Sculpting global leaders

Energy Transition Policy options for sustainable development in South Africa

Applied Research Project

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Submitted by

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DECLARATION

I, Clive Mathe, declare that this research report is my own work except as indicated in the references and acknowledgements. It is submitted in partial fulfilment of the requirements for the degree of Master of Business Administration in the University of the Witwatersrand, Johannesburg, South Africa. It has not been submitted before for any degree or examination in this or any other University.

Clive Mathe…………… …………………………

Signed at …….Johannesburg…………………………………………..

On the ….8th………….day of………. April….. 2024……

DEDICATION

This work is dedicated to my late mother, Namakawu Mathe. I miss you every day. You taught me to always put my best foot forward.

Acknowledgements

I would like to thank God for the continued spiritual and emotional support, that has allowed me to complete this research project and dissertation. I would like to thank Ademola Ayodele, my supervisor, for his continued and thorough insights into the research. He availed himself with energy and enthusiasm towards the work of this research. His thorough and structured guidance made this work possible.

I would like to thank the several energy industry experts that contributed immensely in the success of this work. The hours of meetings committed to this work is a tremendous investment in the insights that surfaced in this study, and follow-on work that will emerge.

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Lastly to my family. Your presence and support is all I live for. Thank you for always believing in me. I will always put my best foot forward!

SUPPLEMENTARY INFORMATION

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ABSTRACT

The South African energy sector is at a critical point in the nation's macroeconomic journey, playing a significant role in base industrial activities and standing as Africa's highest producer and consumer of energy. However, it faces challenges such as a disproportionately high Greenhouse Gas emissions compared to similar economies. South Africa's commitment to decarbonize the sector and achieve net-zero emissions by 2050 presents both opportunities and risks, influenced by various factors with high inter-factor causality.

To unlock actionable insights on the energy sector transition, this study aims to model the energy system comprehensively, considering its complexity and dynamism. Specifically, it seeks to assess the implications of South Africa's decarbonization commitment, explore the potential of renewable energy adoption, and identify strategic pathways and mechanisms to accelerate the transition towards net-zero emissions.

A combination of two computer-simulation-based modeling and analysis approaches is adopted for the research work. Systems dynamics is employed for secondary quantitative data modeling, capturing relationships among energy sector factors. Fuzzy cognitive mapping, coupled with expert knowledge solicitation through semi-structured interviews, unveils important causality relationships among systemic parameters. The integration of these approaches forms a hybrid model, overcoming limitations and providing actionable insights crucial for sector transition policy considerations.

Through quantitative modeling, it is projected that coal decommissioning and renewable energy expansion could decrease power-sector carbon emissions by over 90% from approximately 0.26 Gt of CO2 in 2019 to around 0.02 Gt of CO2 by 2050. However, meeting the investment requirements for the proposed transition pathway remains a significant challenge. Accelerating renewable energy development by 20% is suggested to mitigate risks and activate a greener economy, leading to socio-political and economic benefits.

In conclusion, the imperative for decarbonization in South Africa's energy sector is underscored, aligning with global decarbonization targets and ensuring socioeconomic stability. Strategic interventions, particularly in accelerating renewable energy deployment, are essential to navigate the transition effectively and realize the full potential of a sustainable energy future.

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CHAPTER ONE: INTRODUCTION

1.1 Purpose of the Study

The purpose of this research is to explore potential policy pathways for the South African energy system, with consideration of energy transition to greener options, while maintaining the strategic goal of achieving economic efficiency and social equity. A System Thinking approach is used to tackle the dynamics, interrelatedness, and complexity of various components of the national energy system.

1.2 Context of the Study

This work is guided by the objectives of the White Paper on Energy Policy that was released in 1998. The energy sector in South Africa has been pivotal to the economic development of the country. The economic growth in South Africa has been capital-intensive in its structure, relying on energy-intensive primary industry as a significant driver for this growth (Department of Energy, 2019). The mining industry contributed over 45% to the country's energy consumption, and together with primary industry, plays a significant role in the economic growth and export activity in the country (Department of Energy, 2019). The mining industry contributed over ZAR 480 billion to GDP in 2021 (Minerals Council South Africa, 2021), equivalent to approximately 10% of South Africa's GDP in nominal terms. The energy demand of the nature of heavy-industry operations has resulted in South-Africa's growth being fueled by immense energy-intensity and demand, with the country contributing to 50% of the continent's energy consumption, despite the country contributing only 5% of the continent's population (International Energy Agency, 2022).

These energy intensive primary industries utilize the nation's comparative advantage on the availability of low-cost low-grade coal, resulting in one of the lowest costs of energy globally (International Energy Agency, 2022). However, access to energy by poor households is still lower than targeted levels, and this is due to affordability and lower energy generation capacities by ESKOM (Nkomo, 2005). The growing economy, and its reliance on energy supply increases energy demand. Due to several reasons, energy generation capacity has not been able to meet demand, with the past few years being characterized by significant capacity shortages at ESKOM, and the resulting electricity blackouts (Walsh, Theron, & Reeders, 2021). Reliance on low-grade coal results in large GHG emissions and other forms of negative environmental impact such as water pollution (Department of Energy, 2019), and capacity expansion will have to be achieved through more sustainable and greener mechanisms. South Africa has one of the highest solar insolation rates (5.5 kWh/m^2/day) in the world (Spalding-Fecher, 2002) and can utilize this comparative advantage to increase energy generation capacities, while transitioning to be strategically positioned for global energy realities of the future. Despite these opportunities, the nation's progress towards sustainable energy transition has been slow (Todd & McCauley, 2021), and the progress has been impeded by several factors, with the main theme being summarized in the so-called minerals-energy complex, which is a powerful technological and political symbiotic relationship between these two pillars of the South African economy (Todd & McCauley, 2021).

The complexities that underlie policy options, that would ultimately achieve environmental and social equity and economic efficiency implied by the White Paper, are systemic and can be classified into political, technological, social, economic, and environmental dimensions. The monopolistic position of ESKOM has significant implications on the structure of the energy system in South Africa, with the state-owned enterprise (SOE) generating and distributing 90% of the nation's energy (Calitz & Wright, 2021). This increases the risk of opportunism from industry gatekeepers. For instance, ESKOM has been accused of having monopolistic control on energy research and development, usually favoring coal-related work that contributes to its competitive advantage and capabilities and has been deemed to be anti-transitionary (Nkomo, 2005). Another political dimension that impedes energy transition involves trade and labor unions that endeavor to protect the interests of mine and ESKOM workers (Todd & McCauley, 2021), whose jobs would be lost if other sources of energy are introduced at large scale. These powerful stakeholders have strong relationships within the mining and heavy-metals industries that are benefiting from the comparative advantage of relying on low-cost coal (Hlongwane, 2014). On the other hand, deregulation in the sector and a transition to renewable energy sources at scale has the potential to increase access to both industry and residential, achieving both social equity and economic efficiency (Todd & McCauley, 2021). Improvements in technology on the sector have proven large-scale possibilities of achieving new efficiency frontiers in the energy system. However, complexities do exist that need to be strategically approached.

It is therefore necessary to approach policy scenario analysis in a systemic way, in view of all the main systemic elements involved. This research uses Systems Thinking, and more specifically, System Dynamics to explore the complexities, interrelatedness, and dynamics of various components of the South African energy system. Policy options and strategic pathways will be simulated computationally using the System Dynamics approach, with the objective of identifying the most optimal pathways for sustainable energy transition in South Africa.

1.3 Problem Statement

Systems Dynamics is a Systems Thinking methodology with the tools to transform and change a complex organizational problem that would otherwise not be understood through a formula expressing a relationship between a dependent variable and linear and/or nonlinear effects and/or higher-order interactions of independent variables. For example, (Nkomo, 2005) through experience explicated the continuance of the use of coal for energy production as a dependent variable, based on mental modes that would deliver a certain level of social equity for economic efficiencies.

The complexities and dynamics involved in this new dispensation of digital transformation and change lend to a shift in paradigm of telling the story using a “rich picture” which reflects careful thought and analysis and enlightens and informs. The problem is that people are stuck in the former paradigm of social equity vs economic efficiency as opposed to a new paradigm of leadership & intent against digital enablement and adoption. That is to say, in the former paradigm, there is less understanding of the energy system resulting in tactical responses to unexpected behavior as opposed to the latter with enhanced understanding and predictability through strong overarching digital vision.

1.4 Objectives of the study

The main objectives of this study are segmented into two. The first segment is to investigate the usefulness of computer-based simulation and analysis of the energy sector as a complex and dynamic system. The second segment is to investigate the key factors that should considered as the energy sector transitions, and how the insights relating to these factors should be used as inputs for policy making and implementation. These objectives are given below:

Investigate the usefulness of computer-based simulation and analysis of the energy sector as a complex and dynamic system:

- Investigate the complexity of the South African energy sector, and its transition towards net-zero carbon emissions.
- Investigate computational analysis methods for assessing sector transition, and how these could be adopted by policy-makers and analysts for making and implementing policies towards the energy transition.

Investigate the key factors that should considered as the energy sector transitions:

- Investigate key factors that should be considered by the South African energy sector in its current state for positive social and economic impact.
- Investigate key factors that should be considered by the South African energy sector as the sector transitions towards net zero emissions in 2050.
- Investigate the causality among these factors, and identify systemic behavior behavior under key sector transition scenarios.
- Identify key insights emerging from systemic behaviour, and derive policy implications that should be adopted for positive impact on economic efficiency and social equity as the sector transitions.

1.5 Significance of the study

The study will provide guidance to policy makers on analyzing complex systemic scenarios and being able to predict unexpected systemic behavior. The deployment of the System Dynamics approach for Policy analysis will be useful skillset for decision makers and analysts with the possibility of factoring more complex scenarios and factors that normal mental models cannot capture. It also provides visualization of mental and cognitive models of Policy makers and analysts, providing a platform for their improvement. As such, it will aid, and be aided by, Policy makers and analysts' mental models.

The study will provide direction in policy options that optimally achieve strategic goals set out in the White Paper on Energy Policy of 1998.

1.6 Delimitations of the study

The various system elements in the South African can be classified into the political, social, economic, and technological factors. This research will go in-depth on the technological, environmental, and economic factors, with high-level presentation of the political and social factors. The study will also only consider solar, wind, and natural gas as alternative energy sources in the analysis and will not include nuclear energy and other potential sources such as hydro-electric sources. Furthermore, only technological trends and possibilities that have been verified as of today and that are within the short-term possibilities will be considered. Far-fetched technological possibilities in the energy sector (e.g., Nuclear Fission) will not be considered in this research work.

CHAPTER TWO: LITERATURE REVIEW

2.0 Introduction

This chapter assesses already published literature in the energy sector and investigates key factors that are important to consider as the South African energy system is set to transition over the next decades. It will set a direction and be an initial guidance on the approach and key levers to investigate for this research work.

2.1 Energy in South Africa

The energy sector in South Africa has been pivotal to economic development of the country, with the structure of main industries and economic growth classified as energy intensive (Department of Energy, 2019). Any discussion on the energy sector in South Africa should begin with the recognition of the so-called ‘mineral-energy-complex’ (MEC), which is a powerful technological and political symbiotic relationship between these two pillars of the South African economy (Todd & McCauley, 2021). MEC heavily relies on the availability of low energy prices and has been a key driver in developing the energy sector in South Africa (Spalding-Fecher, 2002), through the utilization of low-grade coal by ESKOM for energy generation. The low cost of energy in South Africa is a competitive advantage that has attracted new investments into South African industries over the past decades (Nkomo, 2005). This structure of the energy sector development was resultant of pre-1994 energy policies that mainly focused on energy supply and security (Nkomo, 2005). There has, however, been a shift in the paradigm of policies post-1994, with focus centered on economic efficiently and social equity (Nkomo, 2005).

The transition in the energy policy paradigm was officially articulated in the White Paper on Energy Policy that was released in 1998. The policy objectives and priorities, which are set out to align the energy sector with sustainable development, are summarized below (Spalding-Fecher, 2002):

- To increase access to affordable energy services
- To improve energy governance
- To stimulate economic development
- To manage energy-related environmental impacts

- To secure supply through diversity.

There are however tensions within the policy structures such as apparent tradeoffs between public interests and commercial interests, and these have been reflected in uneven implementation (Sustainable Energy, 2005). The capital-intensive growth, as opposed to labor-intensive growth, has mainly benefited commercial interests (Spalding-Fecher, 2002), and this raises questions on whether the development in the energy sector and the implementation of the energy policies have been consistent with the objectives and priorities of the White Paper. The policy framework however provisions for the derivation of value in implementations that benefit both commercia and social interests. For example, Robinson *et al* (1990) show that restructuring the mining industry in South Africa to also include focus on the semi-manufacturing and final stages of the mining value chain has greater potential for employment creation, with these downstream components of the mining value-chain being more labor – intensive, as opposed to capital intensive, than the upstream elements of the value chain such as mining and initial processing. This would turn the comparative advantage the country has on low-cost energy, into a competitive advantage. Implementation of such strategies alongside energy transition efforts is likely to achieve both social equity and economic efficiency, minimizing the tradeoffs between the two.

It is necessary, therefore, to structurally assess some of the challenges that exist in the energy sector in South Africa, that have been key in minimizing the effectiveness of policy implementations hitherto, with regards to the five key policy objectives set out in the 1998 White Paper. Firstly, the supply and demand structure of the energy industry is best described as monopolistic, with Eskom Holdings (Eskom) as a vertically integrated pure monopoly that generates and distributes close to 90% of South Africa’s electricity (Calitz & Wright, 2021). Despite the 2021 100MW deregulation on generation power limit for Independent Power Producers, Eskom is a price maker and largely controls supply volumes in the economy.

As aforementioned, Eskom tariffs are one of the lowest globally (Spalding-Fecher, 2002), and this is due to several reasons such as large resource availability of low-grade coal, the use of technology that have achieved economies of scale for Eskom, and spatial distribution advantages of Eskom power stations that are located close to coal mines. These factors lower variable costs of energy production. With most of the generation units already paid, this allows Eskom to charge low prices for energy access (Nkomo, 2005). Nkomo (2005) argues that these lower prices charged by Eskom do not account for environmental externalities and costs of the resources used, and that the full cost of production is higher than borne by Eskom, with costs of capacity expansions and investment in efficient technologies and renewables not accounted for. This has implications of an unsustainable energy model.

The use of low-grade coal is a double-edged sword. It has been accepted that the resulting competitive advantage has fueled economic growth, and several arguments also have asserted that the resulting economic growth result in social upliftment through job creation (Nkomo, 2005). Nevertheless, the resulting environmental effects of the utilization of low-grade coal have placed South African Green House Gas (GHG) emissions highest in the continent, and in the top 15 nations globally (Todd & McCauley, 2021). The graph below depicts the highest CO_2 emissions by nation, for the year 2019 (World Wide Review, 2022).

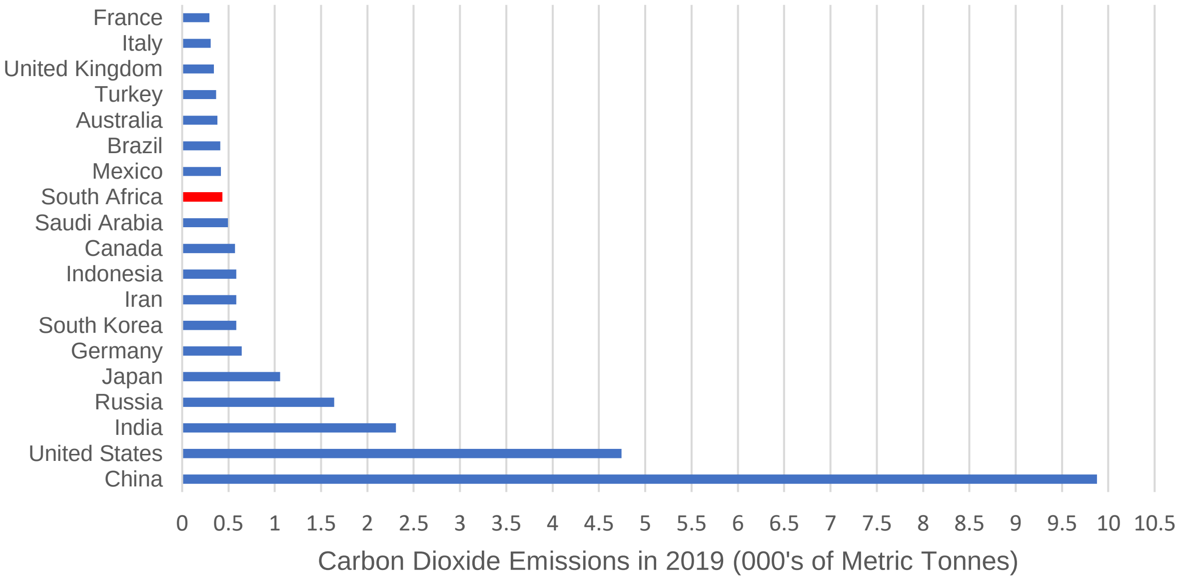


Figure 1: Carbon Dioxide Emissions by country in 2019 *(World Wide Review, 2022)*

The relatively large carbon-dioxide emissions in South Africa are plausible considering the energy-intense primary industries established through the minerals-energy complex. The country accounts for 50% of Africa's energy consumption, with 45% of South Africa's energy consumption attributed by the mining and metals industry.

The above argument makes the relevant the need to transition into environmentally friendly and more sustainable sources of energy (Spalding-Fecher, 2002). South Africa possesses vast natural renewable resources, with solar being one of the most promising options. South Africa has an average solar insolation rate of 5.5kWh/m^2/day (Jain & Jain, 2017), which is highly favourable compared to countries like the United Kingdom with an average solar insolation rate of 2.65kWh/m^2/day (Jain & Jain, 2017). The access to solar natural resources, combined with access to technology, places South Africa at the idea position to lead energy transition towards sustainable and renewable sources (Todd & McCauley, 2021). The potential comparative advantage of access to relatively high insolation rates becomes an attractive transition option. However, a number of structural and policy factors have been instrumental in delaying progress of the transition, with the main reason being the minerals-energy-complex's reliance on low-cost low-grade coal as a comparative advantage.

The International Panel on Climate Change (IPCC) called for "rapid far-reaching and unprecedented changes in all aspects of society in an effort to limit global warming to 1.5°C" (Todd & McCauley, 2021, p. 1). The South African Government task Force committed to the goal of achieving carbon -neutrality in South Africa by the year 2050 (Todd & McCauley, 2021). This was after South Africa became a signatory of the Paris Agreement on Climate Change on the 22nd of April 2016 . The main objective of the Paris Agreement om Climate Change is to strengthen global response to the threats of climate change by keeping temperature rise in the 21st century below 2 °C above pre-industrial level. The above commitments have been an impetus to the adoption of renewables in South Africa, currently representing just over 11% of the country total energy according to 2022 data. The pie-chart below depicts the energy mix in South Africa in 2022.

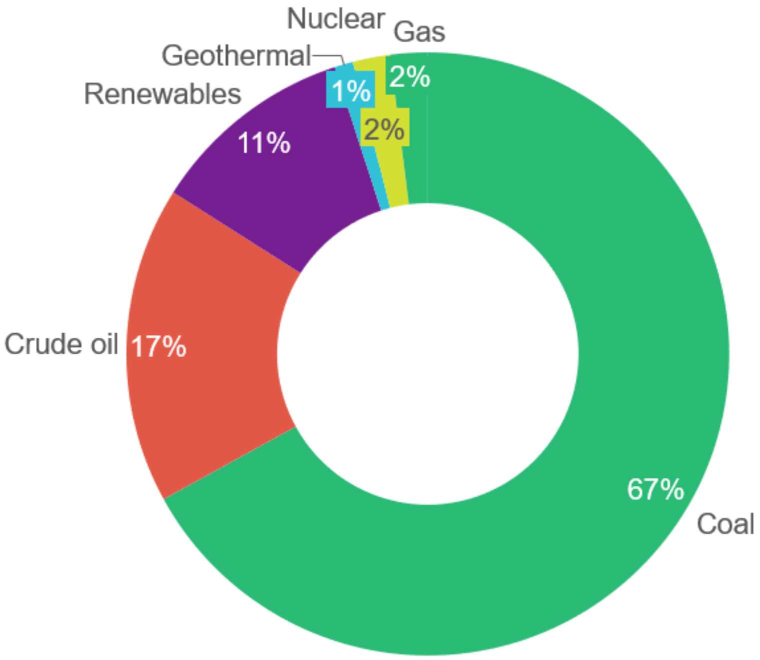


Figure 2: Energy Mix in South Africa, 2022

Research by the Council of Scientific and Industrial Research (CSIR) reached conclusions that South Africa is perfectly conditioned to introduce large quantities of variable renewable energy sources for electricity generation. Cost effectiveness and technological improvements over the past decades have increased the attractiveness of renewable energy, with cost effectiveness projected to increase due to both increased economies of scale that technological improvements will bring, and the increased efficiency of solar panels for solar energy. Despite these factors, the adoption of solar energy in South Africa has been slower than expected, owing to a number of policy constraints. Todd and McCauley (2021) identified four main policy constraints that are acting as barriers to effective energy transition. These are:

- Several weaknesses and monopolistic position of the state electricity utility ESKOM.
- Government: A lack of strategic direction, the display of weak institutions, and characteristics of bureaucratic and corruption traits that are acting as barriers to effective policy development at a national strategic level.
- A lack of strategic direction at municipalities
- Immense political power of the mining industry and unions in South Africa.

Todd and McCauley (2021) argue the above to be the main reasons for the gross disproportion of renewable energy uptake when viewed from the perspective of available renewable resources in South Africa.

2.2 Computational Applications for exploring Complex Systemic Issues

The synopsis in the preceding sub-section reveals several interdependent factors that affect and are affected by the energy system in South Africa. There are many factors that must be considered when exploring possibilities of sustainable energy transition in South Africa, which fulfil the objectives of social equity and economic efficiency. Furthermore, these factors change in time in their causal relationships, and thus, have to be considered as complex systems. For example, a complete deregulation in the energy industry changes the competitive industry forces, affects the structure of investments into the industry, and affects the social and political forces within the country. My assertion is that these effects will also be different based on timeframes. Chan (2001) characterizes complex systems as those that have several interacting sub-systems that are difficult to understand and fully explore and require the development and use of new scientific tools, non-linear models, out-of-equilibrium descriptions, and computer simulations (Chan, 2001 as cited in Nair, Reckien, & Maarseveen, 2019).

System Dynamics (SD) and Fuzzy Cognitive Mapping (FCM) are two computational methodologies that have been applied in research extensively for simulating complex social systems, and specifically for policy analysis and exploration. The following sub-sections explore these.

2.2.1 System Dynamics and its applications in Policy Analysis

System Dynamics is a Systems Thinking methodology that utilizes computational modelling and analysis to potentially enhance managerial and policy makers' understanding of system behavior, resulting in better decision making. It requires a good understanding of the system and the system components to accurately model system behavior (Rahim, Hawari, & Abidin, 2017). The main advantage of the use of System Dynamics is its ability to predict unexpected systemic behavior due to the complexities it introduces in the analysis methodology, as opposed to cognitive models and experience that managers and policy analysts normally use for decision making (Macmillan & Woodcock, 2017). As such, due to the constrained predictability of the current paradigm of cognitive models used, this results in policy makers and implementers being faced with unexpected systemic scenarios, forcing their actions and decisions to be tactical as opposed to strategic (Teimoury, Nedaei, Ansari, & Sabbaghi, 2013). Sterman (2000) states the importance of System Dynamics in enhancing understanding of systemic policy resistance (Sterman, 2000).

Systems Dynamics has been used successfully to overcome these limitations, both at a microeconomic and macroeconomic level. It utilizes archetypes, which are describe the dynamic system through the interaction of system components using both causality cycles, which can either be reinforcing or balancing loops (Mutingi, Mbohwa, & Kommula, 2017). This is useful in helping policy makers and analysts to understand and predict unexpected energy system behavior. The four main System Dynamics generic problem archetypes that have been identified are:

- Underachievement archetype: The semi-generic archetypes under this are Limits to success, and Tragedy of commons.
- Out-of-Control archetype: The main semi-generic archetypes under this are Fixes that fail, Shifting the burden, and Accidental adversaries.
- Relative Achievement: The semi-generic archetype under is the Success to the successful archetype
- Relative Control: The semi-generic archetypes under this are Escalation and Drifting goals archetypes.

Mutingi *et al* (2017) categorized policy formulation problems within the energy system into three broad categories of energy, economic and environmental factors. They used System Dynamics as a prospective tool for predicting unexpected energy system behavior. In view of their scope, they identified and formulated five archetype models for understanding energy policy formulation. The five key relationships that were identified, and the respective archetypes utilized are as follows (Mutingi, Mbohwa, & Kommula, 2017):

- Energy demand and supply management models (Mutingi, Mbohwa, & Kommula, 2017): Many researchers consider macroeconomic factors that drive energy demand and supply factors such as economic growth, investment propensity, the level of industrial activity and technological supply factors that directly impact energy supply. There are however several constraints to be considered as well such as resource availability and energy generation capacity at a given time. A sample causal loop diagram for this archetype is depicted below:

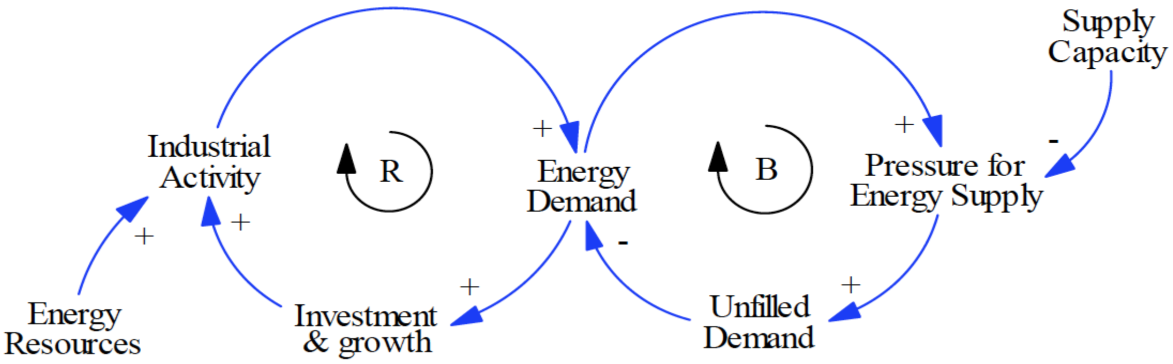


Figure 3: Energy supply and demand using the Limits to growth generic archetype

- Innovation in the energy sector models (Mutingi, Mbohwa, & Kommula, 2017): This consideration is important due to the significant and constant innovation in the energy sector with efforts that continuously aim for new efficiency frontiers through entrepreneurship. These efforts that invent new mechanisms of power distribution, better ways of energy extraction from natural resources, and even efforts to increase energy conversion efficiencies have been common. There are several considerations in this archetypical presentation such as the availability of financial resources to fund research and design and entrepreneurial activity all the way from idea stage through prototyping and testing, and eventually commercialization and value delivery. Another key factor to consider is the time it takes for this process and the probability of success, the role of the regulatory framework in supporting entrepreneurial intent in the sector, and the strength of partnerships with the research and development community to enhance efforts in the sector. These models fall under the generic archetype of Limit to growth, and an example of the causal loop diagram is depicted below:

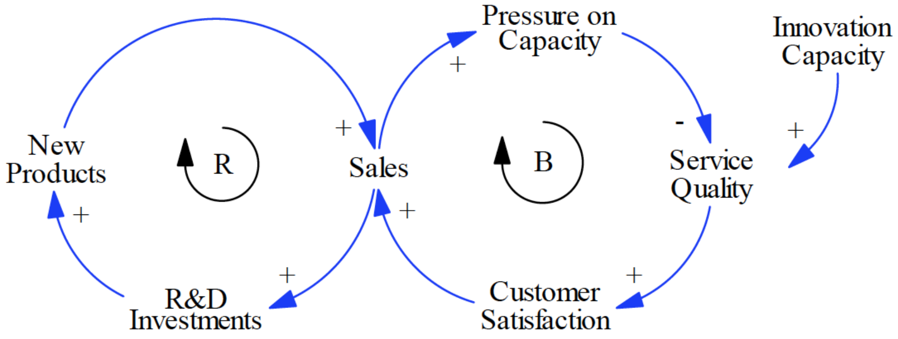


Figure 4: Causal- loop diagram for energy technology innovation using the Limit to growth generic archetype

- Energy capacity management models (Mutingi, Mbohwa, & Kommula, 2017): These models have to do with how policy makers manage capacity adjustments as a function of energy demand factors. Subject to energy generation and supply capacity and availability of resources, increase in industrial activity, for example, increases sales and demand of energy, which in turn enhances energy prices. Other factors such as price elasticity of demand are also coupled into this model. The energy pricing model also has its own separate causal-loop analysis model, and we look into that next.
- Energy pricing models (Mutingi, Mbohwa, & Kommula, 2017): The models assess the complexities and non-linearities in the interrelatedness of energy prices, energy supply and energy demand. Other factors such as governmental regulations on prices of energy. In the South African context, this is regulated by the National Energy Regulator of South Africa.
- Energy, the economy and the environment models (Mutingi, Mbohwa, & Kommula, 2017): These models seek to establish a balance between energy structure, economic efficiency, and sustainability of energy resources across the whole value chain. For example, is a stakeholder causes pollution, policies implemented under the these models pay by removing the pollution and / or compensates for those that are affected by the pollution. An application of this is the concept of carbon credits for car manufacturers. In the year 2021, the USA-based electric vehicle manufacturer Tesla Inc generated close to US$ 1.5 Billion in revenue from just selling its environmental emission credits to other car makers. A causal loop analysis diagram example for this archetype is depicted below:

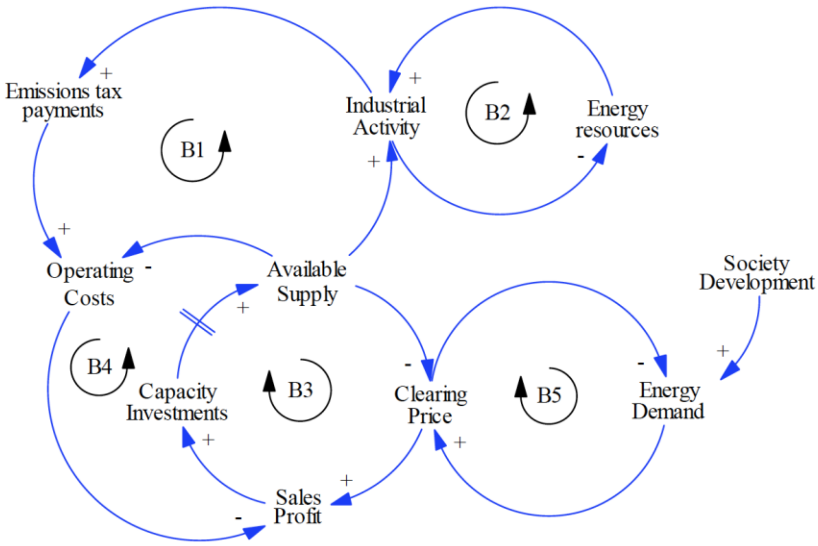


Figure 5: Energy, the economy and environmental factors

Blumberga *et al* (2022) segmented energy policy analysis into national climate goals, general policies, energy supply, energy demand, and macroeconomics & population factors, with each being represented by archetypical causal-loop analysis framework as discussed previously (Blumberga, Gravelsins, & Blumberga, 2022). Their aggregated structure is depicted below (Blumberga, Gravelsins, & Blumberga, 2022):

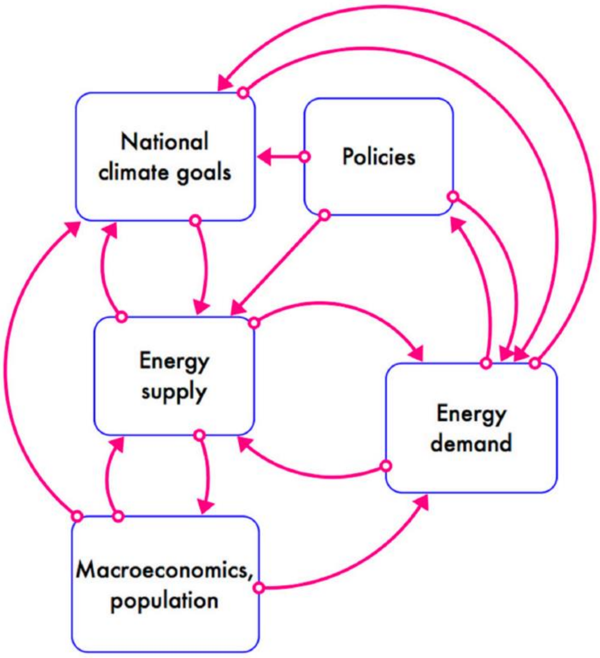


Figure 6: Aggregated System Dynamics Causal-loop analysis structure for energy policy analysis

System Dynamics has been used successfully for strategy exploration and policy making. Mirzamohammadi and Hosseini (2010) explored pioneering system dynamics models in the field of fossil fuel resource analysis, revealing impressive possibilities in the future of fossil fuels. Blumberga *et al* (2022) analysed energy transition policy pathways in Europe using System Dynamics, and their results reveal how the soft power position of Russia can potentially lock in energy transition in Eastern European countries through the enablement of policy choices with additive effects towards energy transition.

