Fostering Sustainable Energy Transitions in South Africa: A System Dynamics Approach to Achieving a Sustainable Electricity Sector

By

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Declaration

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December 2017

Abstract

South Africa is currently experiencing numerous challenges, such as low economic growth, social disparities, and poor governance. However, despite these challenges, South Africa's electricity sector is pursuing a transition to sustainable energy. This is evident by the number of mechanisms driving the transition, including the National Growth Plan, the National Development Plant and the Integrated Resource Plan for Electricity. For a transition of this magnitude to be successful a holistic perspective of sustainability is required across several sectors. A Sustainable Energy Transition (SET) is vastly complex and requires a multi-disciplinary approach to address societies' developmental and economic growth needs. Moreover, it simultaneously needs to address climate change challenges and resource constraints. SET frameworks address multiple issues, which include but are not limited to: the link between energy production and consumption, sustainable technology adoption and the socio-technical impacts, the required paradigm shift for policy-making and the clear environmental constraints.

The study aimed to contribute to the knowledge base of fostering SETs, within the electricity sector of South Africa. Therefore, the study focuses on the ability of the electricity sector to successfully achieve an SET in the long-term, while managing several social, economic and environmental constraints. This is achieved by using a dual-narrative approach. The approach consists of a narrative phase, which involves a systematic review of literature. The review assesses various aspects of transitions and the related complexities. Secondly, the approach includes a modelling phase, where an appropriate modelling methodology is selected through a benchmarking process. As a result, a model is developed to model the SET on a country level, for the South African electricity sector. An output of the narrative phase was the development of a set of criteria by which to assess the SETs progress, in terms of the rate and scope of change over time. The selected methodology for the modelling phase was system dynamics. Using this methodology, a model is developed to model the Integrated Resource Plan for Electricity for South Africa, as well as determine alternative scenarios - which could achieve a transition to sustainability. The model was built with the aim of engaging stakeholders, from various backgrounds, in discussions and using the model to generate possible futures, develop foresight and strengthen policy development processes.

The model scenario results were assessed in terms of the developed set of criteria. The results showed that the current policy is insufficient to achieve an SET by 2050 and scenarios with electricity mixes, constituting of more renewable energy technologies, were most effective in fostering SETs. However, challenges that need to be considered are: considerable financial investments, the intermittence of supply and the required dispatchable electricity needed to meet demand. These scenarios are discussed in detail and a key recommendation is that the dynamics of the electricity sector, such as the effect of decommissioning capacity and possible delays of adding new capacity, should be considered in the future and complacency may result in history repeating itself.

Overall the study provided an alternative approach to assess the ability of South Africa's electricity sector to foster an SET, and contributed to the SET knowledge base of South Africa.

Opsomming

Suid-Afrika ondervind tans talle uitdagings soos lae ekonomiese groei, maatskaplike ongelykhede en swak staatsbestuur, maar ondanks hierdie uitdagings streef die elektrisiteitsektor van die land na ’n oorgang na volhoubare energie. Dít blyk duidelik uit die aantal meganismes wat hierdie oorgang bevorder, waaronder die Nasionale Groeiplan, die Nasionale Ontwikkelingsplan en die Geïntegreerde Hulpbronplan vir Elektrisiteit. Die sukses van so ’n omvangryke oorgang berus op ’n holistiese beskouing van volhoubaarheid oor ’n aantal sektore heen. ’n Volhoubare energieoorgang (VEO) is uiters kompleks en vereis ’n multidissiplinêre benadering om in die samelewing se ontwikkelings- en ekonomiese groeibehoeftes te voorsien, en terselfdertyd klimaatsveranderingsuitdagings en hulpbronbeperkings die hoof te bied. VEO-raamwerke sluit verskeie kwessies in, wat onder meer insluit die verband tussen energieproduksie en -verbruik, die ingebruikneming van volhoubare tegnologie en die sosio-tegniese impak daarvan, die vereiste paradigmaskuif vir beleidvorming, sowel as die ooglopende omgewingsbeperkings.

Hierdie studie het ten doel om by te dra tot die kennisbasis vir die bevordering van VEO’s in die elektrisiteitsektor van Suid-Afrika. Daarom konsentreer die studie op die vermoë van die elektrisiteitsektor om ’n VEO te bewerkstellig en terselfdertyd ’n aantal maatskaplike, ekonomiese en omgewingsbeperkings te bestuur. Dít word deur ’n dubbelnarratiefbenadering bereik. Die benadering behels ’n narratiewe fase, wat bestaan het uit ’n sistematiese literatuuroorsig om die verskillende aspekte van oorgange en die verbandhoudende kompleksiteite te bepaal, sowel as ’n modelleringsfase, waartydens ’n toepaslike modelleringsmetodologie deur ’n normvergelykingsproses gekies en ’n model gevolglik ontwikkel is om die VEO vir die Suid-Afrikaanse elektrisiteitsektor op nasionale vlak te modelleer. ’n Uitset van die narratiewe fase was die ontwikkeling van ’n stel kriteria waarvolgens die vordering van die VEO met betrekking tot die tempo en omvang van verandering oor tyd beoordeel kan word. Die gekose metodologie vir die modelleringsfase was stelseldinamika, waarvolgens ’n model ontwikkel is om die Geïntegreerde Hulpbronplan vir Elektrisiteit vir Suid-Afrika te modelleer en alternatiewe scenarios te bepaal wat ’n oorgang na volhoubaarheid kan bewerkstellig. Die model is ontwikkel met die doel om belanghebbendes van verskillende agtergronde by gesprekke te betrek en om toekomsmoontlikhede te skep, versiendheid te ontwikkel en beleidsontwikkelingsprosesse te versterk.

Die resultate van die modelscenarios is aan die hand van die ontwikkelde stel kriteria beoordeel, en dui daarop dat die huidige beleid onvoldoende is om teen 2050 ’n VEO te bewerkstellig. Die resultate toon ook dat scenarios met meer hernubare-energietegnologieë doeltreffender is om VEO’s in die hand te werk. Uitdagings wat egter oorweeg moet word, sluit in die aansienlike vereiste finansiële belegging, die wisselvallige aanbod, en die beskikbare elektrisiteit wat vereis word om aan die vraag te voldoen. Hierdie scenarios word uitvoerig bespreek en aanbevelings word ook gedoen.

Die studie bied in die geheel ’n alternatiewe benadering om die vermoë te evalueer van Suid-Afrika se elektrisiteitsektor om ’n VEO te bewerkstellig, en dra by tot die VEO-kennisbasis van die land.

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BRICS	Brazil, Russia, India, China and South Africa
c/KWh	Cents per kilowatt hour
CCTG	Combine cycle gas turbine
CLD	Causal Loop Diagram
CO_2	Carbon Dioxide
CSIR	Council for Scientific and Industrial Research
CSP	Concentrated Solar Power
DEA	Department of Environmental Affairs
DES	Discrete Event Simulation
EE	Energy Efficiency
FGD	Flue Gas Desulphurisation
FFP	Fabric Filter Plants
GDP	Gross Domestic Product
GHG	Greenhouse gases
GW	Gigawatt (10^9 Watt)
GWh	Gigawatt Hour
IEA	International Energy Agency
IEP	Integrated Energy Plan
IRP	Integrated Resource Plan for Electricity
IPP	Independent Power Producers
KW	Kilowatt
KWh	Kilowatt Hour
MCO	Multi-Criteria Optimisation
MEC	Mineral Energy Complex
MLP	Multi-Level Perspective
MW	Megawatt (10^6 W)
MWh	Megawatt hour (10^6 Wh)

NDP	National Development Plan
NERSA	National Energy Regulator of South Africa
NEMA	National Environmental Management Act
NGO	Non-Governmental Organisation
NO_x	Nitrogen Oxides
OECD	Organisation for Economic Co-operation and Development
O&M	Operations and Maintenance
LP	Linear Programming
PPA	Power Purchasing Agreement
PV	Photovoltaic
R&D	Research and Development
RE	Renewable Energy
REI4P	Renewable Energy Independent Power Producers Procurement Programme
SA	South Africa
SAGEM	South African Green Economy Model
SD	System Dynamics
SET	Sustainable Energy Transition
SNM	Strategic Niche Management
SO_x	Sulphur Oxides
ST	Sustainable Transition
STT	Socio-Technical Transition
SWH	Solar Water Heater
TIS	Technology Innovation System
TM	Transition Management
W	Watt
WWF-SA	World Wildlife Fund – South Africa

1 Introduction and Background

Developing countries are faced with a two-fold energy challenge in the 21st century. The first is energy access for all. The second is meeting the targets for affordable and clean renewable energy. These challenges are addressed by the seventh goal of Sustainable Development, which is to *"ensure access to affordable, reliable, sustainable and modern energy for all"*(United Nations, 2017). With around 1.6 billion people – a quarter of the world's population, living without access to electricity, it is necessary for these developing countries to meet the needs of people who lack access to basic electricity services. While simultaneously participating in the global transition to low carbon energy generation systems (Ahuja & Tatsutani, 2009). The global goal of reducing carbon emissions and achieving a sustainable energy transition has resulted in international discussions, and multiple plans to achieve global decarbonisation (Center for Climate and Energy Solutions, 2015).

With the increasing pressure from the international community to tackle climate change issues, South Africa has made concerted efforts to decrease its carbon emissions. These efforts were initiated in 1998, when the White Paper on energy policy was published (Department of Minerals and Energy, 1998). Since then, South Africa has set its sights on a trajectory towards sustainable growth and development. More recently, the Green Economy summit, held in 2010, aimed to catalyse the effects of sustainable development in South Africa (Musango, Brent, Smit van Niekerk, Jonker, Pienaar, York, Oosthuizen, Duminy & de Kock, 2015). In addition, after the international financial crisis of 2008, limited resources and carbon emissions became global topics of concern. The international communities have come together to address these issues through the initiation of sustainable development strategies and policies. These strategies and policies aim to secure water and energy resources, and tackle climate change (Department of Economic Development, 2011).

These initiatives started the 'green economy' concept, and the modern transition of economies to low carbon sources of energy generation (Musango, Brent & Bassi, 2014). The United Nations Environment Programme (UNEP, 2011) defines a 'green economy' as: "*improved human well-being while significantly reducing environmental risks and ecological scarcities*". UNEP (2011) further states that in a green economy, growth in employment and economic income are driven by the reduction of carbon emissions and pollution. In a green economy, there are investments that enhance energy and resource efficiencies, and prevent the destruction of the environment. These investments need to be built on policy reforms and changes in regulations. The key to such transitions towards sustainability, is enabling economic growth and investment, while simultaneously increasing social and environmental quality (UNEP, 2011).

However, South Africa's journey to sustainability has not been without challenges, especially when one considers the provision and production of electricity to the nation. In 2008, the monopolistic power producer, Eskom, implemented load shedding[1] to limit commercial and industrial power supply, which had significant

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[1] A controlled blackout in local areas implemented by Eskom as a prevention mechanism to respond to unplanned events and protect the electricity power system from a total black out.

effects on the economy (van der Nest, 2015). South Africa has since been looking to alternative sources of electricity generation. To date these alternatives include, renewable energy resources in the form of solar photovoltaic (PV), Concentrated Solar Power (CSP), wind and hydro which have been added to the electricity supply mix (Department of Energy, 2015a).

Renewable energy sources have continued to gain attention over the last two decades. Furthermore, renewable energy technology has since proven its ability to contribute to the grid is sufficient, not only in delivering capacity to the power system, but having a positive impact on the economy, society and the environment (Camaren & Swilling, 2011; Department of Energy, 2015a). However, the intermittence of the renewable energy supply, grid stability and the ability of renewable energy to connect and transmit electricity, remain challenges for the South African electricity sector (Hedden, 2015a). Thus, plans to update and improve the transimission and distribution of electricity within South Africa need to be considered to allow for more fleixibility with the addition of renewable energy to the electricity mix (Hedden, 2015b).

Given South Africa's numerous efforts and initiatives to secure a future with reduced emissions, electricity supply security, a prosperous economy and social equality, a policy was developed. This policy is called the Integrated Resource Plan (IRP)[2] for Electricity. The IRP aims to ensure that different energy resources are being considered from a generation and financial analysis perspective, to adequately evaluate the performance of various generation technologies (Department of Energy, 2011).

With the world's attention on the climate crisis, little attention has been focused on the dynamics that transitions have on an international level, or even on a country level. To date, no society has managed to enable a large-scale Sustainable Energy Transition (SET), and an energy transition has not been fully dependent on a single resource type such as: coal or gas. Instead, resources have shifted from one application to another, depending on factors, such as: availability and price (Sgouridis & Csala, 2014) . An example of this can be seen in the historical global transition from coal to petroleum, with the move from coal-steam-ships to modern petroleum-powered ships (Sgouridis & Csala, 2014).

Socio-technical transitions (STT) can be defined as, a deep structural change such as the evolution of a country's energy or transport system. These evolutions involve complex, long-term reconfigurations of policy, society, technology, knowledge domains and cultural practices (Geels, 2005). South Africa is currently undergoing an STT, with deep structural changes occurring, particularly for this context, in the electricity regime. The country is currently faced with multiple challenges, one such challenge is excessive CO_2 emissions, since South Africa is the largest greenhouse gas producer on the African continent. The country's emissions are considerably high for a developing country with low economic growth and a high poverty rate (Baker, Newell & Phillips, 2014). In December 2009, President Jacob Zuma addressed the Copenhagen

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[2] The IRP is a living plan that is reviewed on a regular basis, the most recent review, the 2016 Draft IRP, received much criticism with regards to the forecasted electricity demand due to the rising electricity prices, poor economic growth, and reducing energy intensity, along with the associated risk of large inflexible nuclear projects. Other criticism includes artificial constraints imposed on renewable energy.

Climate Change Summit, and pledged to reduce South Africa's greenhouse gas emissions. Eskom, South African's electricity utility, has been struggling to generate enough supply, as well as add new generation capacity to the grid. The utility is also the largest greenhouse gas emitter on the continent, due to its primary generation of electricity from coal resources. Moreover, the country's coal suppliers are amongst the most intensive electricity users (Baker *et al.*, 2014). With the current economic climate deterring investment, South Africa has many challenges to overcome within the electricity sector, which include: Infrastructure development, sustainable generation capacity additions, electricity price increases, social development and decarbonisation, to name but a few. The National Energy Regulator of South Africa (NERSA) approved a 2.2 per cent average electricity price increase which was implemented on the 1 April 2017 (Inglesi-Lotz, 2011; Eskom, 2017a,b). Since then, Eskom has submitted a tariff proposal to NERSA for a 19.9 per cent tariff hike from 1 April 2018, however there has been much resistance to this proposal (Creamer, 2017a).

There is a need to analyse and evaluate South Africa's progress, with regards to the implementation of the IRP, and determine whether a transition to sustainable sources of energy, specifically for electricity generation, is achievable for South Africa. Therefore, further research is required to investigate South Africa's electricity sector SET progress. Preliminary questions that can give an indication as to whether South Africa can achieve sustainability by 2050, are: At what rate is South Africa transitioning? Is there certain criteria by which South Africa can access its transition success?

Consequently, these questions are investigated through the use of a dual-narrative approach, presented in more detail in Section 1.6.1. Literature is analysed via a systematic review process, followed by the construction of a model to determine the technological, financial, social, and environmental impacts associated with the transition. Finally, various interventions are implemented to determine possible pathways to a successful sustainable energy transition for the electricity sector.

1.1 Research Problem

From the overview provided above, and more specifically when reports and initiatives such as the IRP, National Growth Plan (NGP) and the National Development Plan (NDP) are considered, it is evident that South Africa is aiming to transition over the 2010 to 2050-time period. The transition to a state of sustainability is a complex undertaking, and multiple economic,technological, social and environmental development objectives need to be acheived. When considering the sustainability of a country from a holistic perspective, sustainability transitions are required across several sectors; one such a transition is a Sustainable Energy Transition (SET). An SET can be defined as, a transformation of a society's economy that was previously based on fossil fuels, to an economy that is renewable-energy based (Sgouridis & Csala, 2014). In order for an SET to be successful; energy supply and demand transformation is necessary, along with sufficient supply to consumers within the resources constraints (Sgouridis & Csala, 2014).

South Africa is experiencing numerous challenges, such as low economic growth, social disparities, and poor governance. All these challenges prove to significantly impact the progress that should be made to foster and eventually achieve, an SET. Key aspects of the problem that directly affect the electricity sector are:

i. South Africa's energy sector relies heavily on fossil fuels for the production of electricity creating a number of problems, such as high carbon emissions (Department of Minerals and Energy, 2003; Montmasson-Clair, Ryan & Moilwa, 2014)
ii. South Africa has seen a number of 'initiatives' in the energy system, such as, but not limited to: increases in tariffs, supply-side crises, the introduction of renewable energy into the energy-mix, Independent Power Producer Programmes, carbon taxes. (Eberhard, Leigland & Kolker, 2014; Department of Energy, 2015a; Eskom, 2017b) .
iii. South Africa is faced with many socio-technical challenges such as: inequality, unemployment, and a lack of skilled workers (Department of Environmental Affairs, 2011; National Planning Commission, 2011).
iv. Transitioning to more sustainable production and consumption patterns are of paramount importance to society if South Africa wants to achieve a sustainable future (Camaren & Swilling, 2011; Musango, Brent & Bassi, 2014).

Historically, little attention has been paid to the impact that sustainability transitions have on a country and country-specific indicators that measure developmental progress. Thus, an investigation into whether South Africa is fostering an SET, and will ultimately achieve an SET by 2050, is required. The investigation will be intitiated by determining the need for South Africa's electricity sector to transition to sustainability, along with the mechanisms driving the transition. The following problem statement can therefore be derived from the stated challenges: It is indefinite as to whether an SET will be achieved in South Africa within the determined time frame (i.e. by 2050), and, it is uncertain as to whether the current mechanisms (such as the IRP) are sufficient to foster a transition to sustainability within the South African electricity sector.

1.2 Research Question

From the overview of the existing literature, and the problem statement discussed above, it is evident that several developmental challenges exist within the South African context. Challenges that are particularly relevant to this study, given the focus on the sustainability of the South African electricity sector, includes, amongst others, questions surrounding whether South Africa will uphold its commitments to reduce greenhouse gases, follow the guidelines set out in the multiple policies, and achieve the targets set in the revised IRP.

Thus, when the sustainability, or the process of transitioning to a state of sustainability, of the South African electricity sector is considered, the primary research question that needs to be addressed can be expressed as: Is South Africa fostering an SET in the electricity sector?

With the aim of the research to contribute to the effective knowledge towards fostering an SET in the South African electricity sector, two secondary research questions stem from this primary question:

i. By what criteria can an SET be defined for South Africa?
ii. Is South Africa's rate and scope of change of the electricity sector's transition to sustainable sources of generation sufficient, thus will the current efforts bring about an SET within the desired / necessary timeframe?

Therefore, there is a need to determine the status quo of the South African electricity regime's SET, and the impact it is has on a country level. Also, further definition of an SET needs to be developed in the form of some criteria. This will be developed within a South African context, from existing transition-theory literature and frameworks. Finally, there is a need to investigate the reasons as to what may be inhibiting South Africa's SET and determine what can be done to foster an SET in South Africa. These questions are to be answered through the application of an appropriate research methodology, which will assess the state of South Africa's SET over the time horizon 2010 – 2050.

1.3 Research Objectives

To guide the research process, research objectives have been defined to support the research aim. The following objectives have been defined to answer the first secondary question: *By what criteria can an SET be defined for South Africa?*

i. Investigate the emergence of the sustainability concept and the role of sustainable development and the green economy concept both globally and for the South African context.
ii. Critically review SET-literature by using a systematic review, to analyse existing transition theories;
iii. Study SET-literature and determine if existing SET criteria are applicable to a South African context; and, if not,
iv. Develop a set of criteria for an SET based on the existing literature that is applicable to the South African electricity regime.

The objectives that will support the second secondary question: *Is South Africa's rate and scope of change of the electricity sector's transition to sustainable sources of generation sufficient, thus will the current efforts bring about an SET within the stipulated timeframe?*

i. Investigate the current state of South Africa's SET using an appropriate model;
ii. Investigating appropriate modelling techniques and employ a benchmarking process to select the best methodology;
iii. Develop a model, using the selected modelling technique, to model South Africa's SET;
iv. Develop, test and evaluate possible future scenarios with the model; and
v. Develop possible solutions for South Africa's SET, and make recommendations.

In summary, it is necessary to determine whether a set of criteria, by which to measure the sustainability of South Africa's electricity sector exists, and if not; develop such a set of criteria for the South African context. Also, determine the rate at which South Africa's electricity sector is transitioning to sustainability, and whether this rate is sufficient to achieve the policy goals. Furthermore, the developed criteria will guide the development of the appropriate model type to determine the transition progress by modelling the IRP policy and alternative scenarios, to determine possible pathways to successfully foster an SET.

1.4 Significance of Research

The purpose of this research is to add to the effective knowledge of SETs, particularly for an electricity sector in the South African context. The research will lead to a better understanding of the current challenges that encompass an energy transition of this magnitude, how to measure or define the scope of the transition, and, to build a model with the intension of testing possible futures by inforcing various system constraints and analysing the systems likely evolution over time. Finally, the research aims to look at the co-evolution of social, environmental, economic and technological aspects and examine them coherently to observe feasible pathways towards sustainability.

The research output aims to initiate discussions between varying audiences, from technical and non-technical backgrounds, in terms of the development of more informed, holistic and inclusive policies and mitigation strategies that foster a transition to sustainability at the required rate. These discussions help to create an awareness between stakeholders, of what is necessary in terms of strategic collaboration and concessions that are necessary to achieve a sustainable electricity sector in the future.

The study could be used to reanalyse the current policies and make the necessary adjustments to achieve South Africa's economic, social, environmental and technological goals. Thus, the research will be beneficial to multiple actor groups, including government and policy-makers. This study could also be used by the private sector to gain foresight into possible issues and develop action plans from which to advise the government and other private sector actors. Finally, the study could also be used by students and academics to gain an understanding of the energy sector and its sustainable transition in further detail, and more specifically the electricity sector and its' socio-technical impact on provincial and municipal levels.

1.5 Limitations and Assumptions

The following limitations and assumptions are stated for this research:

The research is limited to the electricity sector of South Africa and assumes a socio-technical frame of reference, with a focus on the national innovation system on a country level. The existing electricity system will be used as the baseline measure for the implementation of various scenarios. A set of criteria, by which to measure the transition, is developed based on existing frameworks and transition theory literature as the first step in a dual-narrative approach (see Section 1.6.1), and a model was developed in Chapter 7. The criteria and the model correspond with one another to determine the electricity sector's transition status.

The research focuses on a systems-level of detail and thus, assumptions made with regards to lower level details are explicitly stated throughout the document. Endogenous, exogenous and excluded variables are clearly stated and all calculations and data used in the modelling process are openly available.

A modelling technique that is suitable for modelling complex, dynamic transitions is used to model various scenarios for the South African electricity system. This technique was determined by conducting a simple benchmarking analysis.

The research assumes that the South African electricity sector's grid structure and transmission infrastructure will be able to accommodate the various model scenarios. The model also assumes political neutrality. However, it focuses on various social, technological, and economic aspects of the electricity transition. The model assumes a timeframe from 2010 to 2050, as according to the most recent IRP's timeframe.

1.6 Research Approach

The stated primary research question (Section 1.2) requires systems thinking and a multidisciplinary approach to propose interventions that consider the environmental, social, technological and economic perspectives. Therefore, the literature review makes use of a systematic review methodology to analyse sustainability, existing policies relating to the electricity sector, as well as various frameworks and transition theories (see Section 1.6.1). Three methodologies are reviewed and the most appropriate method to model the complexity of an energy transition to sustainability was selected by conducting a benchmarking analysis. These three methodologies include: System Dynamics, Multi-Criteria Optimisation, and End-Oriented Simulation, which are presented in Chapter 6, for a more detailed outline of each chapter's contents refer to Table 1.1.

Table 1.1: Chapter Objectives

Chapter	***Chapter Objective***
Chapter 2	*Sustainable Development and The Green Economy* Provide a brief overview of the green economy concept and sustainable development with the aim of understanding why it is necessary for society to transition to sustainability.
Chapter 3	*Transitions Theory* Introduce existing transition theory literature, to gain insight into the various theoretical frameworks that have been used to define and understand transitions on different system levels and contexts. Review energy transition literature with the objective of determining what it entails and the complexities it encompasses in terms of the role of policy, technology and governance. Analyse global energy transition progress to gain insight into the status of other states in transition.

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Chapter 4	*The South African Electricity Sector* Review the South African electricity sector to gain a better understanding of the structure of the sector as well as the mechanisms driving a possible transition to sustainability.
Chapter 5	*Sustainable Energy Transitions Criteria Development* Review existing sustainable energy transition frameworks and develop a criterion with possible indicators for an SET in the South African context.
Chapter 6	*Modelling Methodologies* Investigate the three possible methodologies: Multi-Criteria Optimisation Modelling, Discrete Event Simulation Modelling and System Dynamics with the aim of understanding the various offerings and capabilities of each methodology. Determine the best approach to model the SET through a benchmarking analysis of the three Methodologies.
Chapter 7	*Problem Structuring and Model Development* Introduce the system dynamics methodology and provide a brief outline of the model development process. Define the model boundary, period of analysis and explain the data acquisition process. Present and explain the causalities shown in the developed Casual Loop Diagram. Define the mathematical logic of the model structure for each sub-model. Test, verify and validate the model development process. Present the planned model scenarios.
Chapter 8	*Results and Analysis* Present and discuss model scenario results in the form of graphical and tabular results with the aim of linking the results to the set of criteria developed in Chapter 5.
Chapter 9	*Conclusion and Recommendations* Conclude the model results with the aim of determining the ‘status’ of the South African electricity sector’s SET. Make observations and recommendations for the way forward for the SET and comment on the effectiveness of the systems dynamics modelling technique in answering the research question

1.6.1 Introduction to Literature Review Methodology

The Systematic Review Method relies on rigorous, systematic and transparent methods to minimise the bias in results. Bias, the systematic distortion of an estimated effect, is to be avoided and a true reflection of the status of the sustainable energy transition is to be reflected throughout the review.

Further motivation for the use of this method includes (O' Conner , E; Whitlock , E; Spring, 2008):

i. The method provides transparency due to the explicitly stated objectives/ questions that need to be answered;
ii. Risk of bias is reduced due to the systematic method of searching literature;
iii. Consistent evaluation of available information also reduces the risk of bias; and
iv. Transparency is increased as the reader is given information from multiple sources.

Due to the transparency of this method, it enables literature to be updated more easily as new information is published. To conduct the systematic review process, literature from a variety of sources such as: articles, reports and policy documents are reviewed.

