meeting the demand in a cost-effective way. They find that is static and does not conclude on what other renewable sources to integrate over a period of time, given the non-dispatch nature of wind power; it is more suitable as a solution to back-up power.

Kabakian and Sayyed (2015) determine the optimal energy mix for Lebanon considering the cost burden to the government. Their study incorporates the capacity potential of the three renewable technologies (hydropower, wind power and solar Photovoltaic (PV) and concentrated solar power technologies). Their study showcases the importance of renewable energy in the portfolio of electricity supply under the cost criterion. They concluded that if renewable energy sources are incorporated into Lebanon's energy mix, the overall cost to the economy will be reduced. They also recommend a set of policies to maintain stable investments in the power sector and to supply reliable, efficient and affordable electricity to consumers.

Vidal-Amaro et al., (2015) recommended a methodology they named the Minimum Total Mix Capacity (MTMC) for the determination of the optimal mix of Renewable Energy Resources (RES) and fossil fuels in an electricity system by taking into account the hourly values of RES production and electricity demand. They applied this methodology to the Mexican electricity system in a bid to assess the optimal RES mix that could aid the attainment of a Mexican congressional mandated to limit fossil fuel-based electricity generation to 65% by the year 2024, 60% by 2035 and 50% by 2050. Vidal-Amaro et al., (2015), applied their MTMC model to determine, "…based on actual hourly production values for every RES involved, an optimal energy mix to cover demand using the total RES production share, backup capacity and EEP as optimization criteria". Their methodology, however, focused on maintaining capacities through the assessment of the potential for RES integration into the Mexican electricity and energy source substitution at designated times. Additionally, their data simulation was based on the hourly production of data. Although their model addressed the optimal energy mix requirements of their study, it did not address the issue on a year-on-year basis and may have required hourly data for the years to be projected and that dataset was not available.

South Africa is in the process of an energy transition, as highlighted by Baker et al (2014), "South Africa is to some extent already undergoing a transition from an era of 'energy opulence' to one of restraint imposed by a series of infrastructural, economic, environmental and physical constraints. Meeting these challenges will involve difficult trade-offs about how to manage conflicting pressures in a way which protects jobs, assists socio-economic development and addresses the economic disadvantage of the historically marginalized population". Swilling et al (2015) argue that, "a just transition can be understood as a structural transformation that results in the achievement of two linked goals: developmental welfarism and a sustainable transition. But for both these goals to be achieved, a socio-political regime committed to the building of relatively autonomous publicly accountable institutions will be needed".

Prasad (2008) found that there are limited studies focusing on the energy transitions in sub-Saharan Africa. Since then, it has been found from the literature review that several studies have been conducted on energy transition due to the growing international policy interest in low carbon energy transitions. Baker et al. (2014) state that the term energy transition provides both a description of a process of transformation from one energy system to another as well as a set of tools and concepts to explain and enable such transitions. Studies by Rip and Kemp (1998); Meadowcroft (2005); Meadowcroft (2011); Geels and Schot (2007) and Scrase and Smith (2009) seek to understand how, when and where transitions to low-carbon socio-technical regimes can come about. These transitions are classified as socio-technical transitions. Geels (2011) defines the term socio-technical transitions as deep structural changes in systems such as energy and transport, which involve long-term and complex reconfigurations of technology, policy, infrastructure, scientific knowledge, and social and cultural practices to sustainable ends. This is also known as the widely used Multi-Level Perspective (MLP) which analyses systems change from the level of landscapes, regimes, as well as niches and it is useful because it attempts to capture the way in which technological and political change is embedded within and affected by broader global processes such as is the case with South Africa (Baker, Newell, & Phillips, 2014).

Baker et al (2014) further highlight that the advantage of the MLP is its ability to provide a "useful theoretical idiom to explore change processes" and an "impressive set of historical studies of system transitions". Geels (2005) and Geels and Schot (2007) quoted in Meadowcroft (2011:21)further state that as a system, the MLP concerns the manner by which occupant systems lose soundness and in this way experience transitions because of the influence from the niche and landscape levels (Byrne et al, 2011:57). Such a point of view can possibly give a multi-dimensional examination of the elements of basic change (Geels 2011) and the complex and frequently contending communication between various advancements in technologies, actors, establishments, systems and procedures, all of which work inside the socio-technical system (Lawhon & Murphy 2011). It offers, along these lines, a significant beginning stage for understanding the multi-scalar developments occurring in South Africa's energy sector (Baker, Newell, & Phillips, 2014).

In conclusion, Swilling et al. (2015) argue that a just transition is only conceivable if the general objective is human prosperity (income, education and health) within a sustainable world (decarbonization, resource efficiency and ecosystem rebuilding). For this to have direction, more extensive socio-technical influence ought to all in all be seen by key actors inside the socio-political system as prodding verifiable procedures that fortifies the regulating cases of these objective explanations. Distinct advantages developing out of specialty advancements ought to likewise be combining around reasonable options. Nonetheless, the basic changes required for a just transition might be accomplished when there is a socio-political system that lays on a key alliance of interests that offer this worldview, utilize state organizations to drive a just transition and adopt a proper strategy and administrative program that is lined up with the general objective. This study intends to fill the gap and make a contribution by conducting an empirical analysis to determine an optimal energy mix transition for South Africa.

2.4 Conclusion

It is evident from the literature above that extensive studies have been conducted in order to inform what optimal energy supply mix entails and how to attain it. It is clear that there is a global consensus on the transition to more sustainable and cleaner energy sources and technology types. Extensive studies have been conducted to assess the impact of this on the economy as well as in the importance of expenditure towards R&D in order to accurately explore and determine which exact resource and technology type should be invested in. The literature review also confirms that energy policy in South Africa, particularly the IRP promotes the expansion and transition to more renewable energy inclusion in the energy supply mix despite the many obstacles. Schedules and policies are still required to enable the expedition, execution, and implementation of electricity technologies. The proposed strategies in the present study include the creation of an organizing committee; increasing public awareness; investment assurances; as well as capacity and skills development. It is also evident from the literature study that the basic changes required for a just transition might be accomplished when there is a socio-political system that lays on a key alliance of interests that offers this worldview, utilizes state organizations to drive a just transition and adopts a proper strategy and administrative program that is lined up with the general objective. This study intends to fill the gap and make a contribution by conducting an empirical analysis to determine an optimal energy mix transition for South Africa.

Based on the literature examined above, the overall aim of the thesis aligns and complements this analysis with an examination of whether and how renewable and non-renewable energies in the supply mix impacts the South African economy. As noted from the literature above, the studies in the energy and environmental economics literature examining the case of South Africa had focused either on the economy-energy-environment interaction (Inglesi-Lotz (2015)) or on the other side, provided supply mix scenarios based on cost-minimizing scenarios only (Østergaard (2009)). Hence, this study contributes: 1) to the economy-energy-environment nexus of the literature by adding the R&D impact to the relationship (proxying technological progress); 2) to the optimization of supply mix literature by complementing the cost-minimization approaches with environmental considerations. Finally, this study is innovative in the sense that it provides a holistic view by combining the analysis of causal relationships among energy, economy and technology with an energy modelling application towards establishing optimality in the energy supply mix with renewable energies playing a major role; all these being founded on theoretically informed frameworks.

Table 3 Selected international and BRICS countries energy causality studies

Authors	Period	Methodology	Country	Causality
Apergis & Payne (2010)	1985-2005	Panel cointegration and error correction model	OECD countries	Bidirectional causality between renewable energy consumption and economic growth in both the short- and long-run.
Apergis & Payne (2011a)	1990–2007	Panel error correction models	Developed and developing countries	Bidirectional causality between renewable and non-renewable energy consumption and economic growth in the short- and long-run for each country panel.
Apergis & Payne (2011b)	1990–2007	Panel error correction model	Emerging market economies	Unidirectional causality from economic growth to renewable electricity consumption in the short-run and bidirectional causality in the long-run.
Lei (2014)	2000-2010	panel cointegration and Granger	China, the United States of America,	Bidirectional causal relationships between coal consumption and economic growth exist in Germany, Russia and Japan. (2) Only a unidirectional causality from

		causality	India, Germany, Russia and Japan.	economic growth to coal consumption exists in China. (3) There are no causal relationships between coal consumption and economic growth in USA and India.
Solarin and Shahbaz (2015)	1971–2012.	ARDL bounds testing method	Malaysia	Feedback hypothesis between natural gas consumption and economic growth, foreign direct investment and economic growth, and natural gas consumption and foreign direct investment.
Destek (2016)	1991 - 2013	Panel fully modified ordinary least square (FMOLS) and the panel dynamic ordinary least square (DOLS)	26 OECD countries	Unidirectional causality from natural gas consumption to GDP growth, which supports the growth hypothesis for the short-run. In the long-run, it is concluded that there is bidirectional causality between natural gas consumption and economic growth which confirms the feedback hypothesis.
Dogan (2016)	1988 to 2012	ARDL model	Turkey	Conservation hypothesis and feedback hypothesis between renewable energy consumption and economic growth in the short run and the long run, respectively, and feedback hypothesis between non-renewable energy consumption and economic growth both in the short run and the long run.
Mengaki (2011)	1997–2007	Random effect model	27 European countries	Empirical results do not confirm causality between renewable energy consumption and GDP, although panel causality tests unfold short-run relationships between renewable energy and greenhouse gas emissions and employment.
Salim et al (2014)	1980–2011	Fixed effects model	29 OECD countries	Bidirectional causality between industrial output and both renewable and non-renewable energy consumption in the short and long run.
Tugcu (2012)	1980–2009	ARDL model	G7 countries	The long-run estimates showed that either renewable or non-renewable energy consumption matters for economic growth and augmented production function is more effective on explaining the considered relationship.
Pao and Tsai (2010)	1971–2005	Error correction model	BRIC countries	Energy consumption–emissions bidirectional strong causality and energy consumption–output bidirectional long-run causality, along with unidirectional both strong and short-run causalities from emissions and energy consumption, respectively, to output.
Pao and Tsai (2011)	1980 - 2007	Error correction model	BRIC countries	Bidirectional causality between emissions and FDI and unidirectional strong causality running from output to FDI. Additionally, there exists strong output-emissions and output-energy consumption bidirectional causality, while there is unidirectional strong causality running from energy consumption to emissions.
Cowen et al (2014)	1990–2010	Panel causality approach	BRICS countries	Regarding the electricity–GDP nexus, the empirical results support evidence on the feedback hypothesis for Russia and the conservation hypothesis for South Africa. a neutrality hypothesis holds for Brazil, India and China, indicating neither electricity consumption nor economic growth is sensitive to each other in these three countries.

				Regarding the GDP–CO_2 emissions nexus, a feedback hypothesis for Russia, a one-way Granger causality running from GDP to CO_2 emissions in South Africa and reverse relationship from CO_2 emissions to GDP in Brazil is found. There is no evidence of Granger causality between GDP and CO_2 emissions in India and China. Furthermore, electricity consumption is found to Granger cause CO_2 emissions in India, while there is no Granger causality between electricity consumption and CO_2 emissions in Brazil, Russia, China and South Africa.
Sebri and Ben-Salha (2014)	1971–2010	ARDL bounds testing approach	BRICS countries	Bi-directional Granger causality exists between economic growth and renewable energy consumption, suggesting the feedback hypothesis,

CHAPTER 3: METHODOLOGICAL APPROACH AND DATA DESCRIPTION

3.1 Introduction

The purpose of a theory and practice review is to investigate the theoretical and practical base of issues discussed in the research problem. This chapter is divided into three parts.

In Chapter 2, the systematic synthesis of the literature was done, this chapter commences by giving a detailed description of the methodologies and data that was used in the study as informed by the literature review in order to address the research questions as identified in Chapter 1. The chapter starts with a brief energy supply mix positioning comparison of South Africa and its BRIC counterparts followed by a review and analysis of the methodologies on the causal relationship between energy and economic growth through Research and Development (R&D). The conclusion is based on the methodology that was followed in proposing the electricity supply mix.

3.2 Positioning South Africa's energy supply mix internationally: Comparative and policy review analysis

3.2.1 Theory and Practice

Collier (1993) states that, using comparative analysis can provide the foundations for proper descriptive analysis towards the formulation of hypotheses and theories which offer the differences and similarities of the studied objects. Nakumuryango and Inglesi-Lotz (2016) also highlight that South Africa is classified as a two-tiered economy; the first tier being its primary sectors that include mining as well as agriculture; manufacturing and the financial sector. It is more advanced and well developed when compared with international markets. The second tier consists of the informal sector and the general poor conditions in some sectors of the economy. Hence, in order to adapt to South Africa's economic nature and in order for a more comprehensive comparative analysis for the present study, South Africa was compared with OECD countries and its other BRIC counterparts which are developed and with developing countries respectively. The BRICS countries share a major characteristic as they are emerging economies. The World Economic Forum (2011) ranked South Africa favourably in comparison with other BRICS countries. South Africa is also committed to the African unity and integration within the Constitutive Act of the African Union (AU) (African Union, 2000). This includes the reinforcement of continental institutions which are important in acknowledging the continent's challenges of poverty, underdevelopment, energy security and stability. South Africa, through its BRICS membership, ensures that other African countries are at an advantage and continue to gain energy; information and communications technology; rail and road infrastructure; and agriculture and food security from the BRICS countries.

South Africa also has characteristics of developed countries, rendering it important to compare and contrast the South African energy supply mix to that of OECD countries, looking at differences, gaps and potential of their energy supply and mix compositions. For each region, the constitution of the energy mix is influenced by; the domestic presence of usable resources or the possibility of imports; the extent and type of energy needs to be addressed; the policy choices guided by historical, economic, social, demographic, environmental and geopolitical factors.

3.2.2 Data

Considering this, additional indicators such as the electricity generation mix for each of the countries are compared. Controlling the size of the economy by normalising the total primary energy supply (TPES) with Gross Domestic Product (GDP) would provide valuable insights, both for the evolution of the South African TPES in comparison with the country's economic growth, as well as when comparing with countries of different economic size.

The data used for the comparative analysis exercise is that of the TPES, which is measured in Kilotons of Oil Equivalent (ktoe) of the BRICS and OECD energy balances, obtained from the IEA database in 1990-2015. The TPES is energy production plus energy imports, minus energy exports, minus international bunkers, then plus or minus stock changes (depending on whether the net stock is an inflow or outflow).

$$\text{TPES} = (\text{energy production} + \text{energy imports}) - \text{energy exports} - \text{international bunkers} \pm \text{stock changes} \quad (1)$$

3.2.3 Conclusions

This gives a holistic picture of the primary energy mix for all the selected country groups. The energy mix alludes to how the final energy consumption for a geographical region is broken down by primary energy source. It comprises of fossil fuels, nuclear energy, waste and other types of renewable energy, including biomass, wind, geothermal, water and solar. These energy sources are used to generate electricity, produce transportation fuel, as well as for heating and cooling in residential and industrial buildings.

In order to comprehend the status quo of the country's energy supply mix and it's positioning vis-à-vis international trends for future policy recommendations and implementation, a quantitative comparison research method was chosen. This method was selected due to its ability to provide a foundation for an extensive descriptive analysis through the formulation of a hypothesis and theories which offer the differences and similarities of the study of interest as highlighted by Colliers (1993), which was most appropriate and enabled the extensive examination of the status quo of the South African energy supply mix as well as its comparison to its BRIC counterparts.

3.3 The causal relationship between energy and economic growth through Research and Development (R&D)

3.3.1 Theory and Practice

The study covers the period from 1996 to 2015 using a panel of five developing countries. The main reason for selecting the BRICS countries is that, except for their similar socioeconomic challenges, they have also made commitments to transition to low carbon energy supply mixes in the future and are also faced with similar socioeconomic challenges. As Sahu (2016) explains, BRICS is the first attempt to cluster together countries based on their future potential and not necessarily on their existing wealth or cultural identity. Russia and Brazil are mainly energy exporters, while the other three countries share challenges related to energy security and demand management. The BRICS countries also accounted for 38% of the global carbon emissions in 2014 – with significantly and rapidly growing populations (almost half the global population). Ndlovu and Inglesi-Lotz (2019) also find that BRICS have remained historically dependent on fossil fuels for energy generation for domestic purposes and exports.

The theoretical framework that was followed for this study was adopted from the combined experience of others, primarily by Emirmahmutoglu and Kose (2011). In this study, the researcher postulates a bivariate or pairwise Granger-causality model to identify the causal relationship between each of the variables. Preceding the panel Granger causality analysis, a prerequisite of the Granger causality test is to conduct stationarity and cointegration tests. Should the variables be found to be stationary once differenced, or I (1) and not cointegrated, then the traditional pairwise Granger causality tests are valid. Should the variables be a mix of I (1) and I (0), then the methodology set out by Emirmahmutoglu and Kose (2011) for mixed panels would have been used.

To test for the existence of unit roots and to determine the order of integration of a panel requires several tests. The formal tests consist of hypothesis testing where the null hypothesis postulates that all series in the panel contain unit roots. There are two approaches which are available for determining whether unit roots exist within the different series in the panel. The first option tests each cross-section separately and makes inference about the presence of unit roots in each individual series. The second option pools all the cross sections together and determines if a common unit root is present in all the cross-sections.

In order to determine whether the GDP, RE, NRE, and RD variables are stationary, three unit root tests were carried out namely, the Levin et al. (Levin, et al., 2002)(LLC); Im, Pesaran and Shin (2003)(IPS) and the Phillips-Perron (1988)(PP) tests.

Similar to the unit root tests discussed above, a hypothesis test is used in this method to determine the cointegration of the panel. Once the stationarity of the variables, InGDP, InRE, InNRE, and InRD is determined, the following step is to test for cointegration between the variables. Cointegration implies the existence of a long-run relationship among the variables within the group of countries. To test for cointegration, the method by Johansen (1988) was used, which estimates two combined likelihood ratios that capture the individual tests.

The two likelihood ratios are based on the two tests as suggested by Johansen (1988). The first test statistic is the trace statistic and the second is the maximum or maximum eigenvalue, statistic. Even though these two statistics utilize an almost exact methodology to derive their respective alternative hypotheses, they are slightly different. The trace statistics are used to test the null hypothesis of r cointegrating relationships against the alternative hypothesis of n cointegrating relationships. On the contrary, the maximum eigenvalue statistic is used to test the null hypothesis of r cointegrating relationships versus the alternative hypothesis of $r + 1$ cointegrating relationships.

The Kao (1999) test of cointegration ensues a similar process to that of the Pedroni test for cointegration. However, the Kao test differentiates between cross sections by specifying that the intercepts are heterogeneous while the coefficients are homogeneous as can be seen in equation 2 below.

$$y_{it} = \alpha_i + \delta_i t + \sum_{m=1}^{M} \beta_{mi} x_{mit} + e_{it} \quad (2)$$

Where:

$t = 1, \dots, T$ and T is the number of time periods

$i = 1, \dots, N$ and N is the number of cross sections

$m = 1, \dots, M$ and M is the number of regressors.

Applying the results from the panel multivariate regression in equation 2, the seven tests referred to in Pedroni (1999) can be calculated. These seven Pedroni tests are divided into four tests which relate to pooling along the within dimension and three tests relate to pooling along the between dimension. The within dimension statistics test the null hypothesis of $H_0: \gamma_i = 1\ \forall i$ versus the alternative hypothesis of $H_A: \gamma_i = \gamma < 1\ \forall i$ while the between dimension statistics test the null hypothesis $H_0: \gamma_i = 1\ \forall i$ versus the alternative hypothesis of$H_A: \gamma_i < 1$. Therefore, the within dimension statistics forces homogeneity across the cross sections while the between dimension statistics allow for heterogeneity across the cross sections.