Chen *et al* (2020) used System Dynamics to analyse Energy Policy transition choices for a sustainable future in Singapore. The results show that adding nuclear energy into the energy mix in Singapore through offshore floating nuclear plants results in the lowest long-term socioeconomic and externality costs. The analysis also shows that within the Singaporean context, the latter recommendation, combined with importing renewable based electricity provide acceptable outcomes in lowering greenhouse gas emissions, and have the potential to promote multilateral relationships and co-development of economies between Singapore and her neighbouring countries (Chen, 2020).

System Dynamics has also been used for many other applications outside of policy making and the energy sector. Moellers *et al* (2019) used System Dynamics for business model innovation at BMW. Their insights reveal a great wealth of information. Firstly, they show the value of System Dynamics in enabling managers to develop more accurate cognitive representations about their business models. Secondly, they demonstrate and re-affirm System Dynamics' ability to predict unexpected business model outcomes, adding to managerial and strategic positioning efficiency. Thirdly, and unexpectedly, they reveal a significant cognitive gap between managers who were involved in the development of the Systems Dynamics model and those that were not, with those that are actively involved having nuanced and better understanding of business model dynamics. Moellers *et al* (2019) developed strategies to overcome this cognitive gap.

The importance and increasing value of the intersection between System Dynamics and operations management has been demonstrated several times (System Dynamics perspective, 2015), with System Dynamics used to enhance understanding and predictability of value chain behaviour. Li *et al* (2012) used System Dynamics to analyse the eco-agricultural system, and develop policy recommendations for Kongton District, Pingliang City, China. The analysis revealed a number of inefficiencies in the agricultural system, and these included the unsustainable excess increase in cattle slaughter, unstable methane production rates and unsustainable energy structure in the district. System improvement policies were offered that are in line with sustainable development and growth of the sector in the district.

2.2.2 Fuzzy Cognitive Mapping (FCM) and its applications in complex dynamic systemic exploration

Fuzzy Cognitive Mapping (FCM) was developed as an extension of System Dynamics, and more specifically for capturing, explaining and simulating qualitative system dynamics (Nair, Reckien, & Maarseveen, 2019). Whereas System Dynamics plays a great role in analysing complex systems, it is difficult to include qualitative (abstract) concepts in the modelling due to the resulting challenges of quantification (Nair, Reckien, & Maarseveen, 2019). Exclusion of these concepts decreases the quality of insights derived from such computational analysis. Carvalho & Tome (2000) assert the need to include qualitative components of the system, especially if they play an important role in the system. One such sub-system in the energy sector in South Africa is society and the public sector, represented by the social-equity objectives of the White Paper.

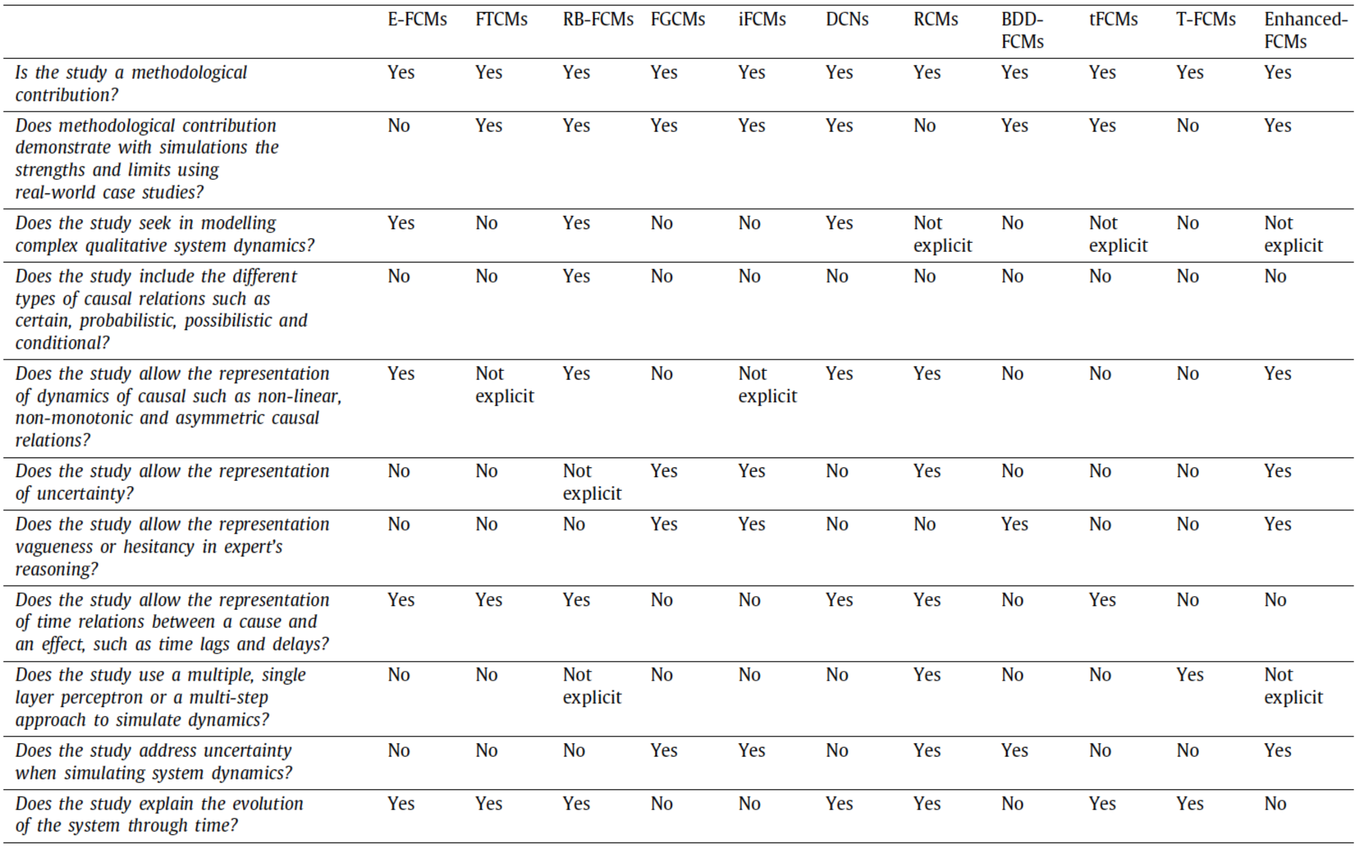
Fuzzy Cognitive Mapping applies Fuzzy Logic rules to describe a system. The system is defined with sub-systems or concepts, and within the FCM methodology, the system is defined to have three distinct characteristics (Papageorgiou & Stylios, 2008), namely:

i. Negative or positive causality of one concept to another, reflecting the direction of causality.
ii. Fuzzy values that denote the strength of the causality, reflecting the degree of fuzziness/ association in causality of one concept from and/or to another.

iii. Dynamic nature of causality links, where causality nodes from one concept to another affects other nodes. This characteristic represents feedback mechanisms within the system, capturing dynamic relationships of all the nodes within the system. The relationships of all the nodes, by implication of the dynamic nature, may have transient characteristics.

Several efforts have enhanced FCM in response to its limitations when modelling qualitative System Dynamics (SD). These developments avoid an over-simplistic representation of rather complex qualitative components of complex systems. For example, conventional FCMs use a single-layer perceptron, which cannot handle x-NOR functions, which are needed for the inherent nature of conditional, probabilistic and possibilistic causal relationships in System Dynamics (Nair, Reckien, & Maarseveen, 2019). Nair *et al* (2019) summarized the enhancements and different versions of FCMs, and evaluated these based on novelty, addressing the limitations of the each work. This is shown in the table below:

Table 1: Evaluation of Enhancements of FCMs in qualitative Systems Dynamics *(Nair, Reckien, & Maarseveen, 2019)*



	E-FCMs	FTCMs	RB-FCMs	FGCMs	iFCMs	DCNs	RCMs	BDD-FCMs	tFCMs	T-FCMs	Enhanced-FCMs
Is the study a methodological contribution?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Does methodological contribution demonstrate with simulations the strengths and limits using real-world case studies?	No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes
Does the study seek in modelling complex qualitative system dynamics?	Yes	No	Yes	No	No	Yes	Not explicit	No	Not explicit	No	Not explicit
Does the study include the different types of causal relations such as certain, probabilistic, possibilistic and conditional?	No	No	Yes	No	No	No	No	No	No	No	No
Does the study allow the representation of dynamics of causal such as non-linear, non-monotonic and asymmetric causal relations?	Yes	Not explicit	Yes	No	Not explicit	Yes	Yes	No	No	No	Yes
Does the study allow the representation of uncertainty?	No	No	Not explicit	Yes	Yes	No	Yes	No	No	No	Yes
Does the study allow the representation vagueness or hesitancy in expert's reasoning?	No	No	No	Yes	Yes	No	No	Yes	No	No	Yes
Does the study allow the representation of time relations between a cause and an effect, such as time lags and delays?	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes	No	No
Does the study use a multiple, single layer perceptron or a multi-step approach to simulate dynamics?	No	No	Not explicit	No	No	No	Yes	No	No	Yes	Not explicit
Does the study address uncertainty when simulating system dynamics?	No	No	No	Yes	Yes	No	Yes	Yes	No	No	Yes
Does the study explain the evolution of the system through time?	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes	Yes	No

Some of the most significant deficiencies of traditional FCMs were “the external interventions (typically from experts) for the determination of FCM parameters, the recalculation of the weights, and the causal relationships every time a new strategy is adopted, as well potential convergence to undesired regions for concept values” (Papageorgiou & Stylios, 2008, p761). Node weight adaptation methods using neural networks techniques, resulting in hybrid neurofuzzy system are proposed as a learning methodology to achieve unsupervised adaptation (Papageorgiou & Stylios, 2008). Further enhancements of FCMs have used Evolutionary Computation Techniques for computational efficiency and system efficient adaptation.

FCMs have been used for modelling complex systems by many researchers. Nair *et al* (2019) proposed a generalized FCM approach for modelling complex systems, and used the approach to investigate the consequences of high intensity rainfall in Kampala City, taking into consideration environmemtal, social, economic, infrastructural, and supply chain factors, among many other factors, in their modelling. Konyalioglu (2020) developed an integrated approach that used System Dynamics (SD) for developing recovery options for a waste management system on small households, and a generalized FCM that evaluated the qualitative relationships on supporting factors of the recovery options.

Fuzzy Cognitive Mapping (FCM) has also been used within the energy sector, and more specifically, in evauating the relationships among key factors within the energy system. Zare *et al* (2021) developed an FCM model for evaluating factors involved that contribute to the long-term sustainability of wing energy in Iran. They analysed relationships and revealed 26 factors categorized in six main factors, and demonstrated that ecnomic and political drivers play a singificant role in the long term sustainability of wind energy in Iran. Alipour *at al* (2017) used a hybrid FCM approach, integrating FCM with STEEP analysis, cross Impact Analysis (CIA) and Morphological analysis in developing an approach with benefits in both quaitative and quantitative analysis. The analysis showed that in 75% of potential scenarios, oil production increased in the medium -to -long term, while the other 25% scenario was a perssimistic pathway mainly driven by lagging investment trends into the oil sector in Iran. Ziv *et al* (2018) used FCM to evauate the impact of Brexit on the energy, water and food sector in the UK. The analysis revealed that energy-related concepts had the biggest impact on the energy-water-food (EWF) nexus, and that demand for EWF would decreased under hard-Brexit pathways. The demand for energy in particular was shown to positively correlate with GDP, whereas UK population size correlated with food and water demand.

2.3 Conclusions

The South African energy sector is faced with immense opportunities of sustainable transition, creating value for industry, the public and the environment. Despite the reliance of the South African primaries on low-grade coal which has over a century of reserves, a transition into an energy state majorly reliant on renewable resources poses advantages that can transform the country's resource comparative advantage into competitive advantages. As aforementioned, the energy industry in South Africa has a number of complexities, and when viewed with current cognitive models that policy makers and implementers use, shows tensions on the main objectives outlined in the 1998 White Paper on Energy Policy. The policy constraints, and the realities and constraints of the paradigm of policy making and implementation have implications on limited understanding on energy systemic behaviour.

The proposed new paradigm of policy analysis, potential path exploration, and implementation, using System Dynamics proposes greater understanding of the energy sector systemic behaviour. It proposes greater understanding and prediction of unexpected behaviour, with the ability to handle counter-intuitive relationships among system elements. Systems Dynamics methodology not only enhances understanding of complex systems, but provides a platform for policy makers and analysts to improve their cognitive models. As such, System Dynamics does not replace Policy makers and analysts' cognitive models and approaches, but it aids and is aided by them. Furthermore, the qualitative concepts of the energy system in South Africa can better be modelled using Fuzzy Cognitive Mapping. This proposes deeper understanding and expert knowledge elicitation using fuzzy variables that provide a domain for quantifying qualitative variables. To benefit from the advantages of both System Dynamics and Fuzzy Cognitive Mapping (and its enhanced versions), it is necessary that both methodologies be adopted in a hybrid manner, in exploring and analysing the energy sector in South Africa.

CHAPTER THREE: RESEARCH METHODOLOGY

3.0 Introduction

The complexities in the energy sector and the long-term planning needed when making policies require robust methodologies for understanding system behavior. System Dynamics and Fuzzy Cognitive Mapping will be used as modelling and analysis methodologies for this study. A crucial step when modelling system behavior is the definition of relationships between different aspects of the system, and system policies are used to guide these interrelationships. Models are not obtained from statistical data (Blumberga, Gravelsins, & Blumberga, 2022), but rather an interaction of decisions, which alter system levels, which in turn affects these decisions, all guided by the policies that exist in the system (Blumberga, Gravelsins, & Blumberga, 2022).

3.1 Research Design and Data Collection

The research paradigm is a mixture of qualitative and quantitative. There are two main sources of data for this study, which can be classified as follows:

(1) Secondary quantitative data in the form of literature review and data that is publicly available upon request from public sector and institution (e.g., the department of mineral resources and energy).

(2) Primary qualitative data collected through qualitative interviews with experts in specific fields within South African energy sector. A questionnaire has been designed for the purpose of knowledge elicitation from industry experts (see Appendix A). The main objective is to define causality relationships among the various concepts identified within each main factor (Table 2).

Table 2: Main factors and relative concepts in the South African energy sector

Main Factor	Concept
Economic	Economic Growth
	Electricity Demand
	Operational Expenses
	Price of Electricity

	Energy Mix
	Investment Risk
	Return on Investment
	Public expenditure in the energy sector (Budget Allocation)
	Oil Prices
	Electricity Supply Stability in SADC
	Electricity Generation Deregulation
	Exchange Rate
Environmental	Environmental Regulations
	Environmental Concerns
Legal	Market Regulations
	Government support and involvement
	Market stability for IPPs & Policy certainty
Social	Population Growth
	Public Knowledge and acceptance of alternative energy sources
Technological	Technology maturity
	National deployment of alternative energy sources e.g. Solar power
Political	Political Stability in the country
	Political relations within the region
	Political relations with power-houses such U.S and China
Other	Other

Moreover, macroeconomic data will be used in the economic modelling of the relationships within the causal loop diagrams. Some of this data will include the international oil prices over the past 20 years. This data will be analyzed using statistical approaches mainly to established directional relationship between international oil prices and other macroeconomic factors such as investment into the South African energy sector, and the price of energy tariffs in the country.

It is important to establish the structural systemic blocks that will be analyzed. These are the economic factors, social factors, technological factors, environmental factors, and policy factors within the sectors. All these are interrelated, and each will have a causal loop analysis diagram with an archetypical structure consistent with the block. For example, the technological causal-loop analysis will have a limit-to-growth generic archetype. With the definition of these broad archetypes, the next important step will be to define the relationships between the different aspects of the archetype using reinforcing and balancing loops, and delay relationships between them. This is a highly iterative process that will need industry understanding, and verification of cognitive models from published work on the subject, and with context of the South African energy sector. An example of a generic stock-and-flow structure for the supply side of the energy sector is depicted below.

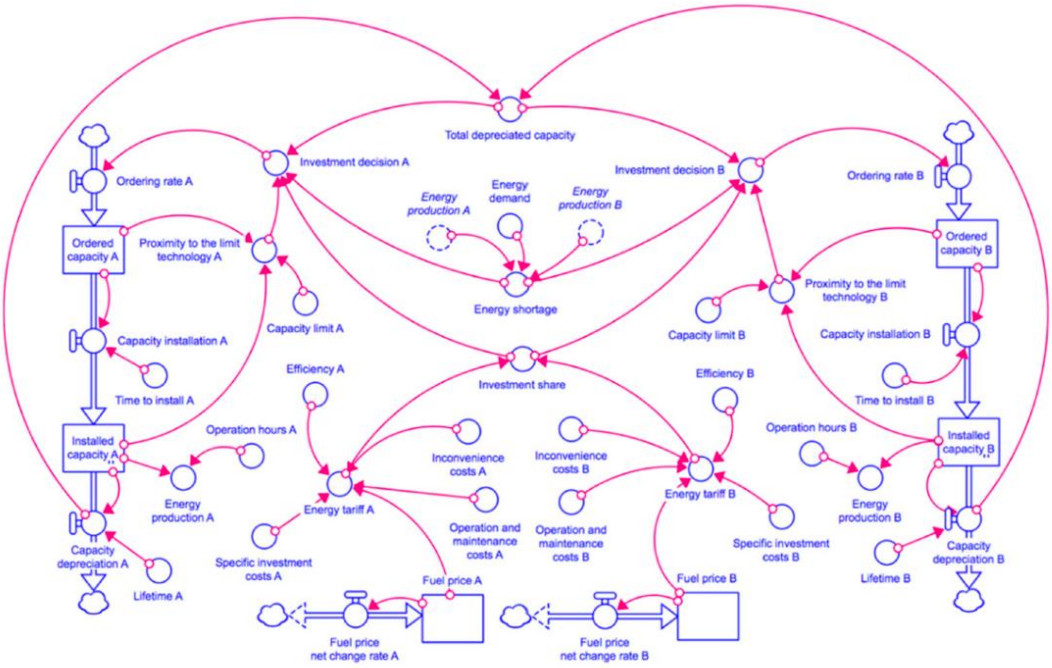


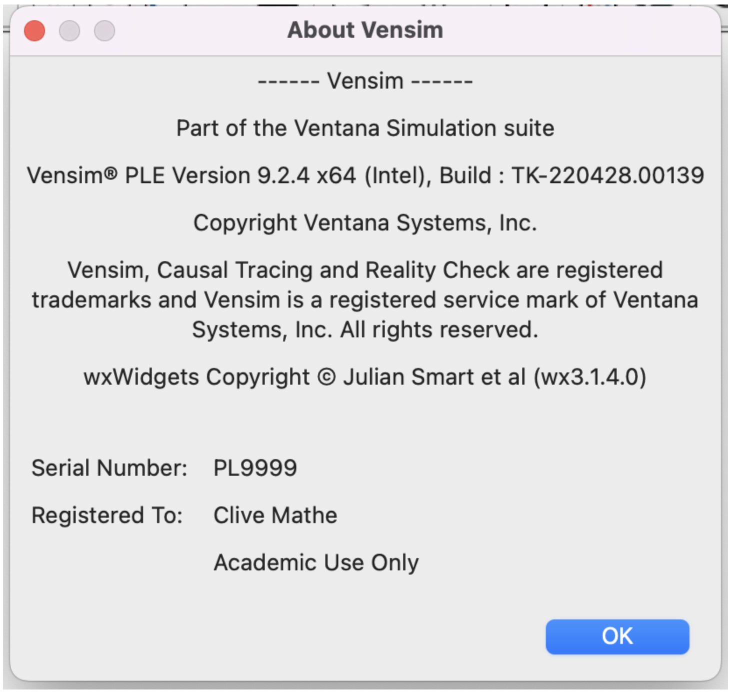
Figure 7: An example of a stock-and-flow structure for energy supply (*(Blumberga, Gravelsins, & Blumberga, 2022)*

3.2 Research Instruments

This subsection assesses the research instruments that will be used for this study. Given the mixed qualitative and quantitative nature of this study, the research instruments will be presented and discussed for each of these.

3.2.1 Quantitative research instruments: Systems Dynamics

Computational modelling and analysis of secondary qualitative data will be conducted on a computational simulation package called VensimPLE, which has an open-source license for academic purposes. The author already has a registered academic license for the use of the software. The image below depicts the registration details.



------ Vensim ------

Part of the Ventana Simulation suite

Vensim® PLE Version 9.2.4 x64 (Intel), Build : TK-220428.00139

Copyright Ventana Systems, Inc.

Vensim, Causal Tracing and Reality Check are registered trademarks and Vensim is a registered service mark of Ventana Systems, Inc. All rights reserved.

wxWidgets Copyright © Julian Smart et al (wx3.1.4.0)

Serial Number: PL9999

Registered To: Clive Mathe

Academic Use Only

Figure 8: VensimPLE license proof of registration for academic purposes

3.2.1.1 Model Validation

Once a model is created, it is very important to validate the internal structure and internal causality relationships within the structure. This increases confidence intervals and significance of the structure. To validate the structure, I propose to use events that have happened in the past in the energy sector in South Africa, to predict system behavior from these system perturbations. The resulting behavior of the model will be compared with actual system behavior, and a more accurate model will have the lowest deviations between the actual and predicted behavior. This back-testing approach is valid since the historical behavior of the South African system was not directly utilized in modelling the system. The more data points of behavior in the South African energy system they are, the more opportunities there are to modify and increase the accuracy of the System Dynamics model. Some of these key important events I propose to use for model validations include the publication of the White Paper on Renewable Energy Policy of November 2003, and the Independent Power Producers (IPP) deregulation of 2021.

3.2.1.2 Policy Exploration and Analysis

Once the model has been validated for accuracy using back-testing, it increases confidence intervals and usability of the model to predict system behavior. Several policy scenarios and strategic possibilities will be simulated to explore the behavior under different scenarios. Sustainability of the energy sector, and the development thereof will be used as factors that signify the success of the energy transition policy, with optimal value being defined for both public, industry, and commercial stakeholders, in accordance with the objectives of the White Paper on Energy Policy of 1998.

3.2.2 Qualitative research instruments: Semi-structured interviews and Fuzzy Cognitive Mapping

Interviews with industry stakeholders, guided by the questionnaire in Appendix A, are the primary instrument for information and primary data collection. Two key levels of information will be the outcome this this. Firstly, industry stakeholders will guide on the key factors that are important to investigate for the South African energy sector for sustainable transition of the sector. Secondly, the industry stakeholders will give their perception of the causal relationships among these factors.

The emerging qualitative factors and the associated causal relationships among them are key input into Fuzzy Cognitive Mapping, using Python programming and AI-enabled algorithms to simulate systemic behavior. Once the initial converged Systems Dynamics models are developed, Systems Dynamics models and the Fuzzy Cognitive models are then combined to formulate a hybrid Systems Dynamics - Fuzzy Cognitive Model.

The interview guide used as an instrument for primary data collection is detailed below:

3.2.2.1 Interview Guide

A Qualitative Perspective research approach will be adopted, with the objective of getting experts views on the causality relationships in the concepts of the energy system in South Africa.

The following section is divided into different parts according to the different factors identified within the South African energy system. Please indicate the grade of relationship between the below mentioned concepts with the grading system as follows:

Negatively Strong	Negatively Medium	Negatively Weak	None	Positively Weak	Positively Medium	Positively Strong
- - -	- -	-	0	+	++	+++
🟩	🟩	🟩	⬜	🟩	🟩	🟩

1. Negatively Strong
2. Negatively Medium
3. Negatively Weak
4. Zero
5. Positively Weak
6. Positively Medium
7. Positively Strong

For the purpose of this research, Part 7 is particularly important. Please, kindly answer all the questions in that part. Thank you very much for your contribution.

Part 1: Economic Factors

1. According to the above-mentioned grading system, how would you grade the influence of *Economic Growth* on:
    a. *Electricity Demand?*
    b. *Price of Electricity?*
    c. *Operational Expenses?*
    d. *Price of Electricity?*
    e. *Energy Mix?*
    f. *Investment Risk?*

    g. *Return on Investment?*
    h. *Public expenditure in the energy sector (Budget Allocation)?*
    i. *Oil Prices?*
    j. *Electricity Supply Stability in SADC?*
    k. *Electricity Generation Deregulation?*
    l. *Exchange Rate?*
2. And vice versa?
3. Do you notice further influences between any of the above-mentioned concepts?
    a. If yes, between which concepts? And to which extent?

Part 2: Environmental Factors

1. According to the above-mentioned grading system, how would you grade the influence of *Environmental Regulations on Environmental Concern*?
2. And vice versa?

Part 3: Legal Factors

1. According to the above-mentioned grading system, how would you grade the influence of *Market Regulation* on:
    1. *Government Support and Involvement*?
    2. *Market stability for IPPs & Policy certainty*?
2. And vice versa?

Part 4: Social Factors

1. According to the above-mentioned grading system, how would you grade the influence of *Population Growth* on *Public Knowledge and Acceptance of Alternative Energy Sources*?
2. And vice versa?

Part 5: Technological Factors

1. According to the above-mentioned grading system, how would you grade the influence of *Technology Maturity* on *National Deployment of Alternative Energy Sources* (e.g. solar power)?
2. And vice versa?

Part 6: Political Factors

1. According to the above-mentioned grading system, how would you grade the influence of *Political Stability in the country* on:
    1. *Political Relations within the region*?
    2. *Political Relations with power-houses such as the U.S and China*?
2. And vice versa?

Part 7: Other Factors

1. Could you identify other concepts which may influence the above-mentioned factors?
2. Could you identify some variables in the above-mentioned different parts which may influence each other?
    a. If yes, which ones?
    b. And to which extent?

3.3 Conclusion

The following approached will be used to derive the important systemic factors that the sector should consider, the associated causal relationships among the factors, and the emerging insights emerging from the simulated systemic behavior:

i. Interviews with 3 industry stakeholders to solicit their perception of and definition of the main problems in the South African energy sector is facing and will face while transitioning. This resulted in the problem definition for purposes of the modeling and analysis scope of this writing.
ii. Interviews with 7 other industry stakeholders to solicit their perception of the key concepts within the South African energy sector, their relationships, and strength of these relationships as linked to the problem definition derived in step (i) above.
iii. Formulation of a dynamic hypothesis or working theory on how the main challenge arose and how it can be solved. This dynamic hypothesis forms the basis on the key variables to be tested during the simulation and data collection, for proof or disproof, and can be modified or even abandoned depending on emerging insights from simulation and system data.
iv. Development of causal-loop diagrams as representative of the modeled problem, which mainly explains the mental models of industry experts, the defined problem, and perception of relationships among energy sector concepts.
v. Translation of the causal-loop diagram into stock and flow diagrams for purposes of simulations and analysis (initial Systems Dynamics model)
vi. Testing the causal loop diagram for model accuracy and system representability.
vii. Development of a Fuzzy Cognitive Mapping (FCM) model for qualitative concepts.
viii. Integration of the FCM model with the initial SD model to form an integrated Systems Dynamics – Fuzzy Cognitive Mapping model.
ix. Exploration of system behavior under different policy pathways and implications on economic efficiency and social equity. This will include the definition of parameters that represent economic efficiency and social equity.

CHAPTER FOUR: SIMULATIONS, MODELLING AND ANALYSIS OF RESULTS

4.0 Introduction

This chapter gives details on the important relationships that emerged from both secondary quantitative data, in the form of concept levels; and primary qualitative data, in the form of industry experts' perceptions on the most important concepts driving the much-needed energy sector transition looking forward to the year 2050. The year 2050 is an important date as it coincides with international targets on reaching net-zero carbon dioxide emissions, which South Africa is a signatory and has committed to. The chapter concludes by developing high probability scenarios that will be used as a proxy for insight development and derivation of policy options for the energy sector.