The review of literature is the first step in the dual-narrative approach, as seen in Figure 1.1. The Stylised Narrative will consist of a funnelled approach. The broader context of sustainability will be investigated; followed by transitions theories, energy transitions and then more specifically for the electricity sector in the South African context as outlined in detail in the chapter aim.

The output of the narrative phase is the developed criteria for South Africa's electricity sector SET, which will inform the model structure. In the final phase, which is addressed in Chapter 8, the model informs the narrative by interlinking model scenario results with the developed set of criteria, to determine possible mechanisms to foster an SET.

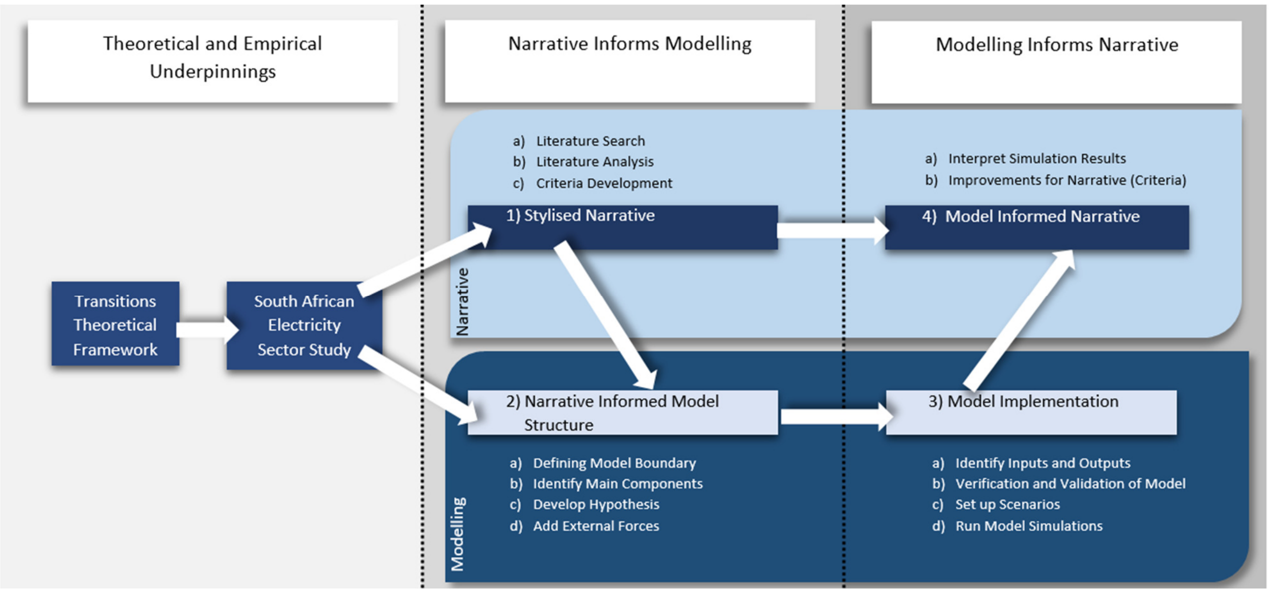

Figure 1.1 The Dual-Narrative Approach

2 Sustainable Development and the Green Economy

2.1 Introduction to Sustainable Development

In 1986, when a global awareness came about that issues such as poverty, environmental degradation and population growth cannot be addressed in isolation, Sustainable Development was seen as a possible means to address these problems. However, at the time, actors were struggling to agree on an acceptable definition for the term - sustainable development (World Commission, 1987).

The notion of sustainable development implies that society must be able to attain social objectives, protect vulnerable groups, and develop institutions for future development without placing the future generations in a detrimental position (The Department of Economic and Social Affairs of the United Nations, 2008). The foundation of sustainable development encompasses the improvement of the current socio-political governance, specifically towards practices that are more equitable and environmentally sustainable.

In the report released by the World Commission "Our Common Future" in 1987, sustainable development was seen as a process of change; where future and present needs are met through a proactive change in use of resources, investments and technological development. According to the report, sustainable development cannot be seen as an 'end goal' to harmony between all domains, but rather the concept implies that there are limitations to the earth's ability to absorb the impact that human activities have on it (World Commission, 1987). The World Commission (1987) also recognises that "painful choices" will need to be made due to the complexity of the change process, and sustainable development rests on the will of political leaders.

2.2 Global Energy Demand

Energy is essential to long-term economic growth. As the world develops and population increases, additional energy is needed to drive economic activities (Grubler, 2012). In order to ensure the prosperity of future generations, two central energy issues need to be addressed: securing a supply of reliable and affordable energy and the rapid transformation of society to a low-carbon, efficient and environmentally sustainable energy supply system (Malyshev, 2009).

In order for a society to prosper and grow its economy, energy is a necessary component. Although, energy, capital and labour are limiting factors to the rate of growth of society (World Commission, 1987). With worldwide, rapidly growing populations; and many countries growing at a rate greater than the average 2per cent per year; energy demand continues to rise (Omer, 2008). Industrialised economies, with high standards of living in many wealthy developed countries, consume 75per cent of the worlds energy supply. Yet, they only hold 25per cent of the world's population, further exacerbating the energy-emissions nexus[3] (Omer,

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[3] The nexus approach investigates the connection or series of connections of two or more factors. The approach has attracted significant interest from the global community of researchers and organisations alike, and is considered a way of tackling the interdependencies between various factors, for example; sustainable development focuses on the water-

2008). Access to electricity remains unevenly distributed worldwide. Sub-Saharan Africa and South Asia are regions with the highest population, which do not have access to electricity and use traditional biomass as their main source of energy (Malyshev, 2009) . Developing countries require more energy to grow their economies. However, developed countries also continue to grow - resulting in an overall increase in global energy demand.

According to BP (2016), there is an improvement in the global energy intensity.– This refers to the amount of energy used per unit of GDP, thus development is requiring less energy, which in turn could offset the global energy demand. Figure 2.1 shows the global primary energy usage and the annual demand growth per fuel type. The International Energy Agency (2015) states that, energy sectors in many parts of the globe are currently transitioning and this can be seen by the restrained growth of the final energy demand in 2014. The growth was a third of the level it would have been, had policies to drive sustainable change not been introduced. Therefore, some improvements can be seen in the global arena, in terms of improved energy intensities and reduced energy demand.

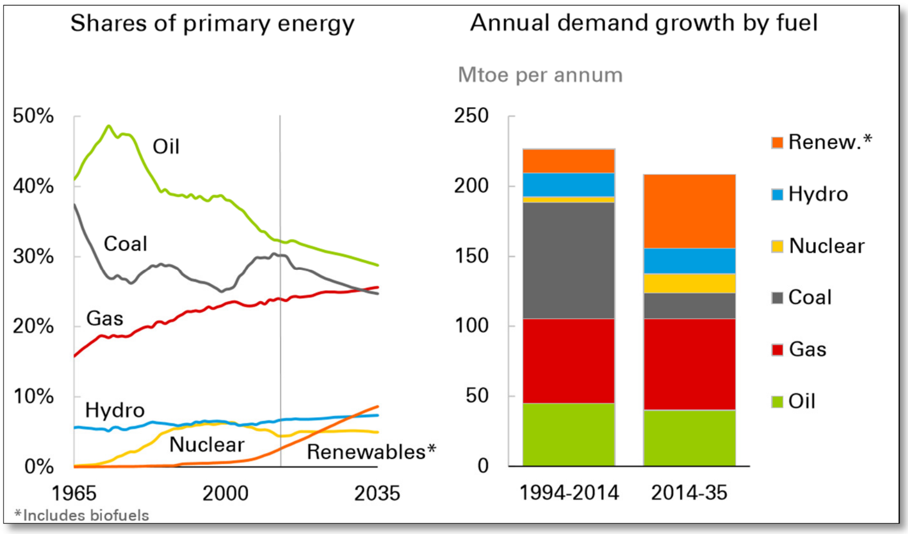

Figure 2.1: The changing global fuel mix for the primary base case: Outlook till 2035 (BP, 2016)

2.3 Transitioning to a Sustainable Growth Path for Energy

In order to achieve sustainable development, a country needs to increase the availability of modern energy services to all its citizens at a rate that is affordable, while ensuring social cohesion and environmental protection (Davidson, Winkler, Kenny, Prasad, Nkomo, Sparks, Howells & Alfstad, 2006).The sustainable development concept can be applied to various sectors. In the residential sector, the concept implies that resources such as firewood and charcoal, are replaced with electricity. The concept can be applied when introducing households to technological innovations, which improve efficiency and tackle environmental problems, such as carbon emissions and waste disposal (Davidson *et al.*, 2006). In industrial and commercial

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energy-food-climate nexus and the urgent need for a joint approach to policy development and practice. For more information refer to: https://www.2030wrg.org/team/water-security-the-water-food-energy-climate-nexus/

sectors, sustainable development implies the provision of energy resources that are sustainable, while simultaneously ensuring the sectors economic competitiveness and future growth (Davidson *et al.*, 2006).

In order to speed up the transition to a low-carbon energy system, a radical transformation needs to take place on both a societal and individual level (Malyshev, 2009). The role of the state is essential in a sustainable energy transition. Governments, at both national and local level, need to integrate strategies and co-ordinate various mechanisms to lead a transition on a sustainable path (Mah, Wu, Ip & Ronald, 2013). Households, motorists and businesses need to shift their mentalities to more sustainable energy usage patterns, and implement energy efficient technologies. Government's role is essential to drive the process and should provide the necessary financial incentives and frameworks to ensure both energy efficiency, energy security and reduced emissions goals are achieved (Mah *et al.*, 2013).

2.4 **Introduction to the Green Economy**

Numerous humanitarian challenges exist on a global scale, such as: poverty, food and water insecurity, unemployment, resource scarcity, climate change, financial crisis, pollution, and excessive CO_2 emissions. Debates centred around these challenges have erupted on multiple levels in the international domain, with regards to what can be done, who is meant to do it, and to what extent (Smit, 2015). These issues drive nations to seek alternatives. One alternative is the green economy concept (Swilling, Musango & Wakeford, 2016).

The green economy concept is a relatively new framework, it aims to catalyse a transition that maintains a balance between sustainability and the development of state (Swilling *et al.*, 2016). The green economy notion has a backdrop in sustainable development and revolves around the complex relationship between social equity, environmental equity, and economic development.

The term 'green economy' first appeared in literature by Pearce *et al.* in 1989. Although, before 2008's global financial crisis, the term had received little acknowledgement. Post 2008, when tensions were high in the global economic recession, coupled with concerns of resource depletion and climate change, the green economy initiative became an attractive alternative and was supported by numerous leading economies, financial institutions, and international organisations (United Nations Environment Programme, 2011; United Nations, 2012; Smit, 2015).

In order to account for the dynamic and complex nature of transitions, a broad perspective definition of the green economy is defined, which considers a holistic approach: "*An economy that not only improves human well-being and lessens inequality but also reduces environmental risks and ecological scarcities*" (United Nations Environment Programme, 2011). A second definition refers to the green economy as, an economy which is sensitive to the need to minimise pollution and carbon emissions. The economy still focuses on the need to reduce environmental damage, by concentrating on sustainable production and services, and sustainable consumer practices (Ocampo *et al.*, 2011). The main priority of the green economy is to demonstrate that the greening of economies should not prohibit or slow growth. Alternatively, the greening of an economy should act as a driver of green growth, through the creation of green jobs and work to decrease poverty (United Nations Environment Programme, 2011).

Figure 2.2 displays the various components that require integration to achieve green growth. Essential questions that are asked by many countries, developed and developing alike, is whether societies can afford to implement the green economy concept, and likewise can they afford not to?

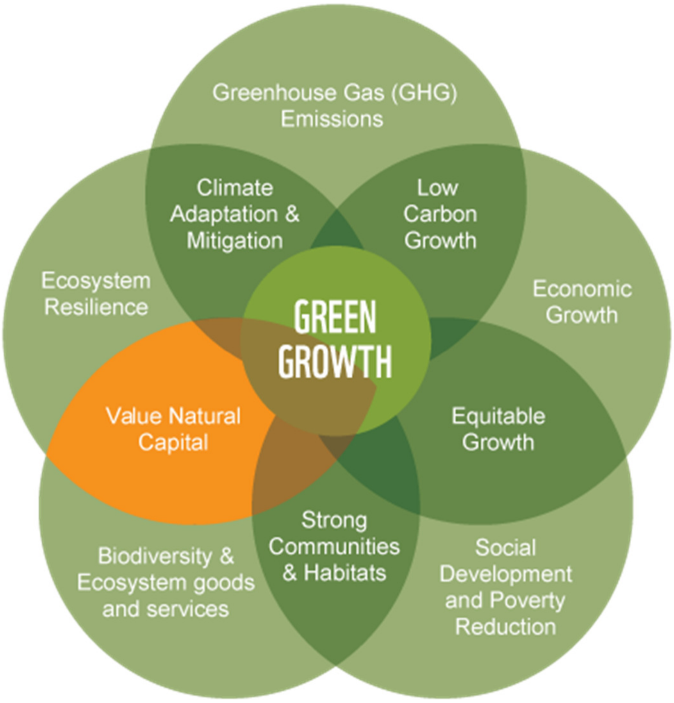

Figure 2.2: The Green Economy Model (Heart of Borneo, 2016)

The green economy concept has received much criticism, due to a number of challenges. Some critics complain of a lack of consensus between international parties on principles such as, defining the level of low emissions, green growth, as well as measuring sufficient economic progress (Smit, 2015). Other criticisms, involving disputes about the knowledge of the benefits of the green economy, versus the amount of financial investment needed for implementation of the concept (Allen, 2012a). Governments are urged to develop their own policies and legislation around the green economy concept, due to varying factors such as the country's level of development, resource availability, stability of state and available financial investment (Ocampo *et al.*, 2011; Allen, 2012a).

A large number of the current policies and academic literature on the green economy focus on integrating concepts from sustainability and environmental spheres, with those from economic and industrial domains - in order to create a feasible solution (Bina, 2013). Policies with a range of solutions exist, from conservative propositions to ones that are optimistic and drastic. Bina (2013) has defined a means of classifying varying policies into three approaches. Firstly, policies that suggest few changes are classified as "Almost Business-as-Usual". Secondly those that attempt to green society – "Greening". And finally, policies that propose radical transformative changes – "all change".

Much confusion has evolved over the past few years as to whether the green economy concept is to replace the sustainable development concept, because of the similarities between the two concepts. However, according to Allen (2012b), the green economy concept goes hand-in-hand with the sustainable development goals, and should be seen as a means to achieving progress in the broader context. Green growth and the green economy are similar terms that both refer to low-carbon development (Bina, 2013).

2.5 Energy and its Role in the Green Economy

The need for an energy transition has become widely apparent as the current energy systems are unsustainable for all domains: environmental, social, and economic (Grubler, 2012). All aspects of the energy generation process, ranging from extraction to conversion to generation, cause major social and environmental problems. The existence of a society that is sustainable; is dependent on the existence of a sustainable energy system (Omer, 2008). The energy utility sector is emerging as a key interest for sustainable planning and strategy development, because of its large resource requirements and emission production. Energy security, economic growth and environmental protection are key energy policy drivers in any country in the world and these aspects are closely tied to the green economy concept (Omer, 2008). Thus, to achieve many of the green economy goals, it is essential that the energy sector transitions to a sustainable pathway.

2.6 South Africa’s Green Economy

With the recent evolution of the green economy, many economies shift to sustainable energy sources by incorporating renewable energy sources into their energy mix. Thus, reducing carbon emissions and easing the strain on depleting fossil fuels. Consequently, with this transition, renewable energy technologies have become a popular and attractive alternative and are continuing to prove their ability to contribute sufficient capacity to the grid (Department of Energy, 2015a).

South Africa has followed the global trend of implementing the green economy concept and set its trajectory towards achieving sustainable growth and development, through the implementation of various policies and strategies. This action is necessary and essential, as the South African economy is currently pushing the limits of its resource constraints – water-scarcity, little arable land, and over-reliance on coal and imported oil, which are contributing factors that could leave the country in serious trouble if not addressed soon (Von Bormann & Gulati, 2014).

The South African government aims to stimulate the local industrial sector through the introduction of renewable energy technologies. The local manufacturing of equipment, parts and components for the new renewables sector could potentially result in substantial economic growth and employment opportunities, while simultaneously expanding the green economy (Department of Economic Development, 2011; National Planning Commission, 2011).

Several documents have been developed, and a summary is provided in Table 2.1.1. The Green Economy Summit, held in 2010, at the Sandton Convention Centre, was a further catalyst for embracing the sustainable development goals in South Africa. Additional motivation includes, realizing President Jacob Zuma's pledge at the Copenhagen Climate Change Summit in 2009, to reduce carbon emissions by 34per cent by 2020 and 44per cent by 2025 (Baker *et al.*, 2014).

Table 2.1: South Africa's Policy Documentation with a focus on Sustainable Development and the Green Economy (Musango *et al.*, 2014)

Year	Policy/ Strategy/Plan	Policy Goal/Objective
2009	South African Framework for Responding to Economic Crisis	Multiple strategies for all sectors were stated. However main priorities were to prevent further poverty and inequality of lower income brackets, and ensuring that all economic activities strengthened the capacity to aid economic growth
2010	National Green Economy Summit and Programme Report	The decision was made to champion the transition to a green economy to achieve a resource efficient and low carbon pro-employment growth path.
2011	New Growth Path Green Economy Accord Green Jobs Report	Create five Million jobs by 2020 (Department of Economic Development, 2011) Minimum of 300 000 green jobs by 2020 (Department of Economic Development, 2011) Evaluation of actual job creation potential of the Green Sector
2011-2014	National Strategy for Sustainable Development and Action Plan	Goal to develop and promote new social and economic goals based on ecological sustainability and build a culture that recognises that socio-economic systems are dependent on and embedded within ecosystems
2011	National Development Plan Vision 2030	The elimination of poverty and reduction of inequality by 2030 through uniting South Africans, promoting citizenry, building a capable state, strong leadership, bringing about faster economic growth, higher investment and greater labour absorption. (National Planning Commission, 2011)
2013	National Climate Change Response Policy	Firstly, to effectively manage the inevitable climate change impacts and secondly to make a fair contribution to the global effort to stabilise greenhouse gas (GHG) concentrations
2010-2050	Integrated Resource Plan for Electricity	The 'living plan' for energy in South Africa

To maximise the long-term benefits that the green economy concept should offer, it is necessary to define a clear national industrialisation strategy, which focuses on investment in industry and infrastructure. Much of the green growth in South Africa is being funded by private capital. However, it is necessary for public finances to fill the gaps and cover the associated risks with new and alternative technologies (Department of Trade and Industry, 2013). Therefore, due to the associated risks with green investments, it is necessary for government to catalyse funding facilities and develop support mechanisms to green industries.

The number of existing policies surrounding economic growth, national development, and green growth can be regarded as the drivers of the transition to greener energy technologies. The introduction of renewable energy into the energy mix, through the REI4P, has played a vital role in South Africa's green growth path (Eberhard *et al.*, 2014). The government aims to further stimulate the economy through the introduction of localised manufacturing and the creation of green jobs in the energy sector (Maia, Giordano, Kelder, Bardien, Bodibe, P., Jafta, Jarvis, Kruger-Cloete, Kuhn, Lepelle, Makaulula, Mosoma, Neoh, Netshitomboni, Ngozo & Swanepoel, 2011; Department of Trade and Industry, 2013).

2.6.1 The South African Green Economy Model (SAGEM)

Previous research concerning the green economy transition in South Africa, consists of the South African Green Economy Model (SAGEM), which modelled the green economy of South Africa using a System Dynamics approach (Musango, Brent & Bassi, 2014). SAGEM focused on four of the nine areas of the green economy (natural resources, agriculture, transport and energy) and investigates whether higher growth can be attained with a more sustainable, equitable and resilient economy. SAGEM explores the transition to a green economy for South African with a specific focus on the ability to meet low carbon targets, resurce efficinety and job-development targets (Modise, 2011). The green economy transition is linked to a number of policies such as the NDP, NGP, National Climate Change Response Policy, and the Industrial Policy Action Plan (Modise, 2011).

SAGEM assessed the impacts of investments in the green economy for three spheres: environment, society, and the economy. The model ran various scenarios to determine the difference between two approaches: the business-as-usual approach, and a green-economy-target-specific approach. The model found no optimal solution that could simultaneously improve multiple objectives, for example: scenarios with increased investment, increased employment, but decreased emissions (Musango, Brent & Bassi, 2014). The researchers involved in the SAGEM project have been asked to update the SAGEM model.

2.7 Conclusion

The global energy demand and its impact on sustainable development was reviewed, and furthermore the green economy concept was investigated for both the global and South African context. South Africa's implementation of the green economy concept, through various policies and strategies implemented by the State, has displayed the willingness to achieve sustainable growth and development. However, the implementation and continuous action of these policies and strategies are essential. South Africa is currently experiencing many constraints, such as poor economic growth, unemployment, resource constraints, water-scarcity, limited arable land, and an over-reliance on coal and imported oil. All of the aforementioned constraints are contributing factors to the complexity of transitioning the system (the electricity regime) to sustainability.

3 Transitions Theory

3.1 Introduction

The array of global issues points to a solution that not only continuously evolves over time, but incorporates a holistic approach to all domains – social, environmental, economic, and political. This is a complex undertaking and requires an understanding of environmental impacts and social effects. This understanding is essential for the successful formulation of policies, social development and investment strategies. The implementation of sustainable development has been noted as a complex process, which is dependent on several stakeholders (Allen, 2012). In order to realise a transition on a country-level, a number of transformations need to occur. Furthermore, the process involves multi-dimensional and long-term based events, which cause the socio-technical systems in place to shift to more sustainable practices and resource usage (Jonker, 2015).

To gain an understanding of what an energy transition encompasses, the chapter has the following objectives:

i. Review various transition definitions;
ii. Review existing transition theories and their applicability to energy transitions,
iii. Understand the complexities surrounding energy transitions,
iv. Explore the multi-level perspective for transitions in a South African context,
v. Understand the role of state in energy transitions and challenges associated with governance,
vi. Define a ‘just’ transition,
vii. Determine the role of technology in an energy transition; and
viii. Determine the mechanisms that are driving a global SET.

3.1.1 Defining a Transition

The word transition, as defined by Berkhout (2008), means: a radical qualitative change in inputs, technologies, and products. A second notion identifies a transition as a radical change in actor networks, or technological capabilities, which constitute socio-technical regimes as being most significant (Berkhout, 2008). Lockwood, Kuzemko, Mitchell & Hoggett (2013) define a transition as, “*a set of processes that lead to a fundamental shift in socio-technical systems, which involve far-reaching changes along different directions such as material, organisational, institutional, political, economic and socio-cultural*.”

A Socio-Technical Transition (STT) can be defined as, a deep structural change, such as the evolution of a country’s energy or transportation system. These evolutions involve complex, long-term reconfigurations of policy, society, technology, knowledge domains, and cultural practices, which are also linked to multinational companies with broad networks (Baker *et al.*, 2014). The Socio-Technical (ST) perspective, from a sustainability perspective, incorporates two key standpoints. The first, is the creation and diffusion of cleaner technologies, which facilitates changes in social, political and economic systems. Secondly, ST recognises that clean technology alone cannot achieve sustainability and thus, changes in energy infrastructure are necessary in order for a STT to occur (Smith & Stirling, 2008).

Sustainable transitions are described as, *"long-term, multi-dimensional and fundamentally transformative processes through which socio-technical systems shift to a more sustainable approach of production and consumption"* (Lockwood *et al.*, 2013). Thus, a sustainable transition focuses on pathways of change that are in line with sustainable development goals and green growth.

According to Geels (2010), socio-technical transitions to sustainability are not easy to achieve and are considered complex , due to lock-in mechanisms. These mechanisms include: sunk investments, behavioural patterns, vested interests, infrastructure, and existing subsidies and regulations in all aspects of economic, social, political and environmental domains, existing energy structures, transportations, housing, food-systems, and so forth. For example; sustainability is a collective good problem, where debates such as the relative importance of various environmental issues revolve around varying stakeholder values and beliefs. Thus, private actors have no immediate incentives to address sustainability problems, thereby leaving public authorities and civil society as crucial drivers of the transition to sustainability (Geels, 2010).

Berkhout (2008) suggests that a sustainable transition is characterised less by new technology in a system (such as renewable energy, bio-fuels or hydrogen), and more on the emergence and maintenance of diverse and adaptive ST systems. Therefore, Berkhout (2008) proposes that, rather than focusing on transitions, it may be of more importance for policy-makers, producers, and consumers to focus on the creation of a variety of environmentally efficient systems - in order to satisfy their essential economic and social needs. Moreover, Berkhout (2008) states that instead of policies focussing on optimal solutions, they should rather encourage a variety of different solutions and then create a market and regulatory conditions, which will permit the diversity to be maintained. Thus, instead of the focus being on a STT from one past to a new future, the focus should be on achieving the fundamental needs. These needs include: warmth, nutrition and mobility, and then aim to meet these needs by fostering diversity through a selection-environment of price structures, regulations, infrastructures, and behaviours. This suggests that a radical mental shift is necessary to conduct a transformation on this level of intricacy.

3.2 Existing Frameworks on Transitions

There is a growing body of literature on managing a transition for a sustainable future. The topic is gaining attention from both policy-makers and academics (Falcone, 2014). Four approaches have been reviewed and are presented here: A multi-level perspective on STT's, Strategic Niche Management, Technological Innovation Systems, and Transition Management.

3.2.1 The Multi-Level Perspective:

The Multi-Level Perspective (MLP) was first introduced by Frank Geels and explains STTs on three dimensions: Landscape, Regime, and Niche (Geels, 2011; Kemp & Van Lente, 2011). The MLP describes the world as being made up of ST systems. These systems consist of people, and their use of technology for activities in society. The behaviour of people is influenced by social norms and existing technical structures.

The high-level dimension, which is the Landscape perspective, is influenced by trends in the global society. This dimension is a macro-perspective that reflects intangible aspects, such as social values and political beliefs. Furthermore, it includes tangible aspects that involve institutions and their functions such as, pricing structures and trade patterns, and factors such as climate change and public awareness (Geels, 2011; Power, Newell, Baker, Bulkeley, Kirshner & Smith, 2016).

The Regime dimension, or meso-perspective, refers to the dominant practices, rules, and technologies that reinforce the existing ST system. The regime involves interdependent elements such as: the network of actors and social groups that adapt to the systems dynamics over time. Secondly, the regime includes informal and formal rules that address behaviours and actions of actors that preserve and steer the socio-technical system. Finally, there is a set of material and technological components that operate within the system (Geels, 2011). For example, in the energy sector, mainstream activities and structures that fall on the regime level include energy generation, energy transmission, and power usage.