Proceeding with the Emirmahmutoglu and Kose (2011) technique to test for pairwise Granger non-causality, the next step involves a Granger causality test procedure combined with the LA-VAR approach of Toda and Yamamoto (1995) for heterogeneous mixed panels. The LA-VAR approach seems to have a good empirical size for large T in mixed panels under the cross-section independence.The Fisher test statistic proposed by Fisher (1932) to test the Granger non-causality hypothesis in heterogeneous panels is used. The Fisher test statistic (λ) is defined as follows:

$$\lambda = -2 \sum_{i=1}^{N} ln(p_i) \quad (3)$$

Where $i = 1, \ldots, N$. in this case p_i is the p-value corresponding to the Wald statistic of the i-th individual cross-section. This test statistic has a chi-square distribution with 2N degrees of freedom. However, the limit distribution of the Fisher test statistic is no longer valid in the presence of cross correlations among the cross-sectional units. In order to deal with such inferential difficulty within panels with cross correlations, the technique utilizes the bootstrap methodology to test the Granger causality test for cross-sectional dependent panels. This method recommends running the following linear panel regression for each of the cross sections:

$$y_{i,t} = \alpha_i + \sum_{j=1}^{k_i + d\,max_i} \theta_i^j x_{i,t-j} + \sum_{j=1}^{k_i + d\,max_i} \beta_i^j y_{i,t-j} + \varepsilon_{i,t} \tag{4}$$

Equation 4 is estimated without imposing any parameter restrictions on it and then the individual Wald statistics are calculated to test non-causality null hypothesis separately for each individual cross section. Using these individual Wald statistics has an asymptotic chi-square distribution with k_i degrees of freedom; we compute individual p-values. The optimal lag orders are identified for each cross section. Thereafter, the Fisher test statistic is given by equation 3. The null and alternative hypotheses can be defined as follows:

$H_0: \beta_i = 0 \; for \; i = 1, \ldots, N$

$H_A: \beta_i = 0 \; for \; i = 1, \ldots, N_1, \beta_i \neq 0 \; for \; i = N_1 + 1, \ldots, N$

Rejection of the null with $N_1 = 0$ implies that all x Granger causes y for all i whereas the rejection of the null with $N_1 > 0$ implies that there are variations of the regression model and causality across individuals. This method is used to control for mixed panels involving I (0), I (1), cointegrated and non-cointegrated in the series of variables.

3.3.2 Data

The data used for the empirical analysis exercise for this study consists of economic growth measured by; Gross Domestic Product (GDP) in constant US $; Total Primary Energy Supply (TPES) of geothermal, solar, biofuels, and waste (kiloton of oil equivalent) which are used for Renewable Energy (RE). The total primary energy supply of coal, crude oil, oil products, natural gas, and nuclear (kiloton of oil equivalent) are used for Non-Renewable Energy (NRE); GERD is research and development expenditure. The annual time-series data for GDP and the research and development expenditure are collected from the World Bank's World Development Indicators in order to maintain the uniformity of the data set for all the selected countries as they have differing data set methodologies in their respective countries. And the data on renewable energy supply, non-renewable energy supply, are collected from the IEA database from the period 1996-2015, due to data availability. Table 2 shows the descriptive statistics of the variables contained within the dataset.

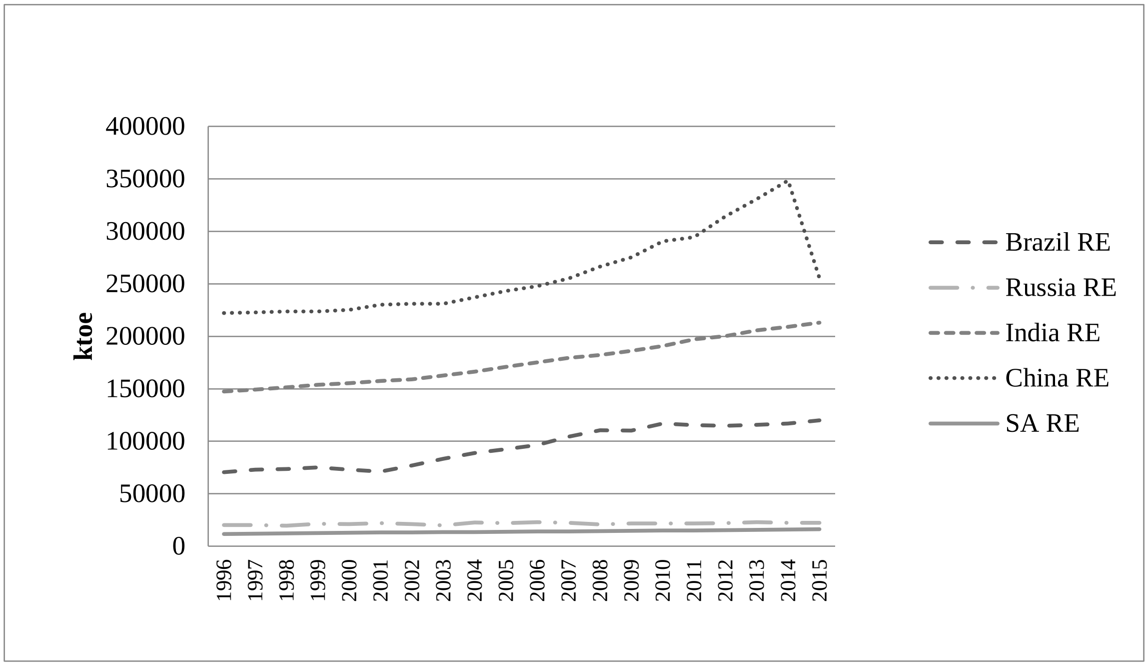


Figure 2. Total Primary Energy Supply (TPES) of geothermal, solar, biofuels, and waste (kiloton of oil equivalent) (RE in paper) Source: Authors calculation from IEA

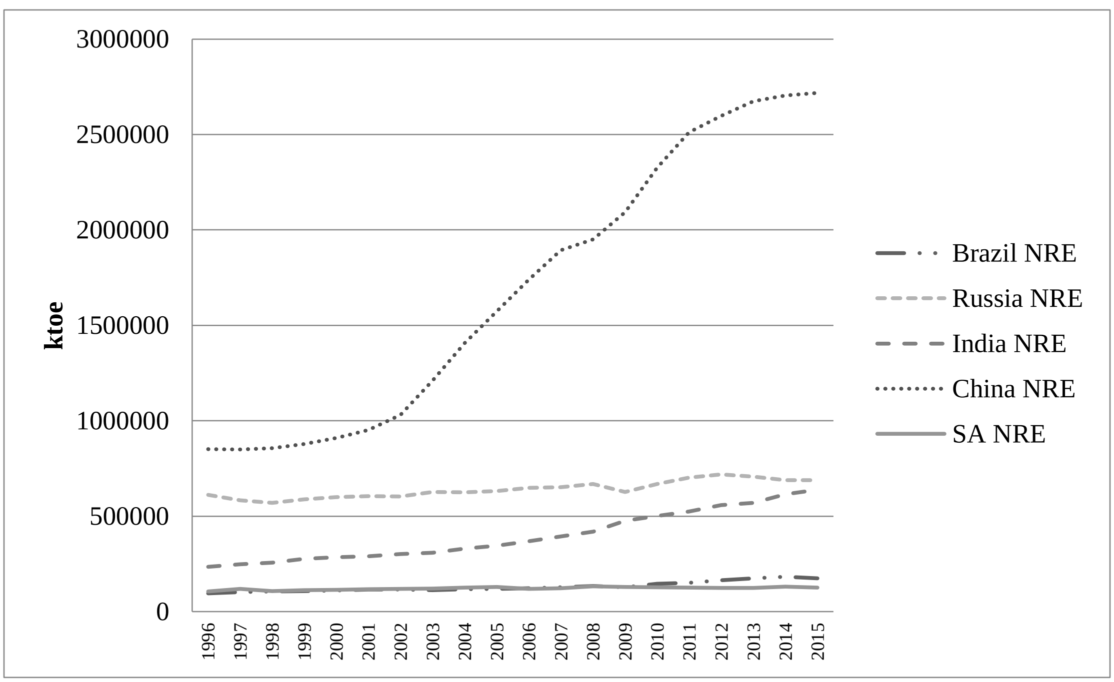


Figure 3. Total Primary Energy Supply of coal, crude oil, oil products, natural gas, and nuclear (kiloton of oil equivalent) (NRE) Source: Authors calculation from IEA

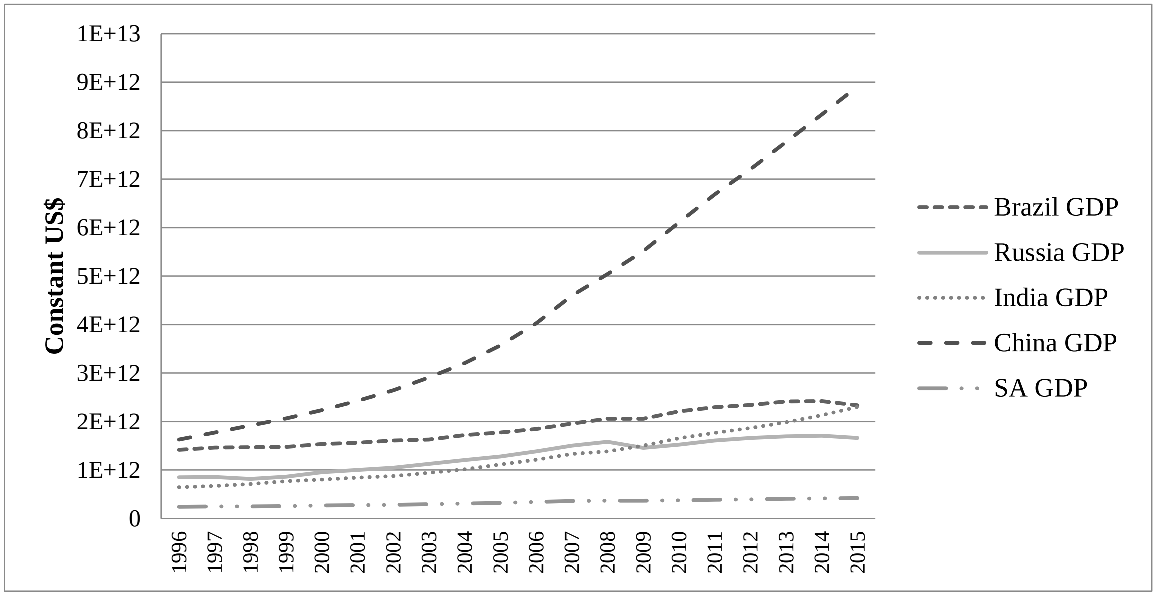


Figure 4. GDP 1996-2015 (Source: Authors calculation from World Bank)

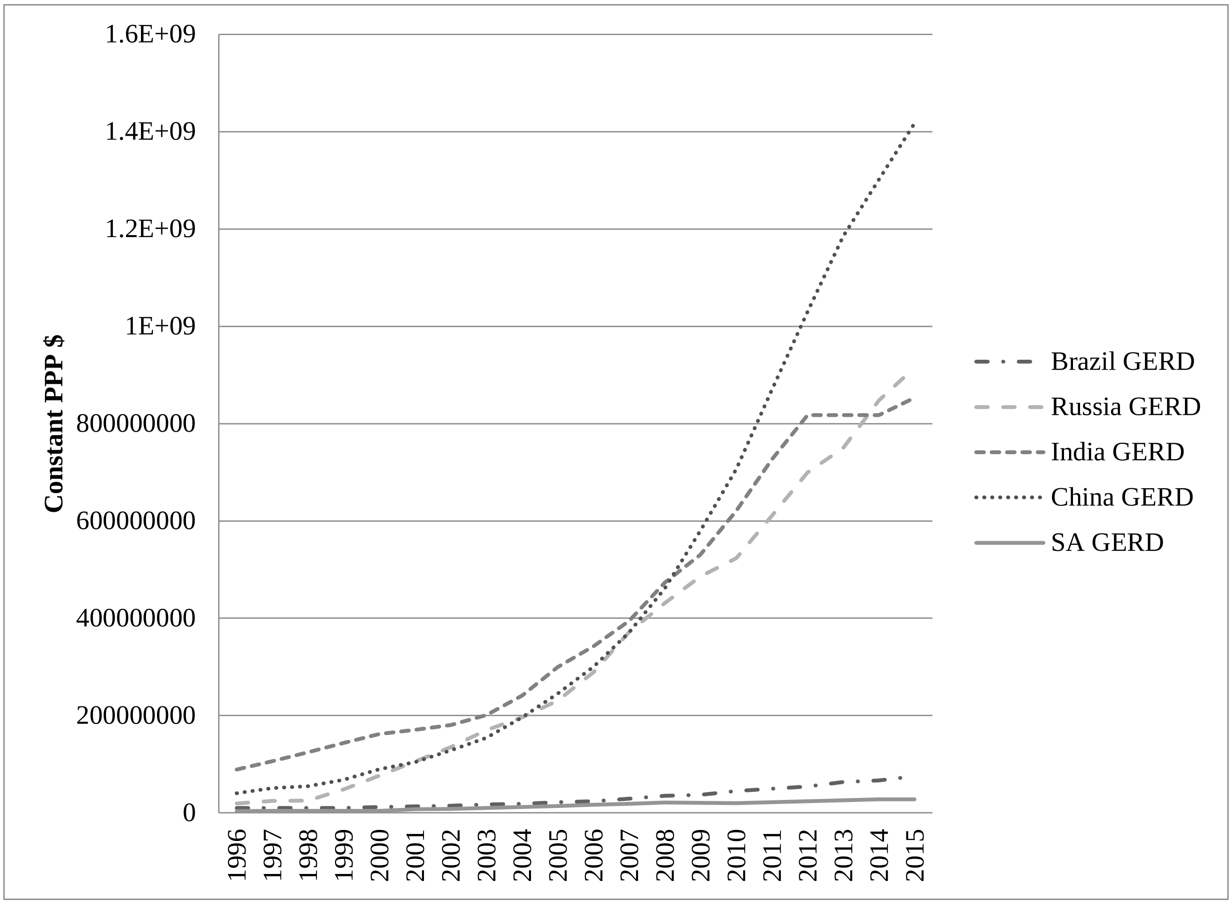


Figure 5. Gross Expenditure in Research and Development (R&D) (Source: Authors calculation from World Bank)

3.3.3 Conclusion

To identify the economic variables that are directly related to the energy supply mix and model the relationship, the Emirmahmutoglu and Kose (2011) theoretical framework was selected for the econometric analysis due to its proven ability to accurately determine whether a long run relationship exists among the variables of interest. This method is used to test for pairwise Granger non-causality. The technique involves testing for Granger causality using the LA-VAR approach of Toda and Yamamoto (1995) in heterogonous mixed panels. For which the demonstrated results of LA-VAR approach under both the cross-section independency and the cross-section dependency have proven to be very robust even when the sample size and frequency are small.

3.4 Energy supply mix transition strategy from fossil fuel to renewables for South Africa

3.4.1 Theory and Practice

To stay abreast with the constant changes in electricity supply needs and to ensure demand is sustainably met with the most optimal electricity supply mix, it is essential that the most adequate theory, tools, and models are utilized in order to realize the preferred electricity supply mix that also enables the transition from a fossil fuel mix to a more sustainable renewable mix. As highlighted by Gruenwald and Oprea (2012), a few classifications can be utilized to recognize models that can be utilized for planning a system for future energy mixes. In order to make this distinction, energy system models are often used. Energy system models depict a simulated representation of the actual system and its related operational components. Prina et al. (2018) state that there are two main approaches in distinguishing the energy system model types, one is in the form of top-down models, which focus on economic theory, and the bottom-up models, which focus on technology analysis.

In order to have the most comprehensive approach, this study applied both a top down economic model as well as a bottom up technological analysis model in the form of an EnergyPLAN model which also includes an economic simulation of the total energy system on the basis of the simulation of the business-economic marginal production costs of each component in the system including an option to calculate total annual socio-economic costs. On the one hand, top down models are generally able to describe the interaction of the energy system and the economy as a whole but tend not to take into full effect the technological detail that fully represents the energy sector in an aggregate form. On the other hand, bottom up models represent the energy system in great detail but tend to not take into full account the macroeconomic feedbacks of the energy system pathway.

The method that was followed is the Minimum Total Mix Capacity (MTMC) method which was developed by Vidal-Amaro et al (2015). It is used to establish the optimal mix of Renewable Energy Sources (RES) and fossil fuels in an electricity system by taking into account the hourly values of RES production and electricity demand. They applied the MTMC methodology to the Mexican electricity system, which greatly depends on fossil fuels with a mandate to limit fossil fuel-based electricity generation with 65% by the year 2024, 60% by 2035 and 50% by 2050. This is similar to the desired mandate and system that is in South Africa.

Using the MTMC methodology, this study examines the impact and potential of RES integration into the South African electricity supply system. The draft IRP 2018 planned capacity energy mix from 2010 – 2030 will be used as the starting point to define the base target scenarios for the proposed energy supply mix. The study will propose from the results a supply mix for South Africa which contains 26% of RE share to meet the forecasted demand as per the draft IRP 2018. With the largest %RES share and lowest emissions level. According to Vidal-Amaro et al (2015), the MTMC methodology pursues to identify the optimal combination of energy sources that can satisfy the demand of an existing energy system when a minimum production of RES is specified or when a limit on fossil fuels or nuclear power is established for a future date. The installed capacity with regards to each energy source (renewable, fossil or nuclear) in the optimal mix design is attained after an investigation of the system's reaction to renewable power production that is introduced into the system. The inputs to the MTMC are capacity ranges of the RES to be integrated, while the outputs are complementary conventional power. The optimal mix configuration corresponds to the combination of RES and conventional power that makes the system achieve the limits defined with the minimum overall installed capacity. This parameter is significant on the grounds that it considers the RES limit as well as the capacity from fossil fuels or nuclear energy, thereby permitting further economic analyses of the investment and operational costs (Vidal-Amaro et al, 2015).

By applying the MTMC using actual hourly production values of all the RES included, people are able to estimate an optimal energy mix in order to meet the desired demand based on the total RES production share, backup capacity and EEP as optimization criteria. This enables researchers to determine specific capacity targets for every RES to be integrated into the desired energy system transition at a particular point in time and the required complementary back up capacity (Vidal-Amaro et al, 2015).

This study also aims to provide in comparison to the draft IRP 2018, a technical analysis of the energy supply system using an internationally recognized methodology and model. This will contribute towards the informed understanding of the current energy supply drivers. As well as recommending the least cost environmentally sustainable alternatives to the current energy supply system which are aligned with our current and future global emissions mitigation commitment goals and targets. Demand forecast scenarios as defined for the IRP demand forecast (to be discussed in detail below) will be simulated and evaluated to warrant optimality and load-following capabilities by using the Energy Plan modelling tool which has a high temporal resolution that ensures that it captures the intermittent nature of the renewable energy sources as well as the variants in the demand. The scenarios to be simulated will correspond to an optimal energy supply mix in accordance to the minimum total required capacity.