4.1 Emerging Problem Statement

There is congruency displayed by the three industry experts in their perception of the problems and challenges that the energy sector is facing and need to solve for, going forward. These factors and concepts are shown in Table (3) below. Primarily, the delays in the commissioning of the Medupi and Kusile coal fleets has resulted in significant load shedding over the past years with the years 2022 and 2023 recording the highest power supply deficits after 1994. The emerging and implied challenge is that of increasing power generation capacity to at least cover the supply deficit. However, the coal fleet decommissioning plan at a national level, the implied phasing out of coal as part of international energy policies and commitments, and the projected increase in power demand as the South Africa economy grows and the industry structure changes; establishes more dynamics that add complexity to the challenges the energy sector is currently facing and makes relevant the need to consider the future of the sector.

It is clear from secondary data and insights that a sector transformation to include renewable energy sources (solar energy and wind energy) presents great opportunities to both increase energy supply while strategically aligning with international community commitments and sentiments of decarbonization for techno-economic value creation, and the increased probability to create measurable positive environmental impact. However, a transformation towards renewable energy and coal decommissioning has direct implications of coal mining job loses, and loss of thermal coal exports due to commitment of the international community to decarbonization and transformation of energy value-chains to reflect sustainable and green sources with minimal carbon footprints. South Africa has relatively high renewable energy generation potential due to the comparative advantages of high insolation rates and consistent high average wind speeds. The energy situation in South Africa therefore poses both threats and opportunities. A problem statement was developed from the above overview of the emerging challenges from discussions with industry experts and from secondary data.

> <u>Problem Statement</u>: *The South African energy sector is faced with an opportunity to transition and decarbonize the sector. The rate at which the sector should be transformed is not clear, especially in view of important implications the transformation will have on socio-economic concepts such as employment and affordability of energy, and techno-economic factors such as reliability of energy supply. What important factors should the South African energy sector consider and what strategic considerations should the sector adopt from a policy perspective to overcome potential risks and socio-economic and techno-economic tradeoffs while achieving the transformation?*

4.2 Qualitative concepts and associated strength of relationships

This subsection gives the important socio-economic, techno-economic, and socio-political factors and concepts that are important considering the problem statement that has emerged with the discussions with industry experts. The causal relationships among the factors and concepts are also represented in Table 4, which is a representation of the industry experts’ perception of the importance and strength of causal relationships among the different concepts in the energy sector.

1.1.1 Key Concepts and factors

Table 3: Key concepts and factors

Key Concept or Factor	Concept ID	Definition, importance and measurement of concept or factor
Time factor	C0	The time for the analysis is aligned with the South Africa's commitment to reach net-zero carbon emissions by the year 2050, as a signatory of the United Nations Framework Convention on Climate Change (UNFCCC), and a signatory of the Paris Agreement on Climate Change in 2016. Predictive analysis will therefore be performed to the year 2050, whereas modeling and diagnostic analysis will be performed from the year 1994 till date if necessary.
Renewable Energy (RE) capacity	C1	The amount of renewable energy generated, distributed, and transmitted to end consumers, from solar energy and wind energy. This is measured in Gigawatts (GW)
Coal Fleet Capacity	C2	The energy production capacity of coal fleet at certain point in time. This factors in the coal fleet decommissioning plan set out by the 2019 IRP proposal. It also assumes efficient operation of Medupi and Kusile power plants. Capacity is measured in Gigawatts (GW).
Demand of coal	C3	The amount of coal demanded from South African coal mining sector. This is the summation of demand from ESKOM coal fleets, demand of thermal coal exports, demand for synfuels production by Sasol, and local use by households and industry. This is measured in Megatonnes (Mt).
Coal Mining jobs	C4	The number of direct jobs linked to coal mining in South Africa.
Impact on jobs	C5	The number of direct jobs created through an action within the energy sector over time. A positive figure

		represents creation of jobs, whereas a negative figure represents net loss of jobs in the energy sector.
GDP	C6	Nominal Gross Domestic Product, measured in ZAR
Exports	C7	Overall exports for a fiscal year.
Thermal Coal Exports	C8	Overall exports for a fiscal due to thermal coal.
International Community Commitment	C9	The commitment of the international community to the transformation and decarbonization of value chains, especially as it relates to international trade policies. For example, European member countries and the European Parliament have agreed to implement Carbon Boarder Adjustment Mechanism (CBAM) as a tariff on carbon-intensive products such as fertilizers and encourage trading partner states to decarbonize.
CO_2 e	C10	Carbon dioxide emissions, measured in Megatonnes ($MtCO_2$)
Energy Demand	C11	The total demand of energy in South Africa, measured in GW
Energy Generation Capacity	C12	The total energy generation, transmission and distribution capacity in South Africa, measured in GW
Energy Surplus	C13	The difference between energy generated, transmitted, and distributed, and that demanded in South Africa. A positive value represents energy surplus whereas a negative value denotes a deficit and results in load shedding.
Energy Generation costs	C14	The average value chain cost of energy production, transmission, and distribution, measured in cents per kilowatt-hour (cents /kWh)

Energy Investment	C15	Investment into the South African energy sector to increase energy generation, transmission, and distribution capacity. This is measured in ZAR.
Technology Development	C16	The development of technology that directly impacts the energy sector value chains.
Green Hydrogen Production	C17	This measures the amount if green hydrogen produced in South Africa per year. This important concept is pivotal as South Africa has the potential to create competitive advantages in green hydrogen generation and become one of the global leading exports of the commodity. The three main reasons for South Africa's potential competitive and comparative advantages in green H_2 production are: (BCG & NBI, 2019) • High renewable energy potential (solar and wind energy). For example, the Renewable Energy Dedicated Zones (REDZ) have the potential to generate 922GW, which is over 500% of what South Africa needs for a complete decarbonization. This comparative advantage has implications of lower relative costs of green H_2 production. • Availability of water and land resources that are needed for green H_2 production. • Engineering and technical sectors in South Africa have high expertise, technology, infrastructure, and process experience relevant for H_2 production. Particularly, South Africa has renowned expertise in the Fischer-Tropsch technology, which is critical in H_2 production.

Jobs Created	C18	The number of direct jobs that can be directed within the energy sector, from actions such as the production of green H_2.
Political Stability	C19	A qualitative measure of socio-political stability directly due to dynamics in the energy sector, *ceteris paribus*. For example, industry experts perceive that a loss of thousands of jobs in the mining sector would result in social unrest and political instability.
Coal Decommissioning structure.	C20	The decommissioning of coal fleets as they are being phased out. For example, it is projected that by the year 2050 only Medupi and Kusile coal fleets will be operational, with all others phased out. 10% of coal power generation capacity would have been phased out by the year 2030, and over 65% would have been decommissioned by the year 2045 (Integrated Resource Plan, 2019).
Carbon Export Tariffs	C21	Tariffs imposed on carbon-intensive South African exports, due to commitment of international community to decarbonization of value chains.

The relationship among these factors was measured based on the perceptions of the industry experts. Interviews were conducted with 10 industry experts in total (3 for definition of key factors, and 7 for defining causal relationships), to solicit knowledge from them on both the polarity and strength of causality. This was combined with secondary data and insights. For quantitative concepts, equations and measurement will be defined, whereas for qualitative concepts a Likert scale is used based on the industry experts' perceptions. The analysis and simulation approach will be detailed in Chapter of this writing. The Likert scale is shown below.

Negatively Strong	Negatively Medium	Negatively Weak	None	Positively Weak	Positively Medium	Positively Strong

- - -	- -	-	0	+	++	+++

Table 4 below shows the weighted causality matrix of the above-described variables, derived from industry experts' perceptions. It is important to note that this is a unidirectional causality matrix. Each row in the matrix shows how all the variables along the row are affected by that row variable. For example, the first row with data in Table 4 shows C1 (RE capacity) as the row variable, and how it affects all other variable from C2 to C21. For example, increasing Renewable Energy capacity (C1) is perceived by industry experts to have a weak but positive effect on Impact on jobs (C5), International Community commitment (C9) and on CO_2 emissions (C10), whereas it is perceived to has a strong positive effect on sector energy generation capacity (C12), energy surplus (C13) and on Green H_2 production (C17). The latter, for instance, is plausible as RE is a key enabler of Green H_2 production as aforementioned (BCG; NBI, 2019). It should also be noted that a concept cannot influence itself, and hence the unidirectional causality matrix is a hollow matrix (its diagonal is filled with zeros).

A heat map is also included in the table to aid visually the identification of key causality relationships that should be part of the modeling and analysis process. This is an important consideration when modeling in Systems Dynamics. It is practically impossible to model an entire system due to time and resource constraints, and hence modelling and analysing a problem within a system (as opposed to modelling and analysing a system) is most efficient and linked to practical value derivation (Sterman, 2000). The following key applies to the heat map of Table [4]. Only three colors are used in the map, denoting the strength of the causality, and not necessarily the polarity of the causality.

Negatively Strong	Negatively Medium	Negatively Weak	None	Positively Weak	Positively Medium	Positively Strong
- - -	- -	-	0	+	++	+++
🟩	🟩	⬜	▨	⬜	🟩	🟩

Table 4: Unidirectional Causality Matrix and heat map of energy concepts

To From	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21
C1	0	0	0	0	+	0	0	0	+	+	0	+++	+++	++	+	++	+++	+	0	0	++
C2	0	0	+++	+++	+++	0	0	0	+	- -	0	+++	++	- -	- - -	-	0	+	0	0	- - -
C3	0	0	0	++	++	+++	+++	+++	- -	- - -	0	0	0	0	0	+	0	- - -	0	0	- - -
C4	0	0	0	0	+++	0	0	0	0	0	0	0	0	0	0	0	0	0	+++	0	0
C5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	+++	0	0
C6	++	0	+	0	0	0	0	0	0	0	++	0	-	0	++	+	0	0	+	0	0
C7	0	0	0	0	0	++	0	0	0	0	0	0	0	0	0	0	++	0	0	0	0
C8	0	0	+++	++	++	+++	+++	0	0	0	0	0	0	0	- -	+	0	+	0	0	0
C9	0	0	- - -	- -	- -	0	- -	- - -	0	0	0	0	0	0	+++	++	++	0	+	0	- - -
C10	0	0	- -	-	-	0	0	-	+++	0	0	0	0	0	++	0	0	0	0	0	- - -
C11	0	0	++	0	0	0	0	0	0	0	0	0	- - -	0	0	0	0	0	- -	0	0
C12	0	0	+++	0	0	0	0	0	0	0	0	0	++	0	0	0	0	0	0	0	0
C13	0	0	- -	0	0	++	++	0	0	0	- -	0	0	0	- -	0	+++	0	+	0	0
C14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	++	0	0	0	++	0	0
C15	+++	++	0	0	++	++	0	0	0	0	0	++	0	+++	0	+++	+++	++	++	0	0
C16	++	0	0	0	0	0	0	0	++	0	0	0	0	+++	++	0	+++	0	0	0	++
C17	0	0	0	0	+++	+++	+++	0	++	0	++	0	- -	0	+++	+++	0	+++	+	0	0
C18	0	0	0	0	+++	0	0	0	0	0	0	0	0	0	0	0	0	0	+++	0	0
C19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	+++	0	0	0	0	0	0
C20	0	- - -	- - -	- - -	- - -	0	0	0	0	0	0	- - -	- -	0	+++	++	0	0	- -	0	+++
C21	0	0	0	0	0	- -	- -	- -	- - -	0	0	0	0	0	0	0	0	0	0	0	0

The matrix above reveals a great wealth of information on the mental models of industry experts. Firstly, it shows that over 70% of the matrix entries are in grey colour, signifying non-causality. This is important as it implies the need to only model and analyse less than 30% of the potential nodes in the form of causal relationship and is aligned with insight-driven problem analysis and solving techniques. Secondly, it also shows that concept C20, the coal fleet decommissioning structure laid out in the 2019 IRP proposal, is not affected by any of the other concepts, even though it strongly affects many other concepts. This means that this concept should be modelled as an exogenous input to the system.

The heat map also shows important concepts that are key to solving the challenges of energy transition. For example, C17 (Green Hydrogen production) is perceived to strongly affect the following notable factors and concepts:

- C5 (Impact on sector jobs), C6 (GDP), C7 (Exports): Scaled production of Green H_2 is perceived to result in increased productivity nationally, with competitive advantages that will place South Africa as one of the leading manufacturers of Green H_2 as noted in preceding sections. This is expected to directly result in the creation of thousands of jobs, and increase in GDP, *ceteris paribus*. The potential comparative advantages that South Africa has, are expected to result in significant net exports of Green H_2.
- C15 (Energy Investment): Proven comparative and competitive advantages in the manufacturing of Green H_2 is expected to attract investment both in the Green H_2 sub-sector and in Renewable energy sub-sectors which are a significant enabler of Green H_2 production in South Africa (BCG; NBI, 2019).
- C16 (Technology Development): Increased investment in the energy sector is perceived to directly increase technology development and speed up technology learning cycles and adoption rates.

Other concepts that are notably important in the heat map are C2, C3, C8, C15, C18, C20, etc.

For example, an assessment of C15 (investment into the energy sector) shows how important this factor is with respect to the stated problem and challenges. Firstly, by assessing the factors that energy investment affects, the matrix shows, as expected, a strong effect on RE capacity (C1), Technology development (C16), and Green

Hydrogen production (C17). Energy Investment (C15) is, on the other hand, strongly affected by Coal fleet capacity (C2), International Community Commitment (C9), Green H_2 production (C17), Political Stability (C19) and Coal Decommissioning structure (C20).

On another example, the decommissioning structure of coal fleets laid out by the IRP has strong effect on the energy sector's coal fleet energy capacity (C2), significantly decreasing the demand for coal (C3) and negatively impacting jobs directly linked to coal mining in South Africa's energy sector (C4). For example, as has been noted, over 65% of coal fleets (by energy generation capacity) would have been decommissioned in the year 2045 (Integrated Resource Plan, 2019). With energy generation through ESKOM demanding approximately 50% of mined coal in the sector, and 30% of total mined thermal coal demand allocated to exports (which are expected to be phased out by the year 2050 (Monteith, 2019), what are the impacts to coal mining jobs? Indeed, the heat map starts making clear the important factors that must be considered.

The examples of emerging insights and mental models presented above are intentional in demonstrating the emerging complexity and need for computational analysis as opposed to static models. The complexity increases further as one cycles through the effects and system behaviour over time as feedback and loops of feedback from many concepts and factors to many other factors are considered. There is need therefore to take the derived mental models and leverage computational analysis for richer and actionable insights over time.

Before modelling the problem in a dynamic environment to understand more clearly the threats and opportunities embedded in the complexities of the energy system, it is important to formulate a dynamic hypothesis.

4.3 Dynamic Hypothesis Formulation

A dynamic hypothesis is a working theory that seeks to uncover the key dynamics within a system that are causing rise to a problem or challenge identified in the problem statement. It follows initial interactions with industry experts as a starting point for the study. This hypothesis-driven approach is important as it efficiently directs efforts to the most probable dynamics giving rise to the challenges. It can however be quickly proven or disproved and give rise to better and insight-led dynamic hypotheses. Please note that this hypothesis does not need to be proven/ disproved using statistical methods but offers guidance for efficient research given a practical high number of variables and relationships that can be researched.

The text in the preceding subsections has revealed a great wealth of information based on secondary data and industry experts' perceptions of the current and potential challenges. It has given initial insights on potential key relationships of concepts within the energy sector that pose a threat to the transition and decarbonization of the sector and has also revealed worthy and significant opportunities to leapfrog some of the threats and create net value in view of economic efficiency and social equity.

4.3.1 Dynamic Hypothesis

The following antecedents place South Africa in a position to decarbonize into more sustainable and greener energy value chains.

- The environmental damage caused by carbon dioxide emissions after the first industrial revolution and the projected further damage in the event of failure to decarbonize.
- The associated commitment by the international community to decarbonize as signified by the Paris Agreement on Climate Change and United Nations Framework Convention on Climate Change (UNFCCC).
- The commitment of South Africa as a signatory of both the Paris Agreement on Climate Change and UNFCC.
- The degradation and planned decommissioning of South African coal fleets.

As a result, the following hypotheses will be the focus of the rest of the analysis.

> H01: A failure to transition and decarbonize the sector has significant negative impact on the economy of South Africa and would likely lead to social unrest and political instability.

H02: A timely and planned decarbonization of the sector minimizes the negative impact to the nation. This, however, may not be enough to eliminate key challenges.

H03: Intentional and timely combination of decarbonization efforts with leveraging emerging economic and social opportunities will be needed to leapfrog the challenges that are inherent in South Africa’s energy transition case. It must be said that energy policy intervention will play a significant role in realizing these wins in the energy sector.

H04: Time delays in the execution of necessary actions might cause disastrous socio-economic problems, and hence collaboration of efforts in all domains of the sector will become important to ensure alignment of efforts and aversion of anticipated socio-economic risks of transition.

4.4 Causal-Loop Diagram Representation

The unidirectional causality matrix above, which is a visual presentation of the mental models of industry experts, and the emerging dynamic hypotheses that have been developed from the important factors and relationships, makes it possible to represent the problem in the form of a causal-loop diagram. A causal – loop diagram is a translation of the modeling of the problem and the mental models in a form that visually shows the different factors, and how they affect and are affected by other factors and concepts in the energy system. Furthermore, the causal – loop diagram tries to represent the direct causality and is a step towards quantitative and qualitative modeling of the problem for dynamic analysis.

A causal – loop diagram for the mental models developed above is depicted in Figure (9) below. The causal-loop diagram adds other important factors that are implied but not directly represented in the mental models above. For example, energy generation capacity will be determined by generation capacity of coal fleets, nuclear power stations, Renewable energy power plants, and natural gas power plants. The associated energy mix will also determine the average cost of power production. The causal loop, as stated above, represents direct causality, and hence secondary causality has been represented as such. For example, according to the causality matrix, Carbon dioxide emissions affect investment into the energy sector. In the causal-loop diagram, the effect of Carbon dioxide on investment is modeled through its effects on carbon tariffs and international community commitment to decarbonization efforts, which then directly impact investment into the sector.

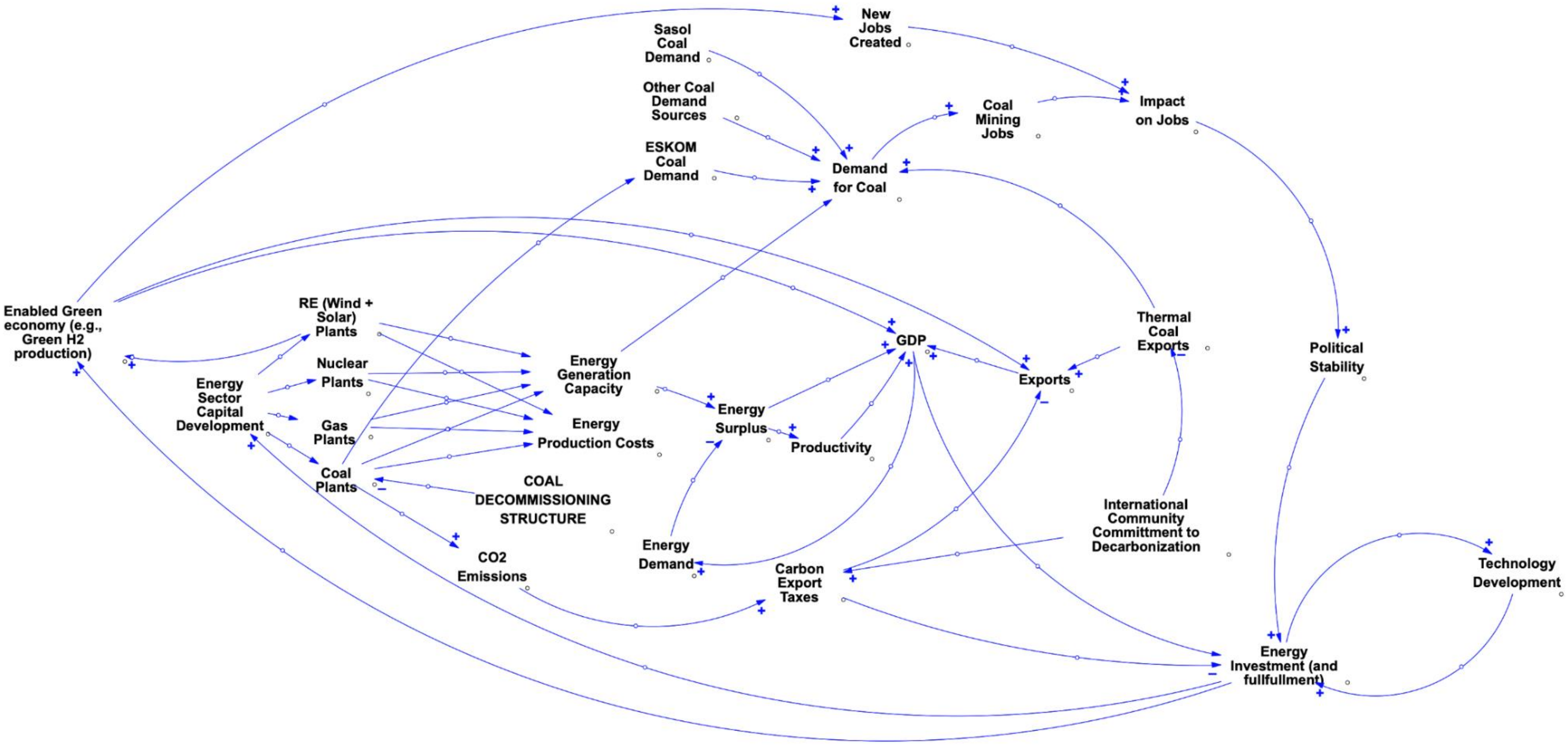


Figure 9: Emerging high-level causal loop diagram

4.5 Dynamic Simulation

This section translates the causal-loop diagram into a dynamic model that will form the basis of our analysis. The energy system concepts that are discussed above are represented as both stocks and flows and makes it possible to measure the associated values at specific times and scenarios. The model is developed in three steps:

i. An initial quantitative model developed from secondary data, to dynamically simulate the quantitative concepts that can be easily expressed and measured in physical units. These concepts and factors are a subset of the factors that the industry experts highlighted to be crucial for the energy sector transition, and such as can be expressed quantitatively from secondary data sources. The concepts include energy generation capacity (C12), Energy Surplus (C13), and CO_2 emissions (C10). Systems Dynamics modelling is used for this step.
ii. A dynamic and fully qualitative model expressing factors that cannot be directly measured in physical units and/or whose practically accurate measurement would require resources and data that are otherwise not accessible at the time of this writing. These concepts are also a subset of the of the factors that the industry experts highlighted to be crucial for the energy sector transition. These include political stability (C19), international community commitment (C9), and carbon export tariffs (C21). Fuzzy Cognitive Mapping is used for this step.
iii. An integrated model that combines the two analysis approaches and two methodologies, resulting in a hybrid qualitative - quantitative Systems Dynamics - Fuzzy Cognitive Mapping model. This is important for deriving 2nd and 3rd order insights that would otherwise be impossible to obtain from the individual models.

4.5.1 Stock and Flow Diagrams – Quantitative Concepts

Energy generation capacity is a key fundamental concept, and the Systems Dynamics quantitative model will be built from that starting point. The model utilizes data publicly available, and for reasons associated with data availability, the model will use the year

2019 as a starting point. Coal energy generation is a key driver of the South African energy system, and we will start with this subsystem.

4.5.1.1 Coal Capacity Decommissioning

Over 259 Megatonnes (Mt) of coal were produced in 2019, with 30% exported[1] and 70% used locally (BCG; NBI, 2019). 67% of the local coal usage goes to Eskom's needs for power production, while Sasol uses 21% for coal gasification and energy generation, and the remaining 12% is used for other industrial and household purposes within the country. The following figure depicts the usage of coal that is produced in South Africa.

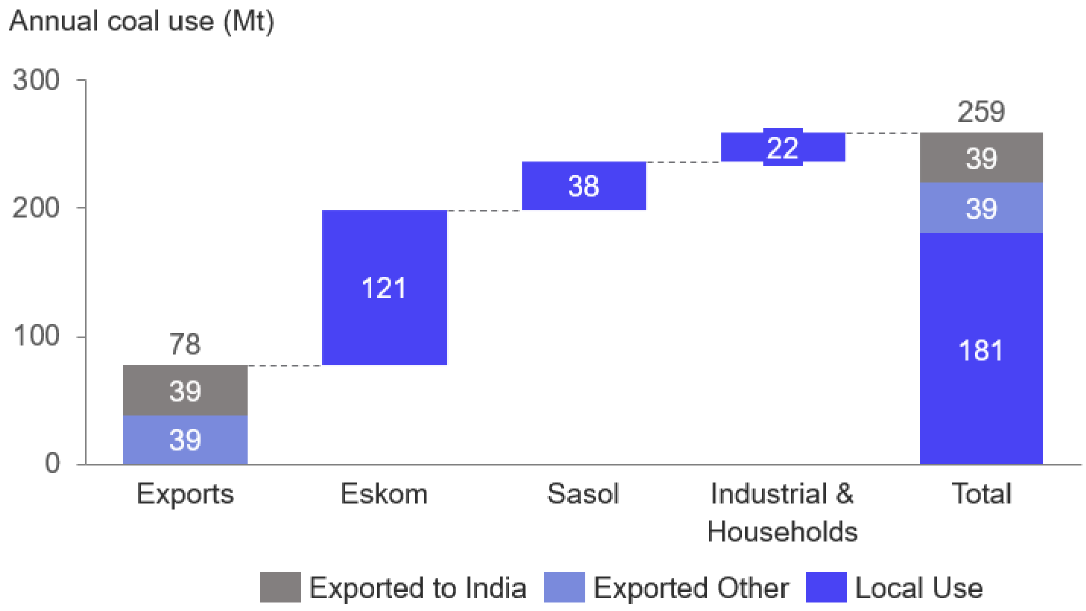


Figure 10: Coal use in South Africa in 2019

To model the coal demand at any given time from 2019, we add the sum of all anticipated changes in demand to that date to the initial state of coal demand, given in Figure (10) above. This is represented as an equation below:

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[1] Indian exports account for close to 50% of total coal thermal exports.

$$Demand_{coal} = \sum_{2019} Coal\ uses + \sum_{2019}^{Year\ n} \sum_{i=1}^{j} \Delta\ coal\ use_i \tag{1}$$

The second part of the equation represents a time-dependent change to a systemic parameter. It can be represented as a flow in the stock and flow diagrams of the Systems Dynamics model. The actual demand is represented as a stock and is a directly measurable variable in the system. An example snippet of the model representing this setup for the Sasol coal usage component is depicted below.

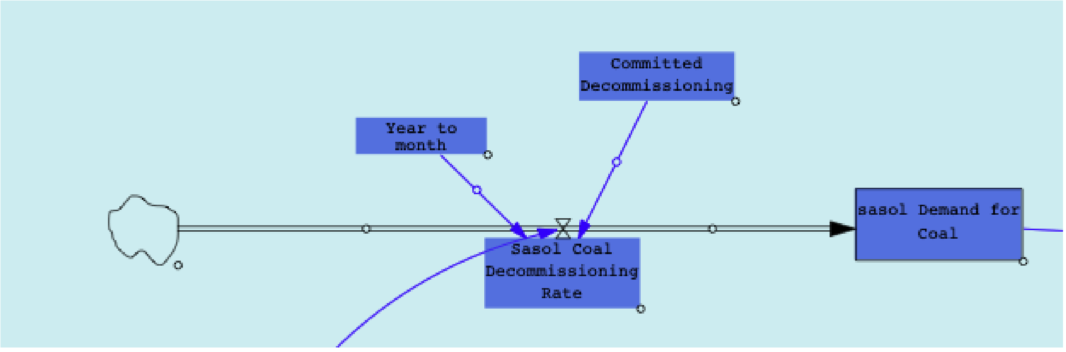

Figure 11: Snippet of stock and flow diagram for Sasol coal usage

It is therefore paramount to assess the projected changes to coal demand for the different coal uses described above. This will be obtained from the policy commitments of the key players driving the usage and demand for coal: Eskom, Sasol, international community, and national energy policies.

4.5.1.1.1 Eskom – Coal decommissioning structure

The Department of Mineral Resources and Energy's Integrated Resource Plan of 2019 details the coal fleet decommissioning plan (Integrated Resource Plan, 2019). The plan is driven by mechanical and operational constraints on the power plants reaching end-of-life operational limits (plant design life: Eskom coal plants were designed with a 50-year life) and the alignment of South African energy policies to transition by 2050. As a result, all coal power plants (including non-Eskom plants) will be decommissioned by 2050. The decommissioning structure proposed in the IRP is depicted in the figure below.

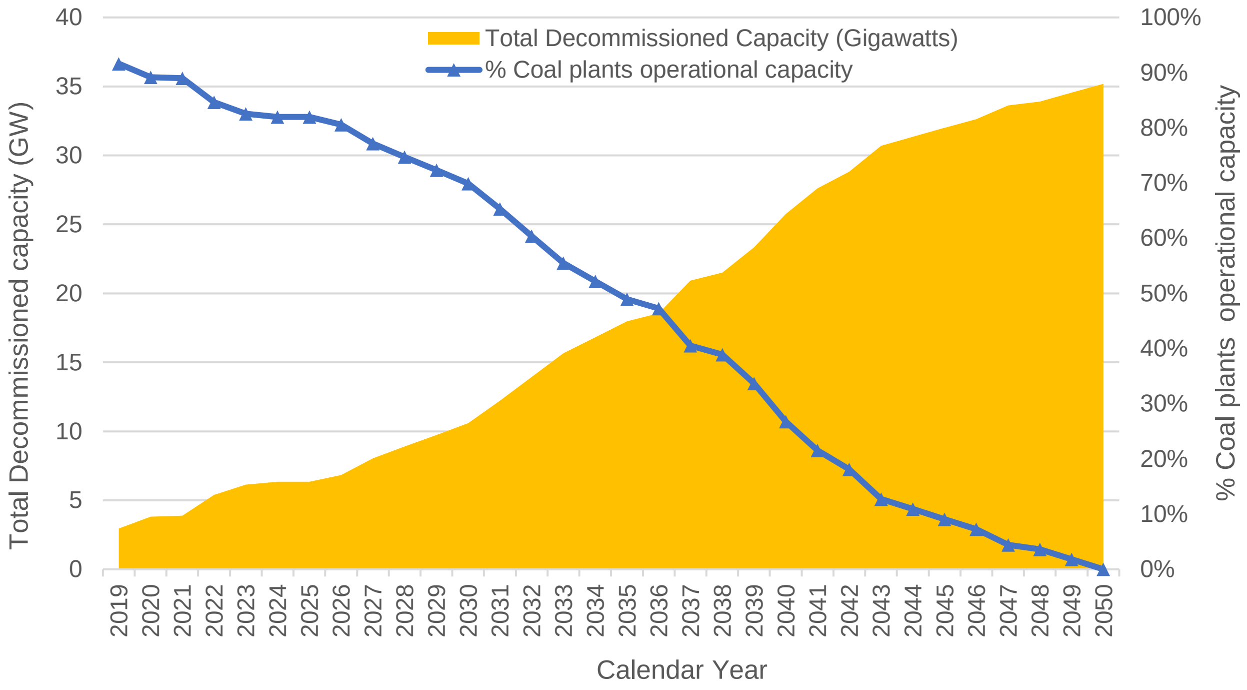

Figure 12: Coal decommissioning structure, Adapted from *(Integrated Resource Plan, 2019)*

The decommissioning structure is incorporated into the dynamic component of equation (1) above and represents the projected change in coal demand for Eskom's energy generation needs. The orange color area represents the total decommissioned capacity, and is represented by the equation below.

$$\Delta\, Demand_{coal,Eskom} = -\sum_{2019}^{2050}\sum \Delta\, coal\ use_{Eskom} \qquad (2)$$

The implied percentage of coal power plant capacity operational at a point in time (with respect to 2019 capacity) depicted on the blue line graph above reveals a principal insight: the steep decline in energy generation capacity (to 0 GW in 2050) implies the need to replace the generation capacity at a rate that is at least the same as the decommissioning structure. Economic growth and change in structure of the South African industry implies a higher rate of needed capacity build, and this will be part of the model being developed.