The niche or micro-perspective is a small protected space where new radical innovations can evolve, away from the pressures of the socio-technical regime. These niche innovations may occur in Research and Development, or university settings where people develop ideas that are protected from mainstream society (Geels, 2011).

When a radical innovation that is developed in the niche dimension, becomes popular, consumers may decide to adopt the new technology or not. If trends in the landscape dimension pressurise the regime, a window of opportunity is created for the niche innovation to convince more consumers to adopt the technology, triggering a structural shift in the regime. When structural changes occur in the regime, 'alignments' between the three levels occur and this results in transformations. Therefore, the way in which the three dimensions interact will impact the form of the transition that unfolds and is indicative of the possible transition pathways (Power *et al.*, 2016). Geels (2011) illustrates the three dimensions of the multi-level perspective in more detail in Figure 3.1.

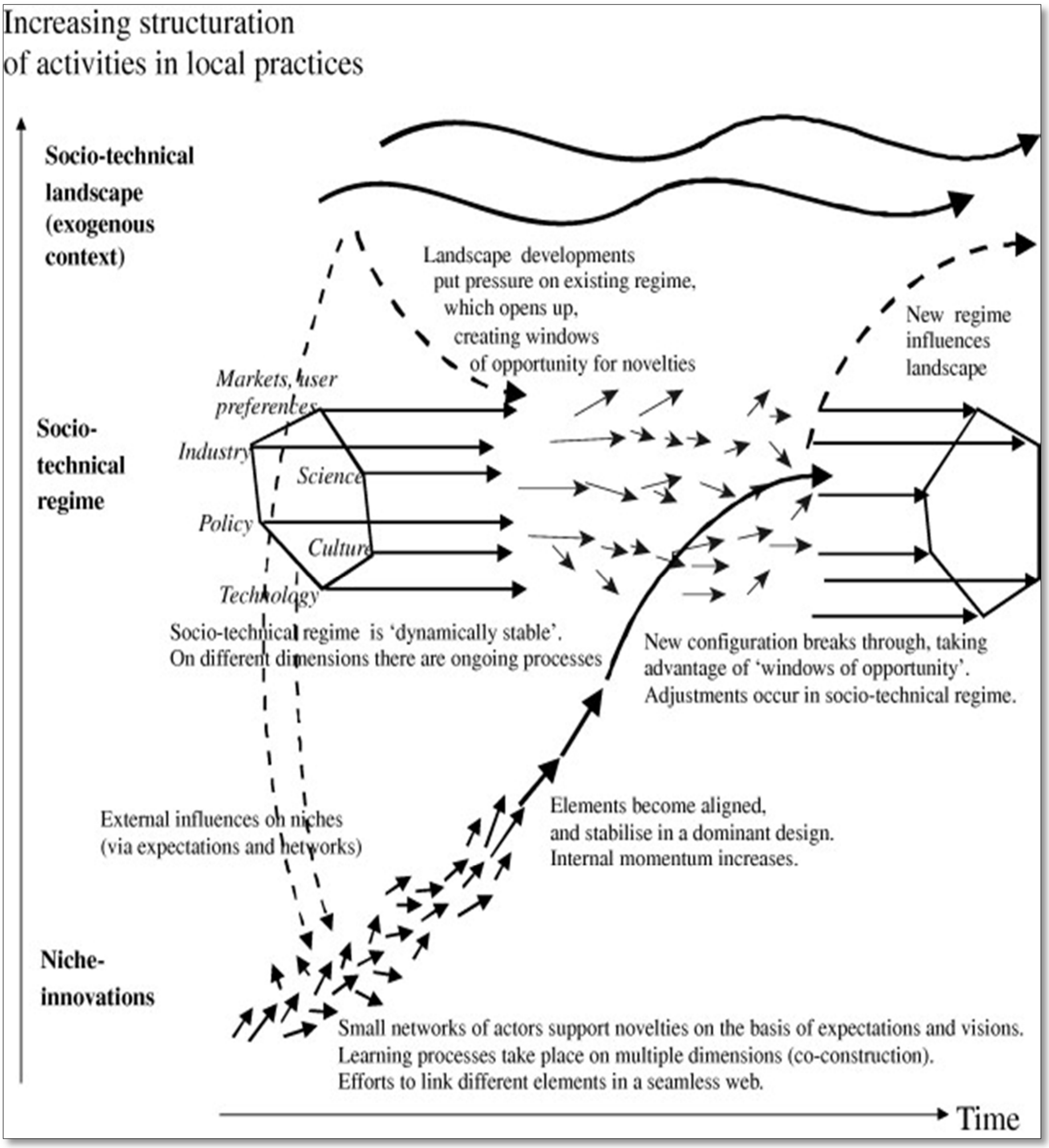

Figure 3.1: The Multi-Level Perspective for Transitions (Geels, 2011)

3.2.2 Strategic Niche Management

Strategic Niche Management (SNM) is a relatively new approach that enables the introduction and diffusion of new innovations that focus on sustainability through experimental pathways (Seyfang & Haxeltine, 2012). SNM entails the management of radical innovations that have diverging characteristics from those of existing infrastructure, user practices and regulations (Seyfang & Haxeltine, 2012). The process is seen as a bottom-up approach, in which innovations find themselves in technological niches. Through adoption, collaboration between multiple parties and exchanging of information; the innovation evolves into acceptable technologies, with wider acceptance, and eventually replace old existing technologies (Seyfang & Haxeltine, 2012; Falcone, 2014). This approach relies heavily on the sharing of information and ideas across various disciplines and between different institutions to successfully release an innovation to consumers.

3.2.3 Technological Innovation Systems

Technological Innovation Systems (TIS) are described by Falcone (2014) as, a combination of all institutional and socio-economic structures that affect the direction and speed of a technological change. The determinants of a technological change are embedded within societal structures. TIS is rooted in evolutionary economics and industrial dynamics, which account for competitive advantage for various domains – actors, technology, and infrastructure (Coenen, Benneworth & Truffer, 2012). The TIS approach focuses on the nature and rate of a technological change and defines it as, the dynamic network of actors that interact under varying economic and industrial areas, which are involved in the development, diffusion and utilization of the innovative technology (Falcone, 2014). Actors, networks and infrastructures are primarily focused on capabilities that will allow the generation of new technologies, products and services at a fast pace and high quality (Coenen *et al.*, 2012).

3.2.4 Transition Management

Transition Management (TM) can be defined as, a methodology that offers many practical tools and techniques to encourage collaboration amongst innovators (Baker *et al.*, 2014). This methodology places emphasis on a ‘bottom-up’ approach, where innovation is the main driver of change. The approach does not focus on the ‘trade-offs’ between social, environmental and economic factors, but rather on ‘integrating’ them and achieving balance between the domains. Transition goals are not fixed, but developed by society; and systems are designed to meet these goals through incremental steps.

TM aims at influencing structural changes within socio-technical systems, while simultaneously optimising the system by developing coherent policies (Kern & Smith, 2008). Thus, the TM approach differs fundamentally from regular policies that are aimed at achieving short term goals and developed and implemented by government (Loorbach, 2007). Rather, TM can be seen as a new type of governance, or as an arena for government and markets to merge thoughts on innovation and social learning; and collectively form goals to meet societal needs. Positive visions of the future play an important role in the development of various pathways to transition goals (Kern & Smith, 2008). Some criticisms for this approach state that TM does not consider the complex landscape in which policies are made, as well as the multinational firms involved in energy transitions that cannot be shaped purely by a single state (Baker *et al.*, 2014).

3.2.5 **Perspective on Transition Theories**

Four approaches to transitions were briefly introduced, however the preferred analytical framework for social-technical transitions is the MLP. This approach was selected because of the rational that focuses on a high-level perspective and the broader context. The approach alsoconsiders not only the emergence of niche innovations as adopters shift to the technologies, but the impact of these technologies on various 'levels' of integration over time. Moreover, it focuses on the ability of these new 'adoptions' to transform and make fundamental changes to the existing system. The landscape-level considers external dynamics, such as climate change, that play an influential role on actors in the regime level. The landscape-level focuses on the market structures, technology types, energy policies and governance, and scientific knowledge.

The TM perspective, in conjunction with the MLP, are key concepts that conceptualise the transition of a social-technical system to sustainability. The TM approach is centric to the idea that inclusive governance and effective policy implementation is key for emerging innovations to meet societal needs and make the desired impact. The TM perspective, when used in conjunction with MLP principles, lays foundations for policy-makers' thought-processes, which can enable an effective large-scale transition to sustainability through the implementation of new sustainable technologies into society.

3.3 Energy Transitions

Energy systems are characterised as socio-technical systems, due to the provision of heat, light and power to fulfil the necessary societal functions (Kern & Smith, 2008). Transitions are described as, a restructuring of social systems and processes over an extended period of time (Kern & Smith, 2008).

3.3.1 The Complexity of Energy Transitions

Energy transitions can be understood as, a set of structural energy systems that go about a deep transformation since the system can no longer accommodate elements of the subsystem. An example is South Africa's electricity sector adding generation capacity from renewable energy resources, to enable decarbonisation and reduce the dependency on the aging fossil fuel generation capacity (Valkenburg & Cotella 2016). Energy systems tend to exhibit strong path dependencies, due to large investments made into the technologies, plants and grid systems. Thus, electricity systems in general are not responsive and require time to transform (Power *et al.*, 2016). Energy transitions involve complexity, due to a number of reasons (Valkenburg & Cotella, 2016):

i. Numerous actors play different roles, have different interests and different transition goals.
ii. The diversity of values provide further challenges as the broad overarching goals of sustainability may be endorsed by all actors however, there are many pathways, existing of short term goals, which display the various priorities of actors in the transition.
iii. Energy transitions involve uncertainties and are based on future events and little factual knowledge is available to predict future outcomes, which makes planning and investments high risk.
iv. The production of knowledge is not linearly correlated with decision making and policy formation processes, rather, these processes are subject to contending power relations and varying agendas.

3.3.2 The Multi-Level Perspective and South Africa

The MLP framework and its assumptions are based on European states, where access to energy is mostly universal. Furthermore, the structures that are responsible for electricity and transportation are heavily regulated and they have not had to deal with supply shortages and outdated grid technologies (Power *et al.*, 2016).

In the South African context, the reality is very different to that of the European states. Firstly, access to electricity is not universal. Secondly, multiple forms of energy are used across various households based on the energy ladder (Mdluli & Vogel, 2010). Finally, many countries have liberalised electricity sectors, whereas South Africa has a monopolistic utility and has only recently (in the past six to seven years) started to connect Independent Power Producers (IPP) to the grid (Power *et al.*, 2016).

To understand the MLP for the electricity sector of South Africa, a brief explanation is given based on Baker *et al.'s* (2014) writing. Baker *et al.* state that the electricity sector is considered the 'regime', which incorporates the state-run, publicly funded electricity sector, policies and structures at a national level. Here, behaviour of the sector is determined by patterns in technology and influenced by policy makers, scientists, electricity users, investors, and other professional groups. In South Africa, a 'niche' would refer to, emerging entrepreneurial clusters of renewable energy IPPs and funders. A 'landscape' refers to demographic trends, political dogmas, economic performance of other sectors, and all other external influences on a macro-level (Baker *et al.*, 2014).

3.3.3 The Role of Policy in Transitions

Energy transition policies refer to, all activities initiated by policy-makers to implement TM. These activities aim to realise a SET, through the collective cooperation of all actors involved in the energy sector, over an extended period of time - which may take decades to transpire (Kern & Smith, 2008).

In the past, the electricity sector has provided investors with reliable, secure, and affordable electricity with low-risk and stable returns. However, the transition to sustainable sources, brought about by rapidly decreasing cost of renewable technologies, along with the drive to decarbonise the sector, has brought about the opportunity to increase energy security and reduce dependencies on imported fuels (World Economic Forum, 2015). But, due to the limitations of some renewable technologies such as the intermittence of supply and the technical and economic limitations of storage technologies for renewables, it is necessary that carbon-based technologies complement the use of renewable energy.

Policy-makers will have an essential role to play in the transition. One role includes pointing the industry towards the most effective pathway to achieve their objectives, by ensuring the most efficient technologies are added to the mix, the accessibility of renewables to the national grid, improving transmission and distribution infrastructure, ensuring fair and just tendering processes for new capacity additions, and promoting efficient and effective demand management (World Economic Forum, 2015). Figure 3.2 shows the evolution of the electricity value chain. Within this chain there is a shifting focus towards a more customer-centric focus where energy efficiency, distributed generation, electrification and flexibility are key areas of focus.

There is a need for policy frameworks that are efficient, stable and flexible. These frameworks also need to recognise the inherent uncertainty of today's technologically driven environment and economy (World Economic Forum, 2015). The World Economic Forum (2015) proposes the following actions for all key stakeholders, including policy-makers, regulators, businesses and investors:

i. **Plan the most efficient pathways to achieve policy objectives** – policy-makers should incentivise investments in energy efficient technologies, demand response services, upgrading of networks and generation plants and exploit renewable energy resources.
ii. **Build in flexibility and work to increase societal support** – policy-makers realise that uncertainties are inherent in the transition, thus incremental investments are more favourable, and the value of such investments should be communicated to society.
iii. **Ensure clear signals** - regulators clearly stipulate carbon pricing regulations and reward efficiencies, reliability and flexibility. Encourage predictability and fast responding supply to balance increasingly volatile supply and demand.

iv. **Create Level Playing fields across boards, businesses and technologies** – regulators remove unnecessary barriers to competition between utilities and new entrants and encourage appropriate physical interconnection.

v. **Engagement between all stake-holders to facilitate discussions and establish the most efficient pathways –** businesses, regulators and policy-makers need to engage with one another to develop strategies and business models that exploit all available opportunities and support the customer centric proposition

vi. **Engagement between investors, regulators and policy-makers to establish the best means of balancing risk and attracting return on investment –** continuous innovation of investment structures and encourage evolving risk profiles for various parts of electricity value chain.

According to the World Economic Forum (2015), energy policy needs to ensure a balance between three key outcomes: economic growth and development, energy security and environmental sustainability.

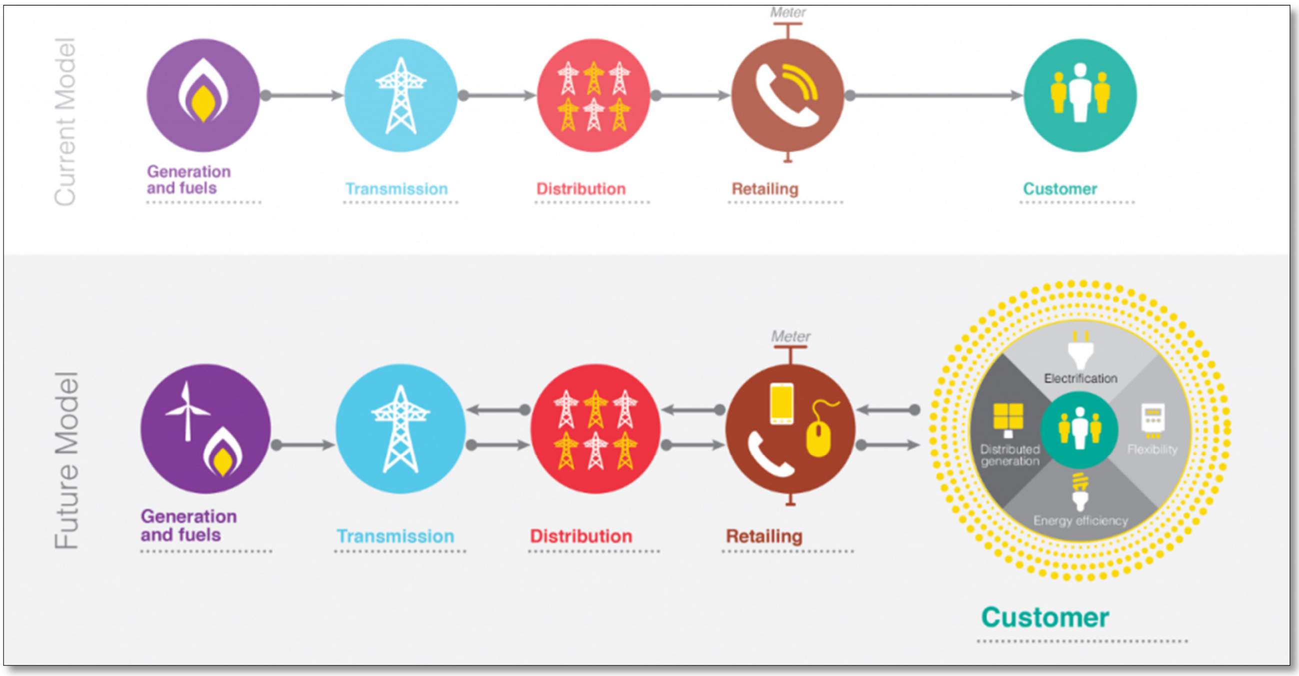

Figure 3.2 The future model for the electricity sector where new business and investment opportunities are customer orientated (World Economic Forum, 2015).

3.3.4 Energy Transition Governance

Governance can be defined as, a guiding process in which a social system coordinates, steers and managers itself (Mah *et al.*, 2013). The purpose of transition governance is to determine heterogeneity and negotiate until shared formulations of the energy system are obtained and commitments are made to set transition pathways (Smith & Stirling, 2008). According to Smith & Stirling (2008), the energy governance process is a 'deeply political process' and all actors involved in the process are required to be reflexive and open to alternative system formulations.

In a study done by Mah *et al.* (2013), to determine the role of the state in a SET in Japan, it was discovered that challenges associated with governance are due to path dependence, monopoly power, resistance to pricing reforms, and behavioural inertia. All of the aforementioned challenges are comparable to the South African electricity regime, which has recently experienced similar challenges (Pegels, 2010).

Heldeweg, Sanders & Harmsen (2015) stress that in order for energy governance between public and private institutions to be successful, a framework of governance needs to be established. This framework needs to uphold principles such as: participation, rule of law, responsiveness, consensus, orientation, equity, effectiveness and efficiency, accountability, transparency and collaboration. According to Mah *et al.* (2013), the government is to play a key role in the implementation of policies and facilitate change, by encouraging sharing of information and improved coordination between actors.

3.3.5 Just Transitions

A just transition refers to, a transition where both the sustainability transition goals and developmental state goals are achieved simultaneously (Swilling *et al.*, 2016). Developmental states are concerned with the structural transformation of a modern economy and are based on the state's ability to sustain growth and development, while maintaining rapid industrial progress (Swilling *et al.*, 2016). Swilling *et al.* (2015) argue that for South Africa to achieve these goals, the socio-political regime and the configuration of interests need to merge to form a suitable sustainability paradigm. An example of the beginnings of just transitions in South Africa, is the state's ability to link renewable energy investments and South Africa's developmental and sustainability interests.

3.3.6 The Role of Technology in an Energy Transition

A recognised driver of long-term economic growth and development, is change in the technologies used by society. In terms of 'technological determinism', technology is depicted as the main agent of change (Wilson & Grübler, 2011). According to Wilson & Grubler (2011), change in technologies, institutions and society are mutually dependent, mutually enhancing, and mutually dampening. Various authors agree on the role that technology plays in ensuring a successful energy transition. They agree that sustainable energy transitions will be a challenge if innovation and technological change are not implemented globally, with specific focus on developing countries (Wilson & Grübler, 2011).

The socio-technical perspective acknowledges the influential and interlinking roles that technology has on society, the economy, and the environment. The complex role that technology plays is wrestled within both research environments, and areas of governance (Smith & Stirling, 2008). The ideologies of society, such as standards of living, social movements, technology adoptions and the use of new technologies, influence the landscape around which the electricity regime is centred, and in turn have a significant role in the SET process (Smith & Stirling, 2008). This can be seen in factors such as electricity demand, energy efficiency, public acceptance of socio-technical changes, and consumer habits.

Power *et al.* (2016) state that the role of technology within a transition from the MLP largely places emphasis on niche-led innovations that rely on a bottom-up approach to transform society, and fail to consider the impact that actors in the landscape or regime have. These actors include multinational firms that have global influence.

South Africa is assumed to be a technology colony, due to the national innovation system still being on a developing level. Therefore, the country relies on the majority of technologies used for sustainable electricity to be imported for use in South Africa (de Wet, 2010). Grobbelaar, Gauché & Brent (2014) assess South Africa's potential to develop a manufacturing capacity, specifically for the domestic CSP industry. The analysis includes various recommendations regarding policy measures and an associated industry roadmap for the development of a competitive CSP industry in South Africa. Grobbelaar *et al.* (2014) also consider de Wet's (2010) perspectives on South Africa as a technology colony due to:

i. The weak flow of technology from the research side of product development,
ii. The large flow of products from developed countries into the technology colony, these products are in the form of licenced product designs, assemblies and finished products,
iii. Most of the business activities occur at the end of the product lifecycle; and
iv. Few activities exist in the research phase of the product development lifecycle, which take place in research councils and universities.

3.3.7 **New Technology Developments in the Energy Sector**

Several sustainable energy generation technologies are in the pipeline, which could have a massive impact on the energy sector in the future. There are three key areas of accelerated change: storage, smart grids (embedded and off-grid), and electricity generation (Zappa, 2014). Storage includes, improved batteries and other cost-effective storage methods. Smart grids integrate various technologies to pair information and electricity usage, to allow for more flexible and efficient generation, which is characterised by more efficient electricity generating sources, as well as the generation of power from unused energy sources (Zappa, 2014).

One such electricity generation technology was developed by a South African company, Heat Recovery Micro Systems[4]. The technology offers a renewable energy power generation technology alternative (in this case

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[4] http://www.ee.co.za/article/renewable-energy-baseload-power.html

waste in the form of heat) which is cost competitive for power utilities and smaller decentralised power generating systems.

Traditional OECD economies, with centralised power generation and transmission and distribution infrastructures, are undergoing major changes - which are disrupting traditional well-established economic models. These models are needed to obtain the necessary capital investments for long-term sustainability and they are necessary for the energy sector to remain attractive to both new and old investors (World Economic Forum, 2015). New electricity generation technologies, which provide clean and cost effective alternatives to current technologies, are favourable to investors (World Economic Forum, 2015).

One such technology is the Hydrogen Fuel cell, which is a storage technology that has gained in popularity and many large companies across the US (such as Adobe, Apple, Google, eBay, Microsoft, Target and Walmart) have adopted the technology, as either a primary or backup source of power (Fuel Cell & Hydrogen Energy Association, 2017). Other storage technologies that are rapidly gaining popularity are lithium-air batteries, and hydrogen energy storage (Zappa, 2014).

An alternative solar powered generator was designed by German architect Andre Broessel, who designed the spherical power generator prototype called '*beta.Ray*'[5]. This generator combines dual-axis tracking systems and spherical geometry principles, while capturing double the yield that a conventional solar panel yields in a smaller surface areas (Alternative Energy News, 2015).

A smart grid technology that is gaining popularity is the 'real time meter'. It records electricity consumption in real time, where the information can be used for remote-load balancing and disabling non-essential devices at peak usage (Alternative Energy News, 2015).

Distributed generation allows generation from multiple small energy sources, and offers economies of scale. Although it wastes power during transmission. Smart energy networks allow the distribution of electricity, from both local and distant sources, through the standardising of energy and power infrastructure allowing electricity to be used interchangeably (Zappa, 2014).

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[5] http://www.alternative-energy-news.info/spherical-sun-power-generator/

3.3.8 **Key Indicators for Sustainable Electricity Generation Technologies**

Renewable electricity technologies consist of sources such as geothermal, solar, wind, combustible renewables (Evans, Strezov & Evans, 2009). It is important to consider these key indicators when selecting technologies for an electricity mix - due to interrelated consequences in terms of lifecycle cost, emissions and social implications. Evans *et al.* (2009) suggest important indicators that must be considered when assessing modern electricity generation technologies:

i. The price per unit of electricity generated must be considered because unfavourable economics are not sustainable.
ii. The amount of greenhouse gas emissions per electricity generation technology and is a key parameter used to define sustainability.
iii. Energy efficiency of the technology; the more efficient processes are, the lower the requirements in terms of resources, and capital and operating costs.
iv. The amount of land used per technology type, since it is competing with agriculture and biodiversity for arable land.
v. The amount of water consumed by each technology type; it is not sustainable to have high consumption and evaporation rates if water shortages are a problem.
vi. Social impacts; the correct determination of human risks and consequences will determine social acceptance and understanding of the technology types.

According to Iddrisu & Bhattacharyya (2015) the following energy sustainability indicators for energy generation are important:

i. Energy security; the use of a country's own resources to generate electricity will decrease the dependence of a country on others.
ii. The degree of economic vulnerability of a country, due to international market conditions and dependence on resources such as oil.
iii. Energy productivity, the inverse of energy intensity; the output produces per unit of energy.
iv. The rate of household electrification.
v. Sufficient energy quantities are provided to meet the country's basic energy needs.
vi. The relative purity of an energy technology in terms of emission levels, where low levels of emissions indicate high sustainability.
vii. The percentage share of renewable energies to the energy mix.
viii. The scope by which of fossil fuels are used.

From the two lists of indicators, it is clear that a number of indicators could be used to measure the sustainability of energy technologies. However, the indefinite number of indicators could possibly be a concern that there is ambiguity and uncertainty. Alternatively, this could suggest that an energy system transition of such magnitude is so complex that multiple system views exist, suggesting that system actors develop indicators - to gain a more comprehensive understanding of an issue or dimension from their perspective. The system view should however remain holistic and include all aspects of sustainability including the environmental, technical, social, political and economic spheres. An energy system impacts all domains and this should be accounted for.

3.4 The Global Transition to Sustainable Energy

Since the global economic crisis in 2008, the world was forced to consider the impact of rapid economic growth on the environment, and to reconceptualise how to achieve development while simultaneously keeping sustainability for future generations in mind (Camaren & Swilling, 2011; United Nations Environment Programme, 2011). With this alternative viewpoint and growing concerns for climate change and resource depletion, several global conferences were held to discuss mitigation methods. One such conference was the United Nations Conference on Sustainable Development in Rio in 2012 and various nations across the globe such as Germany, India, the Netherlands and Spain have initiated greening methodologies.

In 2016, the share of clean-energy spending reached a record high of 43 per cent total energy-related investment (Creamer, 2017b). Furthermore, the global investment in electricity was $718-billion, with fewer coal-power additions, and the largest area of spending being renewable-energy investment (Creamer, 2017b). The year also saw the largest addition of new nuclear capacity in the past fifteen years, amounting to a global total capacity of 10GW that came online in 2016 (Creamer, 2017b).