3.4.2 EnergyPLAN Model

The EnergyPLAN model and software was developed by Aalborg University and follows a bottom up approach. It is a deterministic, descriptive and analytically programmed energy technological economic modeling platform that is used to simulate energy systems with high degrees of renewable energy at a regional or national scale. It is found to be one of the most comprehensive tools that can be utilized to define future energy systems in a very short computational time. The EnergyPLAN model integrates the three primary sectors of any national energy system, which are electricity, heat and transport. This enables the simulation of the interactions between different energy system sectors. The model simulates a regional or national energy system on an hourly basis, thereby making it suitable for modeling non-programmable instability of renewable energy sources. Technical and economical optimization strategies are incorporated in the EnergyPLAN software in simulating the energy system. The aim for the technical optimization is minimizing fossil-fuel consumption without any cost inputs. The main objective of the model is to inform the design of national energy planning strategies through a techno economic analysis of different energy system configurations (EnergyPlan, 2018; Connolly et al., 2010; Østergaard, 2009; Prina, et al., 2018).

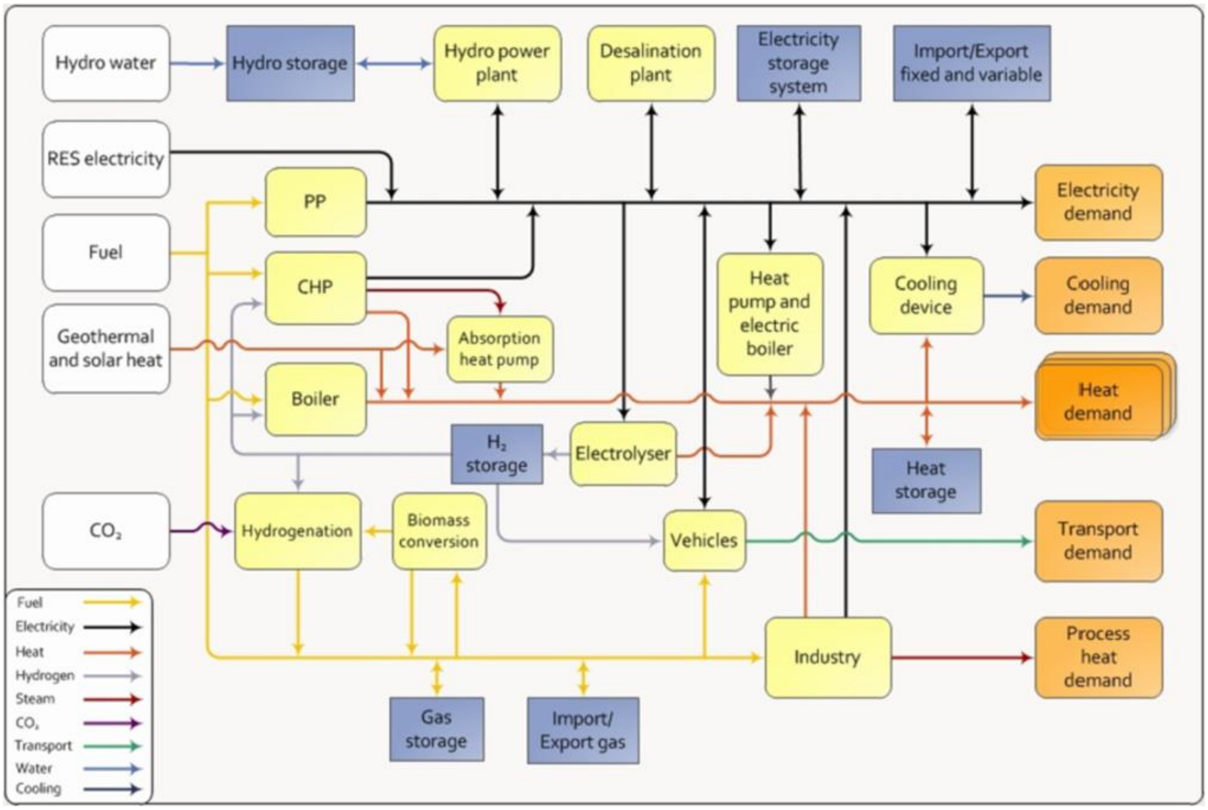


Figure 6. EnergyPLAN Structure Source: EnergyPLAN (2018)

Figure 6 above illustrates the overall view of the energy system as represented by the EnergyPLAN model. According to EnergyPlan (2018) the main inputs of the energy system consist of the following:

- Energy demands (heat, electricity, transport, etc.);
- Energy production units and resources (wind turbines, power plants, oil boilers, storage, etc.) including energy conversion units such as electrolysers, biogas and gasification plants as well as hydrogenation units;
- Simulation (defining the simulation and operation of each plant and the system including technical limitations such as transmission capacity, etc.);
- Costs (fuel costs, taxes, variable and fixed operational costs and investment costs).

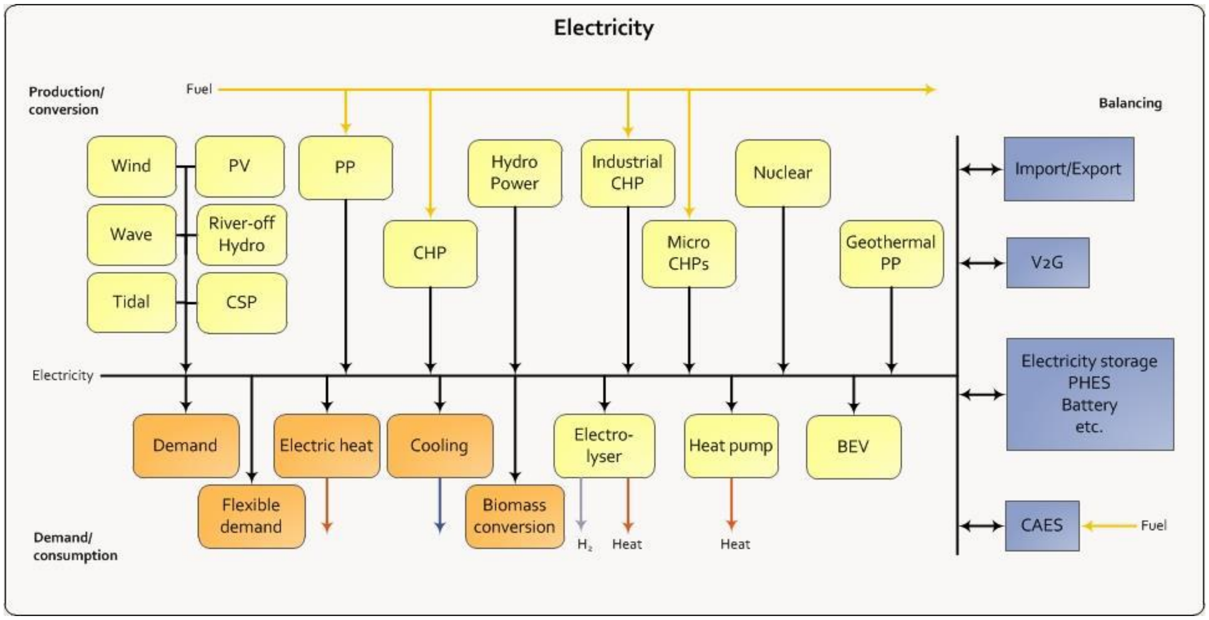


Figure 7. Electricity system structure Source: EnergyPLAN (2018)

Figure 7 demonstrates the components that are used in the EnergyPLAN model when calculating the hourly balancing of the electricity system. The diagram also illustrates the interactions of the electricity system with the other parts of the whole energy system. Some of the components of the EnergyPlan model are not applicable to the South African case and are beyond the scope of this study. Such components are only shown for illustration purposes in order to demonstrate the model's capabilities.

3.4.3 Data and assumptions of the model

The data required to run the EnergyPlan model is annual energy demands, renewable energy sources, energy plant capacities, costs and a number of optional different simulation strategies emphasizing import/export and excess electricity production. The specific data that was used in this study was extrapolated hourly and was sourced from STATS SA which has electricity generated data and hourly renewables (PV, CSP, and wind) data from 1 January – 31 December 2016. The energy plant capacities and costs were sourced from the draft IRP 2018 and EPRI IRP technology report (Electric Power Research Institute (EPRI), 2017).

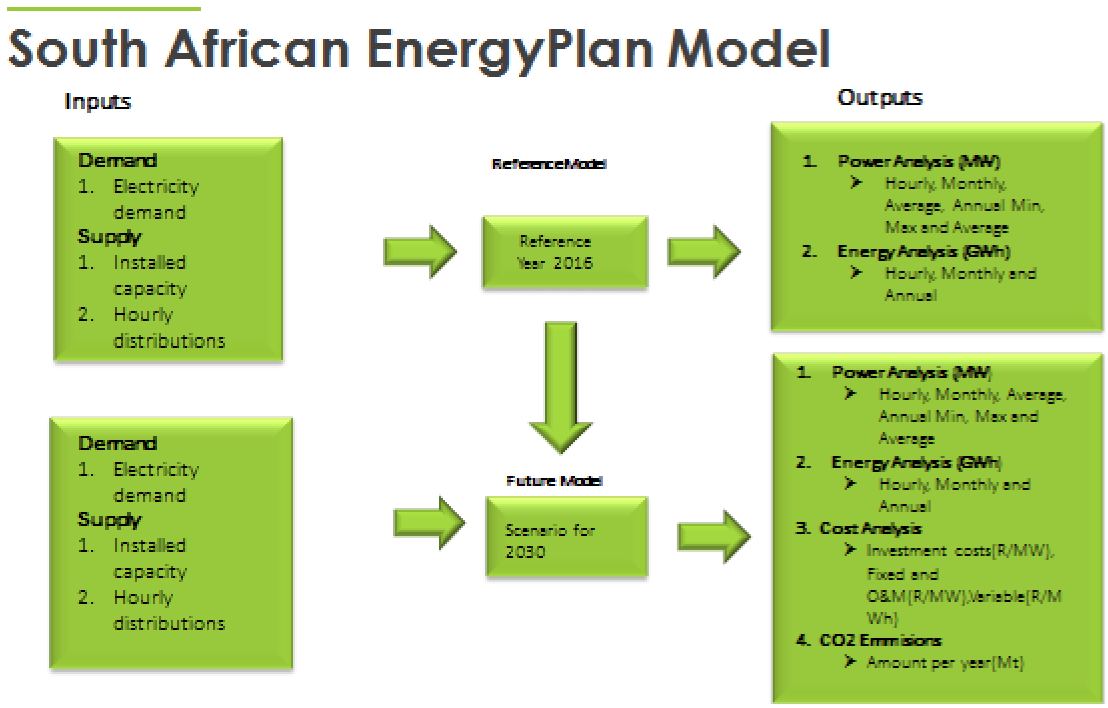


Figure 8. South African EnergyPlan structure overview (Source: Author's own depiction)

Figure 8 above summarizes the modelling approach that was used for this study. A reference 2016 and future 2030 model were created using technical input data in the form of electricity demand, installed capacity and supply hourly distributions. The inputs are described in more detail below.

Demand analysis: The electricity demand is defined by an annual value, D_E (TWh per year) and the name of an hourly distribution data set.

$$D_{E'} = \Sigma\, d_{E'} \qquad (1)$$

If $d_{E'} < 0$ then $d_{E'} = 0$, D_E= Annual electricity demand

Supply analysis: In the definition of the supply side of the energy system's technical characteristics, the capacities and efficiencies are required for each plant, in some cases; a predefined hourly distribution is required.

- Thermal power plants (coal and diesel)

The thermal power units are determined by the following inputs:

$C_{Thermal}$ = Capacity of the thermal Power Electricity Generators in MW;

$\mu_{Thermal}$ =Efficiency of the thermal Power station;

$d_{Thermal}$ = Distribution of the electricity production between 8784 hour values;

$FAC_{Thermal}$ = Correction factor between production and capacity.

The thermal units are considered to be running as base loads and therefore, the power plant does not take part in the active regulation. The electricity production of the thermal unit ($e_{Thermal}$) is simply defined by the capacity, the hourly distribution and the correction factor:

$$e_{Thermal} = FAC_{Thermal} * C_{Thermal} * d_{Thermal} / Max(d_{Thermal}) \qquad (2)$$

The correction factor is used to adjust differences between capacity and production. For example, if the capacity factor is 0.8 then the maximum production will be 80% of the installed capacity.

The efficiency is used only for the calculation of the annual amount of fuel ($f_{Thermal}$), which is calculated by applying the following formula:

$f_{Thermal} = e_{Thermal} / \mu_{Thermal}$ (3)

The fuel consumption is named "Thermal" and is measured in TWh/year in order to be able to compare it to the consumption of the rest of the units.

- Nuclear

$e_{Nuclear} = FAC_{Nuclear} * C_{Nuclear} * d_{Nuclear}/Max(d_{Nuclear});$ (4)

$C_{Nuclear}$ = Capacity of the Nuclear Power Electricity Generator in MW;

$\mu_{Nuclear}$ = Efficiency of the Nuclear Power station;

$d_{Nuclear}$ = Distribution of the electricity production between 8 784 hour values;

$FAC_{Nuclear}$ = Correction factor between production and capacity;

The efficiency is used only for the calculation of the annual amount of fuel ($f_{Nuclear}$), which is calculated by applying the following formula:

$f_{Nuclear} = e_{Nuclear} / \mu_{Nuclear}$ (5)

The fuel consumption is named "Uranium" and is measured in TWh/year in order to be able to compare it to the consumption of the rest of the units.

- Intermittent Renewable Energy Sources

The input data set defines input from RES and hydro power. The resource types that were used were:

-Wind;

- Photo Voltaic;

- CSP;

- River Hydro.

The electricity production input from intermittent renewable energy sources such as, wind power is found by multiplying the capacity by the specified hourly distribution.

$$e_{Res'} = e_{Res} * 1 / [1 - FAC_{Res} * (1 - e_{Res})] \quad (6)$$

$C_{Res1}, \ldots . C_{Res4}$ = Annual electricity production from Renewable Energy Resources

$FAC_{Res1}, \ldots . FAC_{Res4}$ = Correction factor of RES production

Cost analysis: Cost data of the models are divided into: Investment, fuel, operation and maintenance. For the investment cost analysis, the input capacity specifications for the production units are unit prices, lifetimes and fixed operation and maintenance costs. As well as an interest rate for the whole calculation.

- The total investment (I) of each production unit is calculated as:

$$I_x = C_x * P_{Unitx} \quad (7)$$

The model then calculates the annual costs of each component divided into investment costs and fixed operation and maintenance costs.

- The annual costs, $A_{Investment}$, are calculated as follows:

$$A_{Investmentx} = I_x * i / [1 - (1 + i)^{-n}] \quad (8)$$

In which:

- I_x are the investment costs found by multiplying the number of units by the cost unit (MZAR per unit). The unit is shown for each component and the cost is given in million ZAR/MW.

- n is the lifetime given in years.

- i is the interest

- The annual fixed operational costs, A_{FOC}, are calculated as follows:

$$A_{FOCx} = P_{FOCx} * I_x \tag{9}$$

In which:

- P_{FOC} is the annual fixed operation and maintenance costs given in percentage of the investment cost.

For each component:

- P_{Unitx} = Per unit price
- n_x = lifetime of investment
- P_{FOCx} = Fixed annual operational costs in percentage of total investment
- i = calculation interest (real interest) used for socio-economic evaluation

- Fuel cost (ZAR/GJ)

Fuel prices are specified as world market prices and domestic handling costs and taxes, if any.

P_{xWM}, P_{xWM} = World Market Fuel Prices

- Variable Operation and Maintenance cost

Variable operational and maintenance costs are specified for all units. Such costs are used for identifying all relevant marginal production costs which are calculated on the basis of fuel costs, and variable operational costs. Fuel costs consist of international market prices plus local handling costs.

Variable Operational Costs (ZAR/MWh)

P_{VOCRES}, $P_{VOCThermal}$, $P_{VOCNuclear}$, = Variable operational costs in power plants

The actual costs input as defined above for this study were attained from the EPRI report (Electric Power Research Institute (EPRI), 2017).

3.4.4 Conclusion

To evaluate the role of renewable energies in the future optimal energy supply mix of the country, as a general consensus, methodologies for determining optimal energy supply mixes are often catogorized into methodologies addressing economic objectives and methodologies directed at techno- operational targets (Østergaard ,2009); however when determining an appropriate energy supply both categories will be required. This is why the MTCM approach was selected as the most appropriate method for the analysis as it encompasses both techno-operational and economic objectives.

3.5 Chapter conclusion

The purpose of this chapter has been to review, discuss and document the state of energy mixes across the world. It does this by reviewing a number of the more current energy mixes. Firstly, it examined the theoretical background (Paper 1). Secondly, it evaluates those factors /methodologies that are most likely to determine the character and

(In this chapter, papers 1, 2 and 3) a detailed description of the methodologies and the data that was used in the study as informed by the literature review in order to address the research objectives was given. The chapter started with a brief energy supply mix positioning comparison of South Africa and its BRIC counterparts and this was followed by reviewing and analysing the methodologies on the causal relationship between energy and economic growth through Research and Development (R&D). Concluding the chapter is the methodology that was followed in proposing the electricity supply mix.

CHAPTER 4: EMPIRICAL RESULTS

In the previous section, the methodology for data collection and analysis were described. The aim of this chapter is to report on the study's empirical research results. The analysis of data aims to address and link the study's research questions and present the study's findings.

4.1 Positioning South Africa's energy supply mix internationally

In order to examine the potential of renewable energies in South Africa's energy supply mix, one needs to comprehend the status quo of the country's energy supply mix and it's positioning vis-à-vis international trends for future policy recommendations and implementation. A detailed description of the South African energy supply mix and its evolution in the past 25 years is presented. South Africa's energy mixes were compared with the energy mixes from other countries such as its companions Brazil, Russia, India as well as China (BRICS) and those from the Organization for Economic Co-operation and Development (OECD).

The South African electricity supply is dominated by Eskom; it built bigger and more economically efficient power stations near the coalfields as it cost less to transmit electricity by wire than to transport coal by rail. The profits that were gained from the export business enabled the power utility to buy large quantities of coal (Lloyd, 2012). Big coal-powered stations were then built. 'There were eight such stations of 600 MW units, each with its own boiler, generator and associated facilities (Kriel, 1973; Duvha, 1975; Matla, 1977; Tutuka, 1984; Lethabo, 1985; Matimba, 1986; Kendal, 1987; Majuba, 1996 & (Lloyd, 2012). The Koeberg nuclear power station was constructed in Cape Town in 1984 with a 1940 MW installed capacity.

Currently, the main source of electricity generation is through coal-fired power plants, which contribute 93% of the 42 000 MW generating capacity. Eskom supplies approximately 95% of

South Africa's electricity and more than 45% of Africa's electricity. Eskom uses various technologies to generate electricity, the combination of which is called the 'plant mix'. Eskom has several wind, solar, tidal, wave and biomass energy research projects. Coal-fired base load power stations are the biggest plants and they run 24 hours a day. Eskom's generation division has 13 coal-fired power stations with an installed capacity of 37 745MW. Their total net output, excluding the power consumed by their auxiliaries and generators currently in reserve storage is 35 650 MW (Eskom, 2015).