4.5.1.1.2 Sasol - Coal decommissioning structure

Sasol Limited unveiled its ambitious decarbonization roadmap at the November 2021 Annual General Meeting, articulating a steadfast goal of achieving net-zero emissions by 2050 (Sasol, 2022). Seeking shareholder endorsement, Sasol's roadmap outlined key targets, including a 30% reduction in scope 1 and 2 emissions by 2030 (Sasol, 2022). However, despite the approval from shareholders, concerns persist regarding the roadmap's lack of specificity and accountability measures (Sasol, 2022).

The company's 2030 targets involve integrating 600 MW of renewable energy by 2025, accompanied by emission reductions across its energy and chemicals businesses. Notably, Sasol acknowledges the challenges it faces, such as operational constraints and external disruptions affecting energy efficiency (Monteith, 2019). Moreover, the roadmap lacks interim milestones before 2026, raising questions about the feasibility of achieving the stated goals in the short term (Sasol, 2022).

Looking toward 2050, Sasol envisions net-zero emissions for scope 1 and 2 from its energy and chemicals businesses. This long-term commitment includes the neutralization of residual emissions using Carbon Dioxide Removals (CDR). However, skepticism arises from the company's acknowledgment that these reductions will occur in a step-wise fashion, dependent on factors like green hydrogen viability and gas availability (Sasol, 2022). The absence of specific interim milestones before 2026 and concerns raised by external critiques highlight the need for greater transparency and clarity in Sasol's decarbonization strategy (Monteith, 2019).

The above is sufficient to make the following justified assumptions on the expected coal decommissioning structure by Sasol:

a) 30% reduction in coal usage by 2030. The primary assumption is that of 30% reduction in scope 1 and scope 2 emissions, and that there is a direct proportional relationship between CO_2 emissions and coal usage.
b) 100% reduction in coal usage by 2050. The primary assumption is that of net-zero emissions by 2050. Even though net-zero will be achieved by both a

reduction in coal usage and deployment of CCUS[2], it is not clear in the commitments how much CO_2 emissions will be removed using CCUS and for purposes of this analysis, we will assume elimination of coal usage by 2050.

Based on the above assumptions, the following graph shows the emerging change in coal use by Sasol leading to the year 2050.

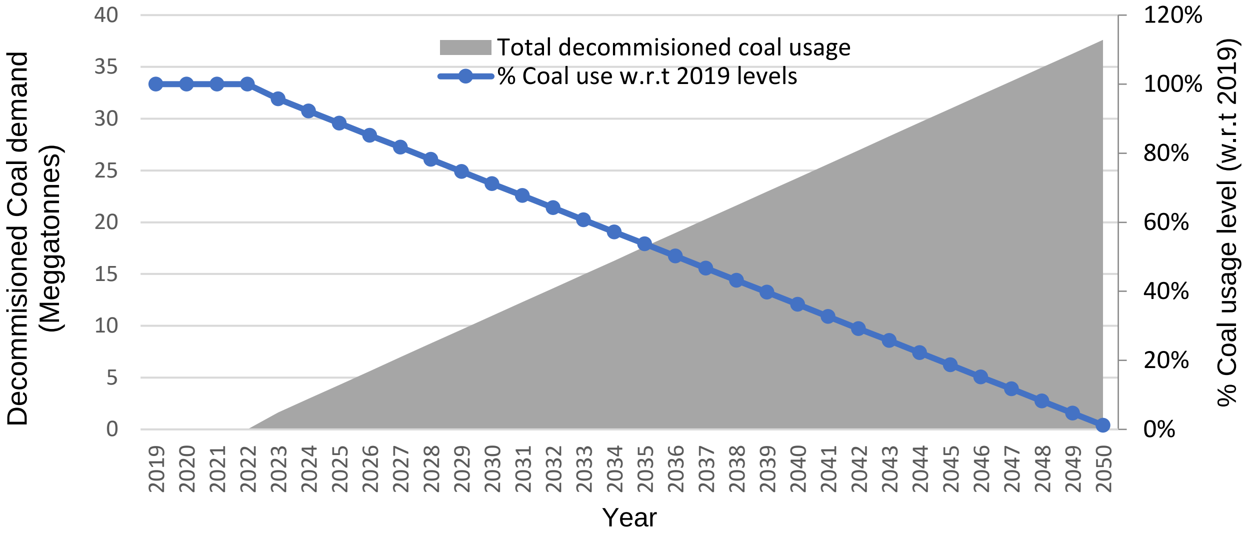

Figure 13: Sasol coal decommissioning plan

<u>Units for decommissioning structure:</u>

It is important to note that the decommissioning structure for Eskom coal usage was represented in power generation capacity of coal power plants (gigawatts), whereas that of Sasol is given in coal usage measured in Megatonnes of coal. This is primarily due to secondary data availability, and for consistency and comparative analysis, we will use coal usage measured in Megatonnes (Mt). To therefore convert the coal decommissioning structure of Eskom into coal demanded, we will use the energy density of coal (measure in Watt hours of energy per kilogram of coal), and the various efficiencies along the energy production chain at the coal power plants. This approach will also require an accurate measurement of the availability factor of all the coal power

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[2] Carbon capture, utilisation and storage.

plants operated by Eskom and is beyond the scope of this report. A practical and easier approach that proves highly accurate uses the following approach, and is based on 2019 value:

- Eskom coal usage in 2019 was 67% of local coal usage. Local usage was 70% of total coal production on 2019. Total coal production in 2019 was 259 Megatonnes (Mt). This results in ~ 121.5 Mt of coal usage by Eskom power plants in 2019.
- Total coal power plants energy generation capacity in 2019 was 36.42GW (BCG; NBI, 2019)
- Based on this, 1 GW of coal energy generation capacity requires 3,34 Mt (i.e., 121.5Mt / 36.42GW) of coal annually, assuming similarity in efficiencies of South African power plants and energy density of low-grade coal that is used by Eskom power plants. Hinrichs and Kleinbach, in their book, give an estimate of 9 tons of coal consumed per day per Gigawatt of capacity for coal plants, which equates to 3.28 Mt per year (Hinrichs & Kleinbach, 2006). This makes our estimate less than 2% away from theirs. This variation can be due to several factors such as the quality of coal used (which determines the energy density of the coal) and the efficiency of the powerplants. Nevertheless, the first order accuracy of >98% is sufficient for us to adopt the conversion methodology.

4.5.1.1.3 Coal Exports

South Africa’s coal exports accounted for ~30% of coal production in 2019, equivalent to just under 80 Megatonnes of coal, mainly to India, Pakistan, China, South Korea, and Sri Lanka (BCG; NBI, 2019). This contributed over US$ 6 Billion to South Africa’s GPD, equivalent to ~1.6% of the nation’s GDP (Stats SA, 2019).

Turbulence in the global coal market driven by geopolitical instabilities has resulted in changes in coal demand from South Africa in the last 2 years (Argus, 2023). The following factors have perturbed this change in coal demand (Argus, 2023):

- Imposed bun from African countries to deliver to Russia because of the Russia-Ukraine war.
- A decrease in the price of coal from Russia, which resulted in increased exports of coal from Russia to India and South Korea, which are South Africa’s biggest importers of coal.

- A recalibration of global coal prices and a convergence of Russian coal prices, which is resulting in a stabilisation of coal export volumes from India and South Korea.

Considering the above, it is conclusive that the shifts in demand as driven by geopolitical events at a global level are transient and will stabilise to pre-war levels, *ceteris paribus*. A key implication of the above is that the main driving factor for the expected change in the demand for South African thermal coal, in the long run, is the coal decommissioning structure of the leading importers of South African coal and their commitment to decarbonization.

Major export destinations like India have strategic plans to reduce reliance on coal imports. In 2018, India accounted for 48% of South Africa’s thermal coal exports (Nicholas, 2019). The dynamics and transition in India’s coal usage is therefore important to the South African coal industry and is a proxy to the commitment of the international community to decarbonisation. As part of India’s commitments to decarbonisation goals, 50% of energy generation will be generated from non-fossil related sources by 2030, and there are prospects of achieving net-zero emissions by 2070 (Das, et al., 2022). India already has over 100GW of renewable energy generation capacity, placing it in the top 5 nations globally in renewable energy capacity (Vats & Mathur, 2022). Forecasts indicate that wind and solar will become cheaper than existing coal or gas-fired plants by 2030, potentially rendering coal-fired power generation obsolete by 2050 (Vats & Mathur, 2022). Consequently, major global mining entities and financial institutions are rapidly withdrawing from the thermal coal market, exacerbating the industry's challenges (Nicholas, 2019).

Other key importers of South Africa’s thermal coal, such as Pakistan and South Korea, are also witnessing shifts away from coal-based power generation, signaling limited growth potential for coal exports (Nicholas, 2019). Similarly, European nations forecast a substantial decrease in demand for thermal coal, creating a challenging landscape for traditional coal exporters (Nicholas, 2019). Furthermore, heightened competition from other major coal-exporting countries like Indonesia, Australia, and Russia compounds the predicament, limiting alternative market opportunities for South African coal exporters (Nicholas, 2019).

The above synapsis is sufficient to conclude that exports of thermal coal from South Africa will decrease to near-zero by 2050, and the rate of this decrease has already been set in motion as witnessed by the already established actions towards decarbonisation of the main thermal coal importers. Although India has provisional targets of achieving net-zero by 2070, the following factors are sufficient to assume near zero thermal coal exports from South Africa by 2050 latest:

i. Between 2008 and 2019, South Africa's contribution to India's thermal coal imports accounted for between 10% and 20%, while Indonesia accounted for ~ 70%, and other exporters such as USA and Australia accounted for between 10 and 20% (Nicholas, 2019). As India's coal imports exponentially decrease, India is likely to have most of its coal needs met by Indonesia way before 2070.
ii. India's 2070 net zero decarbonisation targets include the decarbonisation of both the power sector and other industries (such as manufacturing), and India is likely to decarbonise from coal much earlier than 2050 (Vats & Mathur, 2022).

Even though we took a deep dive into India's proposed strategy, we will assume the other key importers of South Africa's thermal coal will also have similar trends, which is expected based on the congruency of decarbonisation strategies of the signatories of the Paris agreements. We will therefore assume that exports of thermal coal from South Africa will decrease to zero by 2050, and for simplicity, this decrease will be a continual steady slope. The following decrease in thermal coal exports from South Africa emerges.

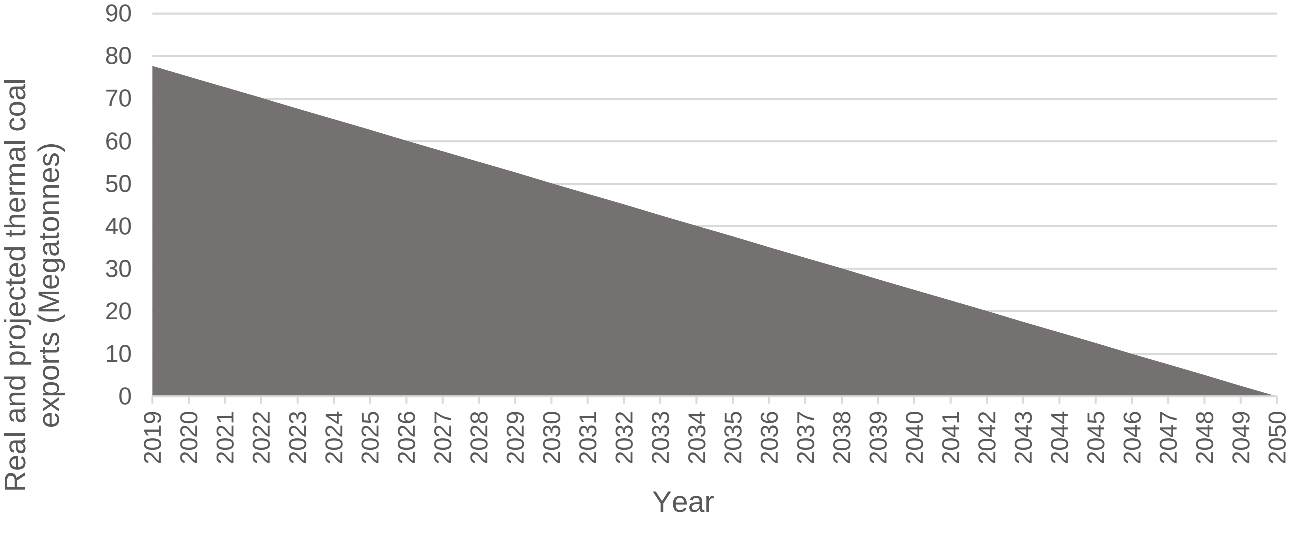


Figure 14: Projected South African thermal coal exports

4.5.1.1.4 Industrial and Household use

As aforementioned, about 8% of South Africa's produced coal is used locally for other industrial purposes (other than by Eskom and Sasol) mainly as a source of, and by poor households as a source of heat for both cooking and warming their houses. The use of coal by households and for other industrial applications is mainly driven by affordability, and this convenience is obtained from the relatively high energy attainment per unit cost, compared to other sources of fuel (Balmer, 2007).

As South Africa deploys renewables at scale, it is expected that the cost of electricity per Kilowatt-Hour will drop as the cost of technology attainment drops, and cost justification is attained such that affordability increases (BCG; NBI, 2019). Furthermore, policy enforcement and decarbonisation by Sasol and Eskom is expected to result in accelerated decrease in coal use by households and other industrial users. As a result, we will also assume a simplified scenario in the dynamic model where coal use by other industrial applications and households will reduce to zero by 2050. The impact of this assumption on accuracy is low given the relatively low contribution to South Africa's coal use. The following projected coal use emerges.

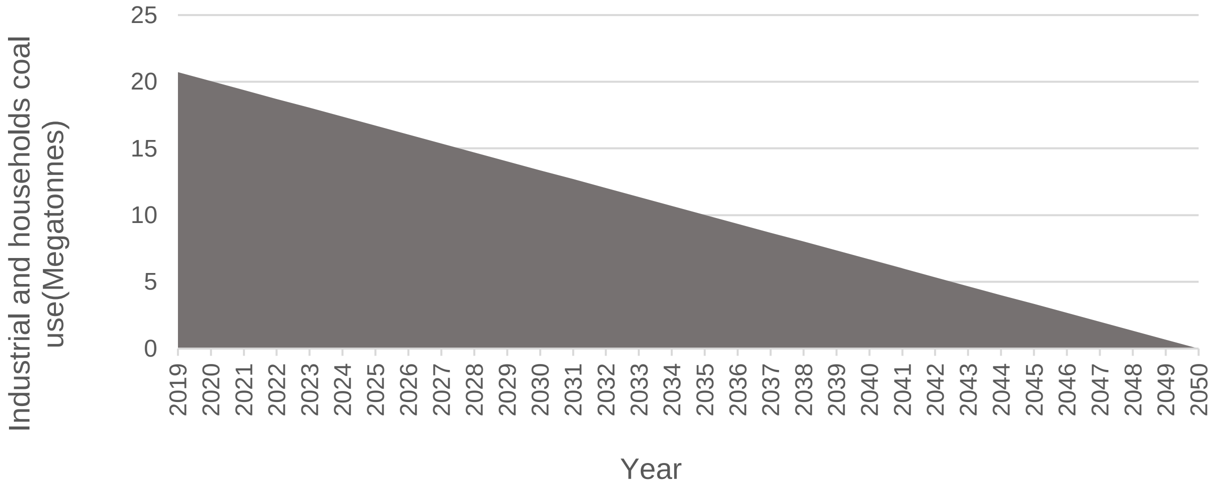


Figure 15: Projected coal use by households and other industrial applications

4.5.1.2 Implications of the coal decommissioning and projected demand

The preceding sections assessed the use of coal produced in South Africa and is a key starting point for the dynamic analysis and modelling for the South Africa energy system. It is necessary at this point of the writing to look at the already emerging insights and implications from the committed and projected use of coal until the year 2050.

It is clear that there is an expected sharp decrease in coal demand for thermal coal production in South Africa, with a near-zero demand projected for the year 2050. A primary implication of this is that coal mining jobs will also sharply decrease to near-zero by 2050. This is perhaps one of the most crucial implications of decarbonisation. To quantify the job loses, and the associated profile (jobs lost for each respective year), we will use the following modeling assumptions and approach.

- As of 2019, South Africa's coal mining sector had ~94 000 direct jobs and produced 259 Megatonnes of coal (BCG; NBI, 2019). If we assume proportionality of production and number of direct jobs, this results in approximately 363 direct jobs per Megaton of coal produced. This direct proportionality assumption overlooks the fact that not all jobs are involved in the direct production of coal, either at the mines or directly involved with the product along the value chain. Some of the jobs are technical support functions while others are at various corporate centers away from mining sites. Using standard organizational structure benchmarks for mining organizations, we can assume that the proportionality of corporate jobs to support jobs to productions jobs is maintained to some degree (Yaschenko, Polyakov, & Sabitova, 2021). This justifies the 363 direct jobs per Megaton of coal estimate above, although deviations will be expected.
- The coal produced will be equal to the coal demanded on the long term. This means that the total coal production in South Africa over time will be the sum of the four components discussed in the preceding section, and expressed the equation below:
    - $Coal_{prod} = Coal_{demand} = \sum_{i=1}^{4} coal_{demand,i} \quad (3)$
        - Where $i =$ Eskom; Sasol; Exports; and Industrial & Household

This approach gives rise to the following variation in coal demand and direct coal mining jobs.

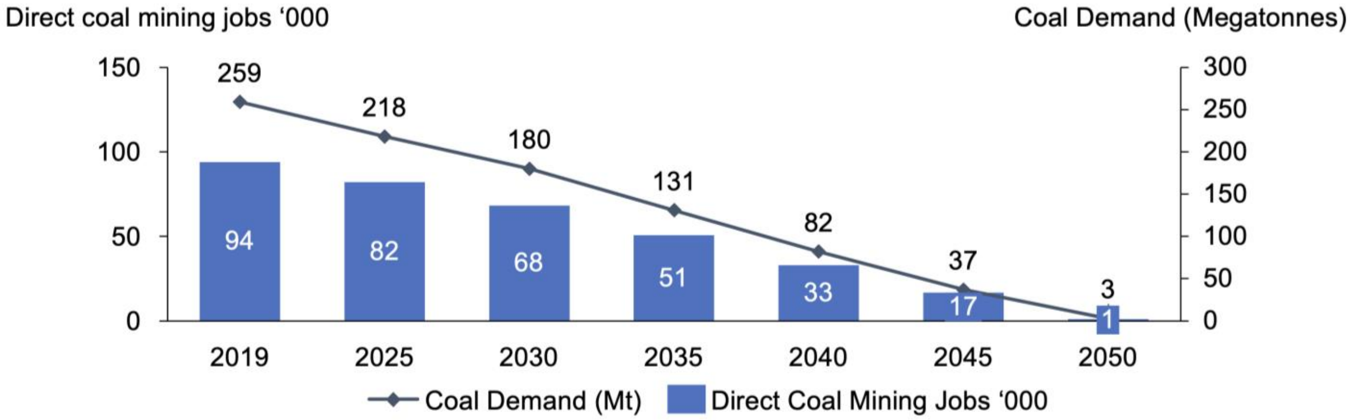


Figure 16: Projected decline in direct coal mining jobs

This dynamic model shows that both the demand for thermal coal and the direct coal mining jobs reduce by approximately 50% by the year 2035. Coincidentally, the Eskom’s coal decommissioning structure also shows that about 50% of coal energy generation capacity will have been decommissioned by the year 2035. The implications of the above insights are profound.

Firstly, approximately 45 000 direct coal mining jobs will be lost by 2035, which is just over a decade from date. There are prospects of creating more jobs through the building of new energy generation capacity in the form of renewable energy and is projected to have a positive net job creation by 2050 (BCG; NBI, 2019). This poses some challenges:

- Although there are prospects to create net positive jobs created through the transition from coal-based to renewable energy-based structure, there is a potential time delay that will see a net negative jobs for some years, depending on the policies that will be implemented.
- Based on the age of employees and level of work and skill, some employees cannot be easily upskilled and re-skilled to operational job requirements of renewable energy-based system.
- Communities and infrastructure have been built around coal mining areas in South Africa. A reskilling and upskilling of the mining workforce for renewable

energy jobs will also require relocating mining communities to areas with high potential for wind and solar resources and infrastructure. This spatial distribution consideration is worth further assessment:

- Coal mining activity is hugely concentrated around the north-eastern side of South Africa around the Mpumalanga area. This is shown in Figure (17) below.
- South Africa has dedicated Renewable Energy Development Zones (REDZ) with potential power generation capacity of over 900GW (for perspective, this is over 20 times more than Eskom's current coal energy generation capacity!). The proposed spatial distribution of these development zones is depicted in Figure (18) below.

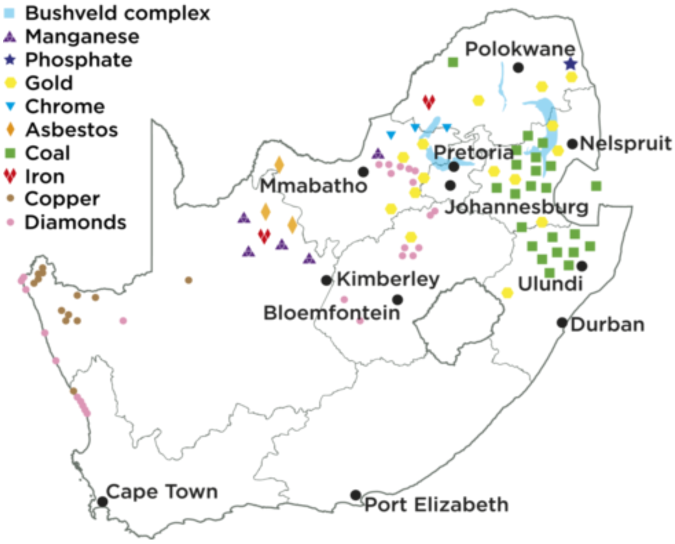


Figure 17: Key South African mining activity areas

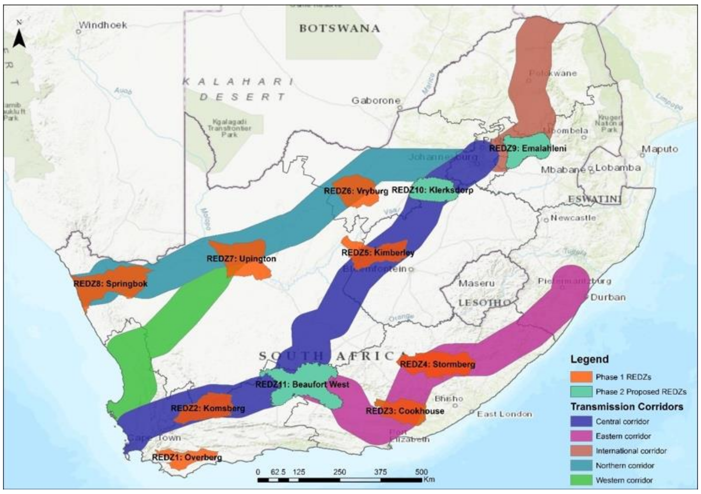


Figure 18: Renewable Energy Development Zones (REDZ)

  - From the above, all phase 1 REDZ are sufficiently far from the concentration of coal mining activity, and only REDZ9 (Emalahleni) proposed phase 2 proposes an opportunity that is close enough to coal mining activity. It is sufficient to conclude that they are challenges that need to be addressed even in a scenario where positive net jobs are created by the transition into renewables based on REDZ. For context, REDZ are proposed and chosen based on opportunity for operational and cost efficiencies such as proximity and availability of infrastructure, and solar insolation rates.
- The high potential loss of jobs and complexities around reskilling and upskilling prompt the need for early actions to be taken to mitigate the negative impact on socio-economic factors. Operational mining jobs in South Africa are highly involved with Labour Unions (Haroon, Karmen, & Derek, 2014). Job losses of tens of thousands are probable to result in social and political unrest if the transition is not approached systemically and systematically.

Secondly, the coal power generation capacity decrease is mainly driven by South Africa's commitment to decarbonisation, and the fact that Eskom's coal power plants are reaching mechanical design end of life. The latter becomes a constraint that imposes low variability in the expected decommissioning structure. The implication is that energy generation capacity will have to be replaced at a rate higher than coal decommissioning rate, given that energy demand in South Africa is expected to increase as the economy grows and the industry structure changes. Failure to build new capacity will be catastrophic from both an economic and socio-political front. In the next section, we will therefore look at the proposed capacity build towards the year 2050.

4.5.1.3 Energy Generation Capacity Building

The department of Mineral Resources and Energy has proposed a plan for building new energy generation capacity in the 2019 Integrated Resource Plan (Integrated Resource Plan, 2019). The plan takes into consideration the coal power plants decommissioning structure, the extension of Koeberg Nuclear power station beyond

2024, and proposes a time-based capacity build for an energy mix that includes Nuclear, Gas, Battery, Renewables (solar and wind), and green hydrogen. The proposed power generation capacity transition is depicted the figure below.

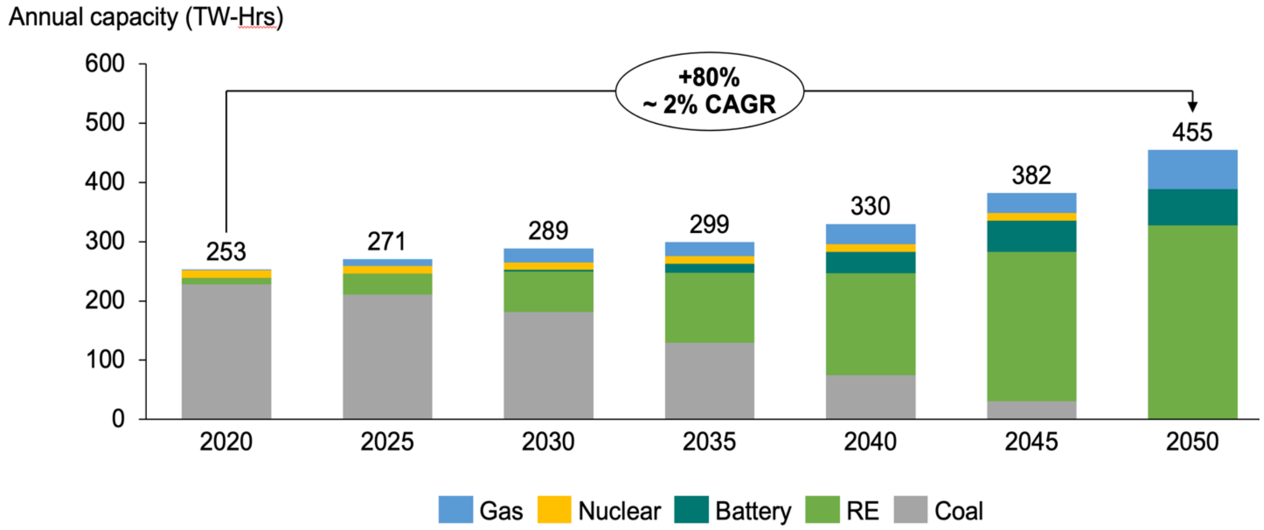
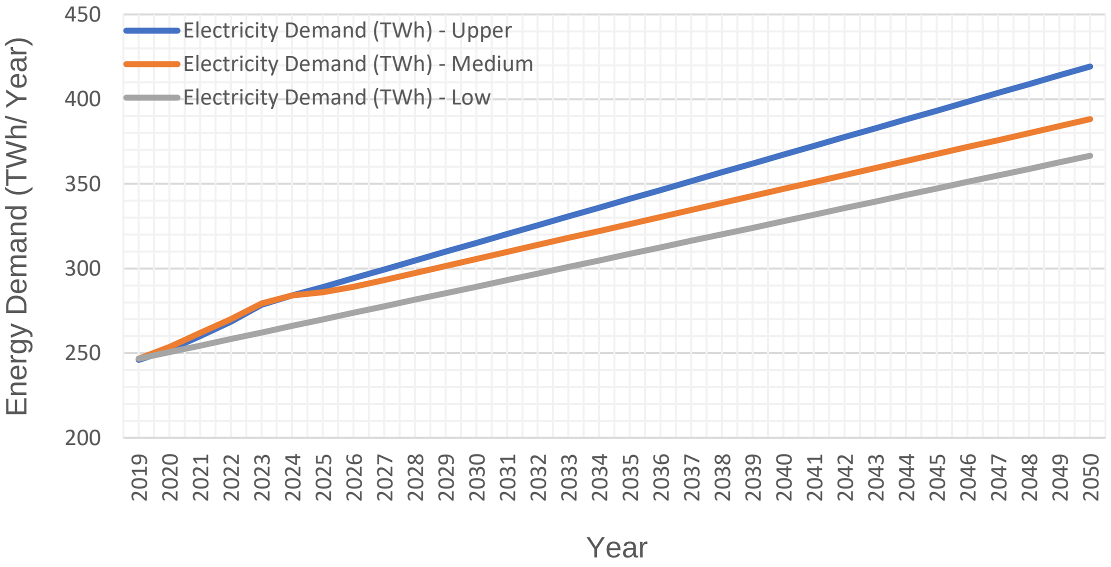


Figure 19: IRP Proposed energy mix transition towards 2050, adapted from developed simulation model and *(BCG; NBI, 2019)*

The above proposed capacity development reveals that the South African energy system needs not only replace the decommissioned coal capacity, but also increase the total energy generation capacity at 2% CAGR from 2020 to 2050, equivalent to a total capacity increase of 80% over the 3 decades. The plan also shows that Gas and Battery capacity will play an important role, mainly in stabilising supply consistency, and in peak periods. Nuclear capacity will be held at a constant of ~13TWh per year (equivalent to 1.86 GW power capacity) until Koeberg power plants are phased out in 2045. Coal power plants will be fully decommissioned by 2050, including the newly commissioned Kusile and Medupi units.