In January 2016, the Netherlands released a report explaining their transition pathway for sustainable energy, Spain followed shortly after with a green energy report. Spain's report explained detailed mechanisms, which they plan to implement to green their energy system (Amores, Alvarez, Chico, Ramajo, Sanchez & Renobales, 2016). This section is limited to these two countries, although there are countries on all the continents attempting an SET. However, due to limitations of this review, the Netherlands was selected due to their popularity in the greening of their power sector, and Spain as they experience similarities in climate to South Africa (HeliosCSP, 2015).

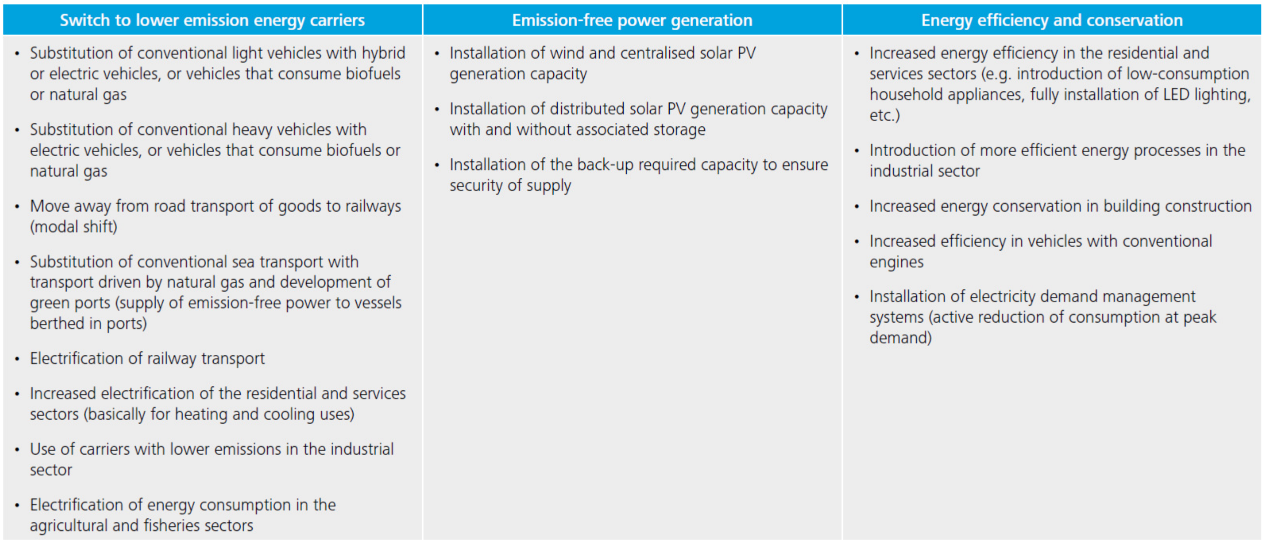
3.4.1 The Netherlands Approach to an SET

The Netherlands released a report in January 2016 outlining the details of their transition to sustainable energy. The Dutch government has been a key contributor in the global transition to sustainable, affordable, safe, and reliable energy. The report mentioned three principles that were key to the sustainable energy transition. Firstly, to focus on the reduction of CO_2 emissions; secondly, to make the most of all economic opportunities presented in the energy transition. Finally, to integrate the energy system through their spatial planning policy (Ministry of Economic Affairs of the Netherlands, 2016). The Netherlands is a part of the Emissions Trading System (ETS) across Europe, which aims to reduce the overall CO_2 emissions across Europe. The Dutch government has admitted to the country's reliance on fossil fuels, which is still around 95per cent, but the depletion of fossil fuels is a significant motivation for the transition to renewable energy; both time and opportunity are necessary to allow for the necessary technological breakthroughs that cannot be foreseen today (Ministry of Economic Affairs of the Netherlands, 2016). The Netherlands have also identified the need for their electricity demand and supply to become more flexible, based on renewable sources' intermittent supply. Although, the production of large-scale electricity supply will remain a priority for large-scale economic needs (Ministry of Economic Affairs of the Netherlands, 2016).

Thus, to summarise the Dutch electricity transition pathway until 2050, the transition to sustainable energy requires an advancement of technology for a successful transition on a macro scale to be realised. Furthermore, much of the focus remains on reducing CO_2 emissions and improving energy efficiency. Concerns about fossil fuel depletion, supply security and climate change, led the Netherlands to focus on transformative change and employ bottom-up processes and involve non-state stakeholders in the transition process. Thus, the state merely guides and facilitates the transition process (Kemp, 2010).

3.4.2 The Spanish Approach to an SET

Spain's intentions to decarbonise their energy system forms a part of Europe's commitments to lower emissions and fight against climate change, by reaching the international community goal of carbon neutrality between 2050 and 2100 (Amores *et al.*, 2016). Spain initiated its decarbonisation scheme and has proposed a number of 'levers' to enable the transition of the energy model over the time period 2016-2030 (Amores *et al.*, 2016). Three broad propositions have been made, which include: switching to lower emission energy sources, power generation that is emission free, and energy efficiency and conservation (Amores *et al.*, 2016). More detail on these levers can be seen in Figure 3.3.



Switch to lower emission energy carriers	Emission-free power generation	Energy efficiency and conservation
• Substitution of conventional light vehicles with hybrid or electric vehicles, or vehicles that consume biofuels or natural gas • Substitution of conventional heavy vehicles with electric vehicles, or vehicles that consume biofuels or natural gas • Move away from road transport of goods to railways (modal shift) • Substitution of conventional sea transport with transport driven by natural gas and development of green ports (supply of emission-free power to vessels berthed in ports) • Electrification of railway transport • Increased electrification of the residential and services sectors (basically for heating and cooling uses) • Use of carriers with lower emissions in the industrial sector • Electrification of energy consumption in the agricultural and fisheries sectors	• Installation of wind and centralised solar PV generation capacity • Installation of distributed solar PV generation capacity with and without associated storage • Installation of the back-up required capacity to ensure security of supply	• Increased energy efficiency in the residential and services sectors (e.g. introduction of low-consumption household appliances, fully installation of LED lighting, etc.) • Introduction of more efficient energy processes in the industrial sector • Increased energy conservation in building construction • Increased efficiency in vehicles with conventional engines • Installation of electricity demand management systems (active reduction of consumption at peak demand)

Figure 3.3: The characteristics of the three decarbonisation levers (Source: *Amores et al., 2016*)

3.5 Conclusion

This chapter provided a brief summary of a number of concepts and frameworks that have been developed to address the complexities society is faced with during a transition. This introduction of the various concepts was necessaery to understaind the complexities of large scale transitions, such as energy transitions that involve various actors, technologies, and dynamic forces that influence one another. STT literature provides a foundation with which to analyse these transitions, so that policy-makers and private and government institutions can work towards achieving holistic sustainability goals. From the outlined research question, a review of the multiple existing transition theories was necessary. Therefore, the following approaches were reviewed: MLP, SNM, TIS and TM. The preferred analytical framework is the MLP. This perspective has the ability to distinguish between the various ‘levels’ of complexity surrounding electricity generation and provision to society. MLP allows the analysis of a complex, large-scale energy transition to be simplified so that the changes the regime undergoes during a transition can be better understood. And also, determine how these changes fit into the greater landscape and the importance of niche innovations to bring about this change.

Section 3.3, energy transitions, dealt with the complexity of energy transitions, and the MLP in more detail for the electricity sector. It became clear that the MLP was developed as a framework for European countries with a decentralised grid and universal electricity access. Thus, South Africa has unique circumstances with several additional complexities such as: energy and social inequalities, monopolistic service providers, numerous new policies and strategies, financing of transition technologies and challenges with governance and political influence. The addition of the REI4P has allowed renewable energy to be added to the energy mix. However, whether this is fostering a sustainable energy transition is uncertain, and thus Chapter 4 addresses the South African context.

4 The South African Electricity Sector

4.1 Introduction

This chapter aims to provide insight into the South African electricity sector. Consequently, this will assist in the development of the model, due to a better comprehension of the influential drivers that impact the sector.

The objectives for this chapter are to:

i. Analyse the South African electricity sector's past and present drivers and influences,
ii. Gain insight into new planned capacity and the role of sustainability in the future electricity mix,
iii. Investigate energy policy in South Africa; and
iv. Examine the financial implication of a transition to clean energy.

4.2 Electricity Sector Overview

South Africa's electricity regime has been shaped by a number of events over the past few decades which include: historic colonisation, apartheid, nationalism, state-led development, and market-orientated liberalisation (Power *et al.*, 2016). South Africa has experienced much criticism in the past, due to its dependence on coal-based electricity generation. At present, the looming issues of increasing electricity tariffs, the imminence of carbon-taxation, and the country wide supply-side crisis; further motivate the need for South Africa to find an alternative electricity supply.

South Africa's Mineral Energy Complex (MEC) plays a role in understanding the forces both driving, and inhibiting, the Sustainable Energy Transition. The mining and energy complex are tightly bound by low-cost state-owned electricity production, cheap labour and high capital investments in the sector (Power *et al.*, 2016). Around 44 per cent of the country's electricity is consumed by the world's largest resource and mining conglomerates, of which thirty-one of their members, form part of the Energy Intensive Users Group (Power *et al.*, 2016).

In March of 2015, South Africa's electrification rate was 88 per cent (Department of Energy, 2016a). By 2025, South Africa aims to achieve 100per cent electrification which translates to over 13 million houses connected to the grid by 2025 (Department of Energy, 2015b, 2016a; Scott, Lindfeld, Martin, Pitso & Engelbrecht, 2016).

The Department of Energy (2015a) reiterated that it is essential to address the country's energy challenges, while stimulating economic growth and achieving sustainability. The government department further stated that they have no intentions of abandoning coal as a resource, but they acknowledge the importance of sustainability. The government aims to implement clean technologies to reduce adverse environmental impacts, while adding additional sources of generation. The coal generation will be reduced to 62 per cent by 2025, as opposed to the 81 per cent contribution in 2015 (Department of Energy, 2015b; Scott *et al.*, 2016).

In September 2014, South Africa signed an agreement with the Democratic Republic of Congo (DRC) to promote cooperation in hydroelectricity, renewable energy and energy efficiency. These agreements are made possible through information sharing, technology transfer, and Research and Development (R&D) coordination (Department of Energy, 2015b). The project has a generating potential of 40 000MW of hydroelectricity, of which South Africa will have a 2500MW off take (Department of Energy, 2015b).

A nuclear power expansion has been stipulated in the Nuclear Energy Policy of 2008. The 2016 updated IRP states that approximately 30 per cent of the percentage share of the energy mix will be generated from nuclear (Department of Energy, 2016b). Motivation for South Africa to pursue nuclear energy include: socio-economic benefits. These benefits range from, reduction of carbon emissions, access to advanced technology, skills development, and the ability to provide stable, clean and cost competitive base-load electricity. Nuclear generation will also have the opportunity to re-industrialise the nation through localised component manufacturing and uranium mining (Department of Energy, 2015b).

The Department of Energy (2015a) is certain that nuclear is the key to providing reliable base-load generation, to stimulate economic development due to the number of active nuclear programmes in all BRICS (Brazil, Russia, India, China and South Africa) nations. Moreover, BRICS are responsible for the construction of over 60per cent of the world's new nuclear power plants. South Africa has safely operated Koeberg, the country's only nuclear plant, for over thirty years and the plant is currently responsible for 5 per cent of the national grid generation (Department of Energy, 2015b). However, an expansion of the nuclear programme will require a critical mass of technical skills as well as high upfront capital costs, where in the current economic climent and the recent downgrade of the South African economy to Junk Status, borrowing capital comes with increased repayment costs.

With the aim of reducing the carbon emissions of the current installed coal capacity, Eskom has retrofitted their power stations with emission abatements, to comply with the Minimum Emissions Standards that were published in section 21 of the National Environmental management Act (NEMA) (Department of Energy, 2016b). The two types of retrofits that are to be installed on the plants are, Fabric Filter Plants (FFP) and Flue Gas Desulphurisation (FGD) and are planned for installation from 2016 to 2024 (Department of Energy, 2016b).

The addition of gas to diversify South Africa's electricity mix will allow more efficient management of the power system and will allow industries to balance the risks and benefits associated with each energy source (Schreuder, 2017a). Gas is viewed as a suitable technology to supplement the variable nature of renewables. Unlike renewables, gas is dispatchable and can be used as a bridge to overcome the intermittence of renewable energy supply (Schreuder, 2017a). South Africa does not currently have large domestic generation potential, with the majority of the gas supply imported from Mozambique via pipeline (Schreuder, 2017a).

If South Africa were to establish a larger gas industry it will need to overcome a number of challenges including securing investors since the establishment of a gas generation capacity is a capital intensive endeavour

(Schreuder, 2017b). The economic and political climate also presents a number of risks, such as: regulatory uncertainty, policy delays and credit downgrades (Schreuder, 2017b).

4.2.1 State Capture and its Influence on the Electricity Sector

In recent years, under Jacob Zuma's leadership, concerns about 'state capture' began to surface in the media and were eventually consolidated in 2016. The Public Protector's office released a report on the "*improper and unethical conduct*" of President Jacob Zuma's dealings with private individuals from the mining sector (Joubert, 2017). State capture is defined as, the circumstances under which the political functioning and decision-making of a state is corrupted by private interests, which influence the state for their own advantage (Joubert, 2017). State capture has become synonymous with the relationship Zuma has with the Gupta family. The Public Protector's report confirmed that the increasing bias of the national broadcaster and the senior executives in Eskom, were heavily influenced by the Gupta family (Joubert, 2017; Swilling, Bhorat, Buthelezi, Chipkin & Peter, 2017a) .

The link between the Gupta family and South Africa's nuclear procurement plan first surfaced when the Gupta's interests in uranium mining were investigated. In 2017, the high court ruled against the South African government's plans to buy in nuclear generation technology from the Russian government. The court ruled that the state did not follow proper procedures in terms of accountability, transparency and public participation (Joubert, 2017; Swilling, Bhorat, Buthelezi, Chipkin & Peter, 2017b).

Since the court ruling, Zuma announced that the plans for nuclear expansion will go ahead and the state is committed to open and transparent procurement processes. However, with South Africa being in a state of recession, the newly appointed Energy Minister, Mmamoloko Kubayi, said the plans to expand its nuclear plan will be reviewed (Reuters, 2017).

4.3 Energy Policy in South Africa

The production of energy in South Africa has contributed to much of the country's social and economic development. Majority of this development has been driven by strong political and economic forces, which have resulted in the various existing energy policies.

South Africa's energy policy periods can be split into three eras: the apartheid regime from 1948 to 1994, the second period 1994 to 2000, and from 2000 onwards (Davidson *et al.*, 2006). During these three eras, the policies were significantly different. During the apartheid period, the policies focused on energy security - due to political isolation. Post-1994 elections, the policies were focused on addressing the injustices of the past. Post 2000, energy policies have focused on trying to achieve government targets and meet energy demands (Davidson *et al.*, 2006).

An additional period can be suggested, from 2010 to present – the sustainable era. This era became apparent with South Africa's interest in renewable energy, and the addition of new clean technologies to the grid, along with its various supporting policies such as the IRP and REI4P.

The IRP was developed through the use of various modelling methodologies that account for factors such as greenhouse gas emissions, feasibility, the ability to meet policy requirements and cost effectiveness (Department of Energy, 2015b). The Department of Energy (2015a) also stipulated that an Energy Master Plan needs to be formed, to transform the current energy mix to one which consists of clean and sustainable technologies.

Figure 4.1 indicates the various policies in the electricity sector, with regards to generation type and regulation, and indicates the organisations responsible for various system functions.

Power Sector regulatory environment

Organisations responsible for energy policies
- Department of Energy

Energy Regulator
- National Energy Regulator of South Africa
- National Nuclear Regulator

Energy policy publications
- Electricity Regulation Second Amendment Bill
- National Energy Regulator Amendment Bill
- Electricity Regulation Act, 2006 (Act No 4 of 2006)
- Electricity Regulation Amendment Act
- National Energy Regulator Act
- Electricity Regulations on new generation capacity
- Integrated Energy Plan
- Integrated Resource Plan
- Liquid Fuels Road Map
- Gas Utilisation Master Plan
- National Energy Efficiency Strategy
- National Transportation Roadmap
- Universal Access to Energy Roadmap
- White Paper on Renewable Energy
- Electricity Pricing Policy

Main entities in the electricity generation market
- Eskom, with IPPs becoming ever more promiment

Main entities in the electricity transmission market
- Eskom

Main entities in the electricity distribution market
- Eskom
- Local Municipalities

Figure 4.1: A brief overview of the electricity sector regulatory environment in South Africa (Scott *et al.*, 2016)

4.4 Renewable Energy Generation in South Africa

South Africa's provision and production of electricity to the nation has been, and remains to be, supplied by a monopolistic entity: Eskom. The energy mix consists mostly of fossil fuels, due to its abundance and affordability. However, with the dramatic reduction of renewable energy generation costs over the last decade, the argument that coal is still an affordable source of energy has lost traction (Walwyn & Brent, 2014). In addition, the impact of coal-based power generation on the environment is becoming a more prevalent issue, due to the high level of carbon dioxide emissions levelled between 470 and 550 million tonnes per annum for the whole of South Africa (Walwyn & Brent, 2014).

The electricity sector is said to contribute approximately 45 per cent to the total carbon emissions (Department of Energy, 2013). Based on the peak-plateau-decline objective, emissions would be allowed to peak in 2025, at approximately 550 million tonnes per annum. The Department of Environmental Affairs published an explanatory note in 2011, for the CO_2 emissions trajectory until 2050, titled: 'Defining South Africa's Peak, Plateau and Decline Greenhous Gas Emission Trajectory', which indicated an upper limit of 428 million tonnes per annum of CO_2 by 2050 (Department of Energy, 2013). These targets were based on international commitments made by South Africa in 2009, to reduce emissions by 34 per cent from business-as-usual levels by 2020, and 42per cent by 2025 (Carbon Disclosure Project & KPMG, 2010).

With the diminishing cost of renewable energy technology, renewable energy has become a competitive source of energy and with this, policy-makers developed a plan to effectively incorporate renewable energy into South Africa's energy mix. The result of this was the REI4P, which is South Africa's comprehensive initiative to install 17.8GW of renewable energy electricity generation capacity over the 2012-2030 period. The main policy driver of the REI4P, was the reduction of carbon emissions due to South Africa's high carbon footprint. Additionally, the opportunity to strengthen the economy through the creation of jobs and also to alleviate the immediate shortage of electricity (Walwyn & Brent, 2014).

The REI4P has received praise for its high-quality regulatory framework, intense qualification criteria and demanding economic development and community ownership requirements. All of these requirements are said to contribute to positive investor and developer involvement in the policy (Baker & Wlokas, 2014).In order to make it through the fierce bidding process, high compliance costs and detailed reports are required by participants, before a project can be initiated. Thus the bidding process requires substantial investment of both time and money, before a project is even initiated, limiting REI4P applicants to large-scale utilities (Baker & Wlokas, 2014).

Since its establishment in 2011, the REI4P has procured approximately 5000MW of renewable energy in its four rounds of bidding. By the end of 2015, seventy-seven projects covering solar PV, onshore wind, small hydro, concentrated solar power (CSP), landfill gas and biomass, were in development. Thirty-two of these projects are operational and are contributing 1500MW of generation capacity to South Africa's grid (Department of Energy, 2015a; Greencape, 2015). According to a study by the CSIR (2015), in 2014 renewable energy on the grid contributed a net benefit of R0.8 billion to the economy. Thus, illustrating the economic benefit that renewable energy can have on the economy.

In 2016, the now former CEO of Eskom, Brian Molefe, announced that no new Power Producer Agreements (PPAs) would be signed with IPPs. Molefe stated that the costs to Eskom for the electricity from IPPs are not higher than their own generation costs, but higher than the selling tariff, which reflects negatively on the Eskom's income statement (Lilley, 2016). So far, Eskom has refused to sign thirty-seven onshore wind and solar PV projects, procured by the DOE in 2015 during the fourth bidding window of the REI4P. Public Enterprises Minister, Lynne Brown, attributed this refusal to Eskom having to purchase the electricity for R2.14/KWh from PPAs; but could only charge consumers R0.84/KWh (Creamer, 2017c). Eskom is in the process of finalising a revenue application to NERSA, which could translate into an electricity price increase of 19.9per cent for 2018/19, where the tariff increase was 2.2per cent in 2017/18 (Creamer, 2017c).

According to the policy goals of the IRP 2011 (Department of Energy, 2011) of the planned additional grid capacity, 42per cent of the new capacity will be from renewable energy. Renewable Energy will then make up 9per cent of the total energy share by 2030, excluding hydro. Figure 4.2 shows the policy adjusted IRP after the Revised Balance Scenario was consulted to determine suitable resource plans. The WWF-SA (2015) proposes that South Africa should increase their renewable energy generation capacity to achieve a possible 11-19per cent generation from renewable sources.

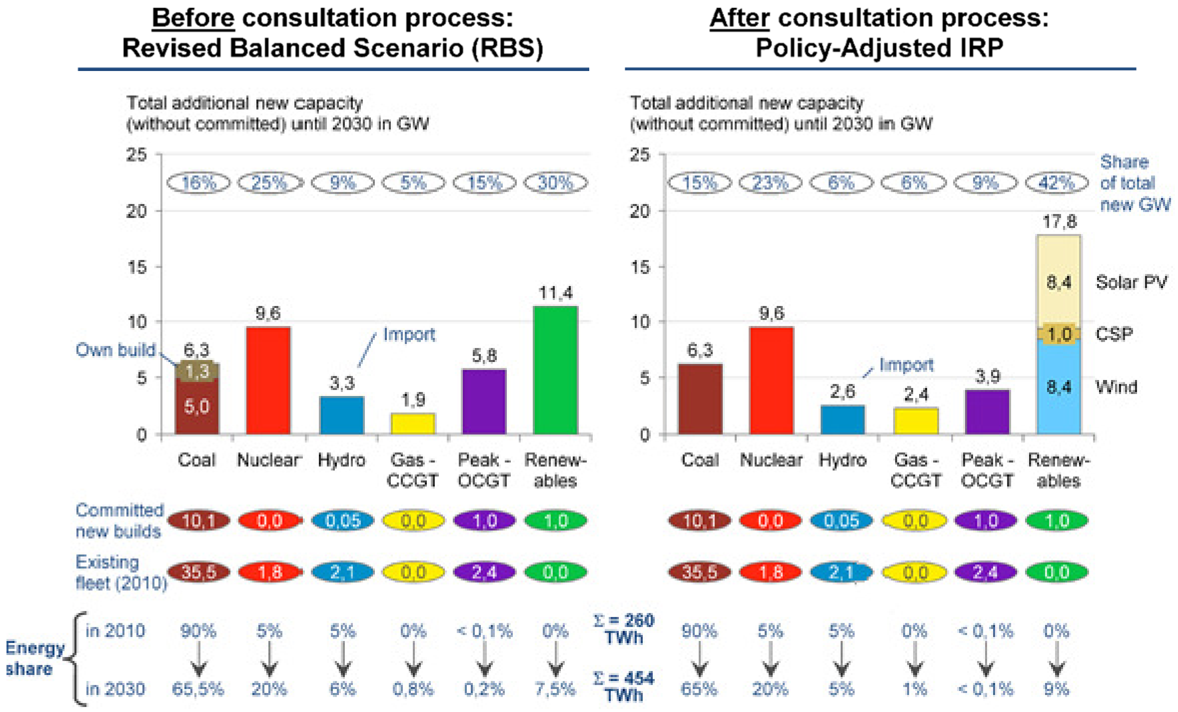


Figure 4.2: The total additional new capacity resource mix for electricity generation until 2030 (Department of Energy, 2011)

The updated IRP released in November 2016, failed to give a detailed breakdown of the planned capacity installations. Instead, a poor-quality graph, was published in the report and shows the percentage share of total installed MW capacity for the periods 2016, 2020, 2030, 2040 and 2050 (Department of Energy, 2016b) Figure 4.3 is adpted from the graph published in the updated IRP report.

On analysis, the percentage share of renewables by 2030, for the 2016 updated IRP have increased, where 9.47per cent is from wind, 4.57per cent from PV, and 1.48per cent from CSP. Compared to the 2013 IRP, which states a total share of 9per cent from renewables by 2030. Furthermore, the percentage share of nuclear by 2030 has decreased from the 2013 IRP prediction of 20per cent, to a mere 4.11per cent. The 2013 IRP only considered the energy mix share up-until 2030, whereas the 2016 IRP outlook has also been extended by twenty years to 2050. Where the energy mix will consist of: 31.6per cent coal, 30.01per cent nuclear, 6.96per cent gas, 0per cent CSP, 6.55per cent PV and 18per cent wind with the remaining percentage share unspecified (Department of Energy, 2016b).

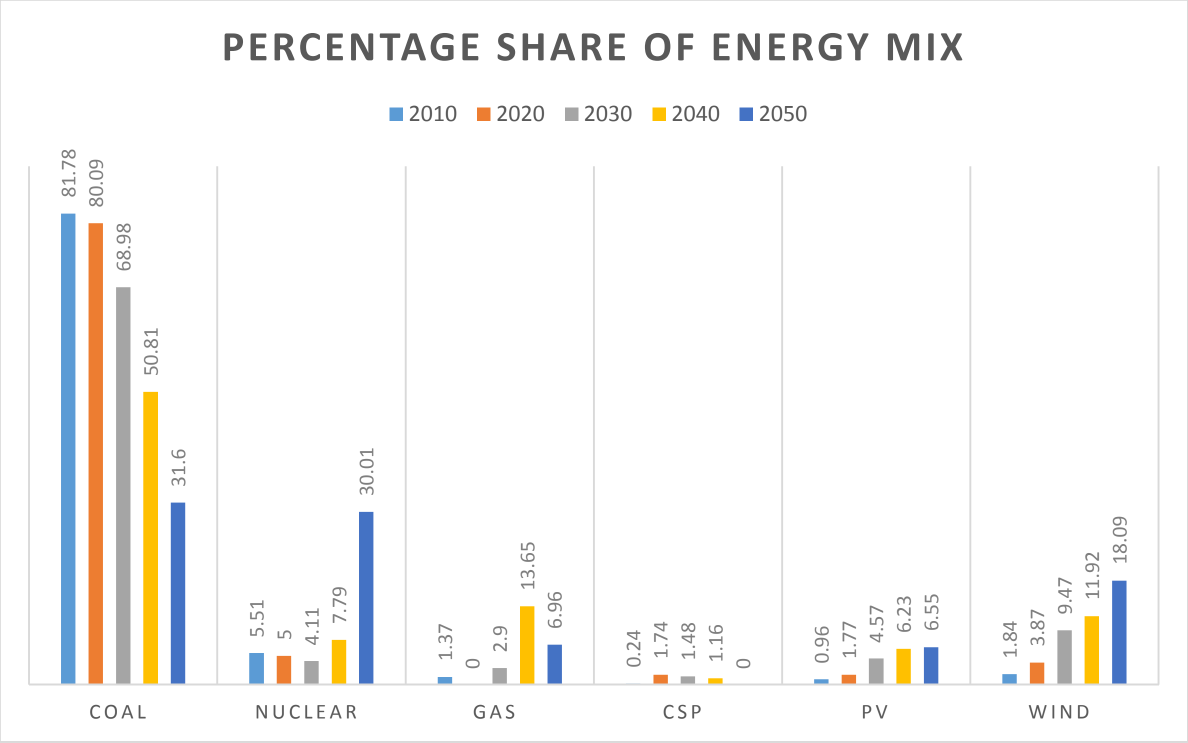


Figure 4.3: Technology Percentage share by Installed Capacity (MW) Adapted from: (Department of Energy, 2016b)

The National Treasury has announced that in February 2018 a lowest cost IRP will be finalised; and the remarks made in public consultation on the updated IRP released in November 2016, will be taken into account (Creamer, 2017c). The latest IRP has been criticised for having artificial constraints for onshore wind and PV. It has been debated whether these constraints were implemented to ensure that the future electricity mix includes new nuclear (Creamer, 2017c). Nevertheless, Eskom has still proceeded with a new nuclear procurement strategy (Creamer, 2017c).