4.1.1 South Africa in BRICS

The BRICS countries' role in the world energy picture becomes more noteworthy when ranking countries by TPES, with four of them featuring in the IEA key world energy trends (International Energy Agency (IEA), 2016). Table 3 shows that China ranked first, accounting for 22% of global TPES; and India and Russia were third and fourth respectively. It is assumed that South Africa was included within the remaining rest of the world category which accounted for 37% of global TPES. Within the BRICS group, China was the main contributor of TPES in 2015, with approximately 60% of the total BRICS contribution; followed by India at 17% and the rest with smaller contributions (Russia, 14.27%; Brazil, 5.99%; and South Africa, 2.86%) (International Energy Agency (IEA), 2016). For comparative purposes, South Africa was included in Table 1, even though it did not feature in the top ten ranking, as it only contributed 1% to the global TPES. When normalizing the TPES with South Africa's GDP (looking at the ratio of TPES divided by GDP), but also when comparing with countries of different economic size such as those in the top 10 ranking in the table, South Africa still featured at the bottom of the ranking with the lowest GDP and TPES.

Table 4

Total Primary Energy Supply (TPES) Top Ten Countries, Plus South Africa 2015 (Own Calculation From (International Energy Agency, 2016).

Country	TPES (ktoe)	Share in World TPES 2015 (%)	TPES (ktoe)/GDP (constant 2010 US$)	Ranking based on TPES/GDP
People's Rep. of China	2 973	22	0.033	(4)
United States	2 188	16	0.013	(7)
India	851	6	0.037	(2)
Russian Federation	710	5	0.043	(1)
Japan	430	3	0.007	(11)
Germany	308	2	0.008	(10)
Brazil	298	2	0.013	(7)
Canada	273	2	0.015	(6)
Korea	270	2	0.021	(5)
France	247	2	0.009	(9)
South Africa	142	1	0.034	(3)
Rest of the world	4 957	37	0.000	-
World	13 647	100	0.018	-

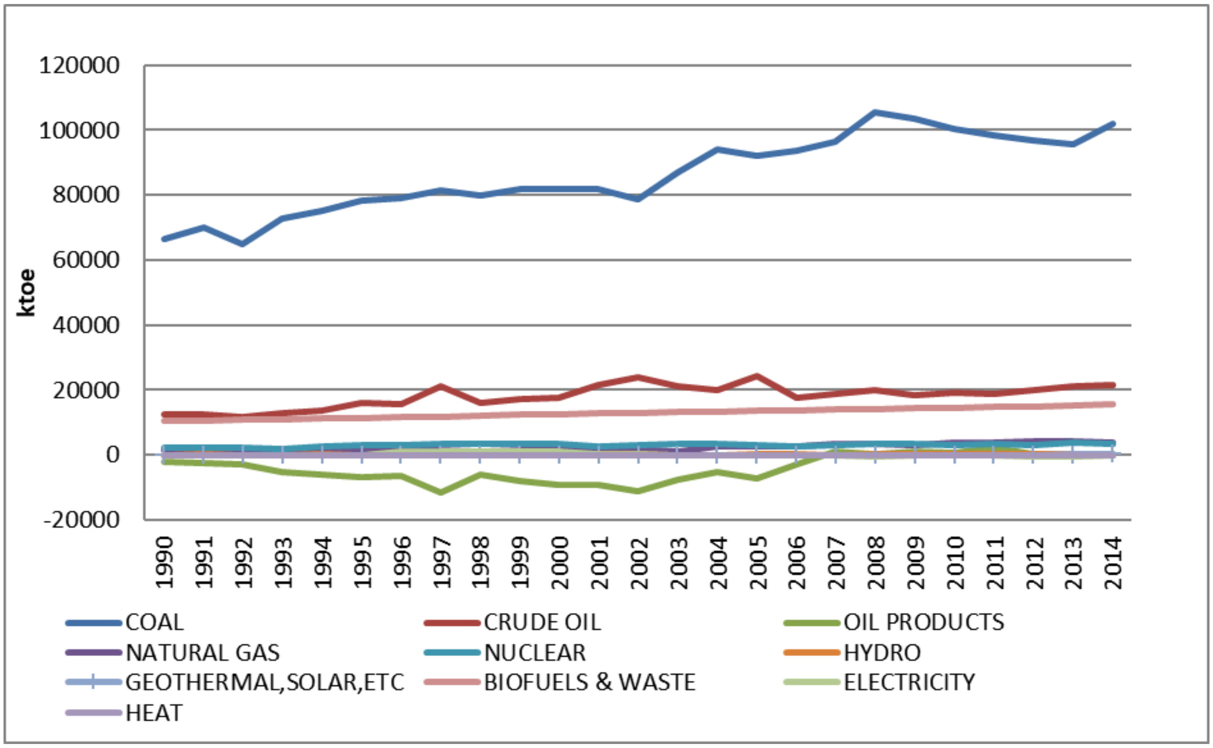


Figure 9. Total Primary Energy Supply for South Africa: 1990–2015 Own Calculation from (International Energy Agency, 2016).

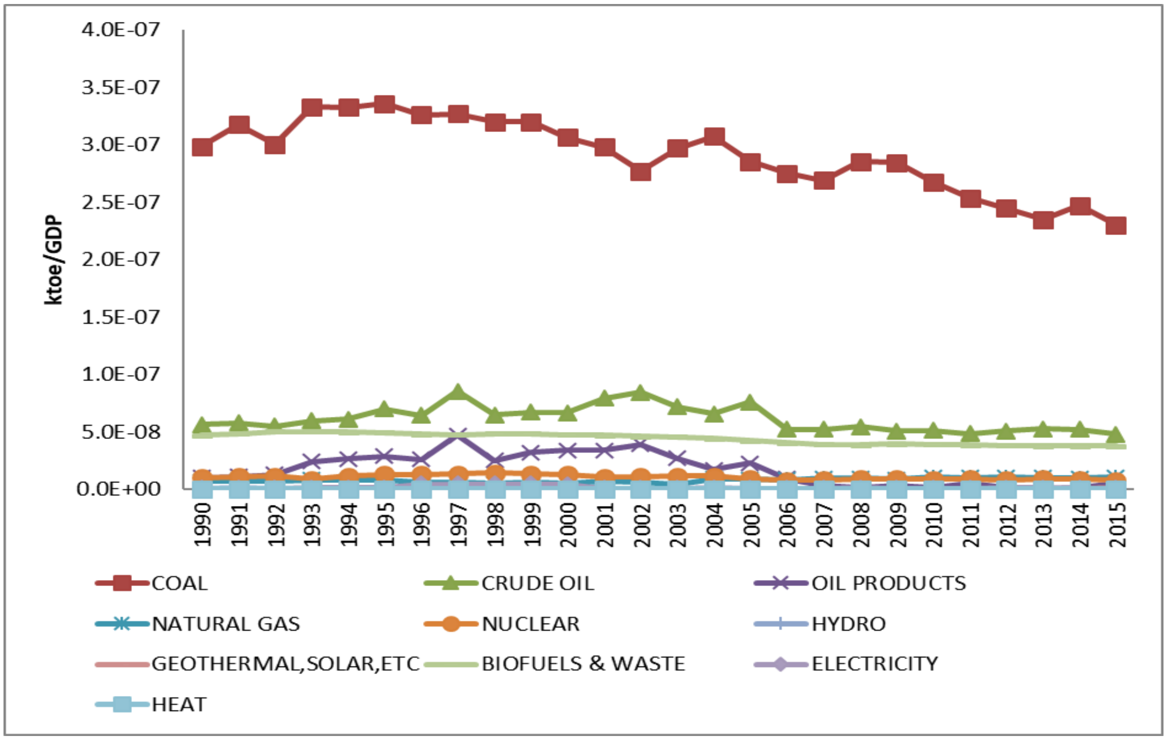


Figure 10. Normalized total primary energy supply for South Africa: 1990-2015. Own calculation from (International Energy Agency, 2016).

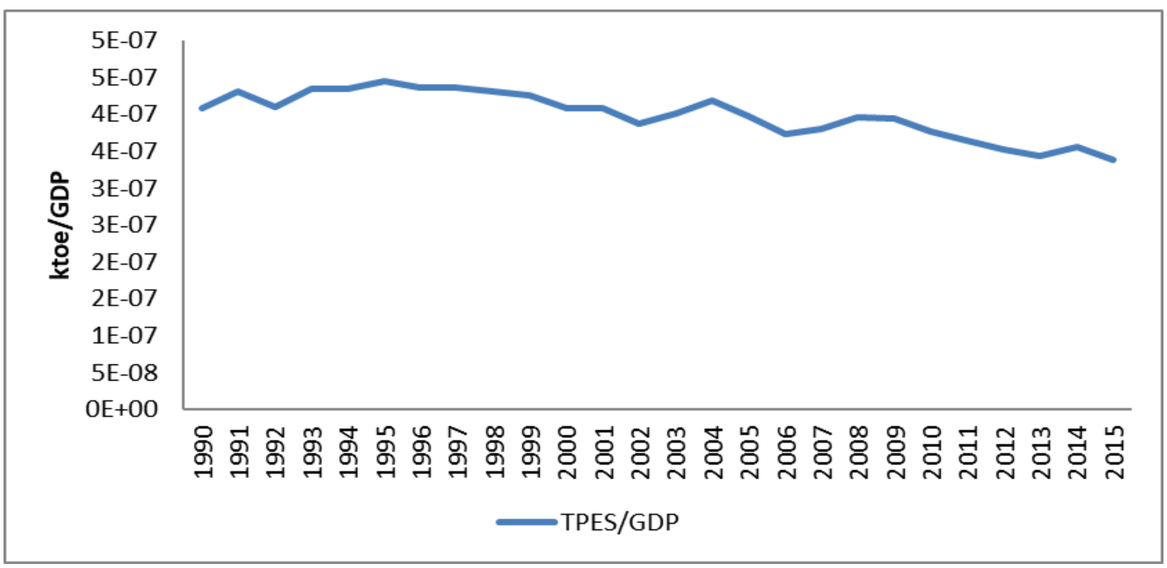


Figure 11. Ratio of total primary energy supply to Gross Domestic Product (GDP) for South Africa: 1990-2015 (Own calculation from (International Energy Agency, 2016).

Figures 9, 10 and 11 highlight the South African TPES source shares for the period 1990 to 2015. During this time, it can be noted that coal and crude oil were the dominant sources, followed by biofuels and waste (possibly as the result of agricultural influences). South Africa had 66.7 billion tons in coal reserves in 2016 which is equivalent to 7% of the World's total (Department of Energy, 2016). The fuel shares of TPES in South Africa had not shown significant changes between 1990 and 2015, with coal decreasing by only 1.87% from 69.57% in 1990 to 67.70% in 2015 and crude oil increased by 0.97% from 13.13% in 1990 to 14.10% in 2015.

Biofuel creation and use was marginally lower in South Africa (10.89% in 1990 and 11.09% in 2015) when compared to BRICS as a whole (13.87% in 1990). Biofuels in TPES had reduced between 1990 and 2015 in the BRICS countries (7.89% in 2015) because of increased electrification. Coal continued to represent a dominating share in TPES. Between 1990 and 2015 the share of coal has increased constantly over the years for the BRICS countries, influenced primarily by increased consumption in China, with coal reaching 48.71% in 2015 from 30.40% in 1990. The impact of the 2008 global economic crisis as well as the electricity crisis in South Africa in 2008 can be seen in Figure 1c, where there was a decline in the normalized TPES/GDP.

As illustrated in Figure 12, TPES for all the BRICS countries more than doubled from 2 286 731 ktoe in 1990 to 5 037 396 ktoe in 2015. In terms of energy, the BRICS countries accounted for 37% of the world energy demand (IEA, 2014). Although in these countries the population growth since the 1990s had been considerable, its effect was not proportional to all energy types as steep increases could be observed for natural gas and crude oil, compared with the rest.

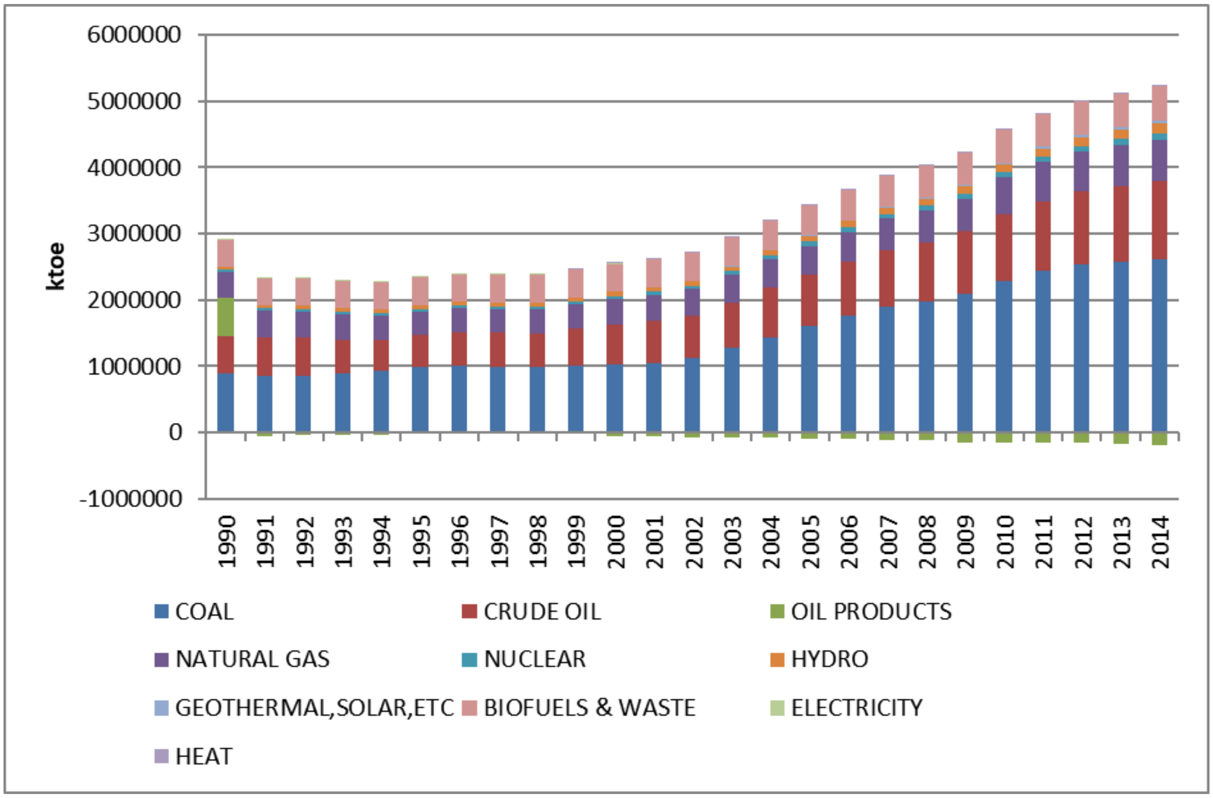


Figure 12. Total primary energy supply for BRICS countries, 1990-2015 (Own calculation from (International Energy Agency, 2016).

In Figure 13, it can be noted that China had the largest contribution in fossil fuels energy production in 2015 contributing 61% to the total BRICS TPES, followed by Russia with 17%.

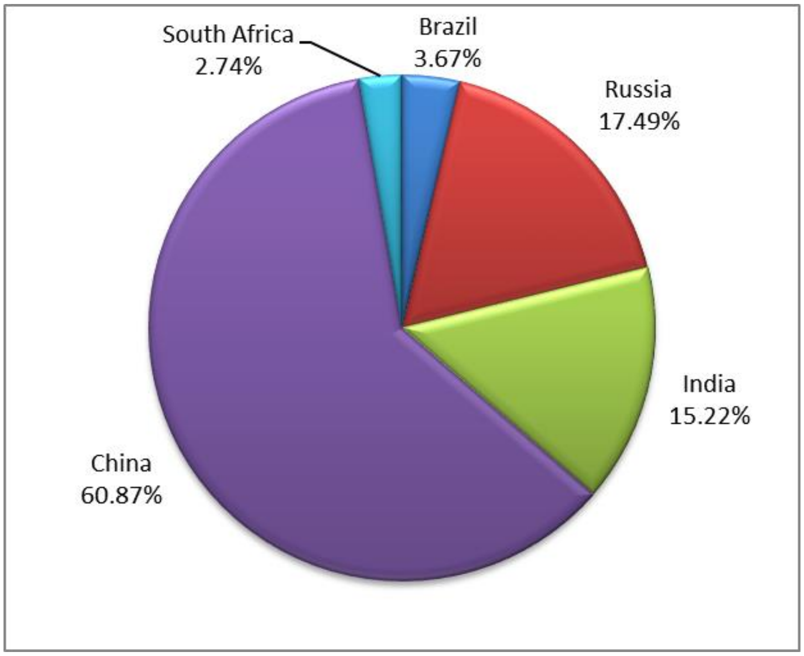


Figure 13. BRICS % Fossil Fuels 2015 (Own calculation)

(Data: International Energy Agency, 2016).

Over the years, BRICS countries remained dependent on fossil fuels for their energy production as well as for export. In 2014, the BRICS countries contributed approximately 38 % of global carbon emissions. With China's share of the contribution making up more than 24 % of the global total, surpassing India the second largest emitter in the group (Green Peace, 2015). Figure 14 illustrates the share of fossil fuels to the total supply mix in South Africa, the OECD and BRICS countries in 1990 and 2015. The TPES from fossil fuels for the BRICS countries has been increasing over the years, significantly so for China and India (International Energy Agency (IEA), 2016). According to Green Peace (2015), there has been a gradual decline in coal use in China since 2014 because of economic rebalancing, a war on air pollution and growth in renewable energy. After a decade of tremendous growth, coal use was down more than 4% in the first nine months of 2015. Coal imports decreased to 31% in the same period partly because of concerns about associated air pollution. China has commenced with exploring alternatives. In primary energy consumption, even though wind and solar energy were still small compared with coal, non-hydro renewables were at 1% of TPES in 2015 (International Energy Agency (IEA), 2016). Despite the Chinese government's push to cap coal shipments levels to 2017 levels, there has been an increase in coal imports, with imports being 3.4 percent above 2017 (Reuters, 2019).