An important factor that was considered in the proposed capacity development is the projected annual energy demand up to the year 2050. This projected annual energy demand is driven by economic growth and change in industry structure as measured by energy intensity. Energy intensity is a measure of energy used by an economy to produce a unit of output and can be measured in TWh of energy per US$ of GDP. As the industry structure changes, it changes energy intensity, and thus, to project a demand in energy both the GDP growth and energy intensity change are needed. Generally, economies that are based on primary industries such as mining, metals processing and manufacturing, have a higher energy intensity than more developed and diversified economies (Sun, et al., 2021). Furthermore, as economies develop renewable energy capacity, the energy intensity is expected to decrease based on the associated change in the industry structure (Yu, Liu, Hu, & Tian, 2021). Yu *et al,* also show that for every increase of 10% in renewable energy development, energy intensity decreases by 0.3% (Yu, Liu, Hu, & Tian, 2021).

The IRP considers three GDP growth scenarios using the above approach, and from that derives associated energy demand projections till 2050 (Integrated Resource Plan, 2019). We use these projections in the Systems Dynamics model created. These projections are depicted graphically in the graph below.



Other factors that are considered in the dynamic Systems Dynamics model include Electricity Availability Factor (EAF), economic productivity as a function of power availability (surplus or deficit), creation of new jobs, loss of coal mining jobs, accumulation of CO2 emissions, etc., We will discuss more of these factors in later sections of this writing. The diagram below is a snippet of the Systems Dynamics quantitative model that has been developed from the approach hitherto.

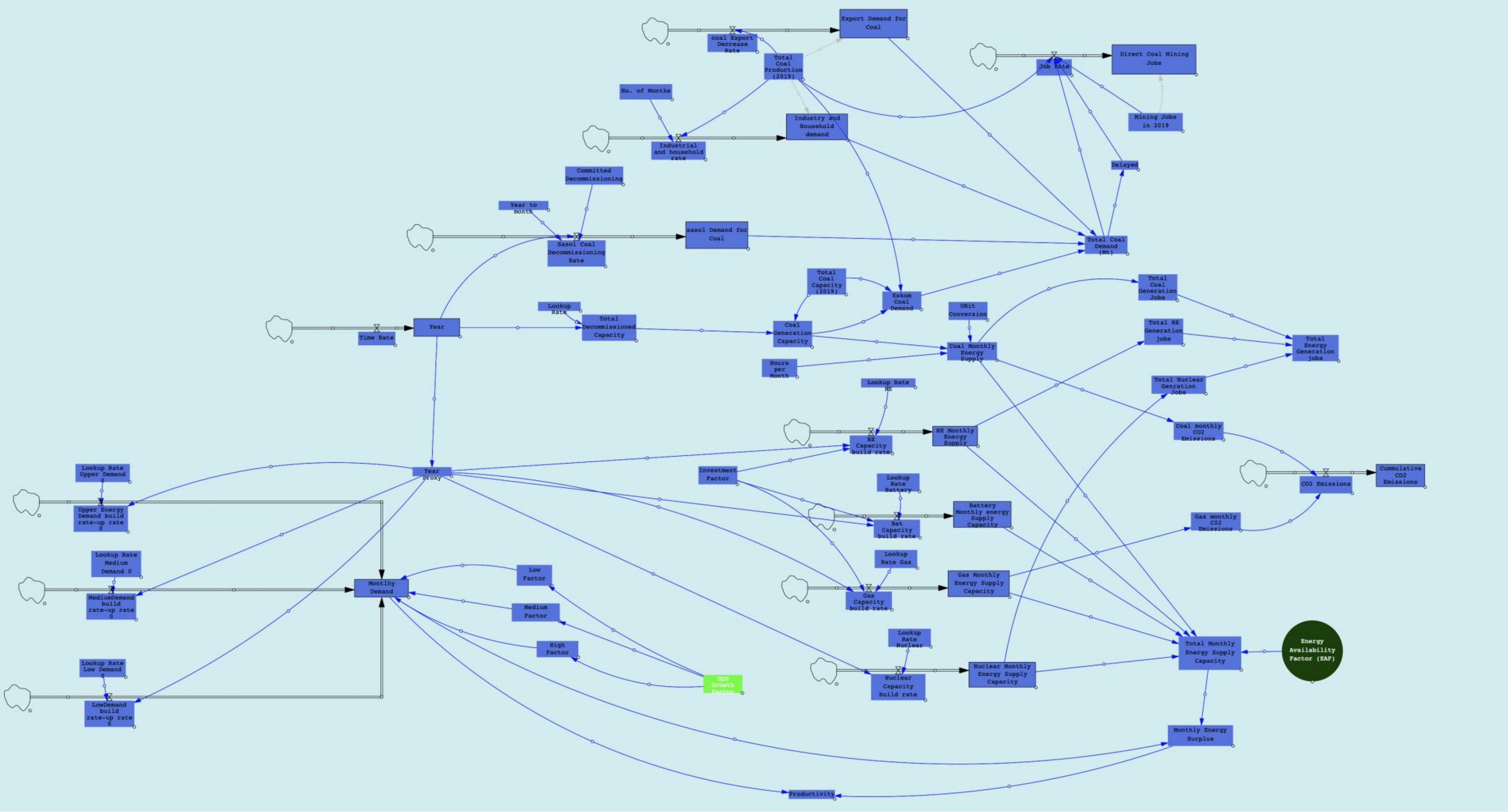


Figure 20: VenSim Systems Dynamics Model for Quantitative concepts

At this point of this writing, we have accessed concepts and factors that can be measured quantitatively, and for which there is commitments and/or policies put in place that make it possible to project dynamic variation of these concepts over time. A review of the key important concepts suggested by industry stakeholders in section 4.2.1 above shows that not all these factors can be directly expressed quantitatively. There are two important considerations the writer used in identifying such factors that cannot easily be expressed quantitatively.

i. Factors that cannot be measured or expressed in physical units. These include International Community Commitment (C9) and Political Stability (C9).
ii. Factors that can be expressed and measured in physical units such as Energy Investments (C15) and Carbon Export Tariffs (C21), but accurately quantifying them would require significantly more time and resources, and thus beyond the scope of this research.

For these concepts, we utilized Fuzzy Cognitive Mapping (FCM) and the perceptions of energy industry experts in South Africa. This is a highly iterative and rich process which involves soliciting expert's mental models, visualizing them, modelling outcomes, re-adjusting the mental models with the experts, and analysing counter-intuitive systemic behavior.

Just like Systems Dynamics modelling approach developed hitherto, FCMs also prove to be useful tools for understanding systemic behavior over time, with the advantage that FCMs can also model qualitative concepts and can easily be integrated with artificial intelligence for optimal modelling and analysis. In the next section, we will review the process that the writer took in understanding and modeling the rest of the important qualitative concepts in South African energy system using FCMs.

4.5.2 Qualitative Concepts using Fuzzy Cognitive Mapping

The concepts and factors that will be assessed using FCMs as discussed in the preceding section are the following:

1. Carbon export tariffs (CO2 taxes).
2. Effort in jobs transition: Includes the reskilling and upskilling effort of coal mining jobs.
3. Investment into the energy sector for capacity development
4. International community commitment to decarbonisation
5. GDP growth and energy demand
6. Political stability
7. Overall impact on jobs: This includes the effort into jobs reskilling and upskilling.

Furthermore, industry experts perceived the following factors to be highly coupled to at least one of the above factors. These are factors have either been modelled in the Systems Dynamics model or can be deduced from the model and are quantitative in nature (can be measured and expressed in physical units). These will also therefore be included in the FCM model:

8. Coal Mining jobs: This is perceived to directly affect overall impact on jobs and political stability.
9. Carbon dioxide emissions: This is perceived to be directly related to carbon export tariffs.
10. Energy generation jobs: This directly impact the net impact on jobs, as it replaces the jobs lost from coal mining.
11. Productivity: This is defined as the ratio of energy supply capacity to energy demanded and directly affects GDP growth.

The first important step in mapping how each of the above 11 factors affect and are affected by each of the other factors, is soliciting the perceptions of industry experts. Please note that this mapping process is a subset of heatmap that was initially developed with industry experts of Table 4 above. Here, we will present just the heatmap relating to the 11 concepts above, and that has been reconfirmed with 7 industry experts after discussions on initial insights emerging from the Systems Dynamics model above. For more details on the Python code used by the writer in converting the heatmap from qualitative perceptions on the relationships among concepts, the fuzzification and defuzzification procedure followed, and the optimisation of causality weights using Herbian Learning as a form of artificial intelligence, etc., please refer to Appendix 7.2.1, which is a detail on the core Python code developed by the writer. FCMPy, which is a Python based Fuzzy Cognitive Mapping library, is utilized for the analysis (Mkhitaryan, et al., 2022).

The following depicts the weight matrix that shows the impact that each of the 11 concepts has on the other concepts.

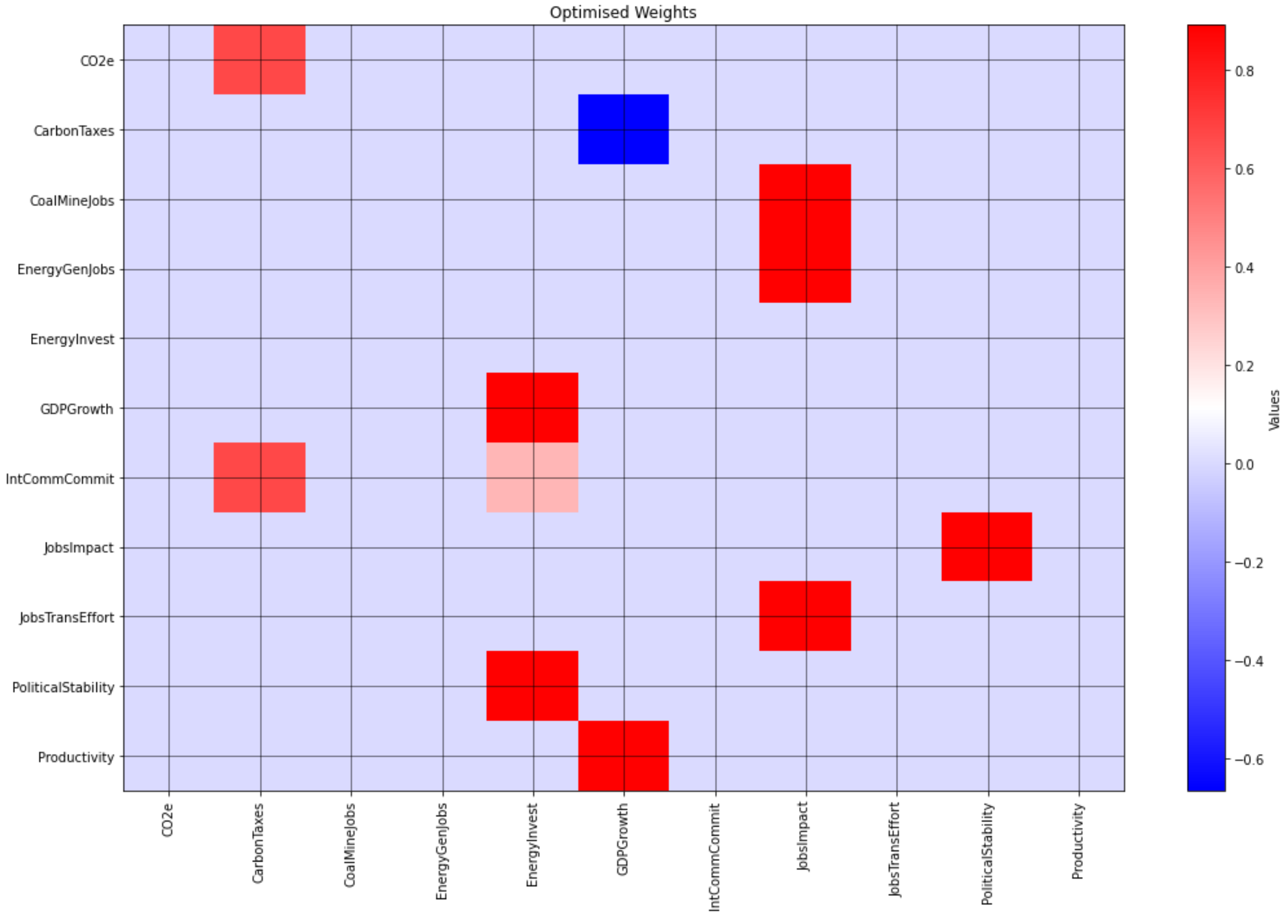


Figure 21: Causality matrix, showing causal weights among the concepts

It is important to discuss the structure of the matrix before discussing the initial perceptions of the industry experts (which in effect represents an aggregated mental model of industry experts). Firstly, all 11 concepts appear on both the x-and y-axis. The values on the map show the impact the concepts on the y-axis have on the concepts on the x-axis. For example, the blue square on the map shows that carbon export taxes (tariffs) have a strong negative impact on projected GDP growth. Secondly, only 9% of the map has non-zero values, and this is important as only important causal relationships are considered as this simplifies computational analysis cost and decreases complexity with minimal decrease in derived insights.

Despite the simplified heatmap, the model is still sufficiently complex. We will demonstrate this complexity through one scenario, while all other factors are held constant. Please refer to the heatmap above for the logic in the illustration.

> Illustrative scenario: All things constant, an increase in CO2 emissions from the map shows a high increase in Carbon taxes/ tariffs. An increase in tariffs results in a significant decrease in GDP growth from the map. A decrease in GDP growth from the map shows a decrease in investment into the energy sector. The loop keeps iterating until a decay or a convergence in causality is attained, and that is what FCM mapping does, but for many variables and scenarios. In the above example, a continued increase (or insufficient decrease) in CO2 emissions results in a decrease in external investment into the South African energy system. This can be due to a decrease in energy investor confidence in economies that do not show transformation over time.

To assess how the many concepts behave under different scenarios, we will use FCM mapping using Python. The code is detailed in Appendix 7.2.1.

It is important that we list the initial conditions of the mapping process. These give the starting point from which the model will then predict energy systemic behavior and most probable conceptual states. These initial conditions are given in the table below. It is important to note here that 0 refers to very low state whereas 1 refers to very high state for these concepts detailed below.

Table 5: Initial conditions for FCM mapping

Concept	**Initial value**	**Rationale**
- Carbon export tariffs	0	The European Union implemented the Carbon Boarder Adjustment Mechanism (CBAM), which imposes taxes on energy-intensive imports into Europe (Perdana & Vielle, 2022). The implementation is still at its early stages and hence starts at 0 as of the starting date of this simulation (2019).
- Effort in jobs transition	0.3	Minimal effort has been invested in defining actionable mechanisms reskilling and upskilling of coal mining jobs, however opportunities have been developed (Integrated Resource Plan, 2019).
- Investment in Energy	0.05	The proposed energy development structure requires a 2% CAGR in capacity till 2050. With respect to this target, South Africa has not marginally increased capacity and associated investment has been low. For example, BCG estimates that approximately 4GW of renewable energy capacity will need to be installed annually to reach targets by 2050, assuming constant capacity development, which is about 10 times more than the current renewable capacity development rate (BCG & NBI, 2019).
- International community commitment	1	At the time of this writing, 195 parties, comprising 194 states and the European Union, are signatories of the Paris Agreement, which is a legally binding international treaty on Climate Change (United Nations, 2023). This commitment has been reaffirmed by the signatories through UN Climate Change Conference in (COP21) through to COP28 in 2023, with more practical and measurable targets being introduced progressively. For example, the Oil and Gas Climate Initiative (OCGI) charter was introduced in COP28 for the oil and gas

		industry to move towards more ambitious decarbonisation goals, and over 50 of the top oil and gas corporations are signatories of the charter.
• GDP Growth	0.5	Medium GDP growth prospects projected. It is important to note that this is the GDP growth as affected by the energy system in South Africa, and hence decouples the projections from other macroeconomic factors that are beyond the scope of this writing. The 0.5 value is chosen as the energy sector poses both opportunities and threats, depending on the policies developed and efficiency of the implementation.
• Political Stability	1	A politically stable starting point is chosen.
• Overall impact on jobs	0.3	A low overall impact is chosen as a starting point. This factor is likely to be affected by other factors as is shown in the causality matrix of Figure (21) above.
• Coal mining jobs	1	Coal production in South Africa is arguable still high given that the key components driving demand (Eskom, Sasol, Exports, etc.,) have not implemented decarbonisation strategies.
• CO2 emissions	0.9	Carbon emissions are relatively still high.
• Energy generation jobs	0.5	Energy generation jobs from coal power plants are relatively high, while the energy generation jobs from renewables are very low given that investment into renewables is still low. Hence a medium value is chosen as starting point.
• Productivity	0.8	Poor performing coal power plants have resulted in Eskom overall Electricity Availability Factor of around 70%, which has had implications of load shedding being implemented to release strain from the grid (Integrated Resource Plan, 2019). We have thus used a starting point for productivity of 0.8 for the simulation.

These initial conditions, together with the causal matrix of Figure (20) are run using FcmSimulator of the FCMPy library in Python to attain converged values for the concepts that meet the convergence criteria and boundary conditions. This Python code for this is detailed in Appendix 7.2.1, and mathematical formulation of the simulation is detailed in Mkhitaryan, *et al* (2022).

The following graph depicts the converged values for the initial conditions detailed above.

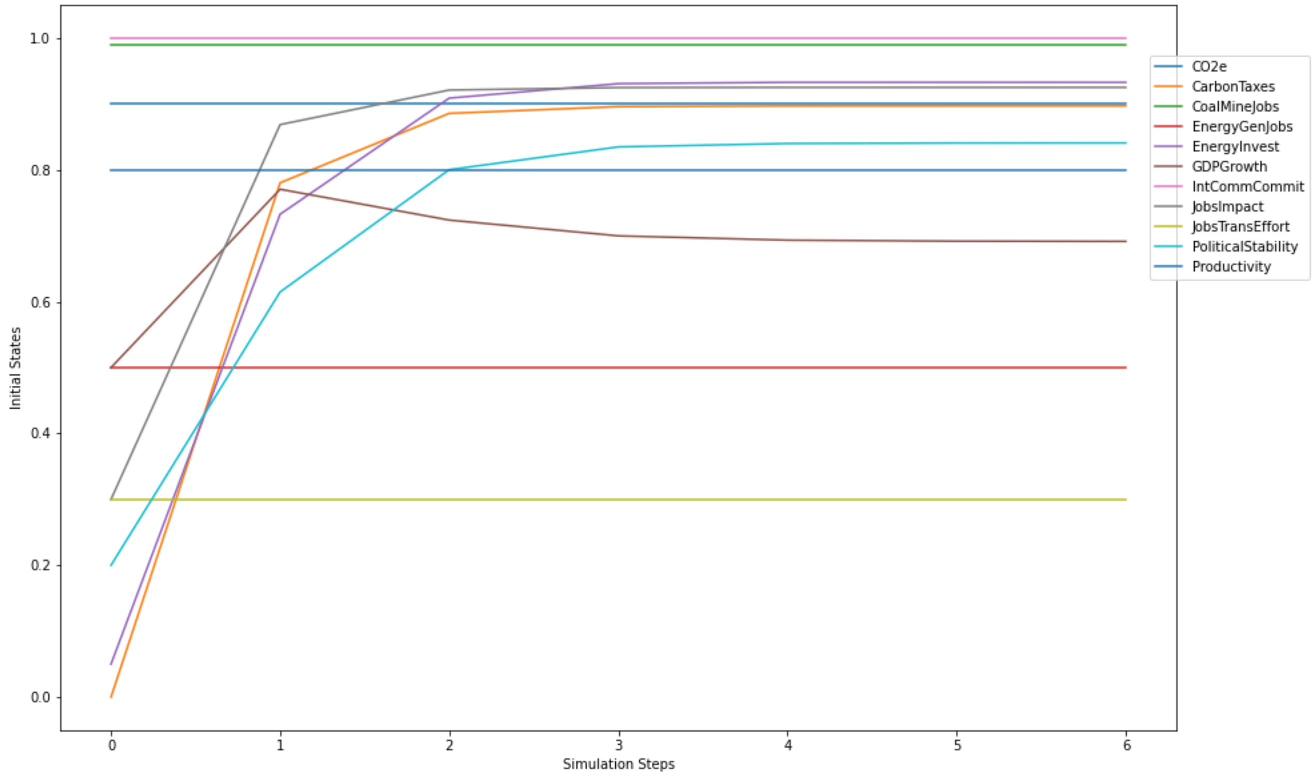


Figure 22: FCM converged values for qualitative concepts

The following vector gives the numerical converged values for the 11 concepts.

$$\begin{bmatrix} CO2e \\ Cabon\ Taxes \\ CoalMiningJobs \\ Energy\ Gen\ Jobs \\ JobsTransEffort \\ EnergyInvestment \\ GDP\ Growth \\ Int.Comm.Commitment \\ Net\ Impact\ on\ Jobs \\ Political\ stability \\ Productivity \end{bmatrix}_{converged} = \begin{bmatrix} 0.90 \\ 0.89 \\ 1.0 \\ 0.5 \\ 0.3 \\ 0.93 \\ 0.69 \\ 1.0 \\ 0.925 \\ 0.84 \\ 0.8 \end{bmatrix} \tag{4}$$

The converged value based on the initial conditions defined show some of the expected systemic behavior. For example, the convergence graphs and the vector show that carbon taxes will increase from the initial state of 0 (very low) to a value of 0.89 (very high). This is expected given that international community commitments to decarbonisation remans high and carbon dioxide emissions also remain high in this scenario.

The results also show counter-intuitive systemic behavior that industry experts and policy makers wouldn't otherwise conclude based on their static mental models. An example of that is the increase of GDP from 0.5 to a converged value of 0.69 and the increase of energy investment from 0.5 to 0.93. This is contrary to expected behavior given that carbon taxes/ tariffs increase, which would be expected to have a direct negative impact on GDP and this decrease would have a negative impact on investment into the energy sector. Based on the convergence, the relatively high starting value for coal mining jobs loops in positive feedback to increase the net impact on jobs, which in turn increases the political stability. The political stability in turn increases the investment into the energy sector, *ceteris paribus*. On the other hand, a relatively high productivity (at 0.8) appears to be a stronger factor than increased carbon tariffs on GDP growth, and hence the GDP growth converges at a value of 0.69.

In fact, the FCM mapping developed hitherto is not complete on its own. The reader would realise that some of the concepts in the convergence curves of Figure (22) are constants and their associated values did not change from their initial values. As aforementioned, these are concepts that were added in addition to the qualitative concepts; that were perceived to be highly coupled to at least one of the qualitative factors and could be directly derived or output from the Systems Dynamics model. This means that their respective values will be determined by the Systems Dynamics Model, but there do affect the qualitative concepts that have been modelled in the Fuzzy cognitive model. This has significant implications on the interpretation of the modelling steps so far, and maps to a very crucial consideration in finalizing the modeling of the full system, considering the scope of this project.

The above formulation implies that some of the modelled concepts in the above represented FCM mapping are dependent on the other factors, while the factors that are constant in Figure (22) above independent in the FMC formulation. This is expressed in mathematical form below:

$$S_{FCM} = \begin{bmatrix} Cabon\ Taxes \\ EnergyInvestment \\ GDP\ Growth \\ Net\ Impact\ on\ Jobs \\ Political\ stability \end{bmatrix} = F\left(\begin{bmatrix} CO2e \\ CoalMiningJobs \\ Energy\ Gen\ Jobs \\ Int.Comm.Committ \\ JobsTransEffort \\ Productivity \end{bmatrix}; year\right) \qquad (5)$$

The above expression is a profoundly important notation as it allows for a great wealth unlocking of analysis to be done. Firstly, the expression is congruent with the 5 factors on the left-hand side of the equation being dependent on the 6 factors that are part of the independent variables. As aforementioned, these are factors that can already be derived from the Systems Dynamics model, except for two factors: International community commitment, and effort in jobs transition through upskilling and reskilling coal mining workforce. These two factors are extrinsic to the model and will be part of the scenario building. The expression above is also consistent with the causality matrix of Figure (21) where all the weights mapping to the 6 independent concepts are zero.

Secondly, given the above realisation and the fact that the independent concepts will not be static over time for different scenarios, it is clear that the simulated scenario depicted in the converged values of Figure (22) is just one of many potential scenarios, and just represents the initial and baseline case. A practical model would then have to carter for different combination of state values, and there are infinite possible scenarios for these, given that the variables are expressed as continuous variables. To overcome this challenge, the writer discretized the six concepts such that instead of having a continuous variation from 0 to 1 in the FCM model, these values are mapped to 4 possible values i.e., 0.25, 0.5, 0.75 or 1. This practical adjustment makes it possible to have a finite number of combinations of initial state values that can be computational simulated.

$$n_{combinations} = 4^{n_{ind}} = 4^6 = 4096\ combinations \qquad (6)$$

The FCM mapping is done for all the 4096 possible combinations. Appendix 7.2.2. is a Python code that runs the FCM mapping for the scenario combinations. The converged values for the simulations are saved in output_data.xlsx (submitted together with this writing). The development of these converged scenario values for the different combinations forms a critical basis for the integration of FCM mapping with Systems Dynamics modelling forming a hybrid Systems Dynamics – Fuzzy Cognitive Mapping model. This is one of the first published writings that dynamically integrate Systems Dynamics and Fuzzy Cognitive Mapping for the analysis of energy system in South Africa.

4.5.3 Integration of qualitative and quantitative concepts and scenario testing

Integrating the two sub-systems requires that the convergence time for the FCM mapping be in sync with the step time of the Systems Dynamics (SD) model. The latter is set in the VenSim program to 1 month per simulation time step. The former is determined in the causal relationship formulation process when framing the objectives with the industry experts. The context set for FCMs was a long-term view that maps to 2050. The implication is that the SD model has a significantly smaller timestep than the FCM set convergence time for each of the different scenarios. This is perceived to be okay for a primary integrated model for purposes of obtaining directional insights. It is however recommended that the FCM be re-adjusted to a smaller timestep for quicker simulation convergence and more accurate transient results.

It is also important to note that for the first time-step in the integrated model, the FCM model variable outputs will be determined by the input SD model output variables (just the same way that the FCM model was separately set-up), but after the first iteration the two models become coupled and reach steady state where all the variables affect and are affected by all other variables in the connected energy system. The integration is done by simple using lookup tables of the 4096 outputs values into the model at each timestep, updating the variables values and running the subsequent timestep to convergence. A snippet of the integrated hybrid model is depicted in the image below. The connections on the right centered on the red block are an expression of equation (5) above with 6 input variables and 5 output variables linked with lookup tables.

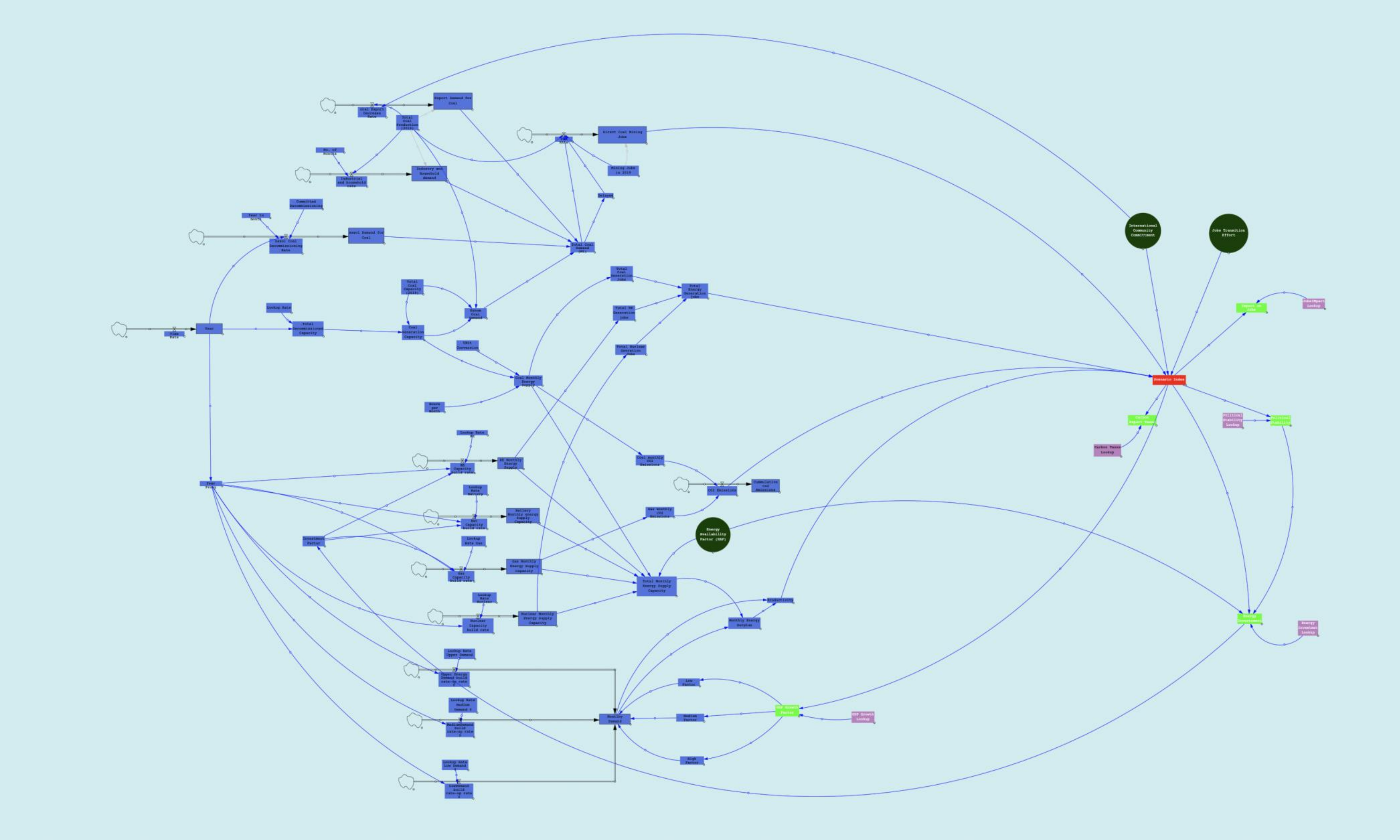


Figure 23: Hybrid Systems Dynamics - Fuzzy Cognitive Mapping Model

The combined model is also attached with this writing, together with instructions on how to open the file. Note that this is first order analysis, and the model was developed using resources and time available to the writer as per the scope of the project, and more refinement is needed for industrial applications and increased confidence levels for full model adoption.