Renewable Energy projects beyond the REI4P, include biogas, small-scale hydro and landfill gas. The South African government is looking into improving technologies and mechanisms, to aid in the implementation and development of these resources, such as the development of a small scale IPP procurement programmes (Department of Energy, 2015a). In terms of the implementation of biofuels, the government is still in the process of developing a programme to reduce the impact of large-scale biofuels on food security and the associated costs (Department of Energy, 2015a).

An alternative for off-grid solutions, to reduce energy-grid demands, include Solar Water Heaters (SWH) for low-income and mid-to-high income households. However, government only managed to install approximately half of the targeted one million SWH (Department of Energy, 2015a). In terms of embedded generation technologies, National Energy Regulator of South Africa (NERSA) has been contracted to regulate the practices and pricing structures around this technology (Department of Energy, 2015a).

The Department of Energy (2015b) highlighted that a reliable power supply is dependent not only on availability of generation capacity, but also on the availability of a stable grid network to deliver sufficient load. Thus, it is essential for adequate network infrastructure to be available in order to transmit enough power through the national electricity grid.

4.5 **Financing a Sustainable Electricity Sector**

The development and diffusion of technology for socio-technical transitions is essential, and this cannot be achieved without the generation and sustentation of finance (Baker *et al.*, 2014). Grubler (2012) states that investments are essential to increase and replace capital stocks in the economy. In order to undergo an STT, considerable investments are needed to account for the additions to the system in terms of infrastructure, maintenance, training, and regulation (Smith & Stirling, 2008). Most renewable energy technologies, excluding biofuels, have no fuel expenses, but require large initial capital investments. Thus, investment decisions are primarily dependent on operational and maintenance costs. Securing reasonable, long-term finances is often considered the greatest barrier, when compared that to the initial technology costs. Therefore, finances is an inhibiting factor of an SET, particularly for developing countries (Oosthuizen, 2016).

According to Sullivan (2011), investors considering investment in renewable energy, clean energy, energy efficiency, and decarbonisation consider the following issues:

i. Supporting policies or regulations in place, investments are considered unprofitable without government support,
ii. The financial attractiveness of the investment relative to other sector-related investments and external opportunities,
iii. The time frame for the policy framework,
iv. Technology maturity; and
v. The possibility that government is likely to change policies or incentives that may affect investments.

Sullivan (2011) also highlights what governments need to do, on a state level, in order to attract private sector investments. These initiatives include: ensuring policies with sustainability aligned goals exist, ensuring that the policies are well designed for transparency, investment incentives and alignment with other sector goals. Finally, the institutions in charge of policy implementation should ensure effectiveness and support the developmental growth.

4.6 Conclusion

The South African electricity mix is undergoing a major transition with the addition of several new generation technologies to the mix, including: gas, renewables and the possibility of new nuclear capacity. The electricity sector has experienced several challenges including: load shedding, corruption, and aging infrastructure. Nevertheless, South Africa has implemented policies to drive the sector towards sustainability, and the public protector is addressing the issues surrounding state capture and government and utility corruption.

The addition of renewables to the electricity mix has encountered both success and challenges. For example, the addition of renewables through the REI4P, is viewed as a beacon of how public and private sectors can join forces for the common good of the country. Although recent events have halted the addition of new IPPs, through Eskom's refusal to sign the agreements, and the debates surrounding the IRP and nuclear procurement debacles. With the high number of events and emerging stakeholder agendas, it is still unclear as to whether South Africa is fostering a transition towards a sustainable future. Thus, the development of a framework or set of criteria may be beneficial for establishing a means by which progress can be measured.

5 Sustainable Energy Transitions Criteria Development

5.1 Introduction

Environmental and sustainable policies in South Africa have become more prominent over the past decade. The combination of policies are collectively referred to as the green economy approach, which has catalysed low carbon growth in South Africa (Swilling *et al.*, 2016).

The objectives of this chapter[6] are to:

1. Analyse various existing frameworks for energy systems pertaining to what a successful sustainable energy transition entails; and
2. Develop a set of criteria to measure the progress of the transition to a sustainable South African electricity sector by 2050.

5.1.1 Achieving a Balance between Development and Sustainability

In order for the whole of society to achieve a just transition, both a sustainable transition and developmental welfarism need to be achieved (Swilling *et al.*, 2016). However, this is challenging due to two opposing points of view: developmental states are mainly concerned with accelerated economic growth that increases the GDP per capital and aim to industrialise and urbanise a state. Whereas the contrasting view is that sustainable transitions are concerned with achieving developmental goals through an economy that is low-carbon and energy efficient (Swilling *et al.*, 2016).

A sustainable transition is rooted in literature from systems' innovation, sociology of technology and evolutionary economics (Swilling *et al.*, 2016). According to Geel's (2011) MLP, socio-technical transitions are complex and occur over a long period of time and result in 'deep structural changes' to a system, where multiple levels of reality (macro, meso and micro) are interlinked and non-deterministic.

Conventional perspectives which are based on more orthodox approaches to energy, productivity, and economic growth suggest that the economy is a closed system. Furthermore, economic growth is the direct result of: increased investment and labour inputs, changes in quality to the inputs, and technical changes (Sorrell, 2010). Hence, changes in energy inputs and energy productivity are assumed to make little contribution to economic growth (Sorrell, 2010).

Ecological economists suggest that economic improvements are a result of massive advances in labour productivity, due to higher quality energy in the form of equipment and technology (Sorrell, 2010). A strong correlation can be seen between the GDP per capita and energy consumption for the United States over a period of 100 years (Heun, 2016).

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[6] The contents of this chapter is published in the TEMCSON Proceedings: http://temscon18.ieee-tems.org/2017/06/07/program/

In order to achieve a sustainable transition for the electricity sector in South Africa, two contradictory approaches need to be taken into consideration, namely orthodox (which is the more traditional approach to business or commerce) and ecological (where the environment and social impacts play a larger role in decision making). Additionally, a major socio-technical regime needs to evolve from a core set of technologies, social functions and interests, market dynamics, policy frameworks and institutional regulations (Swilling *et al.*, 2016). This is a complex and multidisciplinary problem. However, Swilling *et al.* (2015) emphasise that in order for South Africa to achieve a sustainable transition, it is necessary for 'self-same state capabilities' to drive the structural changes and encourage developmental welfarism. Hence, the necessity for the electricity sector to elicit these changes.

Baker *et al.* (2014) state that the IRP's progress thus far has demonstrated that niche actors in private renewable energy, are emerging and gaining support from the landscape level, having successfully achieved a level of change in the electricity mix. However, this success is diminished by niche actors having to compete with powerful landscape actors, with vested interest and political influence, for resources and access to the grid (Baker *et al.*, 2014). Baker *et al.* (2014) further state that when assessing South Africa's degree of transition away from fossil fuels, the benefits of the REI4P are overwhelmed by the introduction of new coal plants to the electricity mix, along with the current mentality of energy intensive user practices that are unlikely to alter in the near future.

Power *et al.*(2016) state that South Africa is on both high and low carbon transition pathways, which are pursued in interconnected and parallel ways; due to the complexity involved in the emerging niche innovations across multiple regimes.

Thus, it is important to understand the dynamics of the socio-technical transition that the electricity regime is currently going through, as opposed to determining a simple yes or no answer as to whether South Africa is successfully transforming its energy sector to sustainability.

5.1.2 **Existing Transition Frameworks**

Numerous frameworks exist for energy transitions that incorporate social, economic and environmental aspects of a transition, as well as consider multiple perspectives and levels of detail from high-level transitions to small utility-scale transitions. Various frameworks have been considered here. The first, is provided by Grubler (2012) who uses a technological development frame of reference. The second by Heun (2016), connects energy and the economy. Csala & Sgouridis (2014) have rooted their framework from a sustainability point of view. While O'Keefe, O'Brien & Pearsall (2010) focus on small-scale utility projects, which may be relevant to a high-level context. Bertsch & Fichtner (2015) analyse the various spheres that play an important role in the development of energy policies, which often drive changes on a sectoral level. Finally, Sorrell (2010) highlights the difference between orthodox and ecological perspectives and their impact on a transition to sustainable energy.

CHAPTER 5: SUSTAINABLE ENERGY TRANSITION CRITERIA DEVELOPMENT

Grubler (2012) provided three precautionary insights into the energy supply; and implied that the drivers of energy transitions are now much more complex, and are no longer the singular perspective of a technology-push based on energy supply. Grubler (2012) cautions against a move that is “too fast, too big and too early”, based on previous energy transitions in history. He emphasises the importance of designing policies that are well balanced, continuously innovative and persistent. The three insights are summarised below (Grubler, 2012):

Insight 1: “The importance of energy end-use in driving energy transitions”

> The driver of an energy transition is dependent on both the technology and the transformation of the involved institution. Energy supply and demand systems co-evolve with innovations, which mutually enhance one another. However, without a change in energy end-use, there are limitations to the change in energy supply. Thus, highlighting the importance of the need for institutions or organisations to change, as well as the significance of early technology adopters, as they are the key to the learning, development and modification of new energy technologies.

Insight 2: “Rates of change are slow, but not always”

> Large developed countries with extensive interrelated infrastructure, will require more time to transition. The bottom-up decentralised and end-use technology driven option could result in faster transitions than the traditional top-down supply. It is also noted that late adopters can transition faster, owing to the experience of earlier adopters and cheaper technology options.

Insight 3: “There are distinctive patterns in the success”

> Improvements in efficiency, costs and scale, are drivers of technological transitions, and long-term growth leads to transitions on a macro-level. The scaling up of technologies (larger turbines or power plants) allow substantial cost improvements through the economies of scale concept, but they take time (sometimes decades) to develop and drive the transition. Essentially, technological designs and industries become standardised, which results in market saturation and the industries growth becomes dependant on the globalisation of the technology and practices.

Heun (2016) made five propositions for energy and the economy, which can be seen in Table 5.1; with a short explanation to provide context for each proposition.

Table 5.1: Five propositions for energy and the economy (Heun, 2016)

Proposition	Explanation
Energy and the Economy are linked	There is a correlation between GDP and energy demands during recession
Fundamentals of energy supply, demand and prices are different now	A very small change in energy demand can have drastic effects on the change in energy prices
Heretofore underappreciated metrics are fundamentally important to understand macroeconomics	Society goes after the easiest resources first, indicated by Energy Return on Investment
The dynamics of the Energy Economy Nexus are an interdisciplinary grand challenge	A sustainable transition is a complex multidisciplinary problem that requires a big solution and it is difficult to prototype on a small scale
Transition to a stable Clean Energy Regime is incompatible with an unstable energy economy system.	An unstable economy is a deterrent from investing in sustainable transitions.

Furthermore, Heun (2016) proposes four possible routes that society could take to transition to a sustainable energy economy. The first route deals with market mechanisms, where exorbitantly high fossil fuel prices drive the move to renewable energy. The second route is one where policy and regulation are the drivers of the transition. The third route is a forced transition due to societal collapse, where society has no choice but to transition to an alternative source of energy. Finally, the fourth transition route is preferred, and is brought upon by experimentation through investment into new technologies and research.

Csala & Sgouridis (2014) outline five propositions in order to achieve an SET. They start by defining an SET as, a controlled process that leads a technically advanced society, on the path to replacing major fossil fuel primary inputs with sustainable renewable sources, while maintaining sufficient energy to satisfy demand. The criteria holistically combine the environment, society and economic domains and addresses sustainable resource management principles. The five propositions are outlined as follows:

i. The rate of emissions from pollution is less than the ecosystems carrying capacity.
ii. The generation of renewable energy does not exceed the ecosystems long-term capacity nor does it compromise it.
iii. Energy demands per capita throughout the SET are met above a set minimum level that is necessary to satisfy societal needs, and no disruptions or discontinuities form in its rate of change.
iv. Before fossil fuel supplies are exhausted, sufficient investment rates and capital stocks for the installation and operation of renewable generation are available to create a sustainable long term renewable energy supply.
v. Future energy consumption commitments are coupled to, and limited, by the availability of energy in the future.

O' Keefe.*et al.* (2010) present the dimensions and characteristics for sustainable energy systems for small scale renewable energy projects in Table 5.2. The authors also highlight the importance of the need for the correct regulatory environment as well as political involvement to drive the projects forward.

Table 5.2: Criteria for sustainable energy systems for small scale renewable energy projects (O'Keefe *et al.*, 2010)

Dimension	Characteristics
Appropriate	Meets the communities needs and matches cultural norms
Exploits Indigenous Renewable Resources	Makes use of local renewable resources such as solar, wind, geothermal etc.
Capacity Enhancing	Enhance the local capacity and contribute to other endeavours such as education, income generation
Adaptable	Capable of expanding and developing to match the communities' growth
Easy to Repair and Maintain	Easy to maintain and repair by the local community, minimising dependence on distant supply lines
Upgradeable	Easily upgradeable and seamless integration of new technology improvements

The criteria in Table 5.2 address a sustainable energy system transition on a low level. However, many of the dimensions can be applied on a higher level, which then become relevant to the electricity sector. For example, the appropriateness of the installed capacity is associated with a variety of social factors, such as technology acceptance and learning rates. Likewise, the enhancement of capacity is essential to the growth of the country's economy and aids social and economic development.

The importance of the technology meeting the community's needs and matching the cultural norms is a key dimension and is often forgotten. Thus, public acceptance and social development is becoming a key element of considerations in many policies today. An example of this is the REI4P, which forces bidders to present proposals that state their intentions for local, social development before a project is accepted (Baker & Wlokas, 2014).

Furthermore, Bertsch & Fichtner (2015) highlight the importance of considering public acceptance as a key dimension when making decisions in the energy sector. Decision processes on all levels, from strategic planning to operations to politics, are complex. Thus, a multi-criteria decision analysis (MCDA) is proposed for the analysis of power systems in Figure 5.1, where four key dimensions are considered pillars of energy policy.

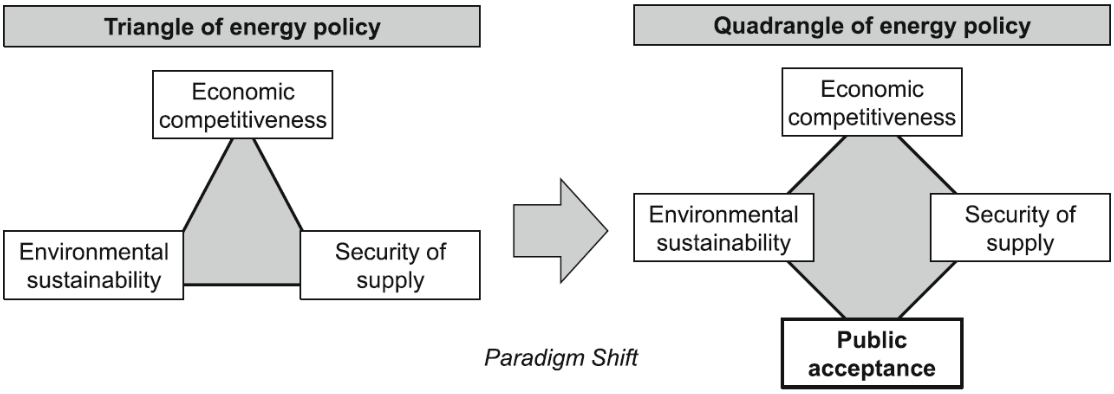

Figure 5.1: The paradigm shift for energy policy (Bertsch & Fichtner, 2015)

The rebound effect has become a prominent phenomenon when it comes to energy efficiency. Sorrel (2010) and Heun (2016) have mentioned the impact of the effect in their writing, saying that the behavioural effect of consumers causes offsetting and unintended consequences. The example used by Sorrell (2010), is a driver replacing their car with a more fuel efficient model - who may now drive further distances more often, due to the cheaper cost. The quantification of the rebound effect is, however, difficult to achieve. The effect needs to be defined in relation to the measures of energy efficiency, relative to the change in energy consumption within some defined system boundary at a point in time. The direct impact of the rebound effect is expected to change as the market evolves and new technologies are developed.

To understand the link between the economy and energy, it is necessary to understand the views of different disciplines. An economist's approach, which is considered to be the more orthodox view, implies that energy, labour, and capital investment are independent of one another and increased economic outputs are a result of technical change (Sorrell, 2010). An ecologist views energy, labour and capital investment as interlinked and interdependent, and changes to one sector have multiplicative effects on another (Sorrell, 2010).

Sorrell (2010) warns against the conventional thinking, of economic theories decoupling energy consumption with economic growth. Moreover, Sorrell (2010) states that the rebound effects are more significant than previously thought, as well as the contribution of energy to productivity improvements and economic growth have been underestimated.

This highlights the important link between energy (electricity), and the economic growth of a country. Thus, the availability of sufficient electricity is vital for the economy's growth, but the impact of the rebound effect on energy efficiency, relative to energy consumption, needs to be taken into consideration. Furthermore, sufficient policies are necessary in order steer the transition to sustainable consumption habits in all sectors, while still maintaining increasing economic growth.

5.2 **A Set of Criteria for South Africa**

South Africa is determined to achieve a sustainable energy transition. However, the transformation process is complex and involves finding a multi-disciplinary dynamic solution set to achieve the multiple objectives. These objectives include, but are not limited to: supply security, emission reduction, economic growth, and social development. This suggests that the implementation of policies alone will not result in a successful transition, instead all actors are required to drive the process forward and assert themselves to committing to sustainable practices – a challenging task.

A set of criteria, for South Africa's transition to an electricity sector that is more sustainable, was developed and appears in Table 5.3. This set of criteria acts as a guideline to measure the progress of the South African SET. The country's numerous policies are drivers of the transition, but Swilling *et al.* (2015) state that without an understanding of the political dynamics, the expected 'just' transition to developmental and sustainable assimilation will not succeed. This statement highlights the importance of understanding the power dynamics of the socio-political regime, which controls much of the sector, consequently the criteria is dependent on these complex dynamics.

Table 5.3: The Set of Criteria for South Africa's SET, specifically for the electricity sector.

	Criteria	Explanation	Possible Indicators
1	***Energy Efficiency***	Energy Efficient practices are followed sector wide and consumption habits improve.	*Energy Intensity* *Minimum Energy Performance Standards (MEPS)* *Product Labels* *Building Codes*
2	***CO_2 Emission Reductions***	A decarbonisation emission rate is achieved by 2030.	*per cent Rate of Decarbonisation per Year*
3	***Economic Competitiveness***	Affordable electricity is supplied to the nation, enabling continued economic growth and sufficient investment is made into alternative sustainable technologies.	*Cost of Unserved Energy to Economy* *Total Levelised Cost of Electricity* *Investment in Sustainable Electricity Capacity*
4	***Supply Security and Generation***	Electricity demand is met, and no disruptions to supply occur. Supply security is guaranteed while ensuring sustainability.	*Demand Supply Ratio* *New Capacity Requirement - Energy Mix Composition* *Blackouts/Year*
5	***Resilience***	Unforeseen or unintended consequences of human and environmental interventions, are dealt with in a manner that do not put the human or ecological systems at risk.	*GDP Growth Rate* *Number of Jobs* *Radioactive Waste Disposal* *Climate Change Indicators*
6	***Innovation and Technology***	Improvements in cost and availability of clean technologies and a socio-technical transition are present.	*Technology Adoption Rates* *Learning Rates* *Investment in RE R&D*
7	***Policy and Public Acceptance***	Government actively supports transition policies and the public recognises and accepts the need for a sustainable socio-technical change.	*Policy Implementation* *Policy Goal Fulfilment* *Governance*

5.2.1 **Criteria Development Process**

The set of criteria was developed using a literature search on the Scopus Database of the search terms mentioned below. Furthermore, a snowballing process was used, where other documentation of relevance was selected based on a brief review of the abstract. A summary of the searches conducted is shown below. The criteria were developed by taking into consideration the various elements of the frameworks analysed in section 5.1.2.

A summary of the literature discussed in Section 5.1.2 appears in Table 5.4 and the presence of the seven criteria in the literature is indicated. The following searches were conducted in October 2016 on the SCOPUS database, and the documents were selected based on their titles and abstract. Upon further analysis of the literature in detail, a decision was made as to whether the content is relevant.

1. *"Energy transitions*" + Frameworks** limited to articles and conference proceedings and in the subject area of energy. Fifty Documents were found however after analysing the document titles and abstracts only nine were found to be specific enough for the context of this paper, and one of those documents was an online book which was not freely available (institutional factors that determine energy transitions).
2. *"Energy transitions*" + Criteria*, limited to articles and conference proceedings and subject area of energy. Six Documents were found of which five were found to have relevant content.
3. *"Sustainable Energy Transitions*" + Criteria* was searched and no content was found.
4. *"Sustainable Energy Transitions*" + Frameworks** was searched and five documents were found and four were found to have relevant content for the transition criteria.
5. *Sustainable energy transitions* and Determinants*, with no further limits eighteen documents were found of which three were relevant.
6. *"Sustainable energy transitions*" and "system dynamics"* resulted in one search which is very relevant and referenced in this paper, by authors Csala & Sgouridis. An alternative search was done where "systems thinking" was substituted instead of "system dynamics" and no results were yielded.
7. *"Energy transitions" and "system dynamics"* yielded eight documents, of which five resulted in relevant content.
8. *Sustainable transitions* and electricity and criteria* resulted in seventeen documents where four of the documents were published over ten years ago. Thus, two sources were deemed relevant.

Table 5.4: Presence of Criteria in Discussed Framework Literature

Author and Year	**Title of Source**	**Presence of Criteria in Literature**						
		Energy Efficiency	**Environmental Sustainability and CO_2 Emission Reduction**	**Economic Competitiveness**	**Supply Security and Generation**	**Resilience**	**Innovation and Technology**	**Policy and Public Acceptance**
Grubler (2012)	Energy transitions research: Insights and cautionary tales			X	X		X	
Heun (2016)	Energy and the Economy: Five Propositions	X		X	X			
Csala & Sgouridis (2014)	A Framework for defining sustainable Energy Transitions: Principles, Dynamics and Implications	X	X	X	X			
O'Keefe *et al.(2010)*	The Future of Energy Use				X	X	X	
Bertsch & Fichtner (2015)	A participatory multi-criteria approach for power generation and transmission planning		X	X	X			X
Sorrell (2010)	Energy, Economic Growth and Environmental Sustainability: Five Propositions	X		X				

5.2.2 **Explanation of the Set of Criteria**

The set of criteria in Table 5.3 is suggested as a guide by which to measure South Africa's SET progress. The indicators in the table are possible indicators for each criterion. However, they may not necessarily be the most appropriate measure and further development may suggest improvements.

The first criterion, energy efficiency, has been introduced in three of the frameworks that were reviewed, namely the frameworks by Heun (2016), Csala & Sgouridis (2014), and Sorrell (2010). Energy efficiency is an important strategy to stabilise the country's energy crisis. So far, the South African government has responded by implementing policies and legislation, to provide industries with incentives that support transition, improved energy efficiency and change in consumption patterns (Swilling *et al.*, 2016). At the Rio+20 conference in 2012, member states declared that improving energy efficiency, increasing renewable energy shares and cleaner, more energy efficient technologies will be essential for sustainable development and climate change (United Nations, 2012). Indicators suggested for lower system levels include the implementation of Minimium Energy Performance Standards, building codes and product lables which create consumer and industry awareness. Heun (2016) refers to a high system level perspective where energy intensity is defined for an entire sector based on the sum of the total energy inputs divided by the GDP contribution for that sector. It is essential that energy efficient practices are implemented sector wide. In addition, legislation and policies drive the shift to technologies and processes that are more efficient and clean. The measure of energy efficiency improvement over time may be indicated by the Gigawatt Hour (GWh) per annum demand per sector.

The second criterion, CO_2 emission reductions, is the most obvious criterion - due to the multiple global policies stipulating goals to reduce the amount of emissions by a certain amount and by a certain time. For example, South Africa's targets are to allow a peak in emissions in 2025 at approximately 550 million tonnes per annum, with an upper limit of 428 million tonnes per annum of CO_2 by 2050 (Department of Environmental Affairs, 2013). Many frameworks use this as a measure to combat climate change, as the reduction of CO_2 is necessary. Csala & Sgouridis (2014) phrase the emissions reduction target as, '*a rate of pollution that is less than the ecosystems carrying capacity*'. This eludes mention of any specific targets and can be used as a universal definition. Thus, emission reduction is a vital part of reducing the effects of climate change and international actors need to collectively work on achieving their reduction targets.

The third criterion, economic competitiveness, addresses the challenge of developmental states and sustainability. It requires that economic growth and social development be achieved, without the expense of environmental degradation and resource depletion. With the declining price of sustainable technologies and the fluctuating price of fossil fuels, sustainable technologies are becoming more cost competitive (Swilling *et al.*, 2016). Thus, economic competitiveness, for this criterion, looks at the cost of technology and technology adoption rates, as well as the level of investment that is invested in sustainable and clean technologies or processes in the electricity sector. The indicators refer to Levlised Costs of Electricity (LCOE) as well as the costs of unserved energy on the economy and dispatachble energy costs.

The fourth criterion, supply security and generation, focuses on two aspects. Firstly, the issue of supply security revolves around fuel prices and fuel imports, as well as looking at the amount of locally generated MW capacity (locally procured resources being coal, solar or wind etc.) supplied to the grid. Secondly, generation looks at the MW capacity supplied to the grid in totality (local and cross-boarders), and includes issues such as demand satisfaction and disruptions to supply for example: load shedding events.