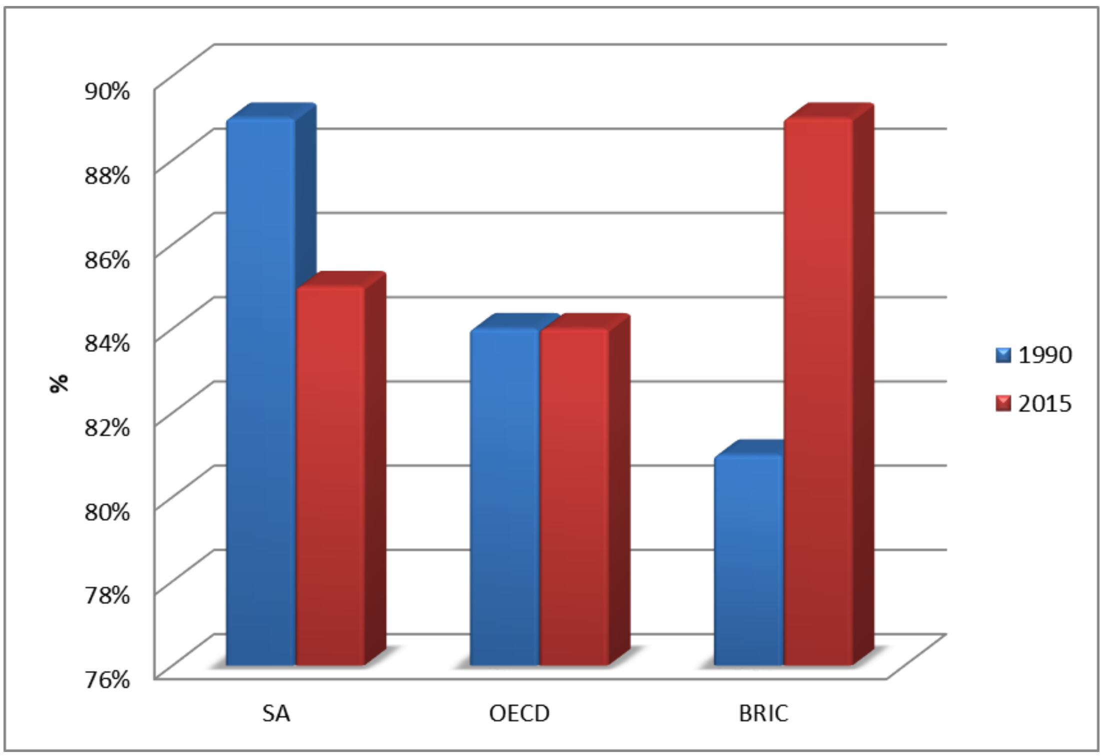


Figure 14. Percentage of fossil fuels in total primary energy supply for South Africa and Organization for Economic Cooperation and Development countries; and its fraction in Brazil, Russia, India, China and South Africa: 1990 and 2015. (Own calculation).

4.1.2 *South Africa and OECD*

Since the 1970s oil shocks, OECD countries have broadened their energy supply, resulting in the fuel shares changes in TPES. Figures 14 and 15 show that although crude oil remained the main component of TPES, its share decreased from 41.35% in 1990 to 37.12% in 2015. The reduction was compensated by an increased penetration of natural gas (from 18.54% to 24.06%). The OECD's share of global TPES decreased from 60% in 1971 to 39% in 2013, possibly because of the steady growth of energy demand from two of the BRICS countries, China and India.

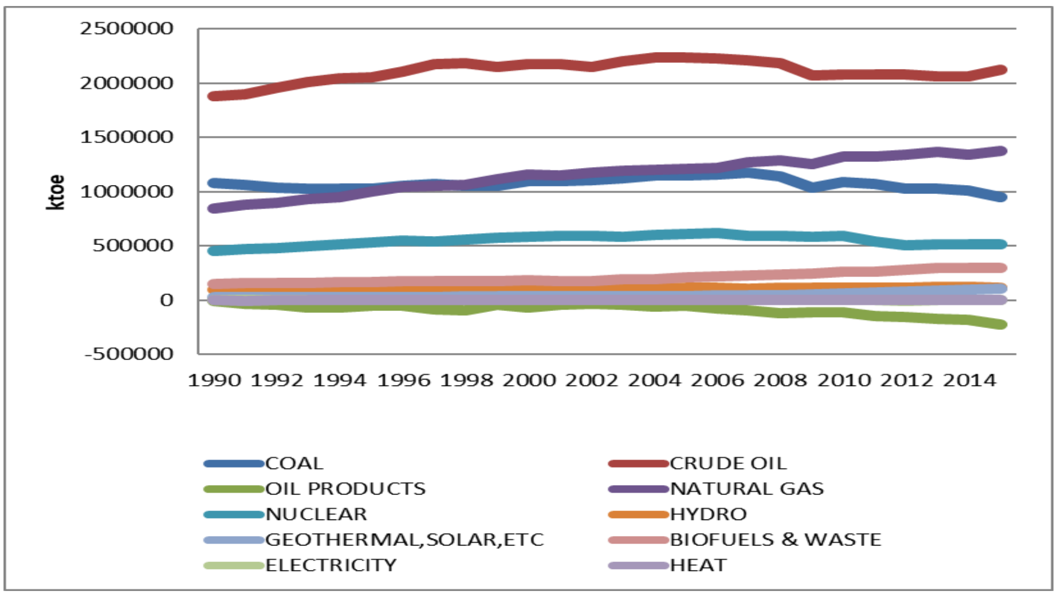


Figure 15. Total primary energy supply for Organization for Economic Cooperation and Development countries: 1990-2015 (Own calculation from International Energy Agency, 2016).

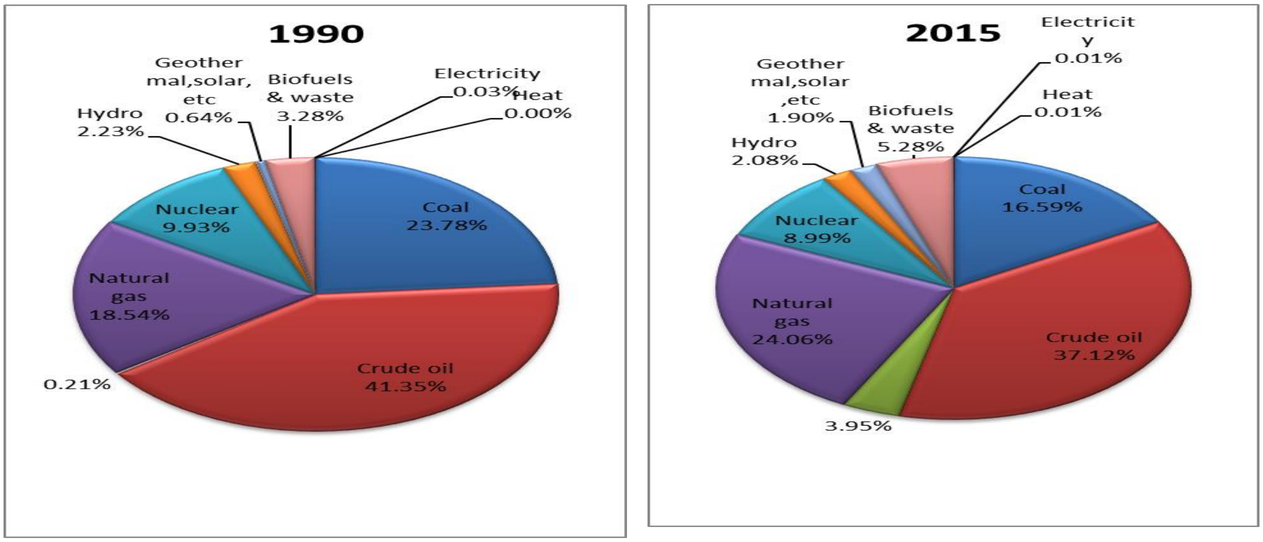


Figure 16. Total primary energy supply comparisons for Organization for Economic Cooperation and Development countries in 1990 and 2015 (Own calculation from International Energy Agency, 2016).

4.1.3 Renewable energy share to TPES

Renewable energy use increased in proportion to demand, as highlighted in Figure 17. Energy demand growth in first world OECD countries is slow, but quicker in some BRICS third world countries. The change from traditional cooking methods to the use of modern renewable energy reduces the renewable energy share.

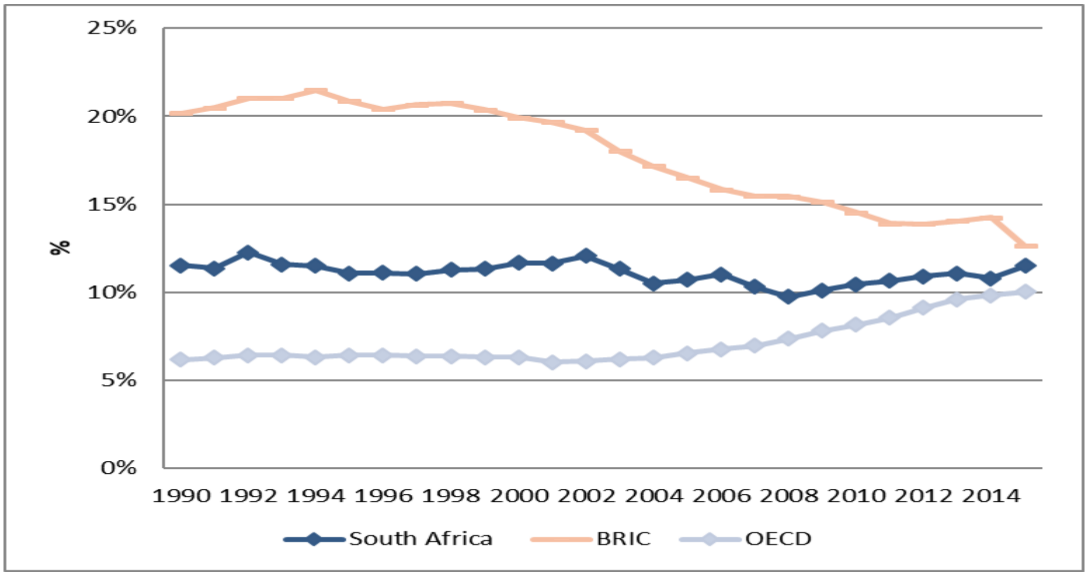
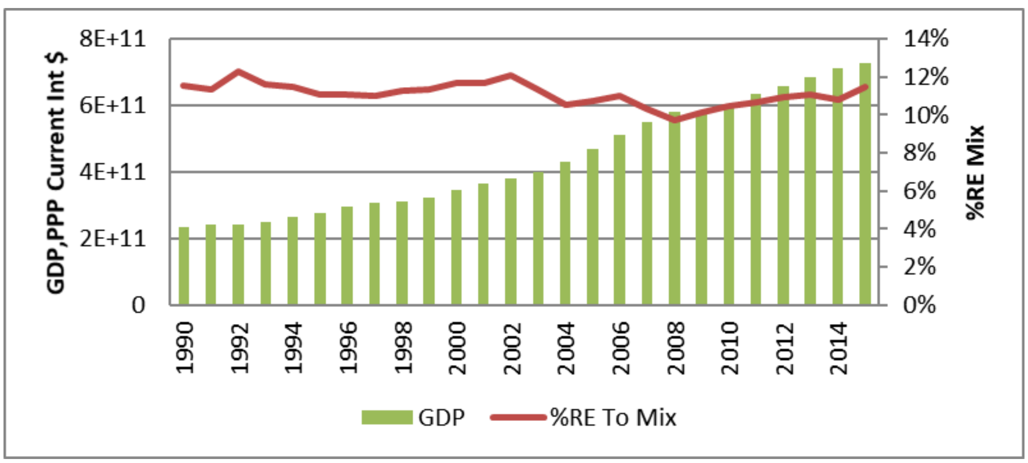


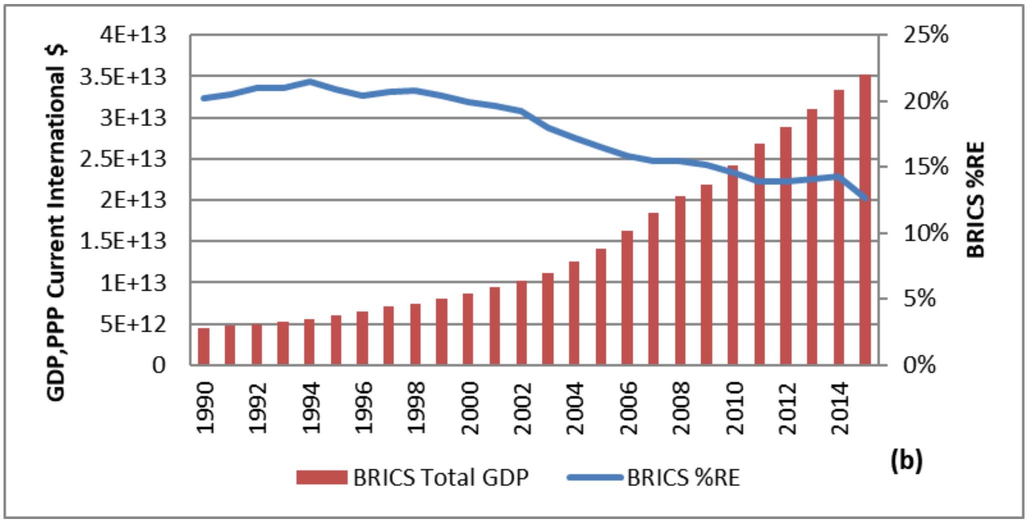
Figure 17. Percentage of renewable energy to total primary energy supply comparisons for South Africa's fraction in Brazil, Russia, India, China and South Africa; and Organization for Economic Cooperation and Development countries: 1990 and 2015. (Own calculations)

In recent years, it has become evident that the optimization and diversification of a country's energy supply mix is fundamental in meeting its various developmental goals and enhancing the security of supply. The main aim of this study is to describe the current South African energy supply mix and to assess how South Africa fares in comparison to its BRIC and OECD counterparts. This was done by conducting a comparison study of the different regions' energy supply mixes. The analysis shows that the global TPES share for non-OECD countries, such as BRICS, is becoming more prominent, with China, India, and Russia being the main contributors. In addition, the OECD's share of global TPES has been decreasing.

Overall, BRICS countries during the period of 1990-2015 had a greater dependence on fossil fuels in their energy mix. Because of that, when commodity prices collapse, as they did after the last super-cycle, it is cheaper to switch back to coal and other traditional sources of energy instead of renewables which tend to be more expensive to install but are cheaper over a lifetime of use (refer to Figure 18b). When economic activity comes down (because of the global economic recession), as it did in most BRICS countries, even China's other input costs come down or increase at a lower rate; all this supports a base energy programme that can push policy makers into lower investment mode. This can also be seen in Figure 8.



(a)



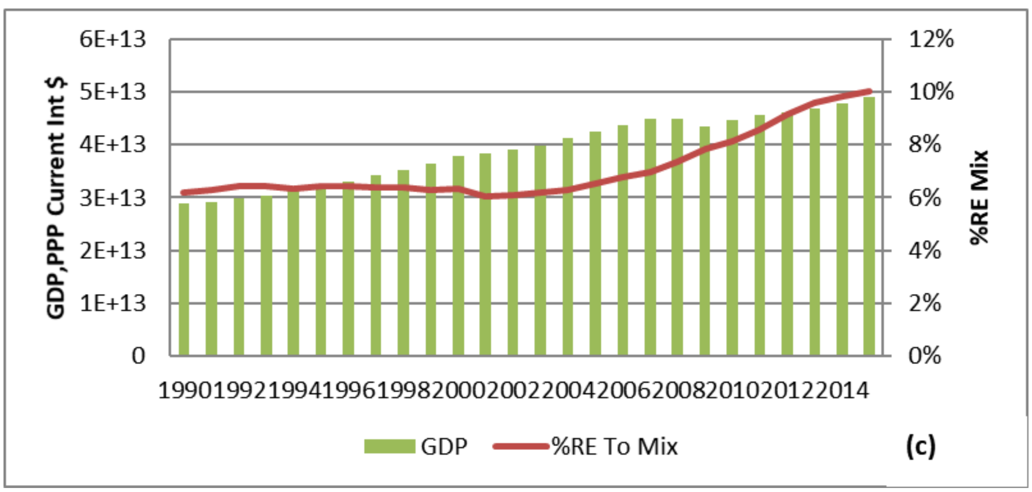


Figure 18. Total Gross Domestic Product (GDP) vs percentage of Renewable Energy (RE) for (a) South Africa's fraction in (b) Brazil, Russia, India, China and South Africa; and (c) Organization for Economic Cooperation and Development countries between 1990 and 2015) (Own calculation).

A green economy is supportive of highly industrialized countries in its net benefit/profit curve in the first investment cycle, which is approximately five years (China Council for International Cooperation on Environment and Development (CCICED), 2012). The OECD countries would tend to keep investing and supporting a green economy, even when the economic cycles do not provide short-term returns, as can be seen from Figure 18. Some of the BRICS countries are resource-rich, but are technologically poor, so they tend to miss the key multiplier effect of any technology revolution such as the renewable energy one. Eventually, the super-convergence of these, inevitably, brings lower cost outcomes faster in the OECD than in BRICS economies.

In the deliberation about the advantages or otherwise of establishing a green economy, Brazil believes that there exists a compromise between economic development objectives and environmental aims and these compromises have far-reaching negative effects on the establishment of the Brazilian economy. As opposed to a the advanced and emerging countries' belief that the establishment of a green economy could result in economic advancement and suppression of scarcity, Brazil's stance is that a green economy would mostly benefit more advanced economies (Wentworth & Oji, 2013). This study also contended that developing countries are not competent in developing new technologies, as taking on the process would require the restructuring of the economy in order to cater for the new costs.

The BRICS' public policy has fundamentally been poised towards a more industrialist framework directed mainly at economic development. Governments of late are making more deliberate determinations in order to integrate societal development onto the growth plan. In so doing, partiality is directed at policy, which is geared at alleviating societal imbalances and scarcity. To realize this, Brazil's societal progression legislation is aligned with the public policy for total development. This has created conjoined policy goals. There is a lack of strategies to advocate for the promotion of greener economies. Some of the BRICS policymakers contend that a green economy can slow down the economic growth. Russia is advocating for the development of a green economy in partnership with other organizations such as the United Nations Economic Programme (UNEP, 2012). Policy implementation in Russia is constrained, so implementation of the plans is slow and inconsistent (Wentworth & Oji, 2013). China has grown economically at the expense of the environment. A green economy can reduce a country's challenges, but the government should have an assurance that the growth is in accordance with its objectives. China's development plans are underpinned by a relative competitiveness that focuses on internal growth. A green economy could obstruct their objectives, hence the need for China to dictate the terms of its engagement on the green economy (China Council for International Cooperation on Environment and Development (CCICED), 2012). A green economy can, however, offer advantages for environmental protection, while feeding into economic output requiring reassessment of projections for growth (Wentworth & Oji, 2013).

In South Africa, prior to 1994, information on renewable energy was mostly known by the government owing to apartheid and this had huge impacts on the sector (Sebitosi & Pillay, 2008). South Africa is now working with other BRICS countries to develop its renewable energy. As the renewable energy sector is regarded as high risk, BRICS countries have relied on loans because of a lack of investors to fund this phenomenon. There are limited finance options in South Africa and Russia for such initiatives. Small and medium-sized enterprises cost from USD1–20 million, but they encounter the most challenges in funding as BRICS governments focus on bigger renewable projects. This results in slow development and discourages creativity (Zeng et al., 2017).

From the comparison, it was discovered that the Total Primary Energy Supply's (TPES) share of non-OECD countries is becoming more prominent, with China, India and Russia being significant contributors. The OECD's ratio of universal TPES decreased between the periods 1990 to 2015. It was evident that there was a heavy reliance on fossil fuels in the BRICS countries, which appealed to the formation of appropriate policies in order to influence and guide the transition from the current fossil fuel-dominated energy supply mix to one that follows international trends but, most of all, to one that appreciates its specific geographic position and natural resources.

4.2 The causal relationship between energy and economic growth through Research and Development (R&D)

As highlighted above that renewable energy is not yet as prominent in South Africa even though the natural resources are available to support renewable energy supply. Now that we have an understanding of the positioning of the South African energy supply mix it is imperative that we gain an in-depth understanding of the dynamics and drivers of the energy resource types of the energy supply mix, as well as the existence and direction of the causal dynamic relationship between energy (renewable and non-renewable) on GDP taking into account the role of R&D expenditure. This section also investigates how South Africa differs from other emerging economies.