4.6 Scenario Testing

We will focus on three scenarios to understand the impact of various factors embedded in South African energy sector transition. The 3 scenarios chosen for this exercise are tabulated below[3].

Scenario	Description	Simulation and model assumptions
IRP Base Scenario	The scenario that has been developed hitherto using the 2019 IRP proposed structure	• All model parameters developed in the preceding sections.
Low R.E Adoption Scenario	This scenario looks at the possibility of lower than needed capital investment in the energy sector, impacting rate of R.E capacity development	• Coal decommissioning structure remains the same. • R.E capacity build at 75% the rate. • Effort in jobs transition = 0.5. • International community commitment = 1.

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[3] The scenarios are chosen as potential pathways that can result from the IRP pathway. The low RE scenario is a feasible scenario that can result if RE build targets are not met fully. The high RE pathway is a scenario that can be achieved with intentional investment and efficient execution of the baseline pathway, with additional resources allocated to RE capacity development.

Higher R.E. Adoption Scenario	This scenario accelerates R.E capacity building by 20% for South African energy needs and for building comparative advantages to both unlock related industries and export to power to regional markets. It also accelerates coal decommissioning by 20% to curb accumulation of emitted carbon dioxide	• Eskom coal decommissioning accelerated by 20%. • R.E capacity build accelerated by 20% • Effort in jobs transition = 1. • International community commitment = 1.

4.6.1 Scenario results

The above scenarios were simulated for the 2019 – 2050 timeframe, with a timestep of 1 month per iteration, and with convergence obtained as discussed above. The following factors were probed and measured during the simulation, and are collectively a proxy of environmental, economic, and social factors being assessed.

- Cumulative carbon dioxide emissions for the considered subsets of the energy system
- Direct jobs created and jobs lost from mining and energy generation activities
- Energy Demand
- Productivity: Simplified and defined as the ability of the energy system to meet the country's energy needs (ratio of energy generation capacity to energy demand)

4.6.1.1 Cumulative Carbon Dioxide Emissions

Carbon dioxide emissions into the atmosphere increase greenhouse gas effect[4] of the atmosphere. This is also true of other greenhouse gases such as methane and

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[4] The greenhouse effect is when molecules in the atmosphere absorb infrared (heat) waves that have been radiated from the earth's atmosphere, and in the process vibrate and re-emit some of the energy back to the earth, resulting in increased average atmospheric temperatures. Gases like carbon dioxide have a molecular

nitrous oxide, but carbon dioxide is the most common greenhouse gas. An important aspect of decarbonisation is the cutting out of further emissions of greenhouse gases, and this will increase the probability of limiting average surface temperatures to 1.5℃ above pre-industrial levels by the year 2100 (as per key objectives of the Paris agreement). In simulating the scenarios therefore, it is important to track the cumulative amount of carbon dioxide emitted into the atmosphere. It is important that we track the cumulative amount and not necessarily the rate of emissions as the greenhouse effect is directly related to the accumulated amount of greenhouse gases in the atmosphere, and not necessarily the rate of accumulation. The graph below gives the accumulated carbon dioxide emissions over the 2019 – 2050 period for the South African energy generation sector, based on the three scenarios.

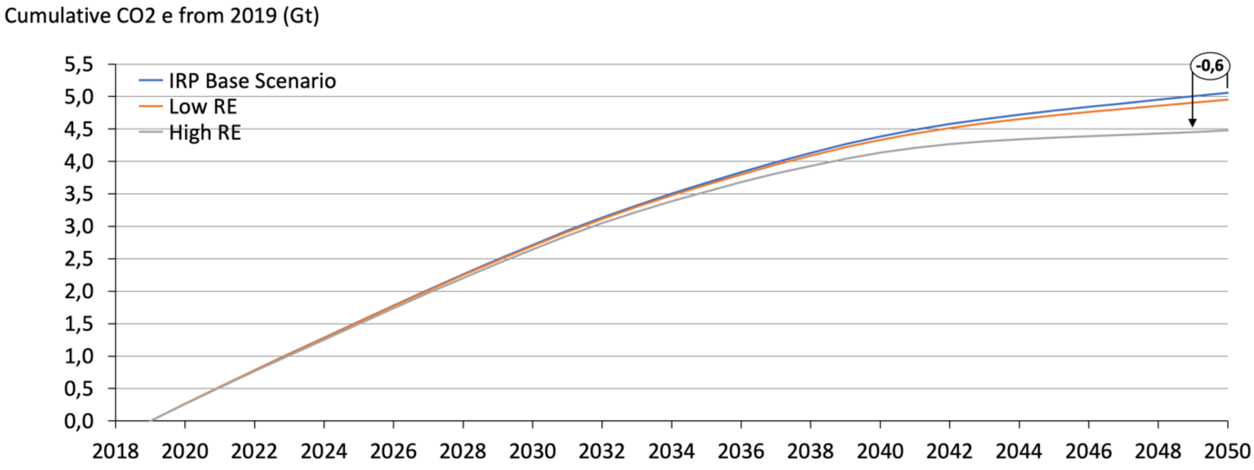

Figure 24: Cumulative Carbon Dioxide emissions for the scenarios

The IRP proposed energy mix development pathway accumulates 5.06 Gigatons (Gt) of carbon dioxide for the period, compared to 4.95Gt and 4.48Gt of carbon dioxide emissions for the low R.E and High R.E adoption pathways, respectively. This represents a difference of 0,6Gt between the base IRP pathway and the high RE adoption pathway (~11% in accumulated savings). For comparison, this is equivalent to over 2 years of Eskom carbon dioxide emissions at current rates. This represents a carbon abatement lever worth considering.

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structure that allows them to absorb electromagnetic waves in the frequency range that includes infrared, whereas much simpler and symmetrical molecules like nitrogen and oxygen absorb waves of much higher frequency, and hence do not cause greenhouse effect.

4.6.1.2 Direct jobs in mining and energy generation

Direct jobs simulated consider coal mining jobs, and direct energy generation jobs. The latter looks at the current Eskom energy generation jobs, and how these are projected to change as coal energy generation capacity changes. It also considers renewable energy generation jobs[5] and how they are projected to change as generation capacity changes. This simulation does not include jobs that will be created in the renewable energy value chain or enabled industries (e.g., jobs to be created from prospects of green hydrogen production and associated value chains); only direct high-certainty jobs are considered. The following three graphs show the jobs created and lost based on the above scope.

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[5] R.E generation jobs are simulated using an assumption of a constant annual number of jobs per TWh of energy generated per year. The benchmark figures are adapted from CSIR's work (Bischof-Niemz, 2017)

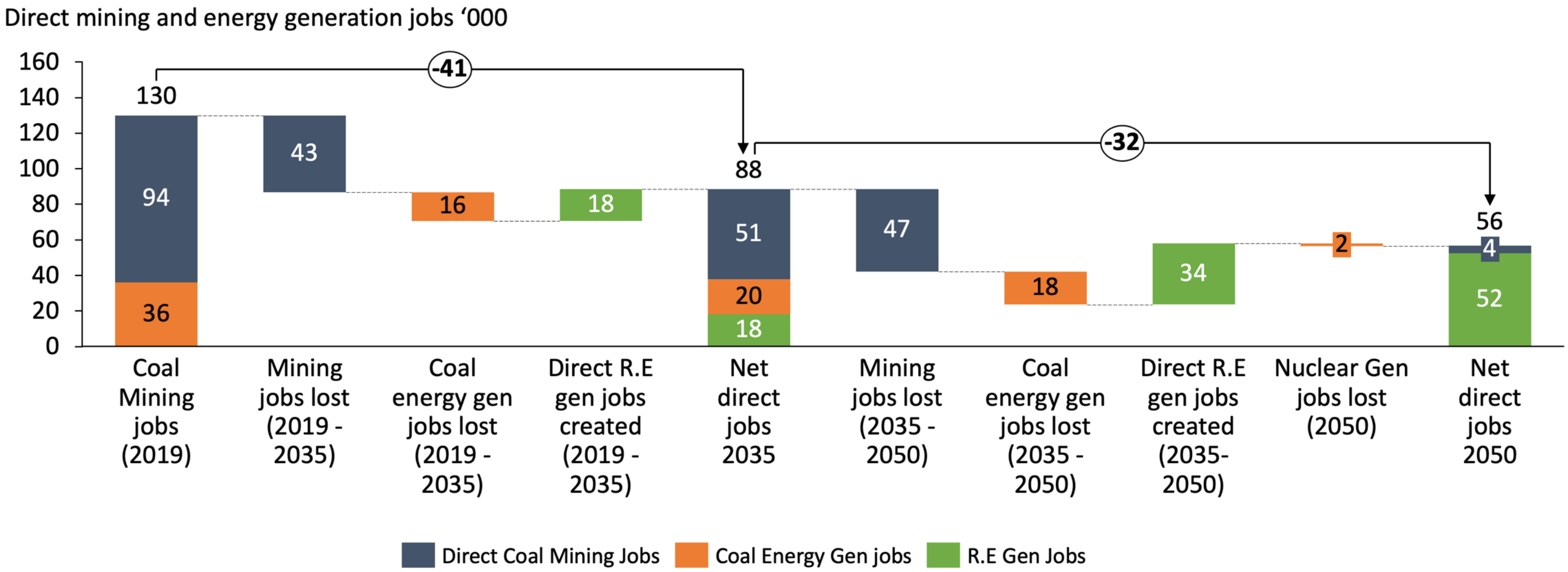


Figure 25: IRP base case

The IRP pathway shows that there is a net decrease in jobs both by the year 2035 and the year 2050, with coal mining jobs being the key driver of the net negative jobs impact as initially asserted. The assessment also shows that a net 16 000 energy generation jobs would be created by 2050, representing 44% increase in energy generation jobs. As aforementioned, this assessment does not consider indirect and value chain jobs (e.g., supplier jobs in the unlocked solar energy value chain). We will discuss the implications later in this writing.

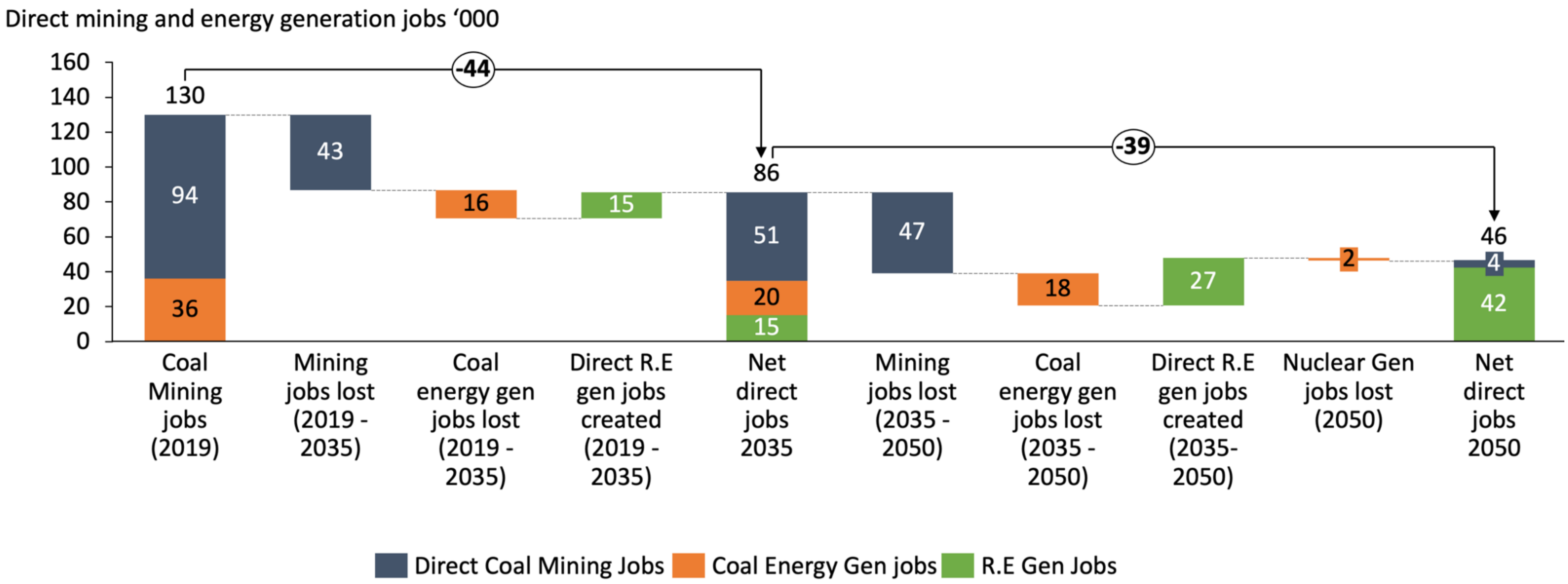


Figure 26: Low RE build pathway

Figure (26) shows the jobs pathway for the low RE build scenario. As expected, this pathway creates less RE generation jobs due to the slowed adoption and capacity development of solar and wind energy system. Although not assessed, this also implies a decrease in RE indirect and value chain jobs to be created.

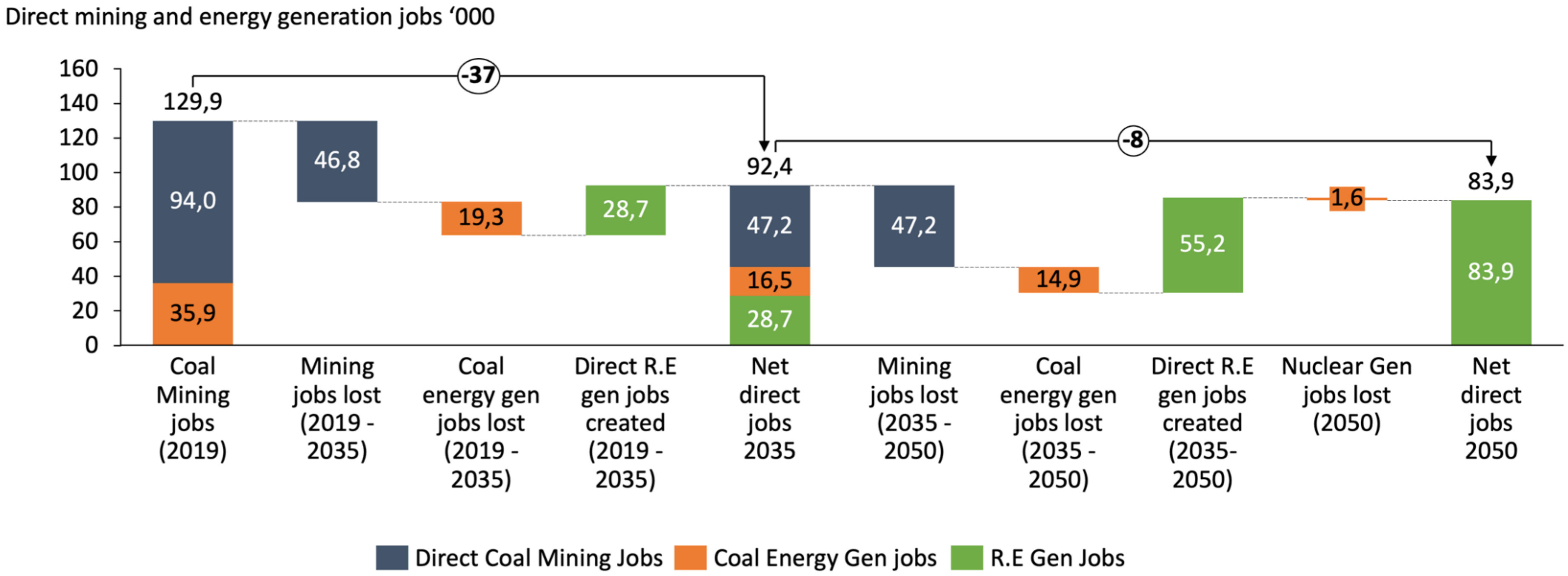


Figure 27: High RE build capacity

The high RE build pathway shows a significant improvement in the number of jobs created for RE generation, with 130% net increase in energy generation jobs by 2050, compared to a 44% increase in the IRP baseline pathway. As expected, and modelled into the pathway, this is an accelerated decarbonisation scenario that still results in negative direct jobs due to the accelerated Eskom power plant decommissioning and resulting decrease in coal demand, resulting in decreased demand for coal miners. Although not simulated, the developed RE economy in this pathway is expected to result in a net positive job creation due to RE indirect and value chain jobs.

4.6.1.3 Energy Demand and productivity

Energy demand for all the scenarios is predicted to rise, mainly driven by an increase in GDP and the associated demand for power for base industrial activity. However, interesting scenarios start emerging as we assess the 3 pathways.

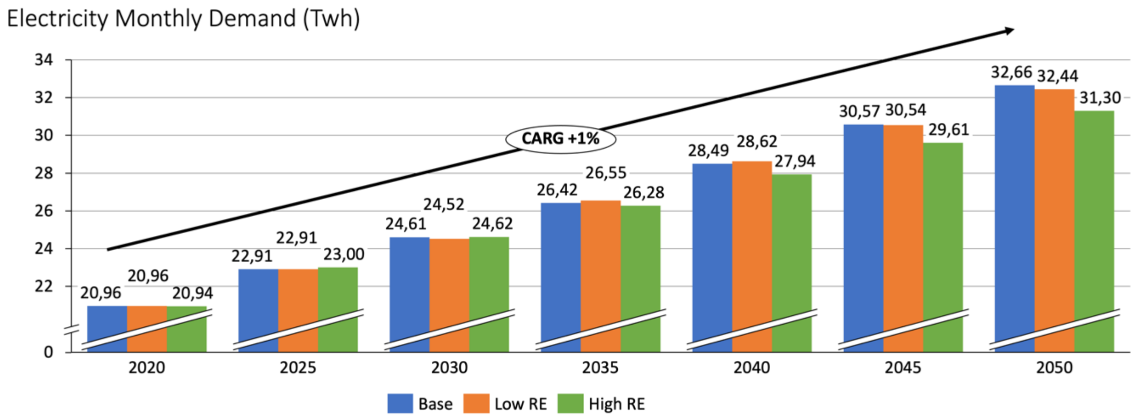


Figure 28: Energy Demand

Firstly, the low RE pathway shows a slightly higher demand for electricity by the year 2035, which is counter-intuitive to what static mental model would have predicted. To explain this, we will need to understand the key drivers of the growth in electricity demand i.e. economic growth and economic structural change as measured by energy intensity of the economy. The higher than anticipated demand for power for the low RE pathway is due to the slower structural change in the economy, resulting in higher demand of energy for a relatively lower economic output. This is consistent with higher energy intensity levels reported by *Yu et al* (2021) for economies with lower adoption of RE (Yu, Liu, Hu, & Tian, 2021).

Secondly, an assessment in the energy demand for the different scenarios by the year 2050 reveals a great wealth of information. The low RE pathway shows lower demand than the base IRP pathway, mainly due to an associated lower GDP growth, consistent with expectations. However, the high RE pathway shows the lowest demand for electricity. Applying the same approach as the low RE case would imply a lower GDP growth pathway for this scenario, which is not the case. The main reason for the lower demand in power for the optimistic high RE adoption pathway is the significant decrease in the energy intensity, driven by an efficient adoption of renewables that drive a change in the structure of the industrial base (i.e., less energy demand to produce a unit of economic output at a macroeconomic level (Yu, Liu, Hu, & Tian, 2021)). This is also a counter-intuitive insight that would otherwise not be easily predicted from static models.

To increase our understanding of how the demand in power is linked to the available generation capacity for the scenarios, we define productivity as the ratio of the two (i.e., available capacity/demanded capacity). This reveals more insights and is depicted in the figure below.

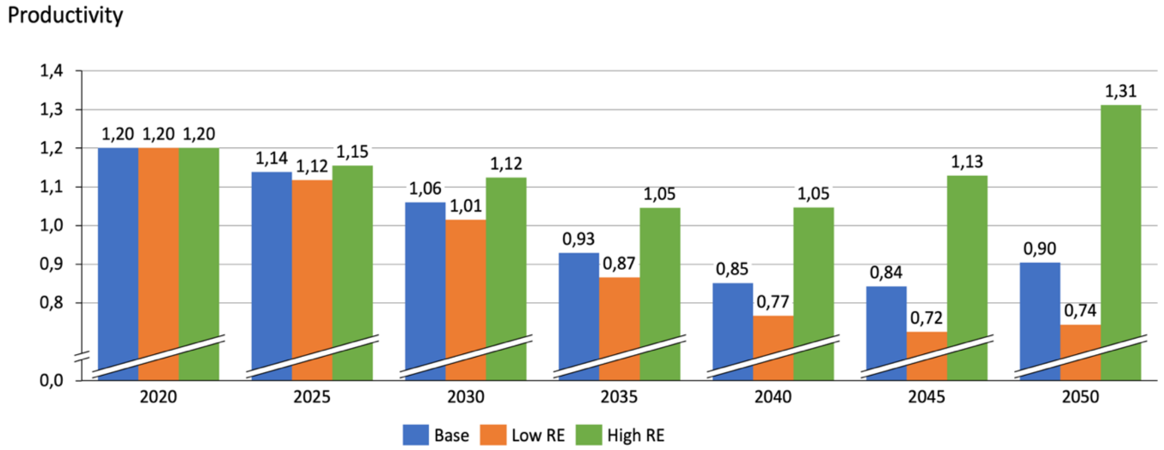


Figure 29: Productivity

Productivity as of 2020 is depicted to be above 100%. This is because productivity, as defined, does not factor in Electricity Availability Factor (EAF), as modelling this in was not part of the scope of this work. In fact, EAF in South Africa has been declining from the year 2019 do date, and the graph below (illustrative) gives its variation from 2020 – 2022 (Pierce, 2022)

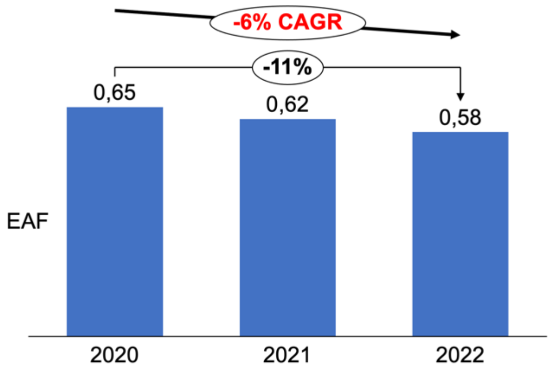


Figure 30: Variation of historic EAF, adapted from *(Pierce, 2022)*

The 65% EAF for 2020 adjusts the 1.20 productivity value to a realized productivity of 0.78, implying that over 20% of demanded power either had to be met from other sources or was not met. This has been the case with the imposed loadshedding for the past few years in South Africa. Anecdotal conversations with industry experts revealed the following to be the main reasons for relatively poor EAF performance in South Africa over the past few years (with EAF declining at 6% per year on average (Pierce, 2022))

1. (Anecdotal) Increased frequency of energy generation unit breakdowns due to the decreased operational efficiency of units aging towards mechanical design end of life.
2. (Anecdotal) Routine and non-routine maintenance schedules are not being followed properly due to negligence at power plants.
3. (Anecdotal) Highly inefficient procurement system at Eskom significantly affecting delivery times and quality of routine and non-routine maintenance and repairs of energy generation units.
4. (Anecdotal) Intentional sabotage of components of generation units for purposes of financial and political gain.

The impact of EAF will remain an important aspect as the energy mix transitions to greener alternatives, and the above four points can be used as starting point towards maximizing value derived from already generated capacity.

The productivity graph (Figure 29) also reveals important aspects of the systems' ability to meet energy needs. Firstly, it shows that the IRP base scenario will fall below 100% productivity from the year 2035 onwards, despite energy generation capacity increasing as discussed before. The main reason for the predicted unmet demand is the increase in electricity demand and energy generation capacity build rate that does not meet the demand. The latter point is worth discussing further.

The projected energy capacity build structure proposed by the IRP is reproduced below for purposes of this discussion. When compared to figure (28), the proposed pathway should be able to fulfill demand (for example, the proposed IRP path in figure 31 shows annual generation capacity of 455 TWh by 2050, equivalent to 37.9TWh per month, which is higher than the 32.66TWh/month demanded in the IRP baseline scenario of figure 28). However, the systemic simulation shows that there is a high probability of capital investment requirements not being met fully, resulting in the sub-100% productivity predictions in discussion. Figure (32) below gives a view of these projected investment ratios for the IRP scenario.

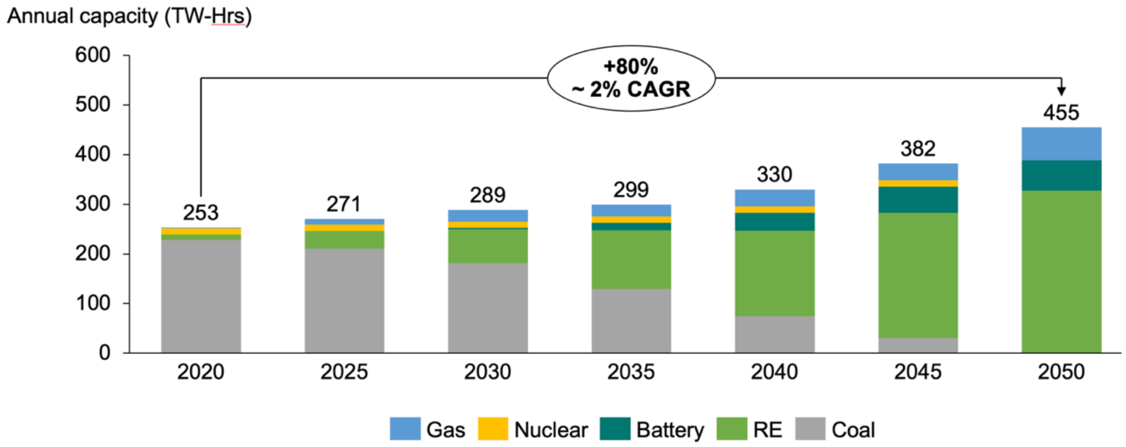


Figure 31: IRP proposed capacity build [reproduced from Figure 18]

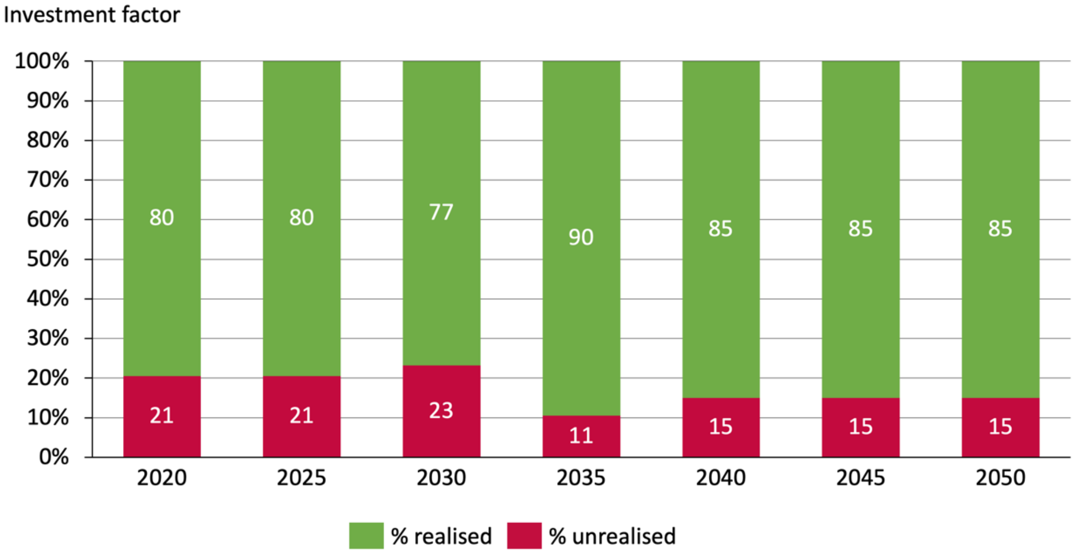


Figure 32: Investment factor for baseline IRP case

The high RE pathway (in figure 29) shows most promising productivity trend. Firstly, it shows that the energy system will always be able to supply demand, given that EAF is managed efficiently as discussed above. It also reveals possibilities to export excess energy to regional demand and/or pivot capacity to unlock related industries such as green hydrogen production, further creating energy sector comparative advantages for South Africa.

4.7 Conclusion

This chapter touched on an extensive number of aspects of the energy sector. We assessed secondary data sources, synthesized primary inputs from industry experts, and developed dynamic simulation systems for understanding and predicting systemic behavior. The chapter assessed a few scenarios for the South Africa energy system transition, using the IRP proposed path as a baseline for comparison. This chapter has revealed a great wealth of insights and critical factors to consider as the system transitions in line with decarbonisation objectives. To maximize the value derived from the exercise, the following chapters will synthesize and add structure to discussions for the purposes of deriving actionable recommendations and policy considerations.

CHAPTER FIVE: DISCUSSIONS AND POLICY CONSIDERATIONS

5.0 Introduction

This chapter discusses key learnings from the research. It starts with an assessment of the research and analysis approach. The latter part of the chapter discusses key insights that are emerging from the South African energy system and proposes actionable policy considerations to avert risks while activating pathways towards energy transition opportunities.

5.1 Analysis approach

The study assessed primary data from industry experts in their perceptions of important factors that will drive and are embedded in South Africa's energy sector, with particular focus on sector transition. Combining these with secondary data resulted in the emergence of primary insights that became useful as part of dynamic modelling. An essential part of this writing was the development of an analysis that investigates systemic behaviour over time, and as such, the 2019 to 2050 period was used. This timeframe is consistent with net-zero commitments and ambitions of the South African energy system as part of the Paris Agreement.

Systems Dynamics (SD) proved very useful in surfacing essential trends. Most of these trends are insights surfaced by many other researchers, with an additional view of when and how these dynamics would translate at a high level. Some of the insights that emerge are counter-intuitive and would otherwise only have been predicted by using dynamic, complex systems analysis. The SD-model's ability to reveal systemic behaviour at specific analysis times is fundamental to deriving actionable insights.

Fuzzy Cognitive Mapping (FCM), on the other hand, demonstrated a rich ability to leverage industry expert perceptions and visually demonstrate their mental models in an iterative process. This then took these mental models further by simulating implied system behavior, revealing how the system will behave under different conditions. This is an expert-interaction-heavy process, one that enriched the developed model beyond measurable and already published secondary data. The process also included model optimization using artificial intelligence models already embedded in FCM tools (e.g., Hebbian Learning model), and this increases the confidence levels obtained from the developed models.