The fifth criterion, resilience, is a broad overarching factor that takes several unpredictable events into account, as well as incorporates the rebound effect of certain events. The factor looks at the ability of human and ecological systems to absorb disturbances while retaining the same basic structure and functionality (Ellis, 2014). This includes the system's ability to cope with, adapt to, and recovery fully or partial from the applied stress or change (Ellis, 2014). This is measurable by examining the ability of the sector to recover from changes, such as job losses as the sector transforms, the possible implementation of nuclear plants, and the sectors ability to deal with the issues surrounding safety and disposal of radioactive waste (O'Keefe *et al.*, 2010). Due to the complexity and interrelatedness of the multiple actors in the electricity sector, it is necessary to account for unpredictable circumstances that may occur and investigate South Africa's ability to cope with these changes. And mitigate risks to avoid disastrous consequences that may put the economy and the environment in jeopardy.

Innovation and technology has been recognised by O'Keefe *et al.* and Grubler (2010; 2012) as a key driver of a socio-technical transitions. Improvements in efficiency, cost and scale are key to the success of long-term macro level growth. Therefore, indicators of a transition to sustainability would include factors such as technology adoption rates, learning rates and the amount of investment in R&D for new sustainable technologies.

The final criterion, policy and public acceptance, combine the socio-political aspect of a transition to sustainability and consider key qualitative factors that drive many processes, such as policy development, implementation and regulation. Therefore, a key determinant is whether the policy goals stipulated in the IRP, for events (for example: additional renewable energy capacity), are achieved in the intended time frame. Political influence is a difficult variable to model, and thus politics, as a variable, is negated in the model. Public acceptance, is another qualitative factor where complexity may arise. A possible factor to determine a shift towards more sustainable sources of generation on a consumer level would involve analysing the country-wide adoption of small-scale renewable energy installations in households, such as solar water heaters.

5.2.3 Validation of the Set of Criteria

To validate the developed set of criteria, a paper titled: *'Fostering Sustainable Energy Transitions for South Africa's Electricity Sector: A set of Criteria'* was submitted to the IEEE TEMS Conference in Silicon Valley, United States (du Plooy, Brent & de Kock, 2017). The paper was peer reviewed and presented at the conference on the 8th June 2017 and received positive feedback. Reviewers were interested in the applicability of the set of criteria to other countries and their individual contexts.

5.3 Conclusion

A review of various transition frameworks was conducted to define a set of criteria by which to determine if South Africa is fostering an SET. The analysis of frameworks concluded that there are many similarities between the frameworks, with the most common issue being supply security and generation. It is essential for energy demand to be met, and a sustainable electricity generation mix should ensure this, while ensuring security of supply and competitive pricing. Energy efficiency practices and economic competitiveness are also considered key components of an SET. Due to the interrelatedness of the environment, economy, social, and political domains, the interactions between them are complex, dynamic and unpredictable. Thus, resilience is an essential aspect for a regime that is undergoing a macro-scale socio-technical transition.

For South Africa to foster an SET, it is necessary to develop and implement mechanisms to collectively transform the electricity sector, as well as incorporate the necessary leadership and skills from all stakeholders to facilitate the changes necessary to drive the transition and successfully meet the set of seven criteria. However, South Africa's ability to foster a transition not only depends on meeting the criteria, but challenges surrounding leadership, policies, politics, and legislation, need to be addressed to achieve a transition to a sustainable electricity sector in the future. This motivates the need for further analysis in the form of a model to determine what 'mechanisms' could possibly foster an SET.

6 Modelling Methodologies

6.1 Introduction

Complexity refers to problems that do not have standard solutions or strategies, and they cannot be split into sub-problems, where sub-solutions can be developed (Valkenburg & Cotella, 2016). This form of complexity emerges when problems are not independent, and solving a part of the problem will cause ramifications in other parts. Most contemporary problems that society encounters, such as the climate change and resource depletion, are a result of unintended consequences from past actions (Musango *et al.*, 2015). It is for this reason that energy transition complexity was investigated in Section 3.3.1 and thus, these complexities should be considered when selecting the modelling methodology.

To analyse South Africa's SET and determine what could possibly foster the transition, it is essential that the correct approach be used to gain further insights. A variety of methodologies exist. However, not all are equally useful under the same conditions, due to them being developed for specific applications. Thus, three methodologies are investigated: Multi-criteria Optimization Modelling, Discrete Event Simulation Modelling, and System Dynamics. Reasons for their selection are presented, along with each methodology's weaknesses and advantages. From this analysis, the most applicable methodology is selected to display the dynamic relationships and effects of the complexity of an energy transition.

To effectively and accurately model the complex socio-technical energy transition, the modelling phase of the dual-narrative modelling approach, (refer to Section 1.6.1.) is considered necessary to incorporate both the dynamic effects, as well as the insights from the extensive body of transition theory literature, in order to achieve a holistic result (Moallemi, Aye, Haan, & Webb, 2016). The set of criteria developed in Section 5.2, informs the model development process.

6.2 Multi-Criteria Optimisation

Multi-Criteria Optimisation (MCO) modelling was selected, due to its prominence in the Industrial Engineering community. Thus, it is a well-understood and respected methodology. The method also has the ability to formulate real world problems, where a decision needs to be made based on a set of criteria (Ehrgott, 2005). MCO involves finding a solution, which achieves the most favourable and advantageous outcome, while also meeting certain constraints. MCO uses three input types to achieve an optimal solution, these being: the objective or goal function, the area of intervention, and finally the system constraints. Models can be used to solve linear and non-linear problems (Winston & Venkataramanan, 2003). In MCO, more than one output variable is specified as a desired state where as single-objective optimisation (linear programming) has a singular optimisation function (Emmerich & Deutz, 2006).

Linear programming (LP) makes use of the simplex algorithm to solve problems (Winston & Venkataramanan, 2003). The issue with LPs is that real world problems contain numerous actors and variables that are difficult to define in goal functions and equations. As a result, problems may arise when the dynamics of the system are encountered. The methodology also struggles to model the cause and effect that various changes to constraints may have on the model. Non-linear programming methodologies, such as Integer programming, Search Heuristics, and MCOs, may overcome the shortfalls of LPs; however, they are very intricate, time consuming and costly methodologies in terms of computational cost.

By using MCO models, one can specify the system output, and experiment with various simulations. Although, the challenge is to choose the correct variable inputs so that the desired output is achieved. In optimisation, modellers either want to maximise or minimise a value of an output variable (Emmerich & Deutz, 2006). For example, a simulation can be designed to find a solution space that meets the following criteria: minimise investment, minimise carbon emissions, and maximise job creation.

MCO is becoming increasingly popular in a number of fields, ranging from engineering and medicine, to economics and social problems. These fields are known to exhibit a high degree of complexity and many competing objectives and technical parameters, which are unstable in time and have many unknowns (Greco, Klamroth, Knowles, Rudolph & Greco, 2015). High computational capabilities are necessary in order to arrive at a feasible solution space, which requires both time and resources, and may be considered a disadvantage (Greco *et al.*, 2015). Another drawback of MCO is its inability to display system feedback and unintended consequences, from the combination of both qualitative and quantitative aspects. The modelling process is very structured and mathematical, thus limiting flexibility, and various scenarios and interventions cannot easily be performed (Emmerich & Deutz, 2006).

6.3 Discrete Event Simulation Modelling

Discrete event simulation (DES) can be defined as, the process of modelling a complex system's behaviour in an ordered sequence of events, where an event comprises specific changes to the system's state, at a specific point in time (Banks & Carson, 1986). An example includes the construction of a plant, or the addition of new capacity to the grid (Banks & Carson, 1986).. DES is considered because the methodology is used extensively in the engineering community, it can be applied to several problem types, and many software packages offer attractive user displays, which could be beneficial in stakeholder discussions.

DES consists of a number of techniques that generate sample paths from which the system behaviour can be studied and characterised (Fishman, 2013). DES models are seen as very flexible (Brailsford, Churilov & Dangerfield, 2014) and they have been used to model complex systems in many fields, such as: engineering, management, health, military, social sciences, and transportation (Fishman, 2013; Brailsford, Churilov & Dangerfield, 2014).

DES can be used to represent both theory and accounts of empirical observations, in particular the methodology serves the following purposes (Fishman, 2013):

i. Allows the modeller to combine both theoretical and empirical observations for a system and deduce logical explanations from the model's behaviour.
ii. Improves the understanding of a system.
iii. Critical thinking is required to determine which details are relevant to model.
iv. Provides the ability to test various system modifications, manipulate variables and implement interventions.
v. Allows more control over sources of variation than the actual system may allow.
vi. More cost effective than directly studying the system.

According to Fishman (2013), DES involves, but is not limited to, seven concepts which are used to formulate models: Work, Resources, Routing, Buffers, Scheduling, Sequencing and Performance. Brailsford *et al.* (2014), however, describe DES models in terms of four fundamental building blocks: Entities, Queues, Activities and Resources. Where entities are items that flow through the system, queues are areas where entities wait to be worked on (buffers), activities are the actual work performed on entities, and resources are required in order to perform activities (Brailsford *et al.*, 2014).

According to Matloff (2008) three world views have emerged due to the difficulties that modellers have experienced in writing and debugging the simulation code for DES. These paradigms are used to separate the different languages to provide more clarity and understanding between coders. These paradigms are:

i. The Activity-Oriented Paradigm
ii. The Event-Oriented Paradigm
iii. The Process-Oriented Paradigm

DES can be used to model both stochastic and deterministic events, and can be combined with other methodologies to achieve even more accurate predictions. Several software packages exist, such as Arena, Simio, Flexsim, and AnyLogic.

The disadvantages of DES are that it is not suitable to analyse human behaviour, it is less effective in showing variability over time, and focuses on events at discrete events, and less on the dynamic changes over time of the system (Sumar, Ibrahim, Zakaria & Hamid, 2013). DES can model vast amounts of detail, over very small-time steps. However, for this research, this is a disadvantage due to the long-time period (decades) that is to be modelled, thus resulting in excessively long computational times. Another disadvantage is due to the stochastic nature of DES; multiple simulation runs are required in order to achieve accurate results, which creates further complications and is time consuming (Brailsford *et al.*, 2014).

6.4 System Dynamics

System dynamics (SD) can be defined as, a method that shows the time-dependent behaviour of a managed system in order to gain an understanding of the systems behaviour. This understanding is achieved through the use of quantitative and qualitative models, robust feedback structures, and the control of policies through simulation and optimization (Coyle, 1996). The methodology was selected due to its emerging prominence in the engineering field, and its ability to define system boundaries, which incorporate both qualitative and quantitative factors. Furthermore, it presents the information in a format that is easily understood by stakeholders from various backgrounds. Jay Forrester and his colleagues at MIT developed the SD methodology in the 1950s. The methodology makes use of feedback systems, understanding decision-making processes, and the use of mathematical models to simulate and compute complex systems (Kambiz E & Cavana, 2007).

The modelling process involves five interlinked phases (Kambiz E & Cavana, 2007):

i. Problem Structuring
ii. Causal Loop Modelling
iii. System Dynamic Modelling
iv. Scenario Planning and Modelling
v. Implementation and Organisational Learning

SD modelling helps one to understand: the structure of the system, its behaviours, and the extent to which various policies influence its functioning mechanisms. SD aims to find solutions to problems and not focus on systems (Musango, Brent & Bassi, 2016). SD modelling is based on the use of: Stocks and flows; Feedback Loops; Delays; and non-linearity. The methodology is able to combine both qualitative and quantitative factors, which makes it useful for modelling policies and organisational problems (Sumar *et al.*, 2013).

Software programs used to model SD include, but are not limited to, Stella and Vensim. Advantages of SD include the ability of the modeller to understand a complex system and identify which factors in the system are cause for concern. The methodology also allows the modeller to analyse different scenarios through the application of interventions (Sumar *et al.*, 2013).

Disadvantages of the methodology are: system dynamic simulations require the modeller to have a good understanding of the system and the problem definition needs to be correct and clearly defined to get the best modelling results. Other complications may occur if the system is too big and too much complexity is present in the problem, making it very time consuming to define and build the model (Sumar *et al.*, 2013).

With regards to the dual-narrative modelling approach, Moallemi *et al.* (2016) have incorporated SD models with transition theories, to perform a policy analysis for renewable energy development in India. Their study provides important insights, which will be helpful to further research and may further motivate the appropriateness of SD modelling for this application.

6.5 Benchmarking of Modelling techniques

To conduct a Benchmarking analysis, an appropriate assessment of the methodologies is necessary. UNEP (2014) suggests a criteria for modelling policies for the green economy, which includes: applicability to country, stakeholder consultation, ease of customisation, transparency, data needs, time of implementation, time horizon, and effort for maintenance. An evaluation criteria was developed from a combination of factors, specifically: the UNEP criteria for green economy modelling, past modelling experience, an understanding of the problem, and research constraints (time, restricted access to data, and funding). The evaluation criteria was used to assess the three modelling methodologies and the methodology that performed the best was selected as the most appropriate method. The benchmarking process involves rating each modelling methodology's ability to perform the required functions in the evaluation criteria. The rating scale is shown in Table 6.1, and the benchmarking results can be seen in Table 6.2.

i. **Computation Time:** is concerned with the computational computer power necessary to find a solution set along with the run time and of number of runs needed to achieve acceptable results.
ii. **Ability to show effect over time:** displays effect of various changes to the system over the time horizon from 2010 to 2050 is essential to the decision-making process, thus output graphs or data will be beneficial and add to the attractiveness of the methodology.
iii. **Ability to handle complexity:** deal with multiple constraints and variables that are interlinked and changeable.
iv. **Ability to model a dynamic system:** shows the effect of system changes from cause and effect relationships.
v. **Flexibility:** ease by which variables, functions and model logic can be changed.
vi. **Ease of Validation:** confirmation that the model reflects a real-world situation and performs necessary functions.
vii. **Outcome Accuracy:** Outputs or solutions, reflect the mathematical functions and constraints of the system.

Table 6.1: Rating Scale

Rating	Value
Inability	-2
Poor	-1
Average	0
Competent	1

Table 6.2: Evaluation of three criterion based on the evaluation criteria

Evaluation Criteria	**Multi-Criteria Optimisation**		**Discrete Event Simulation**		**System Dynamics**	
Computation Time	Poor	-1	Average	0	Competent	1
Ability to Show Effect Over Time	Competent	1	Average	0	Competent	1
Ability to Handle Complexity	Competent	1	Average	0	Competent	1
Ability to Model Dynamic System	Average	0	Competent	1	Competent	1
Flexibility	Poor	-1	Competent	1	Competent	1
Ease of Validation	Competent	1	Competent	1	Competent	1
Outcome Accuracy	Competent	1	Average	0	Average	0
SCORE AND RANKING:	**3rd**	**2**	**2nd**	**3**	**1st**	**6**

6.6 Conclusion of Benchmarking Results

Based on the results from Table 6.2, MCO ranked the lowest due to its poor ability to show dynamic system changes, as well as its inflexibility. Modelling of complex problems, using MCO, also requires excessive computational capabilities. The social dimension of the research question, with unquantifiable variables, may result in a model that is not a true reflection of the real-world problem.

DES was ranked in second place, due to the methodology’s average ability to handle complexity. Although the model can simulate events over time, long time periods (such as the one that is required to be modelled) will result in excessive complexity in the modelling process, which may affect the outcome accuracy. Additionally, multiple simulation runs are required to obtain averages which results in additional computational time constraints.

Therefore, SD is the preferred approach to model the South African electricity sector SET, due to its excellent ability to represent dynamic systems, handle complexity, and show system effects over long periods of time. The methodology’s ease in running interventions and the minimal computation time is an added benefit.

7 Problem Structuring and Model Development

7.1 Introduction

This chapter discusses the development of the SD model for the South African electricity sector. The SD methodology was followed systematically. Thus, the model was first conceptualised in the form of a model boundary chart, and a causal loop diagram. The model was then modelled dynamically and the model logic is outlined in Section 7.6. The model underwent a verification and validation process, in the form of a sensitivity analysis, behaviour tests and validation by industry experts through individual discussions. Six scenarios were run with the model and are briefly discussed.

7.2 System Dynamics Modelling Process

The SD methodology is a rigorous way to help thinking, visualising, sharing and communicating complex organisations issues and their evolution over time (Kambiz & Cavana, 2007). The methodology also involves the creation of operational maps and simulation models that capture mental models and convey interrelationships of physical and behavioural processes, organisational boundaries, policy, information feedback and time delays, test holistic outcomes of different scenarios (Kambiz & Cavana, 2007). Thus, SD is viewed as a means of modelling complex systems in order to enable further insights into complex real world problems over time. SD aids in stakeholder decision-making processes and enables long-term solutions that achieve sustainability (Musango *et al.*, 2015).

Since the methodology's development in the 1950s, it has been used to analyse problems in various fields of society, such as: global, environmental and socio-economic challenges. Several researchers have used SD to model issues surrounding sustainability, including: the sustainability of logistic systems (Qu, Thürer, Wang, Wang, Fu, Li & Huang, 2017), the water-energy nexus (Chhipi-shrestha, Hewage & Sadiq, 2017), water conservation (Sahin, Bertone & Beal, 2017) water resource management, agriculture and rural development (Johnson, Bryden, Refsgaard & Lizárraga, 2008), and climate change mitigation (Li, Zhang, Li & He, 2017). There is a growing body of literature with regards to the application of Systems Dynamics in the energy sector, particularly for low-carbon electricity planning (Momodu, Addo, Akinbami & Mulugetta, 2017), electricity market dynamics (Yang, Wang, Zhou & Zhou, 2006), and electricity grid decentralisation dynamics (Kubli & Ulli-beer, 2016).

Figure 7.1 shows the methodology's process. An example of a basic stock and flow diagram can be seen in Figure 7.2, this is the basis of the dynamic modelling process. These stock and flow diagrams form the basis of dynamic model systems and consist of: stocks, flows, auxiliaries, and constants (Sterman, 2000). These building blocks enable dynamic complexities to be captured. Subsequently, scenarios can be developed and evaluated once the model has been built, by simulating the numerous scenarios with varying parameters. From this level of analysis, new insights can be gained and unintended consequences may surface, which should help actors and stakeholders to make more informed decisions (Sterman, 2000).

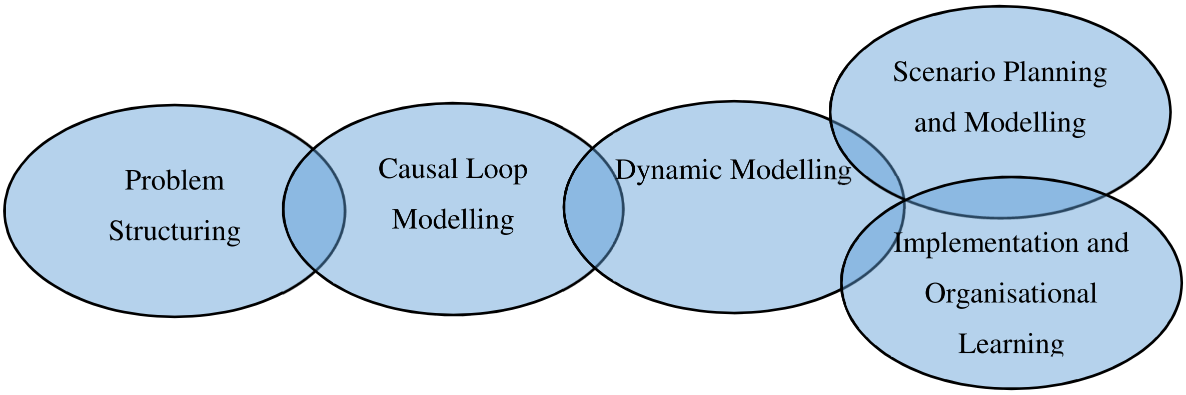

Figure 7.1 Phases of the systems dynamics modelling methodology (Kambiz E & Cavana, 2007)

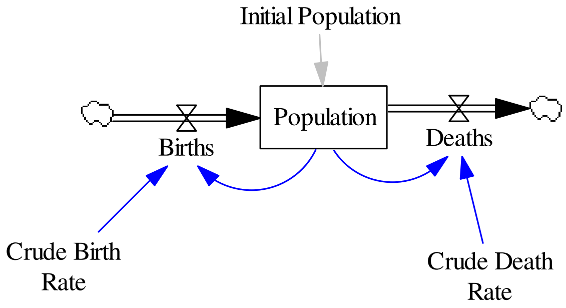

Figure 7.2 A stock and flow diagram

7.3 **Problem Structuring**

The problem structuring phase of the systems dynamics methodology is initiated by the definition of the problem. Defining the gap between the current situation and the ideal situation, the dilemma where conflicts are stated and a brief problem statement. This helps the model simplify the modelling process and define the model boundaries for the causal and dynamics model.

Simply stated the problem South Africa's electricity sector is facing is that it needs to ensure that sufficient electricity supply is delivered to the consumer while reducing high emission rates. As well as, creating jobs to battle the high unemployment rates, and low economic growth, which is negatively affects investment.

A gap exists between the current situation – which is an electricity sector largely reliant on high-emission baseload power generation – and the ideal situation, which is a solution that is lower in emissions, economically competitive and provides many social benefits. Thus, the ideal satisfies the three pillars of sustainability: economic, social and environment.

The problem is that there are several complex interactions in this socio-technical transition. To find a solution that will address the set of criteria for sustainability of the electricity sector, is the dilemma.

There are many key actors that play a role in this model namely; Eskom, NERSA, Government Departments (such as the Department of Energy, Public Enterprises and Economic Development), Independent Power Producers, NGO's, public utilities, and private companies and electricity consumers. Due to the nature of the electricity sector, the network of actors is far reaching; and thus, almost every citizen in South Africa will be impacted by the electricity sector. Likewise, foreign investors and international firms also have a role to play in this sector.

In Figure 7.3, a goal tree, was developed to break up the various sustainability criteria into model goals. The goal tree also helps determine how the model is going to model these outcomes to determine the success of the transition to sustainability over time.

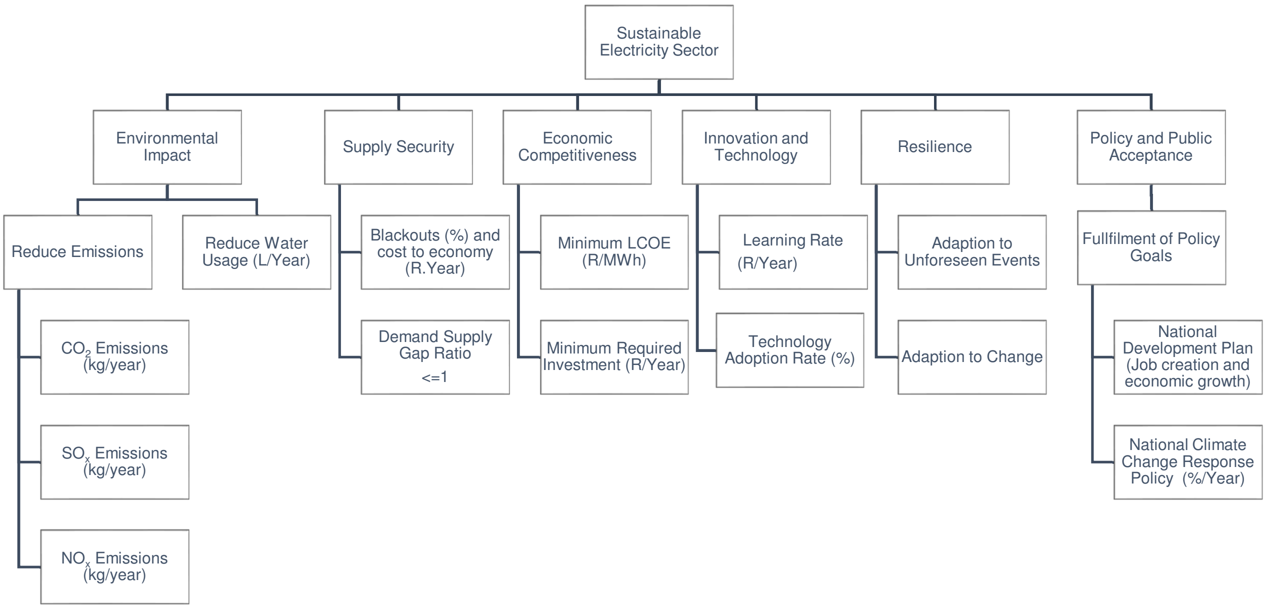

Figure 7.3 A Goal Tree for the actors involved in the SD process with measurable outcomes and units of analysis.

7.3.1 **Model Boundary**

The boundary chart in Table 7.1 divides the model variables into endogenous, exogenous and excluded variables. The boundary chart is conventionally executed before the model is built to allow the modeller the opportunity to establish logical boundaries to simplify the model's complexity and determine what is included and excluded in the model.

Table 7.1 A Boundary Chart for the SD Model

Endogenous	Exogenous	Excluded
Operational Capacities for all technology types	LCOE Data for all Technology Types	Transmission and Distribution Infrastructure
Capacities Under Construction for all technology types	Initial Capacities for all Operational Technology Types	Transmission and Distribution Costs for all Utilities
Planned Capacities for all technology types	Jobs Factors for all Technology Types	Political Influences
Jobs created per Technology Type during, manufacturing, construction, operation and fuel supply phase	Emissions Factor for CO_2, NO_x and SO_x for all Technology Types	Energy Efficiency of Energy Sector
Demand Supply Gap	Imported Electricity	Technological Uncertainties/Risks
Total Generated Emissions for all Technology Types	Exported Electricity	Electricity Storage Technologies
Total LCOE for New Capacity Requirements for all Electricity Types	Cost of Unserved Energy	Complexities of Capacity Requirements surrounding load curves and daily/seasonal fluctuating demand
Required New Capacity for all Technology Types	Renewable Energy Downtime	Per cent Household Electrification
Total Blackouts	Lead Times for Technology Types	Impact of Sector on Unemployment
	IRP Capacity Requirements	Availability of Funds for New Capacity Requirement
	South African Electricity Demand	Impact of Required Dispatchable Electricity on Energy Mix
	Learning rates – Financial	Direct Impact of Blackouts
		Learning rates – Technology Efficiency Improvements

7.3.2 Time Horizon of Analysis and Reference Modes

The SD model will run in the time unit – years, where t=1, over a time horizon of 2010 to 2050. This is based on the same time frame used in the IRP policy which analyses electricity requirements until 2050. Therefore, 't' is representative of time and where t=1 the year is 2010 and so on.

Before the modelling process was completed and scenarios were run the expected model outputs were drawn as seen in Figure 7.4 for conducting a comparison of actual model outputs to expected outputs. The graphs show predications of expected trends that the system should generate, if environmental sustainability and economic growth is achieved.