In past studies such as those of Apergis and Sorros (2014), it has been found that there is a strong relationship between R&D expenses and profitability for energy sector firms that sell renewable energy rather than in firms that sell fossil energy. This can be an indication of the importance of renewable energy and the money spent on R&D. The authors also state that, "this is also due to fossil energy firms' technological innovations being slow to play a substantial role in the profitability, given the pressure on maintaining a clean environment." (Apergis & Sorros, 2014). In agreement with this view, this study also expects to find a strong impact on economic growth through R&D expenditure towards renewable energy rather than non-renewable energy sources. This is due to the global drive for ardent policies that promote the transition to cleaner and sustainable energy sources through technology innovation.

Other studies have chosen R&D expenditure as a proxy for technological progress. It is assumed that the increased R&D expenditure towards the exploration of renewable or non-renewable energy source innovation and production process can be regarded as a means to enhance and increase economic activity. This includes, enabling the substitution and transitioning between the energy sources to ensure sustained and consistent energy generation and supply. The overall assumption is that R&D expenditure has a positive impact on economic growth. With this impact being stronger either in expenditure on renewable energy or non- renewable energy sources.

This study identifies whether a trivariate causality exists between RE; NRE; and economic growth taking into consideration R&D expenditure for the developing BRICS countries. The outcome of this study will enable and direct policy intervention and also inform policy decision in the investment towards R&D expenditure for RE and NRE which will be beneficial to promoting economic growth.

Informed by the Schwarz information criterion, the unit roots resulting from the LLC (2002), Breitung (2000), IPS (2003), ADF (1984), and PP (1988) tests have confirmed that LnGDP, LnRE, LnNRE and LnRD are I (1) in all panel groups (see Table 4).

Table 5

Panel Unit Root Tests

Variable	LLC	Breitung	IPS	Fisher ADF	Fisher PP	Inference
LnGDP	1.150	1.343	1.092	4.237	2.891	Unit root
LnRE	-0.244	-0.672	-0.381	9.566	10.598	Unit root
LnNRE	0.381	0.376	-0.068	10.368	17.938*	Unit root
LnGERD	0.264	1.883	1.047	9.469	6.145	Unit root
ΔLnGDP	-3.294***	-0.307	-0.793	15.222	14.726	No unit root
ΔLnRE	0.186	1.967	-0.159	12.482	36.155***	No unit root
ΔLnNRE	-2.296**	-0.821	-2.375***	23.185**	52.327***	No unit root
ΔLnGERD	-4.339***	-1.435*	-2.471***	23.769***	30.839***	No unit root

*indicates 10% level of significance; **indicates 5% level of significance; ***indicates 1% level of significance (Source: Authors calculation)

Cointegration testing was conducted using the Johansen test of cointegration in order to determine whether one or more cointegrating relationships exist amongst the four variables. Table 5 presents the results of the test that confirms the existence of a long-run relationship among the variables tested.

Table 6

Overall Johansen test of cointegration

Hypothesized number of cointegrating equations	Trace Critical value	Max-eigen critical value
None	58.21***	52.66***
At most 1	17.12	16.14
At most 2	8.459	8.574
At most 3	7.514	7.514

Source: Authors calculation from IEA. ***indicates 1% level of significance

Table 7

Results of Johansen and Kao tests for Cointegration

	With Renewable Energy			
Panel	Johansen test for cointegration			Kao
	Hypothesized number of cointegrating equations	Fisher Trace Test statistic	Fisher Max-Eigenvalue trace statistic	
Brazil	None	22.4434	14.7188	0.3541
	At most 1	7.7246	7.173	
	At most 2	0.5516	0.5516	
Russia	None	29.6871	14.037	
	At most 1	15.6501**	8.9787	
	At most 2	6.6714***	6.6714***	
India	None	29.9351**	19.7044*	
	At most 1	10.2307	9.8322	
	At most 2	0.3985	0.3985	
China	None	39.0701***	28.9942***	
	At most 1	10.0759	10.0654	
	At most 2	0.0105	0.0105	
SA	None	22.9052	14.4073	
	At most 1	8.4979	8.2332	
	At most 2	0.2646	0.2646	

With Renewable Energy

With Non-Renewable Energy

Panel	Johansen test for cointegration			Kao
	Hypothesized number of cointegrating equations	Fisher Trace Test statistic	Fisher Max-Eigenvalue trace statistic	
Brazil	None	35.4585**	26.7867***	0.133
	At most 1	8.6718	8.4988	
	At most 2	0.173	0.173	
Russia	None	23.941	10.4368	
	At most 1	13.5041*	10.1057	
	At most 2	3.3984*	3.3984*	
India	None	18.9204	12.7975	
	At most 1	6.123	5.9976	
	At most 2	0.1254	0.1254	
China	None	28.2066*	17.7654	
	At most 1	10.4412	7.4935	
	At most 2	2.9477*	2.9477*	
SA	None	38.3024***	27.8305***	
	At most 1	10.4719	6.747	
	At most 2	3.7248*	3.7248*	

Source: Authors calculation. Note: * indicates 10% level of significance ** indicates 5% level of significance *** indicates 1% level of significance

Table 6 presents separate cointegration tests including renewable energy (lnRE) and non-renewable energy (lnNRE) respectively to determine the existence of a long-run relationship (cointegration) of each with lnGDP and lnRD. The Johansen cointegration test confirmed cointegration for both energy types for the entire BRICS countries panel. Using the Johansen test for robustness, it is concluded that there exists at most two cointegrating vectors between lnGDP, lnRE, lnNRE and lnRD for all panels.

Consequently, the results of the Johansen and Kao cointegration tests are inconsistent for both the RE and NRE, where cointegration is found for both when testing with the Johansen test but no cointegration is found for both when testing with the Kao test. A possible reason for this is that the results treat all cross sections (countries) homogenously. This further stipulates that the cross sections in the panels are heterogeneous and mixed. This indicates that the countries in the panel differ in their characteristics. These results also validate the decision of choosing to utilize the Granger causality methodology as used by Emirmahmutoglu and Kose (2011).

Table 7 displays the results of the bivariate pairwise Granger causality test between lnGDP, lnRE, lnNRE, and lnGERD as defined above for the entire BRICS countries panel. The test assesses the existence of a causal relationship running from one variable to the other in this model in a pairwise manner for the panel of countries; the LA-VAR Granger causality simulation determines the optimum lag for each cross-sectional unit. The results show that there is causality only from lnRE to lnRD and from lnGDP to lnRD; while all the other hypotheses could not be rejected for the entire BRICS panel.

Table 8

Fisher Test Statistics for Panel Non-Causality Test (Levels) –BRICS

Hypothesis	Fisher Statistic	Conclusion
lnRE ≠ →lnNRE	*15.528*	No Causality
lnNRE ≠ → lnRE	14.667	
lnRE ≠ → lnGDP	10.813	No Causality
lnGDP ≠ → lnRE	11.886	
lnRE ≠ → lnRD	10.090	No Causality
lnRD ≠ → lnRE	8.130	
lnNRE ≠ → lnGDP	20.021	No Causality
lnGDP ≠ → lnNRE	3.214	
lnNRE ≠ → lnRD	25.890 ***	One way Causality from Non-RE to R&D
lnRD ≠ → lnNRE	9.404	
lnGDP ≠ → lnRD	26.403 **	One way Causality from GDP to R&D
lnRD ≠ → lnGDP	10.948	

Granger causality carried out using a maximum of 2 lags. * (**) (***) denote statistical significance at the 10% (5%) (1%) level of significance. Lag orders k_i are selected by minimizing the Schwarz Bayesian criteria.

To account for potential limitations of the test results due to the fact that the panel Fisher test statistics are created for large numbers of cross sections N and the possibility that some countries, due to their size, drive the group's results, Table 8 reports the individual Wald test statistics for the LA-VAR Granger causality approach.

.

Table 9

Individual Cross-Section p-values

Hypothesis	Brazil P value	Wald stat	Russia P value	Wald stat	India P value	Wald stat	China P value	Wald stat	SA P value	Wald stat	Conclusion
lnRE ≠ ➔ *lnNRE*	0.409	1.786	0.560	0.339	0.096*	2.774	0.263	2.670	0.073*	3.204	Two way causality from RE to Non-RE in India and SA and Non-RE to RE in Brazil.
lnNR ≠ ➔ *lnRE*	0.048**	6.079	0.148	2.089	0.329	0.952	0.283	2.522	0.986	0.000	
lnRE ≠ ➔ *lnGDP*	0.132	2.266	0.151	2.063	0.504	0.447	0.804	0.061	0.555	0.349	No causality
lnGDP ≠ ➔ *lnRE*	0.722	0.127	0.167	1.910	0.131	2.278	0.340	0.910	0.488	0.481	
lnRE ≠ ➔ *lnRD*	0.175	1.843	0.453	0.562	0.133	4.038	0.699	0.149	0.876	0.024	No causality
lnRD ≠ ➔ *lnRE*	0.646	0.211	0.915	0.011	0.375	1.960	0.374	0.789	0.207	1.595	
lnNRE≠➔ *lnGDP*	0.007***	7.303	0.352	0.865	0.931	0.008	0.537	1.245	0.037**	6.590	One way causality from Non-RE to GDP in Brazil and SA.
lnGDP≠➔ *lnNRE*	0.629	0.233	0.907	0.014	0.984	0.000	0.363	2.025	0.983	0.034	
lnNRE≠➔ *lnRD*	0.072*	3.245	0.096*	2.775	0.376	0.785	0.001***	13.390	0.749	0.103	One way causality from Non-RE to R&D in Brazil; Russia and China.
lnRD ➔*lnNRE*	0.872	0.026	0.881	0.022	0.306	1.048	0.128	4.106	0.301	1.070	
lnGDP ≠ ➔ *lnRD*	0.865	0.029	0.044**	4.045	0.010**	9.183	0.372	1.976	0.013**	6.201	One way causality from GDP to R&D in Russia; India; and SA.
lnRD ≠ ➔ *lnGDP*	0.344	0.894	0.863	0.030	0.925	0.156	0.107	4.463	0.142	2.156	

Source: Authors calculation. Note: * indicates 10% level of significance ** indicates 5% level of significance *** indicates 1% level of significance

Analyzing the individual cross-section results above in Table 6, there is bidirectional causality found for India, South Africa and Brazil, with the direction running from RE to Non-RE for India and South Africa and the opposite for Brazil with the direction running from Non-RE to RE. The null hypothesis of no granger causality was rejected at a 10% and 5% level of significance respectively; implying that RE and Non-RE have a significant impact on each other.

This makes sense intuitively in the case of South Africa, where RE would have an impact on Non-RE if there is an increase in energy supply through RE it would imply a decrease in the coal (Non-RE) energy supply production, especially in the case of Eskom's (the national utility supplier) sales and revenue where they will be requiring less coal fired electricity. The results also showed that the null hypothesis of RE does not Granger cause GDP and R&D was not rejected for neither of the countries in the panel, thereby implying that there is no causality running from RE to GDP nor R&D. This makes intuitive sense due to the fact that the proportion of RE compared to other forms of energy such as Non-RE has been historically low and has less contribution towards the GDP and R&D of those countries.

Furthermore, the results showed that in Brazil and South Africa the null hypothesis Non-RE does not Granger cause GDP was rejected implying that there is a unidirectional causality running from Non-RE to GDP in Brazil and South Africa. Particularly in South Africa that experienced a crisis in 2008 during the coal shortages, which resulted in load shedding as well as a negative impact on the South African GDP, as was expected. The results also showed that for most of the BRICS countries apart from India and South Africa, the null hypothesis of Non-RE does not Granger cause R&D was rejected implying a unidirectional causality running from Non-RE to R&D in Brazil, Russia and China. This could be an indication that R&D funds are mostly directed at non-renewable R&D in those countries due to their dependence on fossil fuels.

Lastly, it was found that for most of the BRICS countries apart from Brazil and China, the null hypothesis GDP does not granger cause R&D was rejected indicating that GDP drives R&D expenditure in Russia, India, and South Africa all at a 5% level of significance. This implies a unidirectional causality from GDP to R&D in Russia, India, and South Africa, in other words the more these economies grow, the higher their investment to technological developments.

For robustness purposes, another model was estimated with a new dataset of alternative proxies for the variables: RE = renewables as a % to total energy, NRE = non-renewables as a % to total energy, GDP = GDP per capita, RD = number of researchers. It must be stressed that regardless of the findings, their interpretations have different policy implications. For example, if found that the number of researchers has an impact on GDP, that means that the skilled human capacity of the country has the potential to improve the country's economic growth and thus policy makers should improve the universities' conditions to produce more skilled labor that will have the potential to become future researchers in the public and private sector. If it is found that R&D expenditure has an impact on GDP; policymakers should invest in the development of R&D including facilities, materials and labor. Another example is the renewable energy in volume and the share of renewable energies to the supply mix having an impact on the GDP. If the first is used, nothing is said with regards to the volume of fossil fuels volume in the country; in other words, if using the share of RE versus the share of NRE, the one is related to the other (if RE are 30% of total, the NRE is 70%).

The overall results and the results per country for the alternative set of proxies can be found in the Appendix. For South Africa specifically, the new dataset confirmed the impact of non-renewable energy (as a % share to total energy) to the economic growth (measured as the GDP per capita).

In the alternative model, there was a unidirectional relationship running from the non-renewable energy share to total energy to the number of researchers in the economy, thereby demonstrating that the non-renewable energies promote the development of human capital in research positions. To compare with the main model, non-renewable energy does not affect the financial investment to the R&D sector by policymakers in the country, which is as expected for an economically constrained economy.

Finally, in the alternative model, the number of researchers, as a proxy of technology, was found to have an impact on the economic growth of the country. Such a result is also expected as the researchers of the country represent a portion of the skilled labor who are one of the most important factors of production as they produce knowledge and innovation. In comparison with the main model, R&D expenditure (proxy for technology) does not have a causal relationship towards GDP but goes in the other direction; from GDP to R&D expenditure, meaning the richer the country gets, the higher the investment on the R&D sector overall.

The causal dynamics were studied and the results for SA are a reflection of the country's energy supply crisis. The fact that RE does not have an impact on GDP and R&D does not mean that the RE is not a promising option for the future. On the contrary, it might mean that the share of RE and the total R&D were both at low levels historically for them to make any significant impact.

4.3 Energy supply mix transition strategy from fossil fuel to renewables for South Africa

Based on the section above we now have an understanding of the impact RE and NRE have on the economy. The main purpose of this analysis is to investigate and propose an optimal energy *supply mix which is aligned with the current national policy frameworks as well as strategic targets and plans which enable a sustainable and secure energy transition. Using the EnergyPlan energy system optimization model, the technical optimality will be explored; while testing the various scenarios via a Minimum Total Mix Capacity (MTMC) methodology model, we will propose an optimal energy supply mix that will ensure increasing annual energy demand is met with the least economic impact.*

The main purpose of this section is to present the results of the EnergyPlan model in evaluating the stipulated reference and future scenario models, investment costs, RE share, emissions outputs, and lastly the proposed electricity supply mix.

To validate the methodology, the South African electricity supply mix system as per the 2016 actuals in conjunction with draft IRP 2017-2030 installed capacity inputs will be used as the reference scenario case study. The scenarios specific to this study will be defined based on the CSIR 2017 demand forecast (CSIR, 2017) scenario demand growth parameters. The Low, Moderate, High (Less energy intensive), High (Same sectors), Junk status demand forecast scenarios will be used; in doing so there is an inclusion of the economic assumptions from the forecasts into the analysis. As a result, the impact of the projected load demand on the energy supply mix was evaluated. An analysis was done from an overall economy/national point of view instead of a specific sector. As was also highlighted by Mccall, et al. (2019), the 2018 Draft IRP does not consider the economy wide impacts and effects of the electricity price increases on the broader economy.

4.3.1 Electricity demand forecast assumptions

Electricity demand projection was one of the major input assumptions that had to be reviewed in the Draft IRP 2018 due to the previous projections in the promulgated IRP 2010–2030 not materializing. This was due to the actual demand being lower than projected as a result of the stagnated economic growth, technological advancement, as well as a shift in the energy usage and efficiency leading to lower energy usage and demand. For the purpose of this study, focus was on the updated demand forecast from 2017-2030 as stated in the Draft IRP 2018.

The study's scenarios were founded on the CSIR Low, Moderate, High (Less energy intensive), High (Same sectors), and Junk status demand forecast scenarios. According to the CSIR (2017), these scenarios represent the mechanism for introducing uncertainty regarding the future values of the drivers into the electricity forecasts in terms of economic variables such as expected GDP, final consumption expenditure of households as well as the fact that manufacturing and mining indexes were taken into consideration.

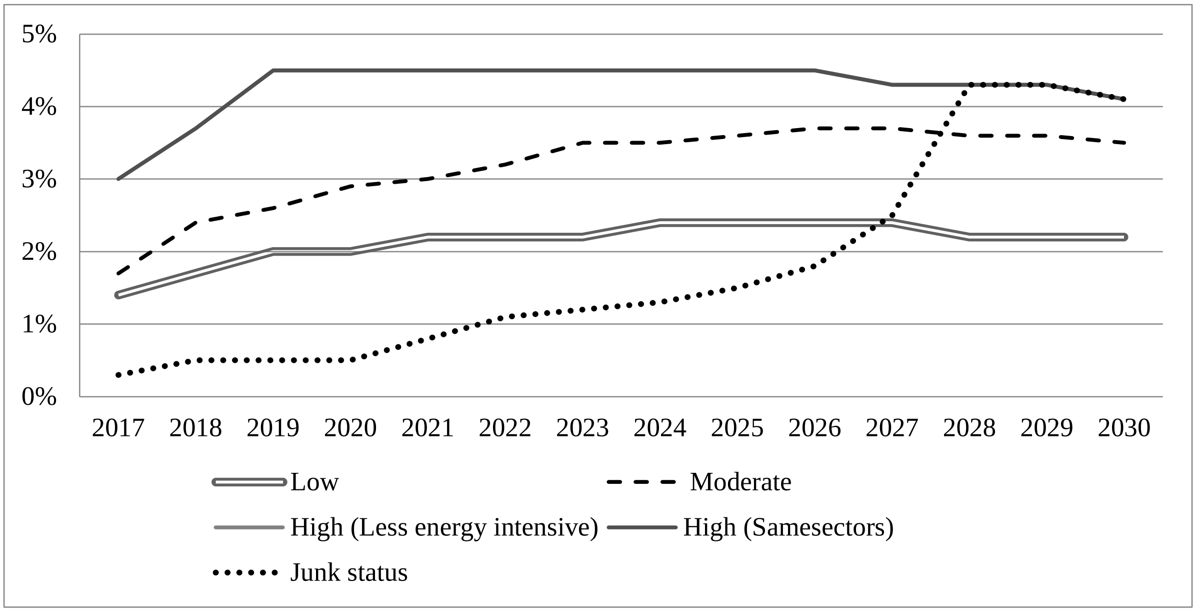


Figure 19. GDP% growth per scenario. Source: Author's own calculation from (CSIR, 2017)

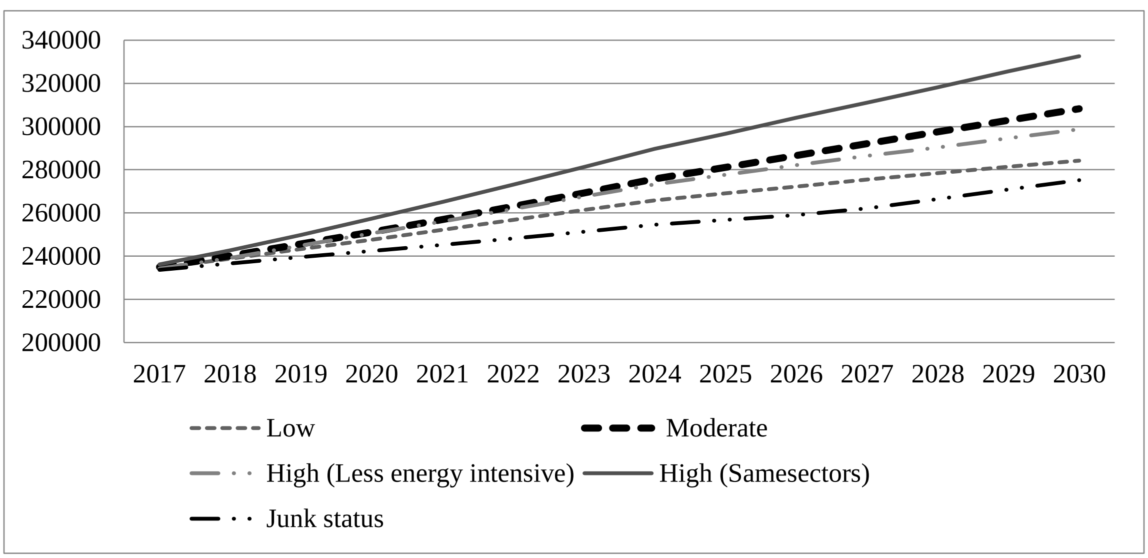


Figure 20. Annual electricity demand forecasts (GWh). Source: Author's own calculation from (CSIR, 2017).