One of the fundamental disadvantages of FCM mapping is the limited ability to give dynamic results that can be linked to specific timeframes. In soliciting industry expert perceptions, the researcher must be explicit on the timeframe reference while describing the causal relationship between different factors and concepts. Otherwise, a mixed timeframe model will ensue. The writer asserts that this is potentially one of the biggest reasons for non-converging FCM models. For example, international community commitment is viewed to have a high positive impact on carbon taxes when viewed from a longer timeframe view i.e., as the international community commits and progresses on decarbonization goals, tariffs on high-carbon imports in importing countries are expected to increase, and this effect is expected to be seen emerging strongly on a 5-yearly, and decade view (consistent with longer timeframe of our analysis). However, there is almost no causal relationship between the two factors on a monthly view – it would be impractical to model the same high causality on a month-to-month basis, as this would result in over-accelerated causality. It is thus important to integrate Hebbian learning (as a form of AI model optimization) for such purposes.

The work then integrated the FCM model with the SD model to take advantage of different model strengths while overcoming the limitations of both approaches. The above discussion on the interpretation of timeframes was an important consideration in integrating the approaches. The ability to combine time-varying quantitative concepts with perception- and relationship-based qualitative concepts proved to be a significant unlock of rich insights into unexpected systemic behaviour.

In interpreting the results of this analysis, it is worth noting that the approach taken was first-order and was constrained by available data while defining proxies for some of the concepts. Therefore, the emerging results should primarily be used for primary directional insights, while detailed absolutes will require detailed analysis with sufficient time, computing, and intellectual human resources. Congruence of the emerging results with already published research increases confidence levels of this writing, however, and is sufficient for purposes of directional insights and references mentioned before.

5.2 Emerging Energy System Insights

This section will discuss insights from the model and vitally important considerations for the South African energy sector, mainly focusing on the modelled power system transition.

5.2.1 Achieving Net-Zero Targets by 2050

Simulation results show that the IRP pathway will achieve many of the objectives of the energy transition. One of the critical, measurable, and ambitious targets is reaching net-zero emissions by the year 2050. As demonstrated, decarbonisation and decommissioning of coal fleets, and energy generation capacity building using renewable sources, are key carbon dioxide abatement levers assessed in this writing. Using these two levers, the IRP pathway improves ESKOM carbon dioxide emissions from over 0.26 Gt of CO_2 by 2019 to under 0.05 Gt by the 2050, with most of 2050 emissions predicted to be from Gas utilisation as part of the energy mix. Adopting the accelerated RE build pathway results in approximately 0.02Gt of CO_2 emissions by the year 2050. This shows that the two considered abatement levers (coal decommissioning and RE build) have a combined abatement potential of between 80% and 95% (of power sector emissions), depending on the pathway followed during the transition.

The other 5% - 20% of power sector emissions must be abated through other mechanisms that include carbon capture, utilisation, and storage (CCUS). CCUS technology has developed drastically over the past decade. For example, in 2021 the Amager Resource Centre’s waste-to-energy facility developed a successful carbon capture pilot with net-zero energy consumption (Bisinella, Nedenskov, Riber, & Hulgaard, 2021). The developed pilot plant can capture 500kg of carbon dioxide per hour, translating to 0.0044 Gt of CO_2 per year. For comparison, this is over 20% of the predicted remaining 0.02 Gt of CO_2 energy sector emissions by 2050 from the high RE pathway or 9% of the 0.05Gt of CO_2 for the base IRP pathway. The implication is that between 5 and 10 of such carbon capture units would be needed, to fully achieve net-zero emissions for South Africa's power sector by 2050. I assert that this is feasible and can be achieved within the 2050 timeframe. It should be noted that in parallel, South African industries such as the petroleum & chemicals sector, transport sector, and heavy manufacturing, must decarbonise to achieve overall net-zero emissions by 2050 (Industrial decarbonisation was not the focus of this writing). The following abatement levers can be used to decarbonise industries that are heavy emitters:

- Reduction of scope 1 emissions by using renewable energy-based processes. For example, Transport sector companies can adopt battery-powered propulsion systems to minimise direct operation-related carbon emissions.
- Reduction of scope 2 emissions by large energy industrial consumers (such as mining operations) by deploying renewable power systems (e.g., solar) to replace power sourcing from the national supply grid. This is an important abatement lever for accelerating RE capacity and will accelerate the systems' decarbonization while decreasing the burden on the national grid.
- Improve process efficiencies to decrease carbon emissions. For example, Summerbell *et al* (2016) assessed a cement production plant in the UK and estimated 8.5% reduction in energy demand and 19.5% reduction in carbon dioxide emissions by optimizing plant operations (Summerbell, Barlow, & Cullen, 2016). This reduces Scope 1 (through direct carbon emission reductions) and Scope 2 (reduced energy demand) emissions.
- Use of CCUS
- Nature-based sinks and offsets (e.g., reforestation)

The above argument establishes the high feasibility of achieving net-zero emissions by 2050 by the South African power sector, and the broader energy sector - a key objective of the Paris Agreement. With that set, we will look at other aspects that emerge within the South African energy sector during the transition.

5.2.2 Jobs lost during the transition

An assessment of the three pathways shows that the number of direct jobs to be lost is more than the net direct energy generation jobs to be created during the transition. This is true by the years 2035 and 2050. The net job losses could be covered by Renewable Energy value chain jobs (indirect jobs) not assessed in this analysis.

These indirect RE jobs are directly linked to the extent that the energy system has transitioned and adopted renewables, and how it has transformed the industry structure.

There are two categories of direct jobs to be lost. The first are coal power generation jobs that will be lost as coal power plants are closed and new RE capacity is built. On this front, all scenarios show that there will be a net positive creation of direct jobs. As most of these coal power generation jobs are at Eskom, there can be transferred directly as Eskom transitions its power fleets to renewables. Skilling, reskilling, and upskilling of the energy generating workforce in line with the transition will be important. This skilling, reskilling, and upskilling must start with immediate effect given that the transition has already started. As of this writing, the latest coal power plant decommissioned was the Komati Power Station, with 1GW of installed power generating capacity. This is congruent with the steep gradients of both the coal decommissioning and RE build graphs in Figure (19) above. “*The die has been cast*”.

The policy propositions and the RE build structure that allows IPPs to own power generation, have important implication on energy sector jobs. IPPs should closely collaborate with other players in the energy sectors in South Africa as part of the skilling, reskilling, and upskilling of the power generation workforce. There should be considerations on who to skill, upskill and reskill for the potential energy generation jobs. Current employees at coal generation fleets and the surrounding communities should take priority as part of this skilling, reskilling, and upskilling efforts, to minimise friction and job losses during the transition. As part of these efforts, the spatial distribution of current coal fleets with respect to future RE generation fleets will have to be considered. In fact, the location of new renewable energy generation units is a key consideration, as it should optimise for several factors, including energy generation potential (e.g., solar insolation rates, average wind speeds), proximity to power transmission networks, and proximity to the workforce (e.g., proximity to current coal power plants, coal mines, etc.,). To solve for opportunities in net positive energy generation jobs, and tackle complexities that emerge with the transition, efficient collaboration models between Eskom, IPPs and the broader private sector are needed as part of these efforts.

The analysis of direct jobs created and lost during the transition using the three scenarios reveals a high sensitivity of net jobs on the rate of the RE build. The high RE energy build scenario results in over 60% more direct energy generation jobs (equivalent to 32 000 more direct jobs) than the 2019 IRP base case scenario, while the slower RE build scenario results in 20% less direct jobs compared to the IRP base scenario (equivalent to 10 000 less direct jobs). As aforementioned, the rate of renewable capacity build therefore presents an important lever for job creation, primarily from the direct jobs created as demonstrated above. However, more jobs are expected to be created from two other avenues, which also demonstrate and favor a higher rate of renewable building.

- RE value chain jobs to be created are directly coupled to the rate of adoption of RE in the economy
- The change in industry structure (as measured by energy intensity) that accompanies RE adoption implies the creation of other jobs that are not necessarily related to the RE value chain, but are activated by the green economy.

The second category of jobs to be lost is the direct coal mining jobs. This is the key contribution to the negative net direct jobs in the 3 scenarios discussed. Over 93,000 coal mining jobs will be lost by 2050, and ~40,000 of these will be lost by 2035. This calls for more urgent action to minimise the negative impact on coal mining communities. A direct source of replacing these jobs would be the surplus energy generation jobs to be created as discussed above, but more is needed to create a positive direct net impact. Policies that accelerate a transition to a fully active green economy that activates the renewable energy value chain and indirect jobs need to be designed and implemented. This consideration also favours the higher renewables build rate pathway, which accelerates industry structure transformation.

The writer asserts that accelerating RE-build and transformation will provide a power supply that supports the industrial base, increasing productivity and hence resulting in productivity-related job creation. This assertion is supported by the fact that the productivity variation for the Higher RE-build scenario is above 1 throughout 2019 – 2050, whereas tin he base IRP and lower RE-build scenarios, productivity falls below

1 by the year 2035 (depicted in Figure 29). The values consider optimal EAF management. Even in the accelerated RE-build scenario, tactical considerations are still needed to avert the negative impact as the economy transitions, which is expected to be until 2035. Not addressing these could result in extensive union involvement (with coal mining jobs lost), negative impact on livelihoods in coal mining communities, social unrest, and political instability. The following tactical measures should be considered:

- Prioritising new renewables capacity development in the proposed REDZ9, which is near coal mining activity. This can allow for a transition of some of the coal mining jobs to renewable jobs.
- Dedication of coal mines for carbon storage (as part of CCUS carbon abatement), as this can provide some employment in the CCUS value chain.
- Early transformation of coal mining communities to reduce reliance of livelihoods to coal-related jobs.
- Investing in transportation, broadband internet, and other critical infrastructure in coal mining communities to make communities more attractive to new industries, and transform the communities from over-reliance on coal mining activity.
- Early skilling, reskilling and upskilling to new renewable energy jobs to prepare communities for the green economy.
- Early collaboration with unions, communities and government on potential job loses to minimise unrest and create transparency and security with mining communities.

5.2.3 Sector investment and economic growth

The simulation and analysis from previous sections show that economic growth is favoured by the pathway with a higher rate of Renewable Energy capacity building. The primary reason for this is the consistently high productivity rate due to the energy sector’s ability to supply energy at a rate higher than the demand. This surplus opens possibilities to export energy to neighbouring power demand in the region. It also provides a platform to activate green economy industries such as green hydrogen and green ammonia production, that have a huge potential of GDP contribution and local job creation.

Simulations also show that the IRP base case will likely converge towards a slower rate of renewable energy capacity building than is planned unless active policy design, implementation, measurement, regulation, and control mechanisms are implemented. The natural system must have proactive efforts to ensure higher renewable energy adoption. The biggest driver for this is the lower-than-needed investment rate, as depicted in the scenario's investment factors. The variation of projected investment factors is depicted and reproduced in Figure (33) below. One of the feasible explanations for this delayed investment trend into the sector would be the lower productivity and political instability that would ensue in this scenario. Low EAF trends that have been observed in the past few years perturb the system into lower productivity and, combined with expected negative net impact on jobs between the years 2019 and 2035, result in lower investment attractiveness into the sector, driven by bearish political stability (from jobs lost) and economic outlook (from productivity).

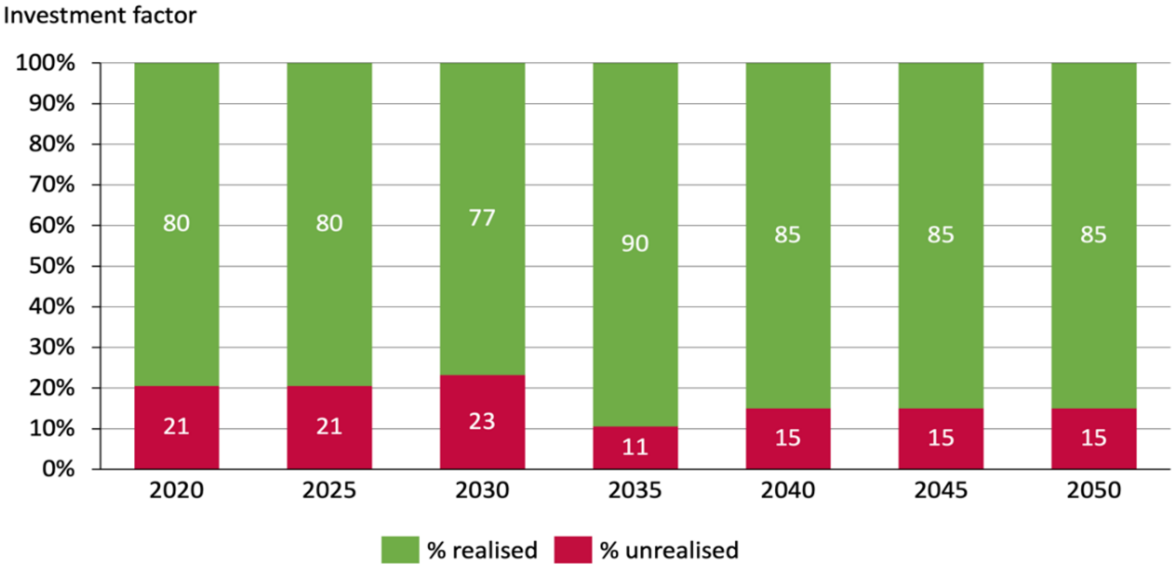


Figure 33: Investment factor for baseline IRP case

The FCM model developed demonstrated that both GDP growth (which is directly affected by productivity) and political stability directly impact the rate of international and external investment into the sector. This is congruent with our assertion.

There is, therefore, sufficient impetus to adopt a higher rate of renewable energy capacity building, given the implications of a lower adoption and the opportunities of adopting a green economy. Intuitively, a higher rate of RE adoption also increases the probability of attracting external funding needed to build the needed renewable capacity. There is a need to activate a higher renewable rate build pathway. As has been demonstrated in the assessments on the three RE-build scenarios, the key benefits of adopting a higher RE-build pathway are as follows:

- Accelerated energy generation capacity building reduces and eliminates surplus deficits and increases productivity and economic growth.
- Aversion of job losses in broader industries due to boosted power-supply-related productivity; job creation due to a stable industrial base*, ceteris paribus*.
- Reduced risk of social and political instability
- Lower cost of energy from a renewable energy-based supply system, adding towards social equity (both from affordability and accessibility) and economic efficiency (lower cost of certain supply).
- Accelerated transformation of South Africa’s industry structure, resulting in lower energy intensity, creation of jobs from activated renewables value chains, and other activated industries (e.g., green hydrogen, green ammonia, electric vehicles markets, renewables-powered crypto-mining, etc.,).
- A higher energy generation capacity, coupled with a lower energy-intensive industry structure, results in an energy surplus, which is key for economic growth through exports to regional demand and activation of green economy value chains (such as green hydrogen production and electric vehicle charging networks).
- These positive factors contribute to economic efficiency and social equity, and increase international investment attractiveness, consistent with the international investments needed to activate this pathway in the first place.

It is essential to note the need for activating this pathway, and recommendations that increase the probability of unlocking key activating factors to the pathway. As been noted, the proposed IRP pathway (as opposed to the high RE adoption pathway) shows a significant probability of not meeting investment needs. It hence results in supply deficit, especially post-2035. The high RE pathway shows a more stable convergence into favorable investment attractiveness, but activation of this investment and pathway is needed. This is important as Eskom does not have sufficient capital to fund the complete transformation (anecdotal), and financing the transition is an essential lever for unlocking the pathway. The following should be considered as the sector unlocks transformation.

- Offer incentives for investments into renewables sector. IPPs can be incentivised to supply energy into the national supply grid, while independent industrial organisations and households can be incentivised for investing in renewables for their own power needs. For example, offering tax incentives to households and corporations investing in renewable energy for their own energy needs could help accelerate capacity building.
- Ensure market stability for the energy sector such that international investors into the sector have a positive outlook on realising positive and favourable economic returns. Ensure socio-economic stability that enables economic stability.
- Invest in green economy skills by partnering with leading private institutions for accelerated skills growth. This increases the sector's attractiveness and the probability of positive and favourable economic returns.
- Offer favourable legal and regulatory frameworks, that notably ensure continued quality service delivery and sector growth, while not defining stringent barriers of sector investment.
- Ensure that key resource enablers and resources have a clearly defined path to activation, in particular:
    - Clear policies for the development of transmission and distribution infrastructure, to allow for accessibility from renewable energy generation farms to end consumers.
    - Access of IPPs and renewable energy investors and developers to dedicated renewable energy zones.

CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

6.0 Introduction

This chapter presents conclusions arising from this study, and the recommendations for the power sector. It also gives recommendations on the study approach and its adoption for future work. These will be given in point format as they summarise insights and implications from previous sections.

6.1 Conclusions on research approach

a) Systems Dynamics (SD) modelling proved to be insightful in surfacing systemic behavior for dynamic variables. The ability of SD approach to accurately attach concepts over time is primary to actionable insights, especially given the time sensitivity of energy transitions and targets that the sector is working towards. It’s ability to combine this with complex analysis made the tool the more useful. Systemic modelling using SD is however limited to quantitative variables, and as such, if the system is driven by a lot of ambiguous factors, it may result in losing out on rich insights on systemic behavior.

b) To overcome this analysis limitation, Fuzzy Cognitive Mapping (FCM) was employed, and proved to be exceptional in not only capturing and modelling qualitative concepts, but as an invaluable tool for soliciting industry experts’ perceptions of causality among system variables. The tool became an active platform of engagement with experts.

c) The SD model and the FCM models were then combined, and this allowed for analysis and insights that would otherwise be counter-intuitive based on static analysis and mental models. This confirms our initial assertion of the energy sector being naturally a complex one. The resulting hybrid SD-FCM model is one of the first academic research attempts for analysing the energy sector in Africa using the tools. Although the analysis was primarily first-order and at a high level due to time and resource constraints, it surfaced some of the important insights and implications that are congruent to assertions of other published work. This establishes a level of model confidence, and the resulting insights can be used for directional insights.

6.2 Conclusions of the Study

a) The study establishes high feasibility of achieving net-zero carbon emissions by the year 2050, for the South African power sector. Net zero goals could be achieved by a combination of abatement levers, including decommissioning of coal fleets, deployment of renewable energy power units, and the use carbon capture, utilization, and storage (CCUS). It is shown that adopting a pathway that accelerates the capacity building of renewable energy by 20% and accelerates decommissioning of coal plants results in direct carbon emissions of 0.02 Gt per year from the power sector in the year 2050, down from 0.26Gt of power sector emissions per year in 2019, representing a 95% abatement lever. The rest of power sector emissions could be abated using CCUS and other active carbon removal technologies.

b) Regardless of the pathway taken, there will a net loss of jobs between the years 2019 and 2035, mainly driven by coal mining jobs. To minimize the negative impact on socioeconomic stability, actions must be taken ahead of anticipated sector transformation, including an early activation of sector investment and green economy acceleration, and transformation of coal mining communities ahead of job losses.

c) Adoption of the higher renewable energy pathway, which accelerates RE capacity building by 20% with respect to the 2019 IRP base scenario, increases the probability of activating investments into the sector, consistent with international investments required for the pathway. This pathway also increases the transformation of the industrial structure, reducing the energy intensity and activating both renewables-related value chains and indirect industries dependent on energy availability and affordability.

d) The proposed IRP plan of 2019 will likely lead to scenario where the sector fails on attracting sufficient investments needed for the proposed renewable generation capacity development. This will result in energy deficits, which will delay the transformation of the sector, lower productivity, and result in more negative socioeconomic outcomes. To avoid this, policies should propose higher renewable energy capacity build structures, and take steps towards activating the pathway and the investments needed. This stance increases the probability of achieving the objectives of the transitioning while realizing positive impact on social equity and economic efficiency.

e) Efforts towards job skilling, upskilling, and reskilling toward the renewable energy economy must be activated immediately, starting with energy generation jobs. This is also an enabler for international investment attractiveness.

f) Collaboration models among IPPs, the private sector, universities, Eskom, and the government are needed to activate and implement skills development for the green economy. These frameworks must be developed and activated as soon as possible for positive outcomes and increased probability of social equity and economic efficiency.

g) As part of anticipating the impact on jobs, the progressive development of renewable energy generating units should consider locations that optimize for transmission efficiency, resource availability (solar insolation rates, average wind speeds, etc.,), and potential impact on energy sector jobs. The latter should consider proximity to coal mining and coal power generation activity.

h) Whereas the decommissioning of coal plants is already set in motion (partly by the expectations in the decarbonisation build plans communicated, and physical design and operational constraints of the coal power plants), resulting in both a decrease in power generating capacity and direct coal mining and energy generation jobs, energy capacity building and sector job creation must be approached with implementation efficiency and careful consideration of key factors involved.

6.3 Recommendations on research approach

a) Energy sector policy makers and analysts must adopt a combination of Fuzzy Cognitive Mapping and Systems Dynamics for analysing and anticipating systemic behavior.

b) More resources must be allocated when analysing complex systems. This includes time, human resources, and computational resources. By so doing, more variables can be included in the analysis with smaller timesteps that will capture transient effects more accurately.

c) When integration FCM and SD models, more effort has to be allocated in making sure that variables are integrated accurately, with a proper alignment of timesteps used in both models. In the FCM model component, the timesteps has to be communicated explicitly when soliciting causality of concepts with industry experts. This will accelerate model convergence and enable a smooth model integration with the SD model component.

d) With that said, future studies of similar nature should focus on dedicating hundreds of hours with industry experts for detailed modelling and analysis of systemic behavior.

Bibliography

Alipour, M., Hafezi, R., Amer, M., & Akhavan, A. (2017). A new hybrid fuzzy congitive map-based scenrio planning approach for Iran's oil production pathways in the post-sanction period. *Energy 135*, 851-864.

Argus. (2023). *South African coal exports shift to Asia as European demand wanes.* Argus.

Balmer, M. (2007). Household coal use in an urban township in South Africa. *Journal of Energy in Southern Africa*, 27 - 32.

BCG, NBI. (2019). *Decarbonising South Africa's power system.* NBI.

BCG, NBI. (2019). *Decarbonising the South African Mining Sector.* NBI.

Bischof-Niemz, D. T. (2017). *South Africa's energy future.* Pretoria: CSIR.

Bisinella, V., Nedenskov, J., Riber, C., & Hulgaard, T. (2021). Environmental assessment of amending the Amager Bakke incineration plant in Copenhagen with carbon capture and storage. *Waste Management & Research*.

Blumberga, A., Gravelsins, A., & Blumberga, D. (2022). Deliebration Platform for Energy Transition Policies: How to make Complex Things Simple. *Energies*.

Carvalho, J., & Tome, J. (2000). Rule based fuzzy congitive maps-qualitative systems dynamics. *19th International Conference of the North American Fuzzy Infirmation Processing Society*, (pp. 407 - 411).

Chan, S. (2001). Complex adaptive systems. *Research Seminar in Engineering Systems* (pp. 1 - 9). Cambridge Massachusetts: MIT Press.

Chen, Z. (2020). *Energy transition in Singapore: A System Dynamics Analysis on Policy Choices for a Sustainable Future.* Massachusets Institute of Technology.

Das, A., Vinay, S., Kirit, P., Parikh, J., Ghosh, P., & Tot, M. (2022). Pathways to net zero emissions for the Indian power sector. *Energy Strategy Reviews*.

Department of Mineral Resources and Energy. (2019). *Integrated Resource Plan.*

Forrester, J. (2010). *System Dynamics: the foundation under systems thinking.*

Haroon, B., Karmen, N., & Derek, Y. (2014). *Trade unions in an emerging economy: The case of South Africa.* Econstor.

Hinrichs, R. A., & Kleinbach, M. (2006). Energy: Its Use and the Environment. In R. A. Hinrichs, & M. Kleinbach, *Energy: Its Use and the Environment* (p. 320). Toronto: Thompson Brooks.

Hlongwane, K. (2014). *Minerals energy complex on the beneficiation policy through the lens of network analysis.* Johannesburg: Wits School of Governance.

Ketelhodt, A. V., & Wöcke, A. (2008). The impact of electricity crises on the consumption behaviour of small and medium enterprises. *Journal of Energy in Southern Africa*, 4-12.

Kiani, B., Mirzamohammadi, S., & Hosseini, S. H. (2010). A survey on the Role of System Dynamic Methodology on Fossil Fuel Resorces Analysis. *International Business Research*, 84 - 93.

Konyalioglu, A. K. (2020). *An integrated model of system Dybamics and fuzzy cognitive mapping approach for waste management.* Instabul - Turkey: GAlatasaray University.

Li, F. J., Dong, S. C., & Li, F. (2012). A system Dynamics model for Analysing the eco-agriculture system with policy recommendations. *Ecological Modelling*, 34-45.

Macmillan, A., & Woodcock, J. (2017). Understanding bicycling in cities using dynamics modelling. *Journal of Transport & Health*, 269 - 279.

Minerals Council South Africa. (2021). *Facts and Fugures 2021.* Minerals Council South Africa.

Mkhitaryan, S., Giabbanelli, P., Wozniak, M. K., Nápoles, G., De Vries, N., & Crutzen, R. (2022). *FCMpy: a python module for constructing and analyzing fuzzy cognitive maps.* PeerJ Computer Science.

Moellers, T., Burg, L. v., Bansemir, B., Pretzl, m., & Gassmann, O. (2019). *System Dynamics for Corporate Business Model Innovation.* Springer.

Monteith, S. (2019). *A qualitative analysis of the South African just energy transition.* Cape Town: University of Cape Town.

Mutingi, M., Mbohwa, C., & Kommula, V. P. (2017). System dynamics approaches to energy policy modelling and simulation. *Energy Procedia* (pp. 532 - 539). Elsevier.

Nair, A., Reckien, D., & Maarseveen, M. (2019). A generalized fuzzy cognitive mapping approach for modelling complex systems. *Applied Soft Computing*, 1-11.

Nicholas, S. (2019). South African Coal Exports Outlook: Approaching Long-Term Decline. *Institute for energy economics and financial analysis*.

Nkomo, J. C. (2005). Energy and econoic development. *Journal of Energy in Sourthen Africa*, 10 -20.

Papageorgiou, E., & Stylios, C. (2008). *Handbook of Granular Computing.* John Wiley & Sons, Ltd.

Perdana, S., & Vielle, M. (2022). Making the EU Carbon Border Adjustment Mechanism acceptable and climate friendly for least developed countries. *Energy Policy*.

Pierce, W. (2022). *Statidtics of utility-scale power generation in South Africa.* CSIR.

Rahim, F. H., Hawari, N. N., & Abidin, N. Z. (2017). Supply & Demand of Rice in Malaysia: A System Dynamics Approach. *International Journal of Supply Chain Management*, 1 - 7.

Robinson, I., & Van Below, M. (1990). Industrial Policy under democracy: apartheid's frown-up infant industries? Iscor and Sasol. *Transformation: Critical Perspectives on Southern Africa. Vol*, 91-98.

Sasol. (2022). *Briefing ahead of AGM on 2 December 2022: Climate-related disclosures and commitments.* Just Share: Center for Environmemtal Rights.

Spalding-Fecher, R. (2002). Energy and energy policies in South Africa: an overview. *NER Quartely Journal*, 1-18.

Stats SA. (2019). *Gross Domestic Product.* Stats SA.

Sterman, J. D. (2000). *Business Dynamics: Systems Thinking and Modeling for a Complex World.* Boston, MA: McGraw-Hill.

Summerbell, D. L., Barlow, C. Y., & Cullen, J. M. (2016). Potential reduction of carbon emissions by performance improvement: A cement industry case study. *Journal of Cleaner Production*, 1327 - 1339.

Sun, X., Jia, M., Xu, Z., Liu, Z., Liu, X., & Liu, Q. (2021). An investigation of the determinants of energy intensity in emerging market countries. *Energy Strategy Reviews*.

Sustainable Energy. (2005). *Sustainable Energy Briefing.* Johannesburg: Sustainable Energy and Climate Change Project of Earthlife Africa Johannesburg.

System Dynamics perspective. (2015). System Dynamics perspectives and modeling opportunities for research in operations management. *Journal of Operations Management*, 1 - 5.

Teimoury, E., Nedaei, H., Ansari, S., & Sabbaghi, M. (2013). A multi-objective analysis for import quota policy making in a perishable fruit and vegetable supply chain: A system dynamics approach. *Computers and Eletronics in Agrriculture*, 37 - 45.

Todd, I., & McCauley, D. (2021). Assessing policy barriers to the energy transition in South Africa. *Energy Policy*, 1-8.

United Nations. (2023, December 15). *United Nations*. Retrieved from Climate Action: https://www.un.org/en/climatechange/paris-agreement

Vats, G., & Mathur, R. (2022). A net-zero emissions energy system in India by 2050: An exploration. *Journal of Cleaner Production*.

World Wide Review. (2022). *World Wide Review*. Retrieved from Green House Gas Emissions by Country, 2022: https://worldpopulationreview.com/country-rankings/greenhouse-gas-emissions-by-country

Yaschenko, S., Polyakov, V., & Sabitova, T. (2021). Organizational structures of mining companies: composition and development. *SHS Web of Conferences.* EDP Sciences.

Yu, S., Liu, J., Hu, X., & Tian, P. (2021). Does development of renewable energy reduce energy intensity? Evidence from 82 countries. *Technological Forecasting & Social Change*.

Zare, S. G., Alipour, M., Tabar, P. R., & Hafezi, K. (2021). Identification of wind energy deployment determinants: Fuzzy congitive map-based method. *International Conference on innovations in Energy Engineering & Cleaner Production* (pp. 1-6). IEECP.

Ziv, G., Watson, E., Young, D., Howard, D. C., & Larcom, S. T. (2018). The potential impact of Brexit on the energy, water and food nexus in the UK: A fuzzy congitive mapping approach. *Applied Energy*, 487-498.

Appendix A: Questionnaire

A Qualitative Perspective research approach will be adopted, with the objective of getting experts views on the **causality relationships** in the concepts of the energy system in South Africa.

The following section is divided into different parts according to the different factors identified within the South African energy system. Please indicate the grade of relationship between the below mentioned concepts with the grading system as follows:

Negatively Strong	Negatively Medium	Negatively Weak	None	Positively Weak	Positively Medium	Positively Strong
- - -	- -	-	0	+	++	+++
🟩	🟩	🟩	⬜	🟩	🟩	🟩

8. Negatively Strong
9. Negatively Medium
10. Negatively Weak
11. Zero
12. Positively Weak
13. Positively Medium
14. Positively Strong

For the purpose of this research, Part 7 is particularly important. Please, kindly answer all the questions in that part. Thank you very much for your contribution.