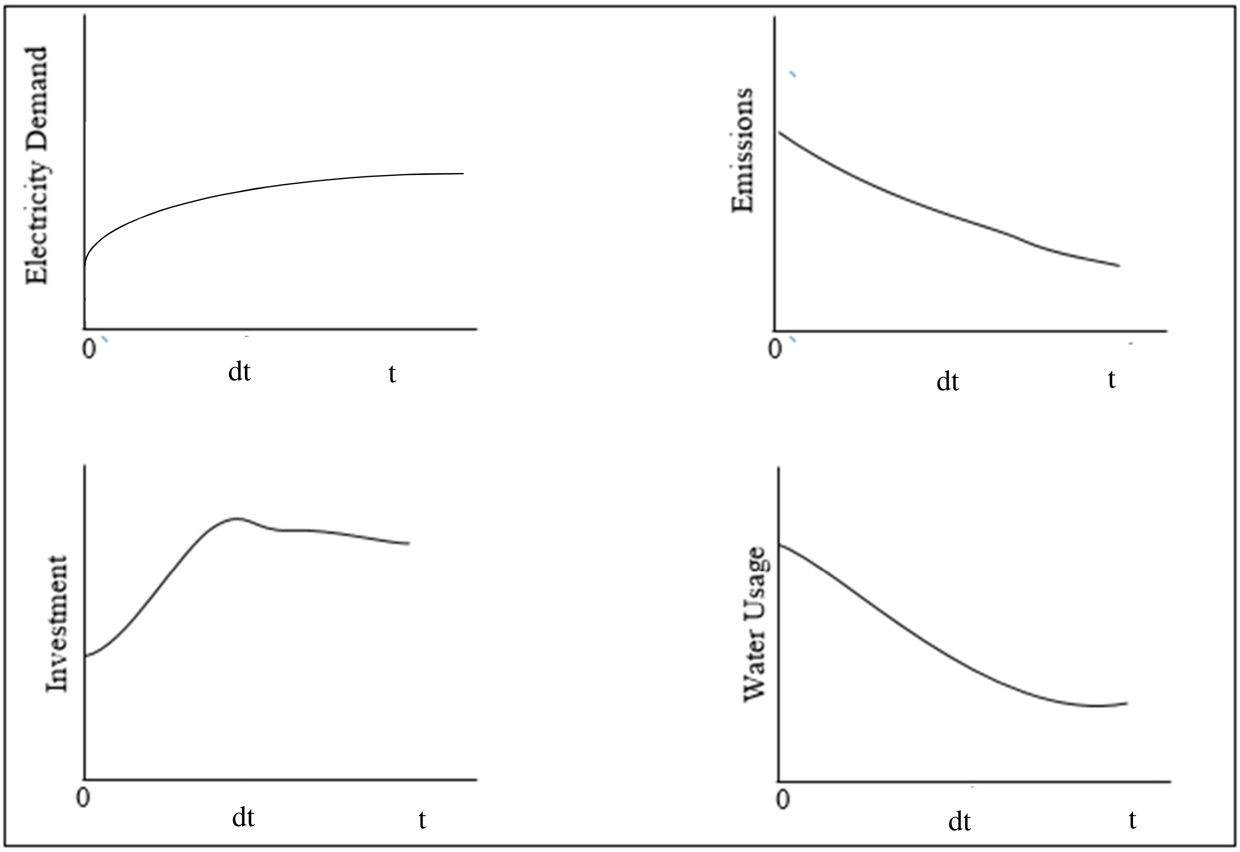

Figure 7.4 Reference Modes expected from SD Model

7.3.3 Data Acquisition

The data obtained for the model was acquired from several sources which are specifically referred to in Section 7.6. All the data used in the model was obtained from open sources and sections of the model logic and data application have been verified by field experts. Some of the data required further analysis and processing in which case excel was used to capture and perform calculations.

7.4 **Causal Loop Modelling**

The Causal Loop Diagram (CLD) for South Africa's electricity sector consists of five feedback loops. Two balancing loops and three reinforcing loops which are explained in more detail. The CLD in Figure 7.5 is one of the first mechanisms in the SD Modelling process used to understand the complexity and determine causality between variables. Therefore, to model the electricity sector of South Africa and determine the rate of transition to sustainability, the CLD is a simplified representation of reality. Several complex interactions with technologies and stakeholders have been excluded according to the established boundaries.

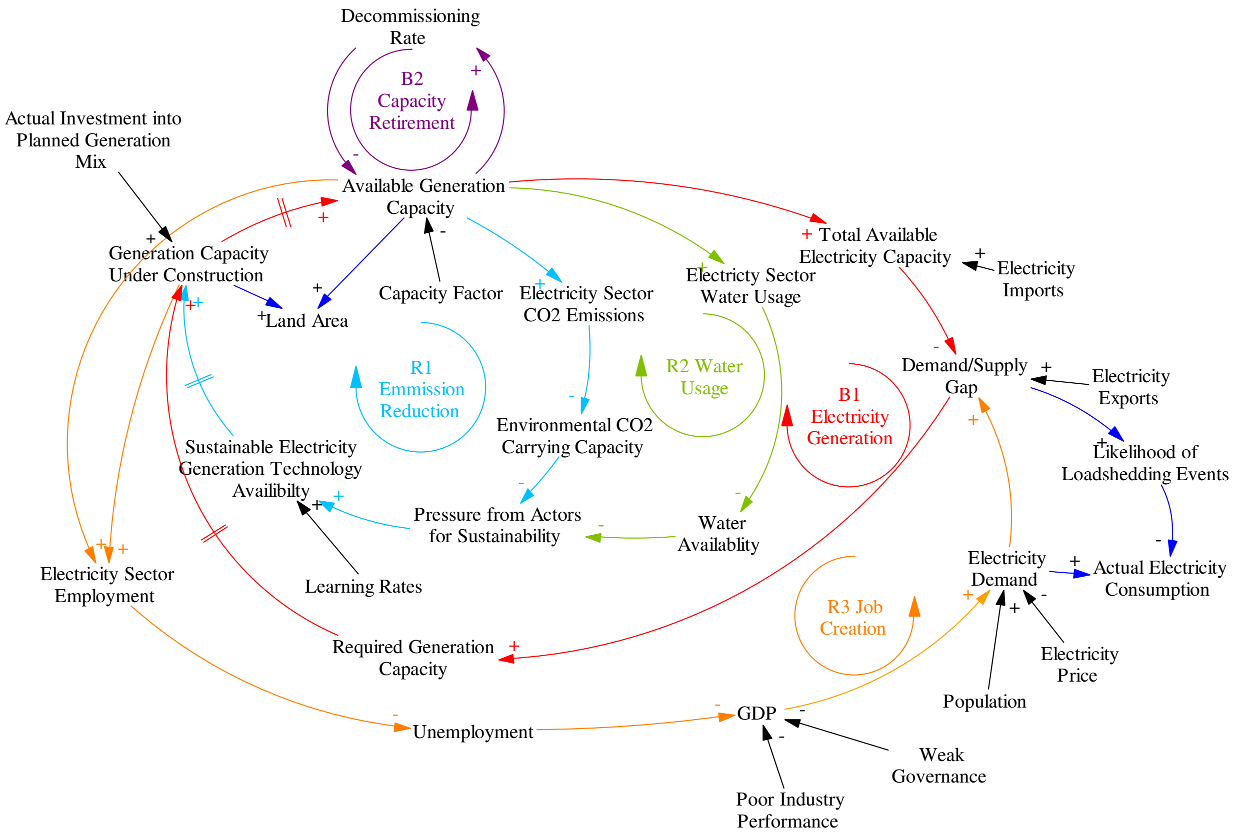

Figure 7.5 The Causal Loop Diagram for South Africa's Electricity Sector

The SD model focuses on South Africa's electricity sector on a high level and models the impact various energy mix combinations have on emissions, land area, financial investment, water usage and employment. The fuel types are modelled on a high level and do not specify the exact engineering process that is used to convert the fuel to electricity, apart from solar energy, where solar PV and solar CSP were modelled separately due to the drastic differences in cost. The various fuel types that are modelled are: coal, nuclear, gas, bio-fuel, hydro, solar PV, Solar CSP and wind.

Electricity is needed because industry, residents, transport, agriculture and government require it to perform daily functions. Electricity is generated from installed capacity from the available fuel sources which are coal, nuclear, wind, solar, gas, hydro and bio-fuel. South Africa imports and exports electricity to/from neighbouring countries. The South African government must ensure that the electricity supplied exceeds the demand to ensure that electricity security is not compromised. If the supply does not meet the demand then events such as load shedding may occur, or electricity will need to be imported or generated from alternative sources, which drives up costs and detriments the economy.

To ensure security of electricity supply, it is necessary to ensure that new capacity is added to the grid. With this addition of new capacity there is an associated cost that requires investment from local, foreign and government sources. The addition of new capacity typically experiences challenges such as, planning and construction delays. Thus, time delays exist between when new capacity is planned and when the capacity is operational and contributing to the electricity supply mix.

To maintain and operate the installed electricity capacity there are associated costs. There are also emission factors associated with electricity generated from coal, nuclear, gas and bio-fuel. Likewise, water usage also varies based on the technology type, and due to South Africa's limited water resources, the least water usage scenario will be favoured in terms of environmental sustainability.

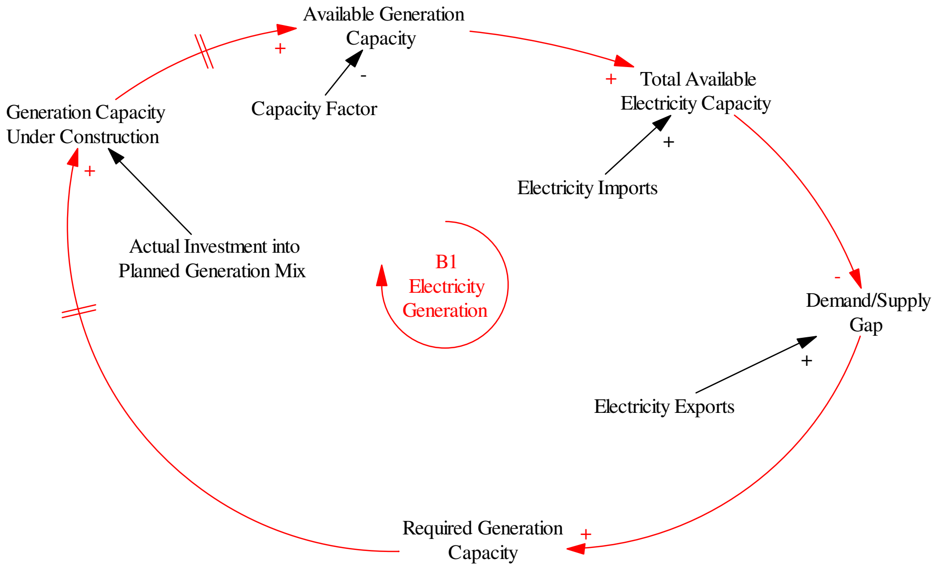

Figure 7.6 Electricity Generation Balancing Feedback Loop

Figure 7.6 illustrates the electricity generation feedback loop where the gap between demand and supply requires additional generation capacity. There is a time delay due to planning between when the electricity is required and when the capacity is constructed, likewise this construction time is also considered a time delay due to the capacity not being available for generation while under construction. Once the additional capacity is commissioned it contributes to the total available electricity capacity. This feedback loop is constantly goal-seeking, due to its need to satisfy the gap between supply and demand.

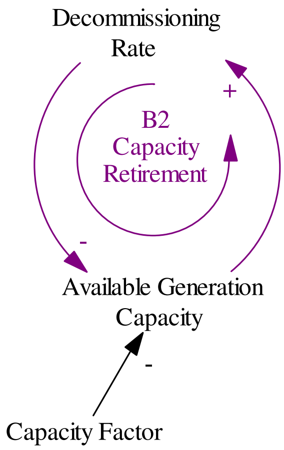

Figure 7.7 Capacity Retirement Balancing Feedback Loop

The second balancing feedback loop demonstrates that the available capacity is decommissioned according to a schedule based on the 2013 IRP (Department of Energy, 2013). The loop is also a representation of aging electricity plants that degrade at a certain rate over time. The aging is based on the assumption that the same capacity for electricity generation cannot be expected of a plant at time ‘t’ and at time ‘t+50 years’. The available capacity also has a certain associated capacity factor at which the electricity plant can operate. This factor is a predetermined engineering constraint associated with the conversion of fuel to electrical energy over time.

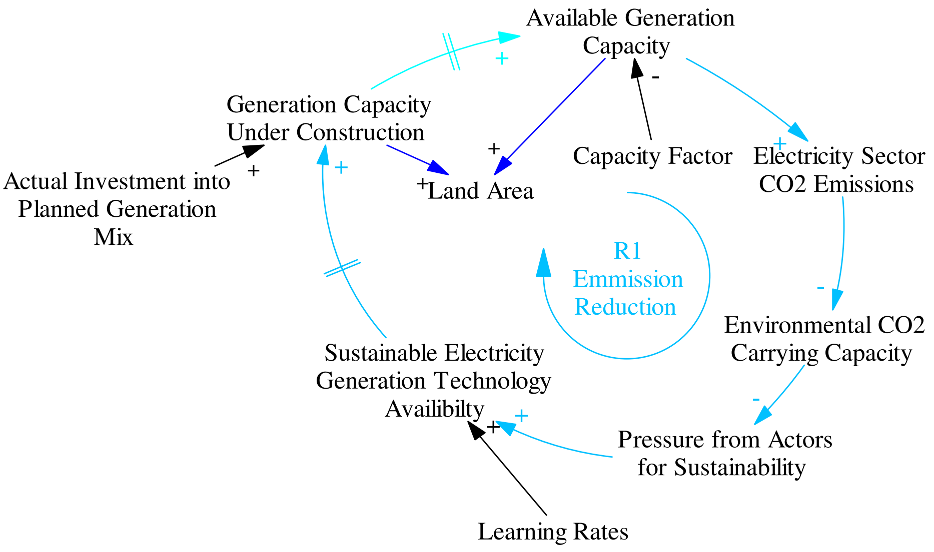

Figure 7.8 Reinforcing Feedback Loop for Emission Reduction

The first reinforcing loop, encompasses emission reduction, to achieve sustainability and satisfy the emission reduction policy. Certain electricity plants generate emissions due to the type of fuel used, these emissions contribute to the total emission carrying capacity of South Africa's environment. This carrying capacity is limited to an acceptable emission amount and if emissions exceed the limit there are implications, such as carbon tax. For this financial reason and other reasons associated with environmental sustainability, actors in the system pressurise the electricity sector to implement more sustainable electricity generation technologies. Likewise, this pressure from actors also results in the further development of new renewable energy innovations and thus learning rates are applicable to these technologies.

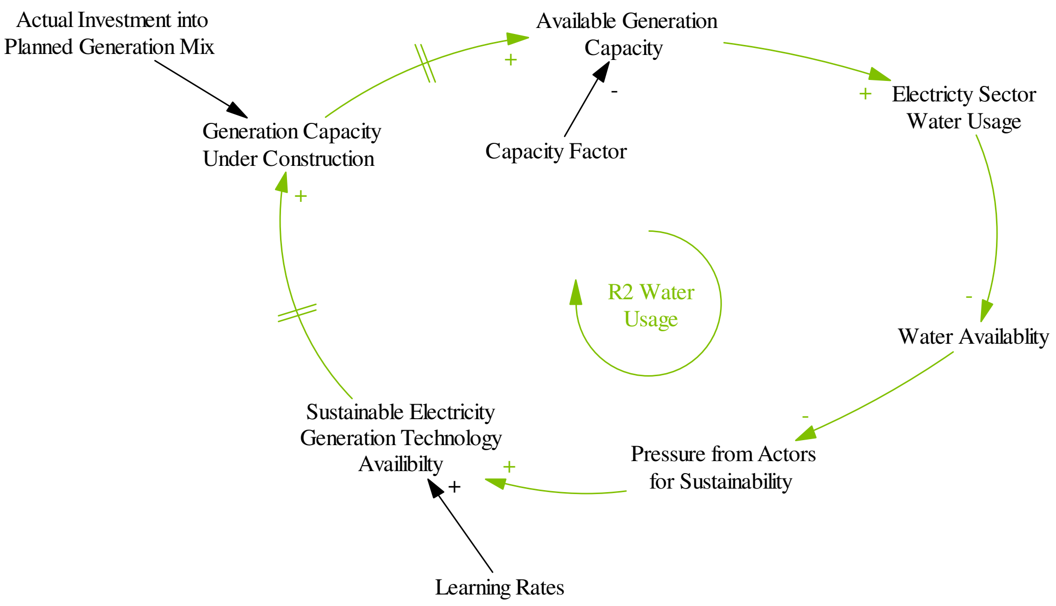

Figure 7.9 Reinforcing Feedback Loop for Water Usage

A similar logic is applied to the water usage reinforcing feedback loop in Figure 7.9. Over the past few years South Africa has struggled with seasonal drought across the country. Consequently, water is a limited resource and technology types requiring large amounts of fresh water, for electricity generation, will receive extra scrutiny from multiple stakeholders. Thus, the technology's ability to sustainability use water is essential.

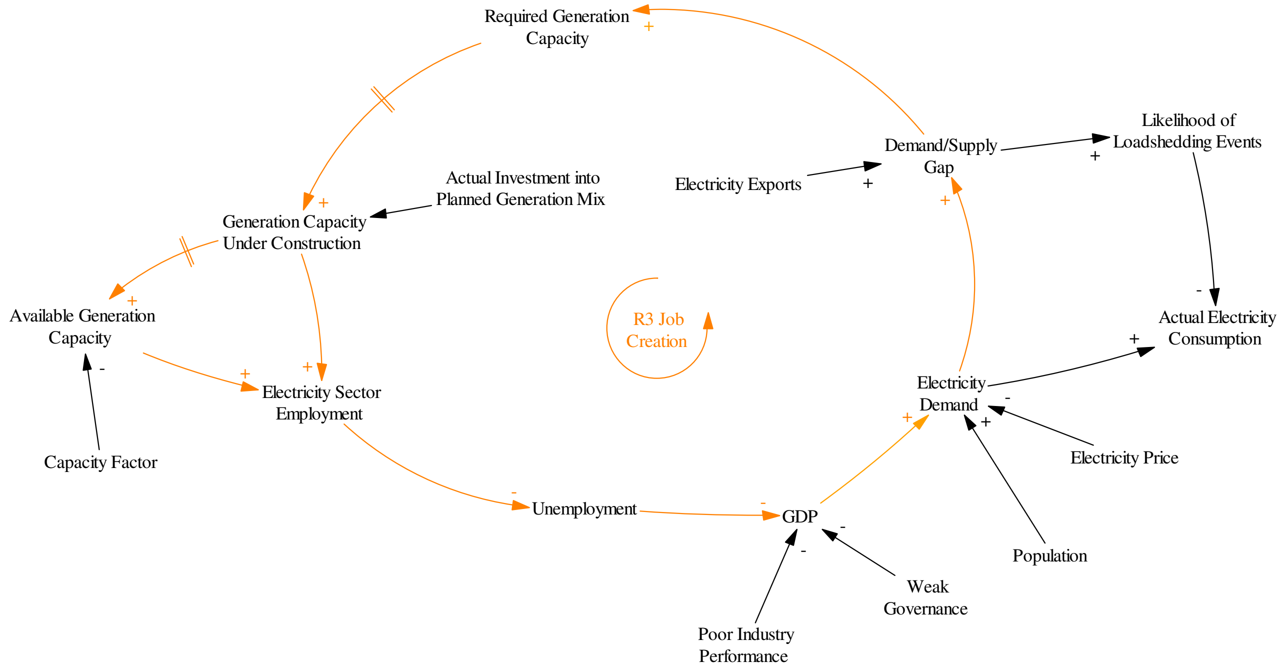

Figure 7.10 Reinforcing Feedback Loop for Job Creation

The third reinforcing loop in Figure 7.10 is the job creation loop, which was formulated with the National Development Plan policy goals in mind. These goals include transforming South Africa's economy and eradicating poverty and unemployment. One of the stepping stones to achieving these goals is the creation of jobs. The electricity sector has the potential to create thousands of jobs, however this is also dependant on the type of electricity generation used. For example, an energy mix containing less coal and nuclear will have drastic impacts on the mining sector.

Resilience is a characteristic much needed by South African policy and decision makers. The new capacity additions could influence not only construction and manufacturing jobs, but fuel supply and operational jobs. Consequently, it will impact the number of jobs created by the electricity sector and thus the country's unemployment rate. The level of unemployment impacts the country's economic growth and GDP. External factors, such as weak governance and poor industrial growth also play a role in South Africa's GDP growth, but these are qualitative factors that have external and unpredictable effects and for this model, are only recognised in the CLD but are not modelled explicitly.

7.5 System Dynamic Modelling of South Africa's Electricity Sector

The SD model was built using Ventana Systems Inc.'s, Vensim DDS Software licensed to Stellenbosch University. The model consists of several sub models which are explained in detail in Section 7.6. Due to the SD model being a representation of the reality several assumptions were made, as follows:

i. It is assumed that the CSIR's demand forecasts are an accurate representation of the future demand of the electricity sector and thus are used as inputs into the model (Mokilane, Makhanya, Koen, Holloway & Magadla, 2016).
ii. Real-time load balancing constraints involved with seasonal and daily demand peaks are not considered, and therefore the model assumes that the electricity demand and generation needs are over a one-year period.
iii. A simplified method for predicting the addition of new capacity to the grid is used which does not consider the complexities of multiple variables.
iv. There are no minimum or maximum limits to the addition of new capacity to the grid.
v. The Levelised Cost of Electricity (LCOE) released in the 2016 IRP has stimulated much debate. Thus, to avoid discrepancies and debates revolving around the LCOEs, the model generates random LCOEs based on a normal distribution with historical data from all previous IRP reports used to calculate mean, standard deviation, minimum and maximum values.
vi. An optimistic assumption was made for the electricity sector employment potential, which is; all jobs (100%) for all technology types are local.
vii. The land area data only includes the km^2 of the physical electricity generation plant, and not the land used for mining or agricultural purposes for bio-fuel production.

7.6 The Sub-Models

The model comprises twenty sub-models, one control panel- which displays the graphs in a central location and, one tabular display which displays the model data over time. A summary and description of each sub-model is presented in Table 7.2. Each sub-model's mathematical logic is described in detail in this section and each sub-model diagram can be seen in Appendix A.

Table 7.2 A brief description of each Sub-Model

Sub-Model Name	***Sub-Model Description***
Electricity Sector Demand	Electricity demand is generated from data tables for the 2010-2050-time frame under low, medium and high economic growth conditions.
Electricity Generation Capacity	The planning, construction, generation, degradation and, decommissioning of electricity capacity is modelled for each technology type, which includes: coal, nuclear, bio-fuel, gas, solar PV, solar CSP, wind and hydro.
Demand Supply Gap	The gap between required electricity (electricity demand) and the available electricity (electricity supply) is calculated and application of an applied 'effect' on this electricity gap will determine the need to add new planned capacity.
Supply Fraction	The percentage of each technology type to be supplied to the grid is decided on for each scenario and the model generates new capacity based on the percentage split.
Employment	The total job potential of the electricity sector is calculated for manufacturing, construction and operation's phases for each technology type. The total fuel supply job potential is also calculated for the relevant technology types.
Emissions	The total amount of CO_2, NO_x and SO_x emissions produced over time are modelled.
Water Usage	The electricity sector's water usage for electricity generation purposes only is modelled.
Land Usage	The total land area used for electricity generation is modelled, excluding fuel supply considerations.
LCOE	For each technology type, LCOEs are dynamically modelled to determine the total cumulative investment required for each technology type and the electricity sector.

Table continues on next page

Table continued from previous page

Dispatchable Electricity	The total MW dispatchable electricity required to respond to intermittent supply from solar PV, solar CSP and wind is modelled, along with the associated costs.
Installed Capacity	The total MW capacity of operational electricity generation infrastructure is calculated.

7.6.1 Electricity Sector Demand

Initially, the South African electricity sector demand was modelled dynamically with data obtained from the 2016 IRP and various other data sources. It was first assumed that the three drivers of demand for electricity were electricity price, GDP and Population. Moreover it was assumed that the effect that these drivers have on the demand for electricity is dependent on the change in the value of the driver itself (Musango, Brent & Tshangela, 2014). To determine the change in driver, it was necessary to calculate its relative real value by determining the change in the variable from its initial value to a value at a certain point in time. This was done by taking the variables value at time 't' and dividing by its initial value. The change in the value was used to determine the change in a variable that it was influencing.

The elasticity of the driver determines the extent of the effect of the driver on electricity demand, or alternatively, the responsiveness of the electricity demand to the change in the driver. However, this methodology of determining demand resulted in many discrepancies, with the demand trends resulting from changes in the elasticities used to model the effect of the drivers. Recent data for electricity price and GDP elasticities for the years 2005-2017 was not found for South Africa. One author Inglesi-Lotz (2011), published data up until 2005, and simple elasticity calculations performed on historic data differed greatly from the data Inglesi-Lotz (2011) published. On further investigation of literature on this topic, it was discovered that there a number of discrepancies with regards to the causal relationships between electricity demand and factors such as: energy consumption, real income and economic growth (Odhiambo, 2009; Lin & Wesseh, 2014).

As a result, due to the demand being an essential part of the model it was decided that these discrepancies presented a too greater risk for inaccurate model results. Thus, the CSIR's forecasts for electricity demand (ED) were used as input tables into the model for low, medium and high economic growth scenarios (Mokilane, Makhanya, Koen, *et al.*, 2016). Therefore, the electricity sector's demand sub-model estimates the future electricity demand for the country for low, medium and high economic growth strategies for the immediate, medium and long-term futures.

The three economic growth pathways are depicted by n where n= {low, medium, high}, each demand forecast in MWh, for years 2010 to 2050 were inputted into a lookup table. The user can then switch demand profiles by changing the value of the 'Demand Switch' Variable. The "Demand Switch" uses "if then else" logical statements as shown in equation 2.

$$ED(t)_n = ED\ Table(t)_n \times Demand\ Switch \qquad (1)$$

$$Demand\ Switch = IF\ THEN\ ELSE(\ DEMAND\ SWITCH = 1,\ ED\ Table(t)_1,$$
$$IF\ THEN\ ELSE(DEMAND\ SWITCH = 2,\ ED\ Table(t)_2, IF\ THEN\ ELSE(DEMAND\ SWITCH =$$
$$3, ED\ Table(t)_3, 0))) \qquad (2)$$

7.6.2 Electricity Supply from Various Generation Capacities

Electricity can be generated from several different technology types. These technology types have varying fuel sources and for the purpose of the model were generalised at a high level, the types include: coal, nuclear, gas, hydro, wind, solar PV, solar CSP and bio-fuel. Each electricity technology type is modelled separately because each technology type has their own unique capacity development process. This process is based on the addition of new capacity from the supply fraction sub-model. Each capacity development process has unique characteristics specific to each technology type, including: time delays and capacity factors.