In Figure 19, the Low GDP growth scenario is forecasted to increase gradually to 2.40% until 2027 and then it slightly decreases to 2.20% until 2030. For the Moderate growth scenario, GDP is forecasted to increase gradually to above 3.70% in 2026 then stabilizing until 2030. For both the High less energy intensive and the High same sector GDP scenarios which are assumed to have the same GDP growth, high GDP growth is forecasted to increase to 4.50% from 2020 remaining stable until 2026 and decreasing slightly to 4,30% until 2030. Even though the Junk status scenario is only forecasted to increase below 1% until 2022, it is, however, forecasted to increase to 4.30% from 2028 until 2030. In Figure 20 based on the GDP growth scenarios and other economic drivers, the electricity demand is forecasted to gradually increase for the Low demand scenario from 234539 GWh up to 284182 GWh in 2030. For the Moderate demand scenario there is an increase from 235063GWh up to 308266 GWh in 2030. With the High less energy intensive demand scenario increasing from 234195GWh to 298719GWh and the High same sector demand scenario increase from 236230GWh to 332604GWh in 2030 respectively. Lastly, there is an expected low demand Junk status demand scenario increase of 233695GWh to 275195GWh in 2030. Table 9 shows demand scenarios against maximum RE share to be achieved as per IRP total for 2030.

Table 10

Demand Scenarios

Scenario	Demand forecast GWh 2030	Maximum RE share to be achieved as per IRP total in 2030
Low	284182	26%
Moderate	308266	26%
High (Less energy intensive)	298719	26%
High (Same sectors)	332604	26%
Junk status	275195	26%

Source: Author's own calculation from (CSIR, 2017)

In the analysis, there is an examination and assumption of a minimum 26% RES electricity share capacity target by 2030 as stated in the Draft IRP 2018 to be integrated into the South African electricity supply system. The 2030 electricity demand forecast values to be used will also be based on the Draft IRP 2018 prescribed demand forecast. The constraints assumed in the model will be demand and supply inputs, installed capacity, fixed and variable costs (R/MW), as well as the selection of the scenario emitting the least CO_2 emissions per MT as per the EnergyPlan output for each resource type. The model estimation will be based on the scenarios and assumptions discussed above.

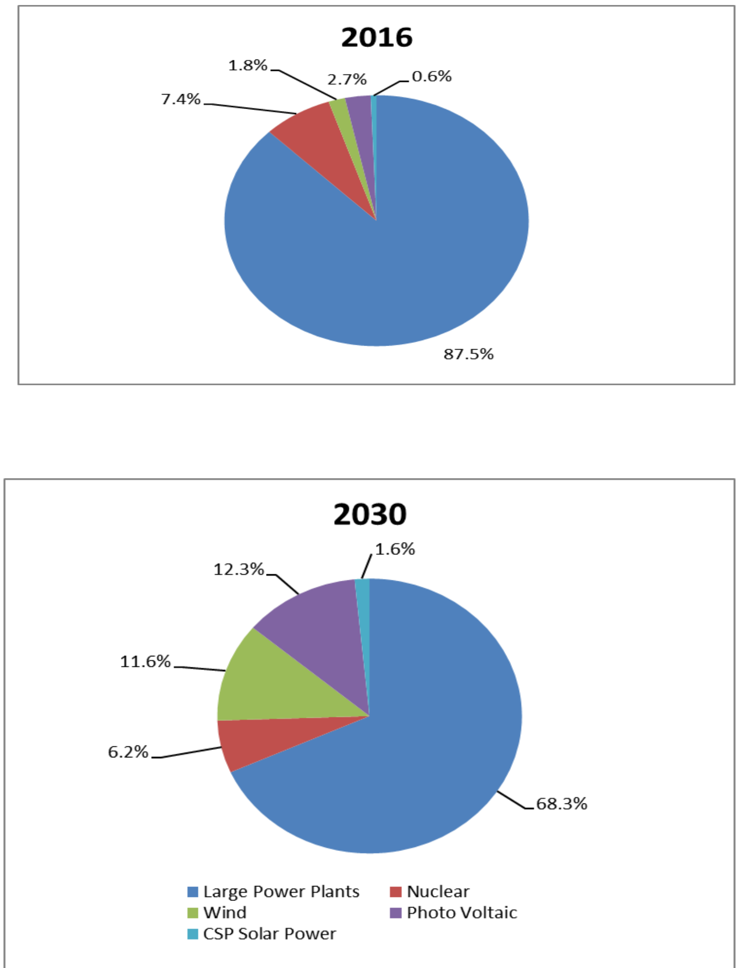


Figure 21. Total Annual Investment Costs 2016 vs 2030 (Source: Author's own calculation from EnergyPlan)

The total investment costs estimated in the models took into consideration the investment costs (also known as overnight investment cost) in R/MW, fuel costs in R/GJ based on the expected lifetime of the resource types as well as the operations and maintenance costs. As can be seen in the Figure 21 as well as in Table 10 and 11 below, it is evident in 2016 that most of the investment costs were spent on coal and diesel large power plants followed by nuclear and very little on RES. But this seems to improve in the 2030 future model where coal and diesel large power plants are still dominantly spent on but there is more diversification and there is significant increased spend on RES when specifically analyzing the selected optimal scenario.

Table 11

Investment Costs 2016 vs 2030

COSTS (M ZAR):	2016 Total Investment.	Annual Investment.	Fixed	2030 Total Investment.	Annual Investment.	Fixed
	Costs	Costs	O&M	Costs	Costs	O&M
Large Power Plants	1651014	55034	54979	1893337	63111	63048
Nuclear	138778	4626	4621	171358	5712	5706
Wind	33340	1667	1667	322596	16130	16130
Photo Voltaic	51228	2049	2049	341454	13658	13658
CSP Solar Power	11747	392	391	43514	1450	1449

Source: Author's own calculation from EnergyPlan

Table 10 shows the annual RES production shares according to the electricity demand scenarios in order to meet the forecasted demand. It is observed that in the 2016 reference model less RES is used in the supply mix with RES only making 8.7% of the total electricity that was produced and 3.3% of the primary energy supply. In total, 21.31 TWh of the electricity produced in 2016 is produced from RES and it consisted of wind, PV, CSP and river hydro, of which the biggest contributor was river hydro which produced 13.52 TWh in 2016.

In the future 2030 model, RES is expected to increase significantly in order to meet the minimum 26% share of RES as stipulated in the draft 2018 IRP. When estimating the demand forecast scenarios it was found that in the high same sector demand forecast scenario and stipulated installed capacity as per the draft 2018 IRP installed capacity for RES people are only able to produce 24.2% RES share of the electricity produced which is less than the desired 26% share stated in the IRP. Meeting 28.4% on low demand, 26.1% on moderate demand, 27% on high demand less energy intensive, and 29.3% on the junk status demand scenario. The reason for the RES electricity produced remaining constant for all the scenarios is due to the fixed minimum installed capacity for RES as stipulated in the IRP. We do, however, see a significant increase in the RES when compared to 2016 with RES electricity produced growing from 21.31 to 80.59 TWh in 2030. The main contributor to the RES being wind 34.71TWh followed by river hydro at 28.91TWh then lastly PV and CSP at 15.5 and 1.48TWh respectively. Meaning the country would be importing less of the river hydro and producing more electricity from wind and PV.

Table 12

RES Share Comparison

RES	Ref2016	2030Low	2030Moderate	2030 High (Less energy intensive)	2030 High (Same sectors)	2030 Junk status
RES share of elec. prod. %	8.7	28.4	26.1	27	24.2	29.3
RES share of PES %	3.8	14	12.7	13.2	11.6	14.5
RES electricity prod.TWh/year	21.31	80.59	80.59	80.59	80.59	80.59

Source: Author's Own Calculation from Energyplan

The environmental impact of the energy supply mix was taken into consideration by analyzing the CO_2 emissions produced from each energy source. It was found that Co_2 emissions are relatively high in 2016 due to the dominant reliance on fossil fuels and due to the low share of RES share of electricity production as is depicted in Figure 22. The analysis also showed that going forward into 2030 based on the different demand scenarios emissions are expected to decrease as the share of RES supply increases. But it was also discovered that if the demand is very high, as is the case in the high same sectors demand scenario, there might not have enough RES to adequately reduce the high emissions produced, thereby suggesting that the 26% RES stipulated in the draft 2018 IRP might not be sufficient.

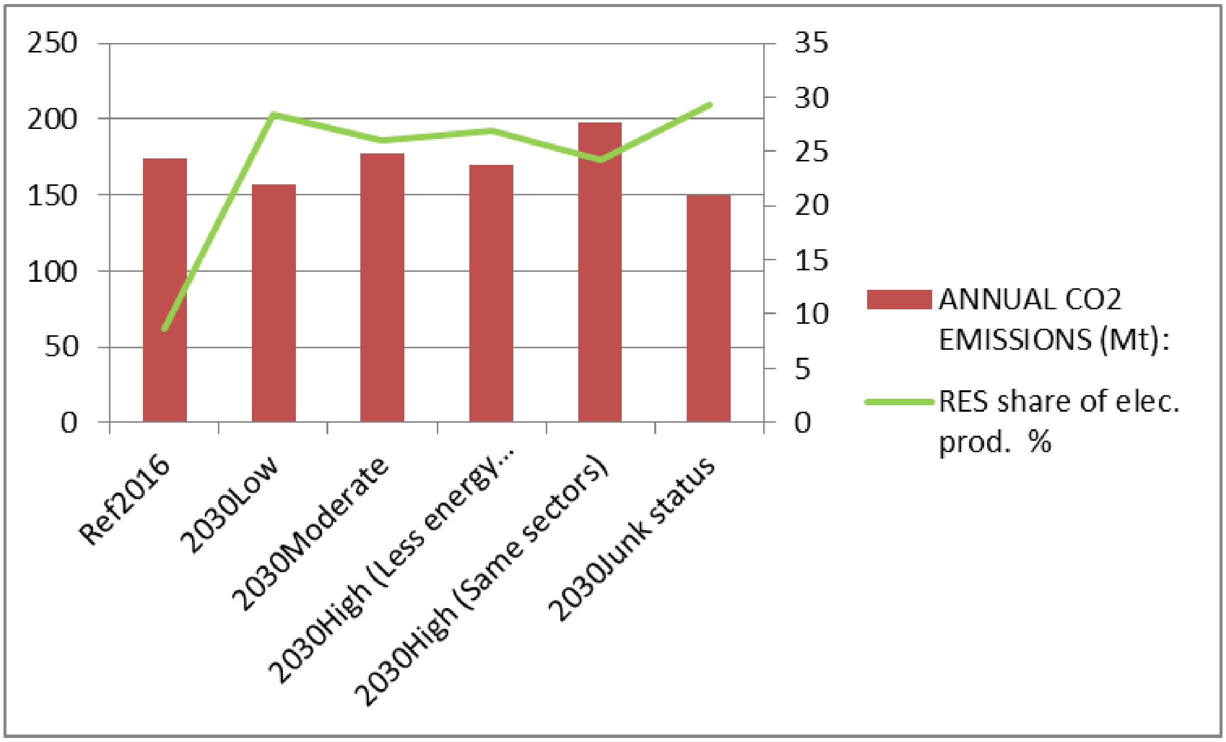


Figure 22. Annual CO2 Emissions vs RES share of electricity produced (Source: Author's own calculation from EnergyPlan)

4.3.2 *Proposed Supply Mix*

After having analyzed all the demand forecast scenarios in terms of meeting the demand at the highest RES share, least cost, and lowest emissions, it was discovered that the "Junk status demand forecast" scenario is optimal when using the MTCM methodology in order to achieve the 26% RES as stipulated in the draft 2018 IRP. The MTCM methodology selects as the most optimal mix, the combination with which the minimum RES share target can be reached resulting in the minimum total capacity. The proposed supply mix to meet the 275.2 TWh as forecasted in junk status demand scenario should consist of 179.69TWh generated from coal and diesel, 34.71TWh from wind, 28.91TWh from river hydro, 15.5 TWh from PV, 14.91TWh from nuclear, and 1.48TWh from CSP. With a minimum installed capacity of 20456MW for coal and diesel, 3952MW for wind, 3291MW for river hydro, 1764MW for PV, 1698MW for nuclear, and 168MW for CSP. As can be seen in Figure 23, when compared to the 2016 supply mix, there has been a significant increase in RES.

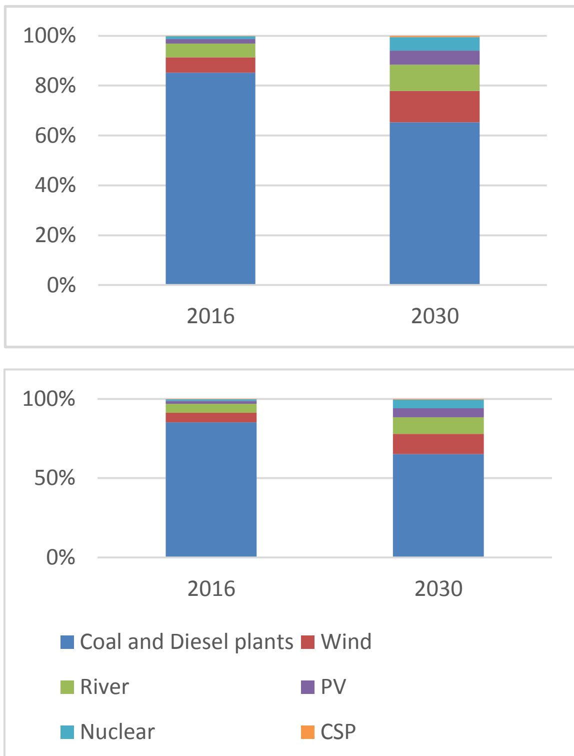


Figure 23. Proposed Installed capacity vs electricity generation

(Source: Author's own calculation from EnergyPlan)

4.4 Conclusion

In this chapter, in a pursuit to gain a deeper understanding of the dynamics and drivers of the energy resource types of the energy supply mix, the existence and direction of the causal dynamic relationship between energy (renewable and non-renewable) on GDP and R&D

expenditure was investigated. The causal dynamics were studied using the method proposed by Emirmahmutoglu and Kose (2011) within a panel data framework comprising of BRICS countries for the period 1996 to 2015. The findings confirmed a bidirectional causality from RE to Non-RE for India and SA and the opposite for Brazil; a one way causality from Non-RE to GDP in Brazil and SA; from Non-RE to R&D for Brazil, Russia and China; and from GDP to R&D in Russia, India and SA. The results for SA are a reflection of the country's energy supply crisis. The fact that RE does not have an impact on GDP and R&D does not mean that the RE is not a promising option for the future. On the contrary, it might mean that the share of RE and the total R&D were both at low levels historically to make any significant impact. Lastly, the researcher investigated and proposed an optimal energy supply mix which is aligned with the current South African national policy frameworks as well as strategic targets and plans which enable a sustainable and secure energy transition. The EnergyPlan and the technical optimality was explored, while testing the various scenarios via a Minimum Total Mix Capacity (MTMC) methodology model. The researcher proposed an optimal energy supply mix that will ensure that an increase in annual energy demand is met with the least economic impact. The main aim of this study was to recommend an energy supply mix, but more specifically an electricity supply mix that will enable the transition from a fossil fuel dominated electricity supply mix to a more renewable energy source supply mix that will sufficiently cover demand and minimize emissions, taking into account installed capacity, investment and technology costs.

CHAPTER 5: CONCLUSION

In this section, findings from the study are summarised and recommendations for future studies are reported. The chapter is structured in the same manner as Chapters 3 and 4.

5.1 Positioning South Africa's energy supply mix internationally: Comparative and policy review analysis

The first research objective in this study was to analyze the energy supply mix of South Africa compared to other countries. South Africa is currently on the correct trajectory in terms of its renewable energy policy implementation and increasing renewable projects growth. However, the South African TPES fuel share is still dominated by fossil fuels, particularly coal and crude oil, and this has been increasing over the years. Similarly, its BRICS counterparts' TPES fuel share is also dominated by fossil fuels, mainly coal, crude oil, and natural gas, growing at a fast pace between 1990 and 2015. Fossil fuels are also the main contributor to the OECD countries' TPES, but there the share of the dominating fossil fuels was decreasing between 1990 and 2015, with crude oil and coal decreasing from 41% to 37%, and 24% to 18% respectively. It is evident that there is a heavy reliance on fossil fuels in South Africa and other BRIC countries. Certainty in the implementation of current policies such as the IRP as well as less bureaucratic disablement is required to influence and guide the transition from the current fossil fuel-dominated energy supply mix to one that follows international trends, but most of all responds to its specific geographic position and availability of natural resources. Additional policy that details alternatives to the current fossil fuel biased supply as well as its structural implantation plan is required to enable a smooth and just transition.

Renewables are still not the preferred source of energy in South Africa and other BRICS countries. The development of a green economy and the increased usage of more renewable energy sources can help to address the challenges that the developing countries face, but seemingly the governments, aware of these strategic options, proceed cautiously, consistently weighing the impact of developing a green economy in the country's overall development objectives. The gap between policy aspirations and actual implementation is often significant in South Africa and some of the BRICS countries, due to the instability of the civil services and the discontinuity of policies compared to the more developed OECD countries.