Part 1: Economic Factors

4. According to the above-mentioned grading system, how would you grade the influence of *Economic Growth* on:
   a. *Electricity Demand?*
   b. *Price of Electricity?*
   c. *Operational Expenses?*
   d. *Price of Electricity?*
   e. *Energy Mix?*
   f. *Investment Risk?*

   g. *Return on Investment?*
   h. *Public expenditure in the energy sector (Budget Allocation)?*
   i. *Oil Prices?*
   j. *Electricity Supply Stability in SADC?*
   k. *Electricity Generation Deregulation?*
   l. *Exchange Rate?*
5. And vice versa?
6. Do you notice further influences between any of the above-mentioned concepts?
   a. If yes, between which concepts? And to which extent?

Part 2: Environmental Factors

3. According to the above-mentioned grading system, how would you grade the influence of *Environmental Regulations on Environmental Concern*?
4. And vice versa?

Part 3: Legal Factors

3. According to the above-mentioned grading system, how would you grade the influence of *Market Regulation* on:
   1. *Government Support and Involvement*?
   2. *Market stability for IPPs & Policy certainty*?
4. And vice versa?

Part 4: Social Factors

3. According to the above-mentioned grading system, how would you grade the influence of *Population Growth* on *Public Knowledge and Acceptance of Alternative Energy Sources*?
4. And vice versa?

Part 5: Technological Factors

3. According to the above-mentioned grading system, how would you grade the influence of *Technology Maturity* on *National Deployment of Alternative Energy Sources* (e.g. solar power)?
4. And vice versa?

Part 6: Political Factors

3. According to the above-mentioned grading system, how would you grade the influence of *Political Stability in the country* on:
    1. *Political Relations within the region*?
    2. *Political Relations with power-houses such as the U.S and China*?
4. And vice versa?

Part 7: Other Factors

3. Could you identify other concepts which may influence the above-mentioned factors?
4. Could you identify some variables in the above-mentioned different parts which may influence each other?
    a. If yes, which ones?
    b. And to which extent?

Appendix B: Fuzzy Cognitive Mapping

Core Function

In [1]:

```
#!/usr/bin/env python3
# -*- coding: utf-8 -*-
"""
@author: clivemathe
"""


from fcmpy import ExpertFcm, FcmSimulator, FcmIntervention
import numpy as np
import matplotlib.pyplot as plt
import pandas as pd
import skfuzzy
import openpyxl
import tqdm
import os
from fcmpy import NHL


# Initial state
initial_state = {'CO2e': .9, 'CarbonTaxes': 0, 'CoalMineJobs': .99, 'EnergyGenJobs'
: 0.5, 'EnergyInvest': 0.05,
                         'GDPGrowth': 0.5, 'IntCommCommit': 1, 'JobsImpact': 0.3, '
JobsTransEffort': 0.3,
                         'PoliticalStability': 0.9, 'Productivity': 0.8}



fcm = ExpertFcm()


fcm.linguistic_terms = {
    '-S': [-1, -1, -0.667],
    '-M': [-1, -0.667, -0.333],
    '-W': [-0.667, -0.333, -0.001],
    'NA': [-0.1, 0, 0.1],
    '+W': [0.001, 0.333, 0.667],
    '+M': [0.333, 0.667, 1],
    '+S': [0.667, 1, 1]
}


fcm.universe = np.arange(-1, 1.01, .01)
```

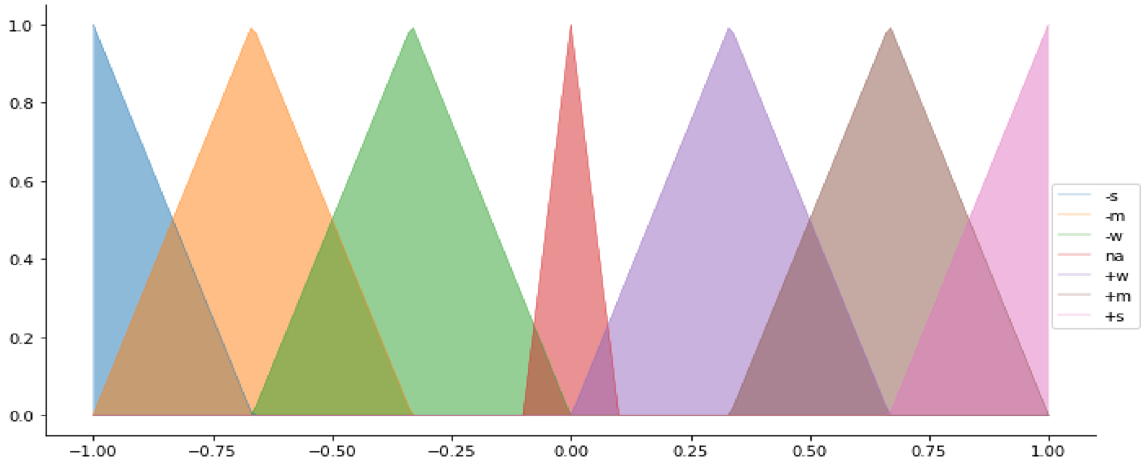
```
fcm.fuzzy_membership = fcm.automf(method='trimf')

# Viewing the created membership functions
mfs = fcm.fuzzy_membership

fig = plt.figure(figsize=(10, 5))
axes = plt.axes()

for i in mfs:
    axes.plot(fcm.universe, mfs[i], linewidth=0.4, label=str(i))
    axes.fill_between(fcm.universe, mfs[i], alpha=0.5)

axes.legend(bbox_to_anchor=(0.95, 0.6))

axes.spines['top'].set_visible(False)
axes.spines['right'].set_visible(False)
axes.get_xaxis().tick_bottom()
axes.get_yaxis().tick_left()
plt.tight_layout()

# Load data from experts
data = fcm.read_data(file_path=os.path.abspath('ExpertDataInput2.xlsx'), check_consistency=False)
entropy = fcm.entropy(data)
sim = FcmSimulator()

# Applying fuzzy implication rule
weight_matrix = fcm.build(data=data, implication_method='Mamdani', aggregation_method='fMax', defuzz_method='centroid')

# Implement Herbian Learning algorithms to get optimised weight matrix
init_states_WT = initial_state
w_init_WT = weight_matrix
doc_values_WT = {'CarbonTaxes': [0.8, 1],'EnergyInvest': [0.85, 0.98], 'GDPGrowth': [0.5, 0.88], 'JobsImpact': [0.7, 1],'PoliticalStability':[0.5, 0.9]}


# Non-Linear Herbian Learning
nhl = NHL(state_vector=init_states_WT,weight_matrix=w_init_WT, doc_values=doc_values_WT)
res_nhl = nhl.run(learning_rate = 0.001, l=.999999, iterations=100)
weight_matric_optimal = res_nhl
```

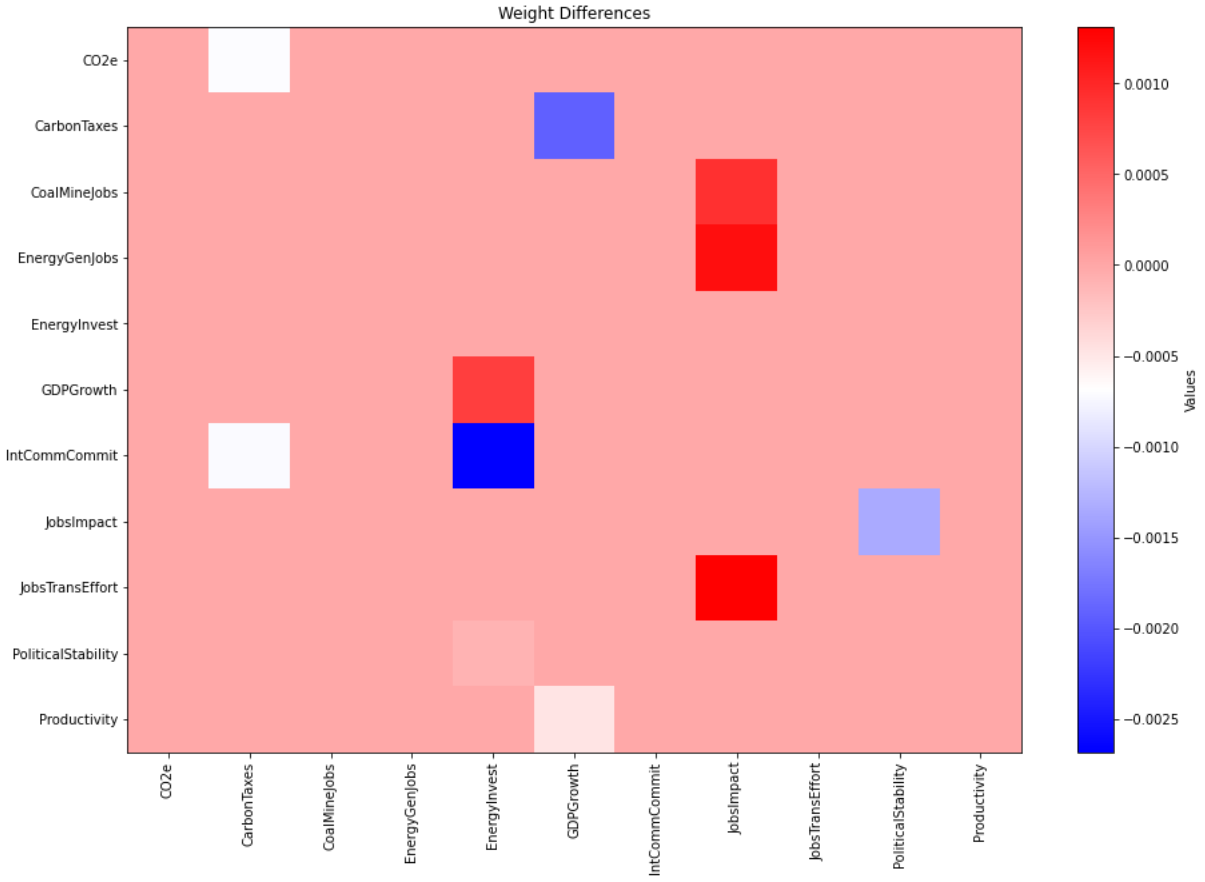
```
#Find the difference between weight matrices

weight_difference = weight_matrix - res_nhl
df = weight_difference

# Set the width of the plot to 100%
fig, ax = plt.subplots(figsize=(15, 10))  # You can adjust the width as needed

# Plot DataFrame as a color map
im = ax.imshow(df.values, cmap='bwr', aspect='auto')
ax.set_xticks(range(len(df.columns)))
ax.set_xticklabels(df.columns,rotation='vertical')
ax.set_yticks(range(len(df.index)))
ax.set_yticklabels(df.index)
plt.colorbar(im, ax=ax, label='Values')
plt.title('Weight Differences')



# Plt Weights

df = weight_matrix

# Set the width of the plot to 100%
fig, ax = plt.subplots(figsize=(15, 10))  # You can adjust the width as needed

# Plot DataFrame as a color map
im = ax.imshow(df.values, cmap='bwr', aspect='auto')
ax.set_xticks(range(len(df.columns)))
ax.set_xticklabels(df.columns,rotation='vertical')
ax.set_yticks(range(len(df.index)))
ax.set_yticklabels(df.index)
plt.colorbar(im, ax=ax, label='Values')
plt.title('Initial Weights')



df = res_nhl

# Set the width of the plot to 100%
```

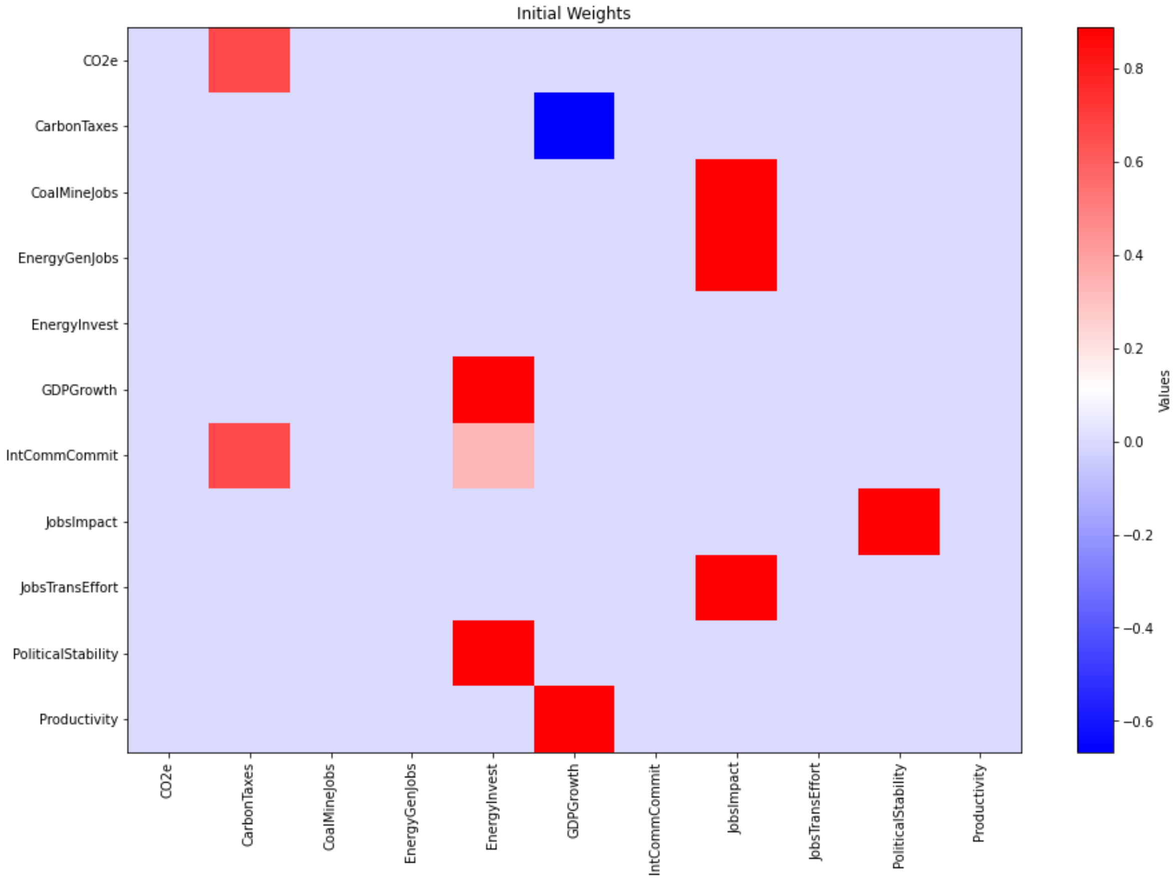
```
fig, ax = plt.subplots(figsize=(15, 10))  # You can adjust the width as needed

# Plot DataFrame as a color map
im = ax.imshow(df.values, cmap="bwr", aspect='auto')
ax.set_xticks(range(len(df.columns)))
ax.set_xticklabels(df.columns,rotation='vertical')
ax.set_yticks(range(len(df.index)))
ax.set_yticklabels(df.index)
plt.colorbar(im, ax=ax, label='Values')
plt.title('Optimised Weights')



# Add gridlines
ax.grid(True, which='both', linestyle='-', linewidth=0.5, color='black')

# Adjust layout to prevent clipping of labels
plt.tight_layout()

# Show the plot
plt.show()

# Add gridlines
ax.grid(True, which='both', linestyle='-', linewidth=0.5, color='black')

# Adjust layout to prevent clipping of labels
plt.tight_layout()

# Show the plot
plt.show()





sim = FcmSimulator()
res_mK = sim.simulate(initial_state=initial_state, weight_matrix=res_nhl, transfer='sigmoid',
                      inference='mKosko', l=1, thresh=0.001, iterations=50)

plt.figure()
res_mK.plot(figsize=(15, 10))
plt.legend(bbox_to_anchor=(0.97, 0.94))
```

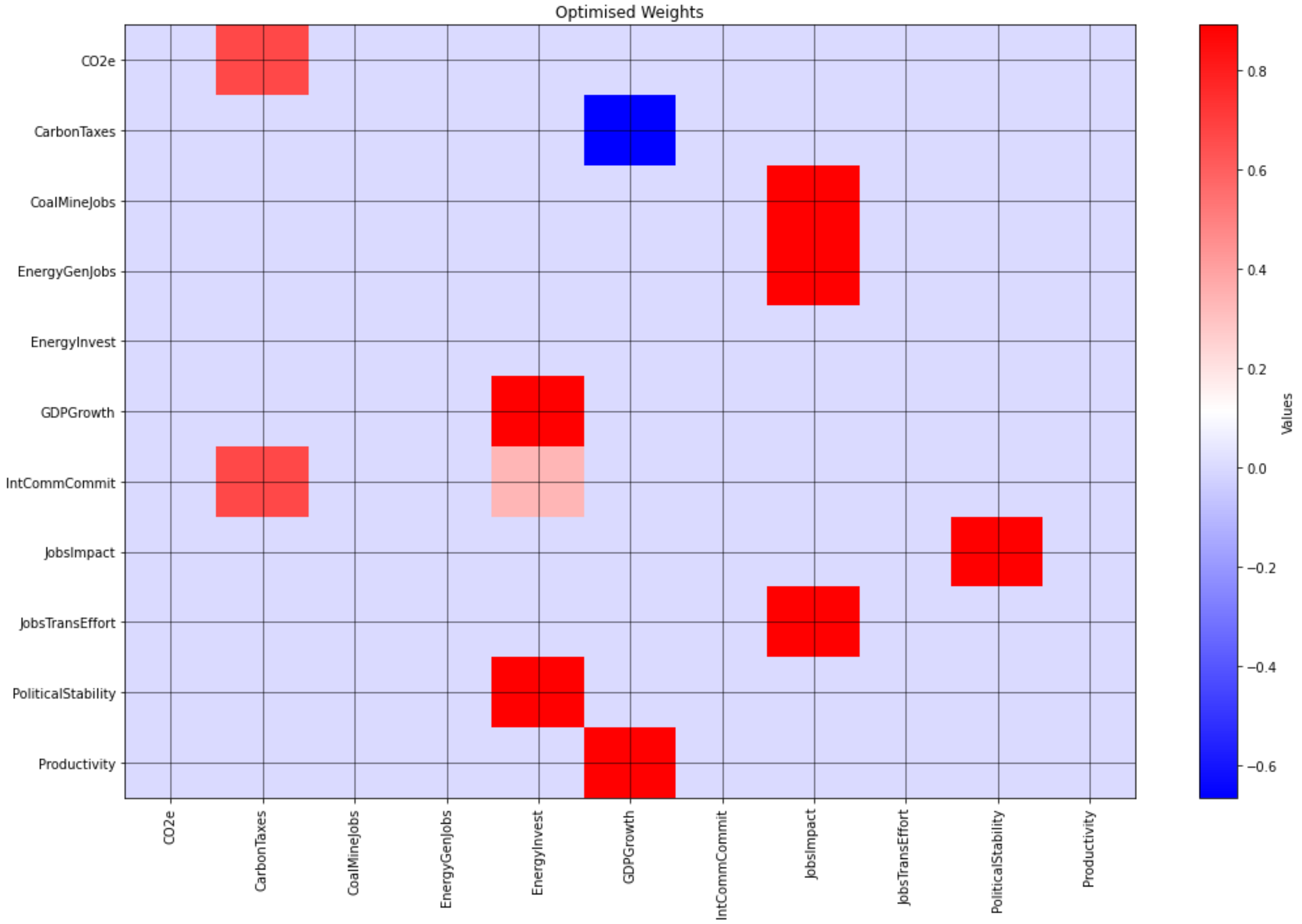
```
plt.xlabel('Simulation Steps')
plt.ylabel('Initial States')
plt.show()
```

```
  8%|█          | 8/100 [00:00<00:00, 1848.02it/s]
The NHL learning process converged at step 8 with the learning rate eta = 0.001 and
 decay = 1!
```

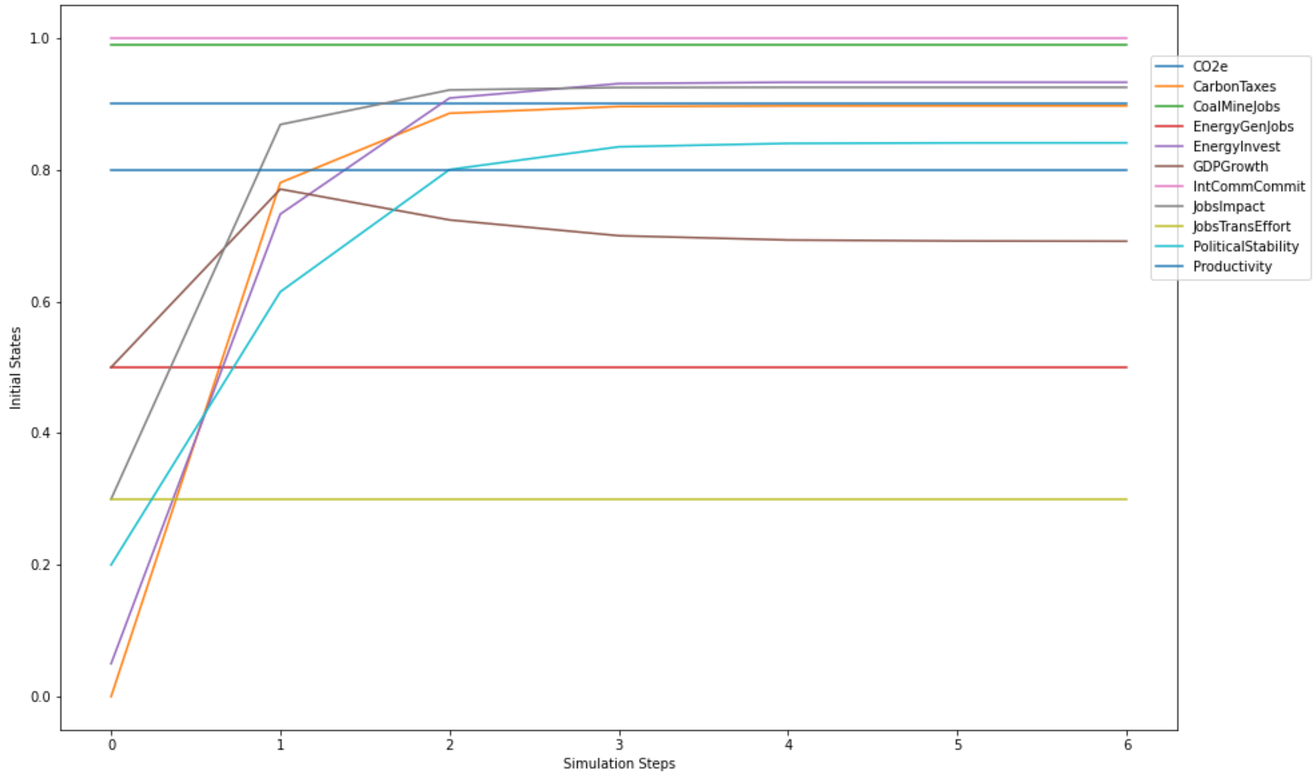





Initial Weights
CO2e
CarbonTaxes
CoalMineJobs
EnergyGenJobs
EnergyInvest
GDPGrowth
IntCommCommit
JobsImpact
JobsTransEffort
PoliticalStability
Productivity
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
Values


Optimised Weights
CO2e
CarbonTaxes
CoalMineJobs
EnergyGenJobs
EnergyInvest
GDPGrowth
IntCommCommit
JobsImpact
JobsTransEffort
PoliticalStability
Productivity
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
Values

```
<Figure size 432x288 with 0 Axes>
The values converged in the 7 state (e <= 0.001)
<Figure size 432x288 with 0 Axes>
```



Scenario Building

In [1]:

```
#!/usr/bin/env python3

# -*- coding: utf-8 -*-

"""

@author: clivemathe

"""


from fcmpy import ExpertFcm, FcmSimulator, FcmIntervention

import numpy as np

import matplotlib.pyplot as plt

import pandas as pd

import skfuzzy

import openpyxl

import tqdm

import os
```

```
def simulate_fcm(initial_state):
    fcm = ExpertFcm()

    fcm.linguistic_terms = {
        '-S': [-1, -1, -0.667],
        '-M': [-1, -0.667, -0.333],
        '-W': [-0.667, -0.333, -0.001],
        'NA': [-0.1, 0, 0.1],
        '+W': [0.001, 0.333, 0.667],
        '+M': [0.333, 0.667, 1],
        '+S': [0.667, 1, 1]
    }

    fcm.universe = np.arange(-1, 1.01, .01)

    fcm.fuzzy_membership = fcm.automf(method='trimf')

    # Viewing the created membership functions
    mfs = fcm.fuzzy_membership

    # Load data from experts
    data = fcm.read_data(file_path=os.path.abspath('ExpertDataInput2.xlsx'), check_
consistency=False)
    entropy = fcm.entropy(data)
    sim = FcmSimulator()

    # Applying fuzzy implication rule to get initial weight matrix
    weight_matrix = fcm.build(data=data, implication_method='Mamdani', aggregation_
method='fMax', defuzz_method='centroid')

    # Implement Herbian Learning algorithms to get optimised weight matrix

    init_states_WT = initial_state
    w_init_WT = weight_matrix

        #Desired Output Concepts
    doc_values_WT = {'CarbonTaxes': [0.5, 1],'EnergyInvest': [0.5, 0.98], 'GDPGrowt
h': [0.5, 1], 'JobsImpact': [0.3, 1],'PoliticalStability':[0.5, 1]}

        # Non-Linear Herbian Learning
    from fcmpy import NHL
    nhl = NHL(state_vector=init_states_WT,weight_matrix=w_init_WT, doc_values=doc_v
alues_WT)
```

```
    res_nhl = nhl.run(learning_rate = 0.001, l=.95, iterations=100)
    weight_matrix_opt = res_nhl

    # Run the Simulation to get state values
    sim = FcmSimulator()
    res_mK = sim.simulate(initial_state=initial_state, weight_matrix=weight_matrix_
opt, transfer='sigmoid',
                          inference='mKosko', l=1, thresh=0.001, iterations=50)

    return res_mK
```

In [2]:

```
import pandas as pd

# Input values:
input_values = [0.25, 0.5, 0.75, 1]

# Initialize empty arrays for output variables
carbon_taxes_values = []
energy_invest_values = []
gdp_growth_values = []
jobs_impact_values = []
political_stability_values = []

# Initialize an empty DataFrame with column headings
output_df = pd.DataFrame(columns=['Coal_mining_jobs', 'CO2_e', 'Energy_generation_j
', 'Int_comm_commt', 'Jobs_trans', 'Prod',
                                   'Carbon_taxes', 'Energy_Invest', 'GDP_Growth', '
JobsImpact', 'Political_Stability'])

# Iterate through all possible combinations of input values
index = 0
for Coal_mining_jobs in input_values:
    for CO2_e in input_values:
        for Energy_generation_j in input_values:
            for Int_comm_commt in input_values:
                for Jobs_trans in input_values:
                    for Prod in input_values:
                        # Set input values
                        state_inputs_initial = {'CO2e': CO2_e, 'CarbonTaxes': 1, 'C
oalMineJobs': Coal_mining_jobs,
                                                'EnergyGenJobs': Energy_generation_j
, 'EnergyInvest': 1,
```

```
                                                'GDPGrowth': 1, 'IntCommCommit': Int
_comm_commt, 'JobsImpact': 1,
                                                'JobsTransEffort': Jobs_trans, 'Poli
ticalStability': 1, 'Productivity': Prod}

                        # Simulate FCM and get converged values
                        result = simulate_fcm(state_inputs_initial)
                        converged_values = result.iloc[-1]

                        # Capture output values
                        carbon_taxes = converged_values['CarbonTaxes']
                        energy_invest = converged_values['EnergyInvest']
                        gdp_growth = converged_values['GDPGrowth']
                        jobs_impact = converged_values['JobsImpact']
                        political_stability = converged_values['PoliticalStability'
]

                        # Append values to arrays
                        carbon_taxes_values.append(carbon_taxes)
                        energy_invest_values.append(energy_invest)
                        gdp_growth_values.append(gdp_growth)
                        jobs_impact_values.append(jobs_impact)
                        political_stability_values.append(political_stability)

                        # Add input and output values to DataFrame
                        output_df.loc[index] = [Coal_mining_jobs, CO2_e, Energy_gen
eration_j, Int_comm_commt, Jobs_trans, Prod,
                                                 carbon_taxes, energy_invest, gdp_gr
owth, jobs_impact, political_stability]

                        print( str(index) + " / 4096 simulations done")
                        index += 1

# Display the DataFrame
print(output_df)
```

```
*** 4096 / 4096 simulations converged using the NHL learning process converged with
 the learning rate eta = 0.001

      Coal_mining_jobs  CO2_e  Energy_generation_j  Int_comm_commt  \
0                 0.25   0.25                 0.25            0.25  
1                 0.25   0.25                 0.25            0.25  
2                 0.25   0.25                 0.25            0.25  
3                 0.25   0.25                 0.25            0.25  
4                 0.25   0.25                 0.25            0.25  
...                ...    ...                  ...             ...  
```

```
4091              1.00   1.00                 1.00            1.00
4092              1.00   1.00                 1.00            1.00
4093              1.00   1.00                 1.00            1.00
4094              1.00   1.00                 1.00            1.00
4095              1.00   1.00                 1.00            1.00

      Jobs_trans  Prod  Carbon_taxes  Energy_Invest  GDP_Growth  JobsImpact  \
0           0.25  0.25      0.746516       0.903019    0.574536    0.814584   
1           0.25  0.50      0.746525       0.908728    0.643807    0.814563   
2           0.25  0.75      0.746525       0.913587    0.706102    0.814563   
3           0.25  1.00      0.746525       0.917599    0.760061    0.814563   
4           0.50  0.25      0.746516       0.903457    0.574536    0.850405   
...          ...   ...           ...            ...         ...         ...   
4091        0.75  1.00      0.903638       0.935830    0.735927    0.968049   
4092        1.00  0.25      0.903648       0.923685    0.540384    0.974401   
4093        1.00  0.50      0.903633       0.928391    0.612061    0.974413   
4094        1.00  0.75      0.903633       0.932413    0.677832    0.974413   
4095        1.00  1.00      0.903638       0.935877    0.735927    0.974413   

      Political_Stability  
0                0.824962  
1                0.824981  
2                0.824981  
3                0.824981  
4                0.830249  
...                   ...  
4091             0.846608  
4092             0.847423  
4093             0.847407  
4094             0.847407  
4095             0.847448  

[4096 rows x 11 columns]
```

In [4]:

```
# Save output_df to Excel
#output_df.to_excel('output_data.xlsx', index=True)


# Save output arrays to separate text files in the specified format
output_arrays = {
    'Carbon_taxes': carbon_taxes_values,
    'Energy_Invest': energy_invest_values,
    'GDP_Growth': gdp_growth_values,
    'JobsImpact': jobs_impact_values,
    'Political_Stability': political_stability_values
}


for variable, values in output_arrays.items():
    with open(f'{variable}_output.txt', 'w') as file:
        for index, value in enumerate(values):
            file.write(f'({index + 1}, {value}), ')
```