5.2 The causal relationship between energy and economic growth through Research and Development (R&D)

The second research objective of this study was to examine the causal relationship between energy and economic growth through Research and Development (R&D) in the case of South Africa. The relationship was examined by studying the existence and direction of the causal dynamics between energy (renewable and non-renewable) on GDP taking into account the role R&D expenditure plays in each country and how South Africa differs from other emerging economies. Using the Johansen (1988) and Kao (1999) test of cointegration approach, the researchers established whether there exists a long-run relationship between the variables after determining their stationarity at first difference. To estimate the causality, the Granger causality methodology as used by Emirmahmutoglu and Kose (2011) within a panel data framework comprising of BRICS countries was used for the period 1996 to 2015.

The selection of BRICS as a cluster of countries with its heterogeneity has its own challenges that are portrayed here as points to examine further and include in future country specific studies.

The disaggregation of energy supply into renewable and non-renewable energy is the first step into decomposing the energy impact on economic growth and depicting their differences, since the BRICS countries' energy supply mix is still highly dependent on coal and other fossil fuels (Ndlovu & Inglesi-Lotz, 2019). However, most of the BRICS countries are oil importers and hence, further investigation on the dynamics of oil will give another perspective too. Furthermore, trade as well as energy market structures and regulation are also important factors that can alter the energy-growth nexus that are not considered in this study that focuses more on the dynamics the technological progress brings into the nexus discussion.

Specifically for South Africa that was the initial focus country, the causality runs from Non-RE (←→RE) → GDP → R&D. From that it is obvious that although the use of fossil fuels, as the dominant fuel in the country's energy supply mix, is detrimental to the environment; it promotes economic growth that in its turn affects R&D improving the country's technological progress. The results found in this study are a reflection of the energy supply crisis that South Africa experienced in 2008 during the coal shortages, which resulted in load shedding as well as a negative impact on the South African GDP. The fact that RE does not have an impact on GDP and R&D in the country does not mean that the RE is not a promising option for the future. On the contrary, it might mean that the share of RE has stagnated at low levels in the studied time period so much so that it did not have any effect. Another possible reason for total R&D not having an impact on RE nor Non-RE might be due to its share in the energy R&D expenditure being too small and hence, R&D is not directed to any specific energy technologies.

Due to the lack of an updated energy policy framework in alignment with RE, Non-RE, GDP, and R&D expenditure, the following recommendations are made specifically for South Africa based on the study results in comparison to its BRICS counterparts:

- As a primary policy change, a benchmark needs to be set on R&D expenditure that is commensurate to the compared block of countries. The reason being as indicated by the results of the study, that the progress towards a growing economy requires investment;
- Implementation of a well-coordinated R&D programme to ensure that the investment is channeled into RE and future technologies. The projects in this programme would have to demonstrate innovation and future value add;
- Given that the economy of a country is measured by its GDP, the influence of RE and Non-RE technologies need to be addressed, as seen from the results of the study that their mutual interrelationships cannot be avoided.

5.3 Energy supply mix transition strategy from fossil fuel to renewables for South Africa

The main aim of this study was to recommend an energy supply mix that will enable the transition from a fossil fuel dominated electricity supply mix to a more renewable energy-dominated supply mix that will sufficiently cover demand and minimize emissions, taking into account installed capacity, investment and technology costs. The draft IRP 2018 planned capacity energy mix from 2010 – 2030 was used as the starting point to define the base target scenarios for the proposed electricity supply mix. The study also aimed at providing a comparison to the draft IRP 2018, a technical analysis of the electricity supply system using an internationally recognized methodology and model. In an aid to contribute towards the informed understanding of the current energy supply drivers. As well as recommending least cost environmentally sustainable alternatives to the current energy supply system which are aligned with our current and future global emissions mitigation commitment goals and targets.

An EnergyPlan model was run to estimate the results following the MTCM methodology as prescribed by Vidal-Amaro et al., (2015). The EnergyPlan model results showed that the most optimal growth scenario would be the Junk status growth scenario based on the least the environmental consequences (emissions) and reaching the targets of RE share. The model further showed that the planned minimum 26% RES share capacity planned in the draft IRP could be surpassed to 29.3%. The MTCM methodology selects as the most optimal mix, the combination with which the minimum RES share target can be reached resulting in the minimum total capacity. The proposed supply mix to meet the 275.2 TWh as forecasted in Junk status demand scenario, the mix would consist of 179.69TWh generated from coal and diesel, 34.71TWh from wind, 28.91TWh from river hydro, 15.5 TWh from PV, 14.91TWh from nuclear, and 1.48TWh from CSP. With a minimum installed capacity of 20456MW for coal and diesel, 3952MW for wind, 3291MW for river hydro, 1764MW for PV, 1698MW for nuclear, and 168MW for CSP. As expected, the Junk status scenario which was found to be most optimal in terms of RES share and least emissions mainly due to the decreased economic activity and low investment would naturally lead to a decreased demand and hence lower emissions. However, policy –wise the researcher cannot recommend that the country should reduce its economic growth in order to meet the environmental agreements and reduce emissions. The results serve as an informed indication where improvements in terms or energy transition can be made by increasing and not restricting the RES capacity to be integrated into the electricity supply mix.

In order to capture and analyze the gradual transition and integration of increased RES into the supply mix over the years from 2017 to 2030, the way forward for future research is to conduct the modelling exercise on a per-year basis taking into account assumptions for annual changes in technology costs in the future up until 2030.

5.4 Summary of key findings in response to the main research objectives and questions

5.4.1 How is South Africa's planned energy supply mix relative to the rest of the world and how has it changed in recent years?

In addressing the above research question, research was conducted in the first paper, which gave a detailed description of the South African energy supply mix and its evolution in the past 25 years. Its current and future energy mix were compared with other countries such as its BRICS companions (Brazil, Russia, India, and China) and in the Organization for Economic Co-operation and Development (OECD). From the comparison, it was discovered that the Total Primary Energy Supply (TPES) share of non-OECD countries is becoming more prominent, with China, India, and Russia being significant contributors. The OECD's ratio of universal TPES decreased from 1990 to 2015. It was evident that there is a heavy reliance on fossil fuels in the BRICS countries, which appeals to appropriate policies to influence and guide the transition from the current fossil fuel-dominated energy supply mix to one that follows international trends but, most of all, appreciates its specific geographic position and natural resources.

On the one hand as predicted by the Analytical Centre of the Government of the Russian Federation, the BRICS block of nations are fast becoming the world's largest energy consumers and producers with statistics showing that by 2040 the BRICS nations will be accounting for 45% of global energy consumption, this was also confirmed by this research. On the other hand, these nations are found to be heavily reliant on fossil fuels which are major pollution contributors and have a negative impact on the environment.

Historically, fossil fuels have always been the source of economic benefit particularly for South Africa but in recent years they have proven to be quiet the concern particularly concerning environmental costs and the burning of fossil fuels has also been placing a human health burden for communities and workers in those industries. Placing an urgent need for a policy response such as the carbon tax to address the rising fossil fuel production and consumption is recommended. Another possible solution being the improvement in scientific and technological advances which could improve the efficiencies of current technologies and even the development of advanced and lower priced carbon free technologies which would result in a reduced demand for fossil fuels and making alternatives more cost competitive. The increasing energy costs specifically coal costs and reduced coal exports are resulting in job losses in the coal sector and are placing an economic growth burden on the economy. Raising the need for policy intervention will address reskilling and introduce different economic activity in the affected regions.

5.4.2 What is the relationship between renewable energy and economic growth in South Africa?

Through the second paper, in a pursuit to gain a deeper understanding of the dynamics and drivers of the energy resource types of the energy supply mix, the existence and direction of the causal dynamic relationship between energy (renewable and non-renewable) on GDP taking into account the role R&D expenditure, and how South Africa differs from other emerging economies was investigated. The causal dynamics were studied using the method proposed by Emirmahmutoglu and Kose (2011) within a panel data framework comprising of BRICS countries for the period 1996 to 2015. The findings confirmed a bidirectional causality from RE to Non-RE for India and SA and the opposite for Brazil; a one way causality from Non-RE to GDP in Brazil and SA; from Non-RE to R&D for Brazil, Russia and China; and from GDP to

R&D in Russia, India and SA. The results for SA are a reflection of the country's energy supply crisis. The fact that RE does not have an impact on GDP and R&D does not mean that the RE is not a promising option for the future. On the contrary, it might mean that the share of RE and the total R&D were both at low levels historically to make any significant impact.

Technological advancement in the Non-RE sector also has an impact on the continued use of Non-RE thereby resulting in the Non-RE resources becoming even more likely to becoming economically productive reserves. On the other hand, there are also technological advancement and developmental barriers such as corruption which lead to the lack of investment as a result of political and economic uncertainty. There is evidently a need for increased investment towards R&D particularly towards the development of RE technology and enhancement of RE such as energy storage technology which will enable the increased usage of RE.

5.4.3 Taking all of the above into consideration what is the optimal energy supply mix for South Africa to assist with the transition from fossil fuels towards renewable energies?

In recommending an energy supply mix that will enable the transition from a fossil fuel dominated electricity supply mix to a more renewable energy source supply mix that will sufficiently cover demand and minimize emissions, taking into account installed capacity, investment and technology costs. In the third paper, the EnergyPlan energy system optimization model was used to determine technical optimality and it was explored and run while testing the various scenarios via a Minimum Total Mix Capacity (MTMC) methodology model in order to estimate the results as prescribed by Vidal-Amaro et al., (2015). The EnergyPlan model results showed that the most "optimal" growth scenario would be the Junk status growth scenario based on the least environmental consequences (emissions) and reaching the targets of RE share. The model further showed that the planned minimum 26% RES share capacity planned in the draft IRP could be surpassed to 29.3%. The MTCM methodology selects as the most optimal mix, the combination with which the minimum RES share target can be reached resulting in the minimum total capacity. Lastly, the researcher proposed an optimal energy supply mix consisting of 65% coal and diesel, 13% wind, 10% river hydro, 6% PV, 5% nuclear, and 1% CSP that will ensure increasing annual energy demand is met with the least economic impact. The increased proposed share of RE into the supply mix will have a positive impact on the GDP through the possible reduction in carbon emissions resulting in the reduction of the impact from policy tax interventions such as carbon tax.

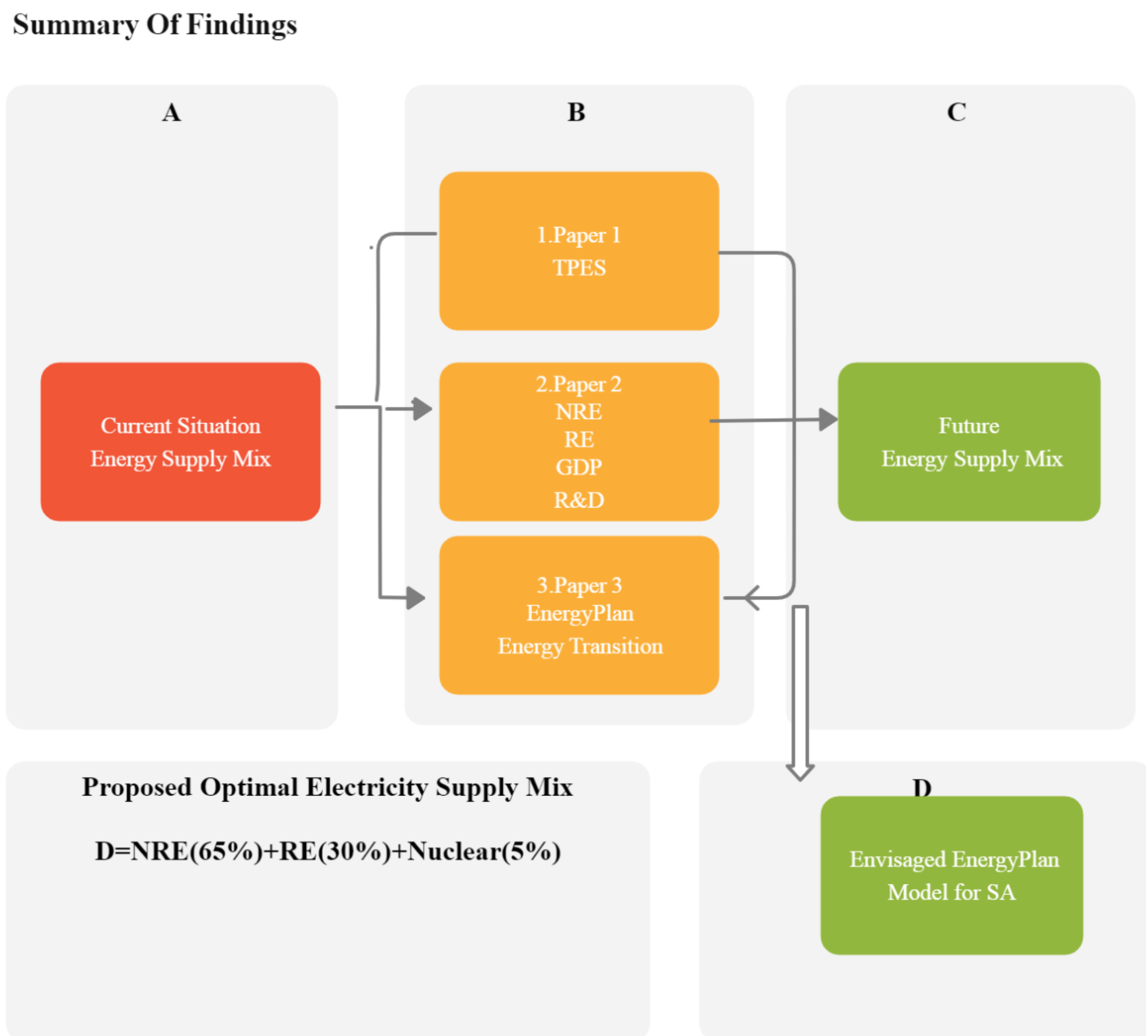


Figure 24. Systematic outline of the research findings

Note: where, TPES is Total Primary Energy Supply; NRE is Non-Renewable Energy; RE is Renewable; GDP is Gross Domestic Product; R&D is Research and Development.

5.5 Recommendations and future work

In conclusion, the study highlights that in terms of its energy supply mix (specifically electricity supply mix), South Africa is still heavily dependent on fossil fuels and there is a need for diversification towards a cleaner and sustainable energy supply mix. As a result, it is evident that non-renewable energy has the most impact on economic growth due to the historical dependence on coal for electricity generation as well as the large dominance of coal economic activity and job creation in the coal mining and exporting industries. The results have also highlighted the need to increase R&D expenditure and energy technology development which will enable technological advancement and exploration of energy alternatives in turn enabling the transition to cleaner and more sustainable energy sources and technology.

In contribution to the body of knowledge, the study provides an examination of the status quo of the country's energy supply mix and how South Africa fares in comparison with its BRICS and OECD counterparts in terms of its current and future energy mix policy. Particularly it's positioning vis-à-vis international trends for future policy recommendations and implementation. Enabling policymakers to comprehend the historical evolution of the supply mix, as energy investments is not short-term and it is dependent heavily on the established supply mix of the past. In addition, it provides insight into international trends thereby giving a direction of the global energy markets and potential trends that South Africa can follow. Enabling informed future policy decision particularly on appropriate policies to influence and guide the transition from the current fossil fuel-dominated energy supply mix to one that follows international trends is also of importance.

As well as examining the existence and direction of the causal dynamics between energy (renewable and non-renewable) on GDP taking into account the role R&D expenditure plays in each comparing how South Africa differs from other emerging economies. In line with appreciating the importance of the potential linkages between energy, economic growth and technological progress, the study provided an empirical examination of the causal dynamics for

South Africa within the BRICS framework, in order to compare and contrast the trends in these emerging countries.

These economic outputs directly and indirectly contribute to and can be accounted for as part of the economic output of a country through the national accounting system which uses GDP as an indicator of economic size. The significance of R&D expenditure and the prospects for these investments to enhance development projections have concurred with or directed the growth in the number and range of countries that are dedicated to science and technology policy and technology-led growth strategies. This study contributed to the enablement and direct policy intervention and also informed policy decision in the investment towards R&D expenditure for RE and NRE which will be beneficial to promoting economic growth.

In addition, providing an in depth investigation of the drivers and determinants of a sustainable electricity supply mix. Recommending an optimal electricity supply mix which is aligned with the current national policy frameworks. As well as strategic targets and plans which enable a sustainable and secure energy transition determined by an internationally recognized energy system optimization model. Which gave the most comprehensive approach by applying both a top down economic model as well as a bottom up technological analysis model which also included an economic simulation of the total energy system on the basis of the simulation of the business-economic marginal production costs of each component in the system. The study proposed an optimal energy supply mix that ensured that the increasing annual energy demand was met with the least economic impact. Proposing an electricity supply mix which promotes the increase and not the restriction of the RES capacity to be integrated into the electricity supply mix by recommending more solar and wind capacity. As opposed to the restrictions proposed in the draft IRP. Lastly, contributing towards the informed understanding of the current energy supply drivers. As well as recommending least cost environmentally sustainable alternatives to the current energy supply system which are aligned with our current and future global emissions mitigation commitment goals and targets.

The limitations of the study include but were not limited to the restrictions on the availability of data for the electricity energy type compared to the other energy types for which data was unavailable. For future research, the expansion of the energy data to include more energy types would infer a more robust analysis if applied at a more detailed granular or regional level. There is also a need to update the costs and capacities as per the recently published IRP and there is also a need to incorporate a more detailed price elasticity analysis into the study in order to determine a more accurate price impact on the economy.

The overall lessons learnt from the analysis led to the below recommendations for further study:

- Certainty in the implementation of current policies such as the IRP as well as less bureaucratic disablement is required in order to influence and guide the transition from the current fossil fuel-dominated energy supply mix to one that follows international trends, but most of all to one that responds to its specific geographic position and availability of natural resources. Additional policy that details alternatives to the current fossil fuel biased supply as well as its structural implantation plan is required in order to enable a smooth and just transition.
- Most of the BRICS are oil importers and hence, further investigation on the dynamics of oil will give another perspective. Furthermore, trade as well as energy market structures and regulation are also important factors that can alter the energy-growth nexus that are

not considered in this study that focuses more on the dynamics the technological progress brings into the nexus discussion.

- As a primary policy change, a benchmark needs to be set on R&D expenditure that is commensurate to the compared block of countries. The reason being as indicated by the results of the study, that the progress towards a growing economy requires investment.
- Implementation of a well-coordinated R&D programme in order to ensure that the investment is channeled into RE and future technologies. The projects in this programme would have to demonstrate innovation and future value add.
- In order to capture and analyze the gradual transition and integration of increased RES into the supply mix over the years from 2017 to 2030, taking into consideration the continuous changes in the energy sector from a policy and technology perspective, the model of this study could be benefitted from a year-on-year forecasting analysis of the costs of technologies until 2030.
- A major hindrance for the successful energy transition in South Africa is the lack of a solid and coherent energy policy. The current IRP is not necessarily an energy policy but more of a model and guide on what new plants should be built but it does not address the social and economic impact. A diverse energy mix based on the least cost and impact to the economy is required which is informed by an energy policy that is a catalyst and stimulus for economic growth for the country.
- It is essential for South Africa to determine an appropriate optimal energy mix that will enable the transition to a decarbonized economy as well as enable economic growth and job creation through skills transformation.

- The basic changes required for a just transition might be accomplished when there is a socio-political system that lays on a key alliance of interests that offers this worldview, utilizes state organizations to drive a just transition and adopts a proper strategy and administrative program that is lined up with the general objective.

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