The electricity supply is determined by summing the various operational capacities from the eight technology types. Thus, each technology type was modelled separately, a generalised stock and flow diagram can be seen in Figure 7.11, where each technology type has four stocks: Planned Technology Capacity (PTC), Technology Under Construction (TUC), Operational Technology Capacity (OTC), and Decommissioned Capacity (DC).

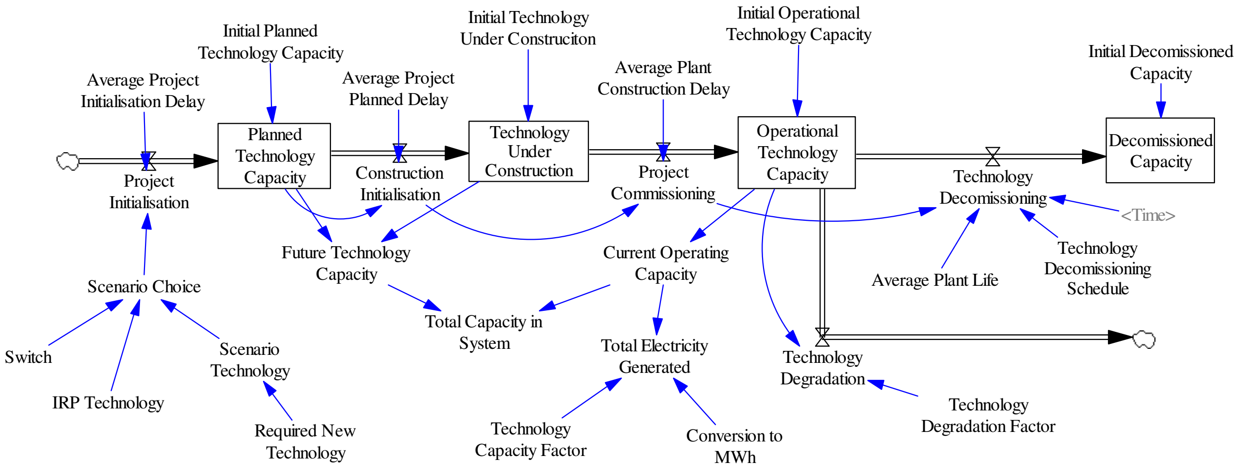

Figure 7.11 A generalised stock and flow diagram for electricity supply.

Project Initialisation (PI) is the start of the process that adds new electricity supply to the grid, which satisfies the demand. Each project for the technology type i, where i, is a set of eight technology types, i = {coal, nuclear, gas, hydro, wind, solar PV, solar CSP and bio-fuel} has new capacity added to the grid based on the Scenario Choice (SC), which has two options, j = {IRP Scenario, Varied Scenario}. The first choice is to run the IRP scenario based on the capacities specified in the 2016 IRP (Department of Energy, 2016b). The second option is to run various scenarios as specified by the user, more detail is provided in Section 7.8 as to what scenarios were chosen for this research. Each project has an associated Average Project Initialisation Delay

(APID) and thus, to account for events where projects may be delayed, a first order delay is used to model these circumstances as depicted in equation 3. The project lead times for each technology type are based on the average lead time in the IRP 2016, specified for new technology project lead times (Department of Energy, 2016b). The initial PTC is assumed to be zero for all technology types and PTC is calculated as shown in equation 4.

$$PI(t)_i = Max(Delay1\big(SC(t)_j, APID(t)_i\big), 0) \tag{3}$$

$$PTC(t)_i = PTC(0)_i + \int PI(t)_i - CI(t)_i \, dt \tag{4}$$

For the Construction Initialisation (CI) flow a first-order delay is used to model the time delay between the initial planning phase and when actual construction starts. The Planned Capacity (PC) is then divided by the Average Project Planned Delay (APPD) to determine the amount of MW to begin construction in that year – time ‘t’. A maximum function is used to ensure non-negative flows as seen in equation 5. The TUC stock is calculated as shown in equation 6, with the initial TUC assumed as zero.

$$CI(t)_i = Max(Delay1(\frac{PC(t)_i}{APPD(t)_i}, APPD(t)_i), 0) \tag{5}$$

$$TUC(t)_i = TUC(0)_i + \int CI(t)_i - PC(t)_i \, dt \tag{6}$$

After construction is complete a project is commissioned. The time taken to construct a plant is modelled as a first order delay of the Average Plant Construction Delay (APCD), from which the Project Commissioning (PC) flow in equation 7 calculates the amount of capacity that becomes operational at year t. This fully functioning capacity collects in the OTC stock. The initial OTC for each technology type i, in equation 8, were inputted as the already installed and operating capacities and data was obtained from StatsSA and Eskom (2012; 2015). The OTC stock is then reduced through two possible flows: Technology Decommissioning (TD) or Technology Degradation (TDG).

TD, in equation 9, is affected by two variables, the first of which being a first order delay based on the Average Plant Life (APL) of a plant, and the second is based on a Technology Decommissioning Schedule (TDS). Data for this schedule was obtained from the “Assumed decommissioning schedule for the existing fleet” table in the 2013 IRP report (Department of Energy, 2013: 60). TDG, in equation 10, degrades technologies at a yearly rate of 1% defined as the Technology Degradation Factor (TGF) with an assumption that technologies become less efficient over time, even though regular maintenance may take place. Decommissioned Capacities (DC) accumulate in a stock based on the TD flow, as illustrated in equation 11.

$$PC(t)_i = Max(Delay1(CI(t)_i, APCD(t)_i), 0) \tag{7}$$

$$OTC(t)_i = OTC(0)_i + \int PC(t)_i - TD(t)_i - TDG(t)_i \, dt \tag{8}$$

$$TD(t)_i = Max(Delay1(PC(t)_i, APL(t)_i) + TDS(t)_i, 0) \tag{9}$$

$$TDG(t)_i = OTC(t)_i * TDF \tag{10}$$

$$DC(t)_i = DC(0)_i + \int TD(t)_i \, dt \tag{11}$$

Furthermore, future capacities are calculated by summing the stocks of planned capacity and capacity under construction. The total Electricity Generated (EG) per technology type, seen in equation 12, is calculated by converting the Current Operating Capacity (COC) at time t, from MW to MWh, by multiplying by a conversion factor. The Conversion factor is stated in equation 13. A Technology Capacity Factor (TCF) for each technology type is also applied to determine the maximum possible energy output of the given installed electricity. The capacity factor is calculated from a ratio of actual electrical energy output over time t, to the maximum possible electrical energy output over time t, the values for each TCF were averages calculated from the Annexure A of the 2016 IRP (Gross, Lyons & Nguyen, 2015).

$$EG(t)_i = COC(t)_i \times Conversion\ to\ MWh \times TCF_i \tag{12}$$

$$Conversion\ to\ MWh = 24 \frac{hours}{day} \times 365\ \frac{days}{year} \tag{13}$$

7.6.2.1 **Coal Electricity Generation**

The type of process used to generate electricity from coal was not distinguished in the model, neither whether emission reduction technology is used nor what type (Carbon Capture and Storage (CCS) or Flue Gas Desulphurization (FGS)). When these variables are considered on a small scale there are notable differences in cost, efficiency and emissions. However, for this model this level of detail was noted but not modelled explicitly due to the additional layer of complexity.

The model allows any amount of MW capacity to be added to the grid per year based on the total required capacity for all technology types, i. Although ideally economies of scale would make the addition of new capacities to the grid cheaper, due to new infrastructure (access roads, utilities, mines etc.) that may be required to make these capacities operational (this is applicable to all technology types).

7.6.2.2 **Nuclear Electricity Generation**

For the nuclear generation technology type, the type of reactor was not distinguished. For example, 5% enriched uranium oxide fuel, reprocessed uranium fuel or 100% mixed uranium plutonium oxide fuel. The choice of fuel will have repercussions on design, fuel procurement, and waste disposal which need to be considered. Likewise, plant designs should not only consider economic competitiveness and environmental sustainability but increased safety.

7.6.2.3 **Gas Electricity Generation**

The model does not differentiate between the type of gas cycle i.e. open or closed cycle. However, it is noted that there are significant differences in load factors and efficiencies. Gas is an attractive electricity generation technology type, due to its ability to be ramped up at any time as demand peaks, for this reason it is considered the dispatchable electricity alternative.

7.6.2.4 **Bio-Fuel Electricity Generation**

Bio-Fuel was used as the overarching term for electricity generation from biomass forestry residue, biomass municipal solid waste, landfill gas and bagasse. It is noted that the LCOE of each type along with fuel costs, emissions and load factors differ. Thus, for each variable an average of all the variants was calculated from the data provided in the 2016 IRP (Department of Energy, 2016b).

7.6.2.5 **Hydro Electricity Generation**

Due to South Africa, limited water resources the hydroelectricity capacity was limited to a maximum of 5% new capacity in all supply fraction choices for all scenarios.

7.6.2.6 **Solar PV Electricity Generation**

For the Solar PV technology type the model considers the time when the sun is not shining and thus electricity is not generated resulting in Solar PV 'downtime'. During this time, it is noted that this technology type cannot provide capacity to the grid and thus an alternative technology type is necessary to respond to demand. The model accounts for this by calculating the electricity 'lost' due to downtime and the required demand response capacity and cost, as well as the cost to the economy if this demand goes unserved which is R77.30 /KWh^2 (Department of Energy, 2016b). The maximum downtime of Solar PV in one year was modelled as an input slider, where a percentage of the year can be inputted to model the technologies unavailability. This variable can be changed to model the hours of daylight in a year, and to determine the impact this has on the required dispatchable electricity capacity, cost as well as the cost to the economy.

7.6.2.7 **Solar CSP Electricity Generation**

Several different CSP variants exist: Parabolic Trough, Fresnel Reflector, Solar Tower and Solar Dish, all of which have different storage capabilities. However, the model does not differentiate between these variants. Likewise, a similar logic that was applied to Solar PV downtime, was applied to the Solar CSP sub-model with the maximum downtime in 1 year as an input slider.

7.6.2.8 **Wind Electricity Generation**

Wind generation is a flexible technology type due to its large variations in windmill sizes. Downtime for wind generation was also considered for when the wind does not blow. However, this is more difficult to establish a reliable figure due to the variations and unpredictability of wind across the country. Similarly, this was modelled as an input slider to determine the effects of wind variability on demand response requirements and the associated costs.

7.6.3 Demand Supply Gap

The Total Electricity Generated by the System (TEGS) is calculated by summing the EG at time t, for each technology type i, as stated in equation 14. A Transmission and Distribution Loss Factor (TDLF) of 4% (StatsSA, 2012) was applied to the TEGS to obtain the NET Electricity Generation (NEG) as shown in equation 15.

$$TEGS(t) = \sum_{i=8} EG(t)_i \tag{14}$$

$$NEG(t) = TEGS(t) \times TDLF \tag{15}$$

The NET Electricity Supply (NES) was determined by summing the NET Electricity Generated by South Africa and the NET Imported Electricity, which was calculated as an average of 10 879 GWh per year (South Africa Data Portal, 2015a). The NET Electricity Demand (NED) was calculated by summing the ED and Electricity Exports which was calculated as an average of 14 649 GWh per year (South Africa Data Portal, 2015b). The Demand Supply Gap Ratio (DSGR) in equation 16,was calculated by dividing the NED by the NES. Depending on the value of the DSGR it has a certain ‘dynamic effect’ on the amount of required electricity to be added to the grid. Thus, the DSGR value generates the percentage required new electricity capacity that is necessary for supply to meet demand. If the DSGR<1 supply is sufficient, and coversely if DSGR>1, demand is greater than supply which is unfavourable.

$$DSGR(t) = \frac{NED(t)}{NES(t)} \tag{16}$$

To generate new electricity a simplified representation of reality was used to determine the possible effect that the DSGR would have on the required electricity supply, Figure 7.12 shows how this effect was modelled. The inputted values for table were determined by a repetitive trial and error process, which consisted of: variable inputs, simulation runs and result comparisons. This process ensured that all scenario combinations would generate sufficient electricity supply without excessive over or under production. The output values were adjusted by a 0.025 difference until the shown values were deemed the most optimal for all scenario runs. The x variable is the DSGR input and the y variable is the percentage of existing capacity, which is the generated value called ‘Effect of DSGR on Required Electricity (RE)’. The Required New Electricity (RNE) capacity is calculated in equation 17 which is the total amount of new capacity to be added to the electricity mix.

$$RNE(t) = Effect\ of\ DSGR\ on\ RE\ \times NES(t) \tag{17}$$

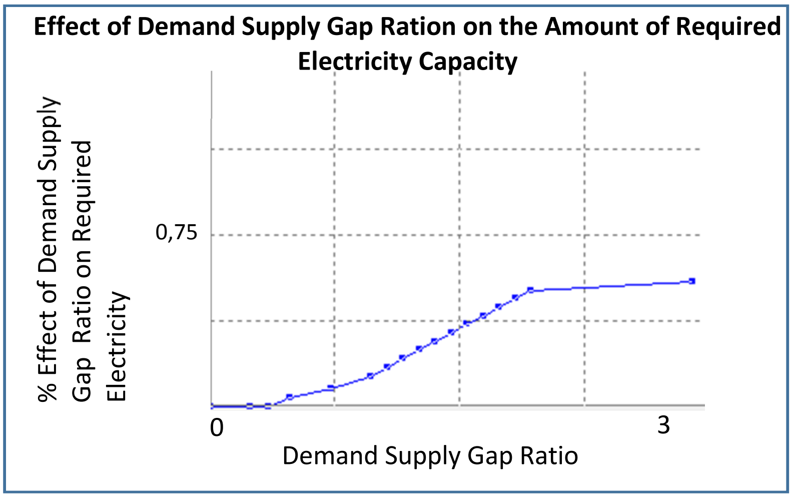

Figure 7.12 The Effect of the Demand Supply Gap Ratio on the amount of Required Electricity Capacity to be generated

The model is a simplified version of real events. It has been noted that in order to generate extremely accurate capacity requirements, intensive calculations involving Load Duration Curves and Screening Curves, to name but a few processes, are necessary. However, this complexity was not incorporated into the model due to time and scope constraints, therefore it was decided to rather focus on the model's greater purpose of generating foresight and generating tools to answer high level questions rather than delve into technical details. Therefore, if it is deemed beneficial in the long-term, this research can be improved by incorporating the exact complexities involved in calculating the required electricity capacities, but for this research it is considered out of scope.

Blackouts where modelled under two circumstances; the first being when Renewable Energy is unavailable. The second, when overall electricity demand is greater than supply. Blackouts, due to renewable energy unavailability are calculated by summing the electricity lost due to Solar PV, Solar CSP and Wind 'downtime'. The purpose of modelling blackout events is to determine whether or not sufficient supply is generated in the various scenarios and if not, calculate the potential MWh loss per year.

7.6.4 Supply Fraction

The new electricity to be added to the mix is then distributed amongst the technology types i, dependant on the user's choice of Supply Fraction (SF) to determine a New Demand (ND) for each technology as specified in equation 18.

$$ND(t)_i = RNE(t) * SF_i \tag{18}$$

From this a Required New Technology (RNT) capacity is calculated by incorporating the TCF and a conversion from MWh to MW as shown in equation 19.

$$RNT(t)_i = (ND(t)_i + (1 - TCF_i) \times ND(t)_i) \times Conversion\ to\ MW \tag{19}$$

7.6.5 Emissions

Three different types of emissions were considered: CO_2, SO_x and NO_x. However, the same process was used to calculate the total emissions. To simplify the equations, the set k comprised of the three emission types is defined, where k = {CO_2, SO_x, NOx}. Therefore, equation 20 defines the Total Emissions (TE) for technology type i and emission type k as the EG (in MWh), multiplied by the Average Emissions (AE) expressed in kg/MWh for each technology type, the values for AE were obtained from the 2016 IRP (Department of Energy, 2016b). The NET Total Emissions (NTE) is calculated by summing the TE for technology types i=4, where the four technologies considered are: Coal, Bio-Fuel, Nuclear, and Gas. It is assumed that renewable energy electricity generation technologies do not emit greenhouse gases in the electricity generation phase and thus are not considered in the emission calculations.

$$TE(t)_{ik} = EG(t)_i \times AE_{ik} \tag{20}$$

$$NTE(t)_k = \sum_{i=4} TE(t)_{ik} \qquad For\, all\, k \tag{21}$$

7.6.6 Water Usage

The water used by the electricity sector during the electricity generation process is calculated here. It is argued that due to South Africa's only nuclear power station using salt water for generation, the average fresh water usage for nuclear is presumed to be zero. Thus, it is also assumed that any new additions of nuclear generation to the electricity mix will also use salt water for generation. Therefore, it is assumed that the water usage for these calculations refers to fresh water. The Water Usage (WU) for technology types i=7, where i= {Bio-Fuel, Coal, Gas, Solar CSP, Solar PV, Wind, and Nuclear}, is calculated by multiplying EG by the Average Water Usage (AWU). Hydro is excluded from these calculations. The AWU values were calculated as averages from the data in the 2016 IRP (Department of Energy, 2016b). However, the water usage may vary for technology types with older generation technologies and likewise future water consumption may change over time as newer technologies are implemented. This calculation is shown in equation 22; the Total Water Usage (TWU) is calculated by summing the WU as shown in equation 23.

$$WU(t)_i = EG(t)_i \times AWU_i \tag{22}$$

$$TWU(t) = \sum_{i=7} WU(t)_i \tag{23}$$

7.6.7 Land Usage

The land used for electricity generation purposes was calculated by taking the average land area per technology type in km^2, for operational capacity. This land area only considers the average size of a power station, and not the land area used for the accumulation of fuel. For example, mining practices for coal and uranium for coal and nuclear generation respectively are not considered, and neither is the farming of crops for bio-fuel generation. Data for South Africa's electricity sector's land use is not openly available and thus data was used from Kim and Fthenakis' (2009) land use life cycle analysis.

The Total Land Usage (TLU) is calculated in equation 24, by multiplying the Land Area (LA) with unit's km^2/MWh by COC with units MW, and by a conversion factor to ensure that TLU has unit's km^2. The Total Land Usage for Electricity (TLUE) is calculated by summing the TLU for seven technology types i (Hydro was excluded as it was considered water surface area) as seen in equation 25.

$$TLU(t)_i = LA_i \times COC(t)_i \times Conversion\ to\ MW \tag{24}$$

$$TLUE(t)_i = \sum_{i=7} TLU(t)_i \tag{25}$$

The percentage of land area used by the electricity sector was calculated in equation 26, a similar process was followed to calculate the percentage of South African land area used by fossil fuels and renewable energy. Equation 27 illustrates the percentage of arable land used by the electricity sector (World Bank, 2016).

$$\%\ Land\ Usage\ by\ Electricty\ Sector = \frac{TLUE}{Total\ Land\ Area\ of\ SA} \times 100\% \tag{26}$$

$$\%\ Arable\ Land\ Usage\ by\ Electricty\ Sector = \frac{TLUE}{Arable\ Land\ Area\ of\ SA} \times 100\% \tag{27}$$

7.6.8 **Dispatchable Electricity**

Dispatchable Electricity is electricity that can be generated safely and rapidly, to satisfy demand if renewable energy is unavailable. This was modelled to determine the amount of electricity that is necessary to respond to demand under these circumstances. In addition, it was modelled to determine the costs involved in dispatching this electricity as well as the costs involved if this energy goes unserved. For this model, gas was selected as the alternative technology type to dispatch when renewable energy technology types i=3, where i= {Solar PV, Solar CSP, Wind) become unavailable. Therefore, the associated cost is the average LCOE for gas.

Equation 28 depicts the flow of the Increasing Dispatchable Electricity Requirement (IDER) into the Dispatchable Electricity (DE) stock, through the Demand Response Requirements (DRR) for technology types i=3. Equation 29 for the DE stock has an initial value of zero and accumulates as the need for demand response grows, as renewable energy becomes available. The aim of this stock is to calculate the total amount of electricity that would go unserved over time if other forms of electricity are not dispatched. Therefore, ideally the dispatched electricity, in the form of gas, would decrease the stock but this would internally effect the amount of gas necessary. Consequently, changing the user inputted SF value. Thus, it is for this reason that the dispatchable electricity amount was calculated to determine the impacts of renewable energy unavailability on electricity. Although, it is noted that these complexities can be added to the model if the research is to be developed further.

$$IDER(t) = \frac{\sum DRR(t)_i}{Time \times Conversion\ to\ MW} \tag{28}$$

$$DE(t) = DE(0) + \int IDER(t)dt \tag{29}$$

The Cost of Dispatched Electricity Output (CDEO) is calculated in equation 30 by multiplying the Cost of Dispatched electricity (CDE) by the DE.

$$CDEO(t) = CDE \times DE(t) \tag{30}$$

The Total Cost of Unserved Energy is calculated as the sum of Unserved Energy (UE) multiplied by the Amount (A) which is equal to R77.30/KWh as stated in equation 31.

$$TCUE = \sum UE_i \times A \tag{31}$$

7.6.9 **Levelised Cost of Electricity**

The LCOE is a metric used to compare different technology types, with unequal life spans, project spans, lifetime costs, risks, returns and operating capacities. Thus, due to the many components that are considered and the numerous methods of calculating LCOEs, there have been many debates in the South African electricity sector as to whether or not the 2016 IRP figures are accurate. Private studies focusing on LCOE, have also been done that have yielded very different results (Sklar-chik, 2017). Hence, it was decided that to model these cost irregularities data on LCOE's from all versions of the IRP were gathered and a statistical analysis was conducted to determine the mean, median and standard deviation.

The Levelised Cost of Electricity Distribution (LCOED) for all technology types i, is calculated in equation 32, using Vensim's built-in random normal distribution function which requires five inputs. These inputs were calculated from the statistical analysis and the model generates random numbers in a normal distribution, which are then considered the LCOED at time t.

$$LCOED(t)_i = RANDOM\ NORMAL(\{min_i\}, \{max_i\}, \{mean_i\}, \{stdev_i\}, \{seed_i\}) \tag{32}$$

The LCOE for each technology type collects in stocks. Thus, the flow equation 33 shows the Investing (I) based on the RNT that is to be added to the grid with a conversion factor applied. Equation 34 shows the Required Investment (RI) for each technology type, with initial RI assumed as zero Rands. The Total Required Investment (TRI), for the electricity sector, to add new capacity to the grid, is shown in equation 35. For some technology types learning rates have been applied as specified in the 2016 IRP (Department of Energy, 2016b). These learning rates reduce the cost of the technology over time and is specified by Cost Reduction (CR) variable for the technology types: Nuclear, Wind, Solar PV and Solar CSP. Learning rates for the technologies improvements in efficiencies were not considered.

$$I(t)_i = LCOED(t)_i \times RNT(t)_i \times Conversion\ to\ MWh \tag{33}$$

$$RI(t)_i = RI(0)_i + \int I(t)_i - CR(t)_i dt \tag{34}$$

$$TRI(t)_i = \sum_{i=8} RI(t)_i \tag{35}$$

7.6.10 Employment

Employment considers the number of jobs in the electricity sector for all technology types, however factors such as the level or quality of jobs where not considered. The job types are split into manufacturing, construction, operations and fuel supply jobs. The data were obtained from a report published by Greenpeace (Rutovit & Letete, 2010). The report stipulates the units - job years/MW, for Construction, Manufacturing and Installation (CMI) jobs, jobs/MW for Operations and Maintenance (O&M) jobs, and jobs/MWh for Fuel Supply jobs. Fuel supply jobs were excluded from the total possible employment opportunities in South Africa, because some of the data included local and foreign job figures. The model also assumed that all technologies are manufactured locally, to enhance the economic potential of the electricity sector. Factors such as job learning rates and decline rates where not considered by the model and thus an optimistic job potential is expected in the results.

The Operations' Jobs (OJ) were calculated in equation 36, by multiplying the COC by an Operations Job Factor. Likewise, the same was done for Manufacturing Jobs (MJ) in equation 37, however Technology Under Construction (TUC) at time‘t’ was multiplied by a Manufacturing Jobs Factor (MJF). Equation 38 expresses the same logic for Construction Jobs (CJ), except a Construction Jobs Factor (CJF) is used.

$$OJ(t)_i = OJF_i \times COC(t)_i \tag{36}$$

$$MJ(t)_i = MJF_i \times TUC(t)_i \tag{37}$$

$$CJ(t)_i = CJF_i \times TUC(t)_i \tag{38}$$

The total amount of jobs as Employment (E) for technology type i, was calculated in equation 39 by summing the OJ, MJ and CJ.

$$E(t)_i = OJ(t)_i + MJ(t)_i + CJ(t)_i \tag{39}$$

Fuel Supply Jobs (FSJ) are calculate in equation 40 by multiplying the EG by a Fuel Supply Job Factor (FSJF), this only applies to four technology types i, where i= {Bio-fuel, Nuclear, Coal Gas}. Total Fuel Employment (TFE) is calculated in equation 41, by summing the FSJ.

$$FSJ(t)_i = FSJF_i \times EG(t)_i \tag{40}$$

$$TFE(t)_i = \sum_{i=4} FSJ(t)_i \tag{41}$$

Finally, the Total Electricity Sector Employment (TESE) is calculated in equation 42 by summing E for all technology types.

$$TESE(t)_i = \sum_{i=8} E(t)_i \tag{42}$$

7.6.11 Installed Capacity

Simple summation calculations were performed to calculate how much capacity is installed at any time t, for fossil fuel generation and renewable energy generation. This was done to determine whether the various model scenarios will achieve the defined renewable energy installation goals in the allocated time frame. Thus, the Renewable Energy Installed Capacity (REIC) was calculated, for all i, pertaining to renewable energy technology types, as seen in equation 43. The Fossil Fuel Installed Capacity (FFIC) was also calculated for all i, related to fossil fuel types in equation 44.

$$REIC(t) = \sum_{i=1}^{i=5} COC(t)_i \tag{43}$$

$$FFIC(t) = \sum_{i=6}^{i=8} COC(t)_i \tag{44}$$

7.7 Model Validation and Testing

The SD methodology is known to exhibit qualities such as: transparency, and ease of communication. Model transparency is the state or quality of being easily observed or understood, which is useful for model users when it comes to understanding the model relationships, data and assumptions (Bragen & Martinez-Moyano, 2014). To ensure greater model transparency an SDM-Doc was generated and is shown in Appendix C. This tool enables modellers to create a practical, HTML-based model document with customizable model assessments. The model was validated by industry experts (see section 7.7.2). Furthermore, a sensitivity analysis was performed, as explained in section 7.7.3.

7.7.1 Model Structure Validity Test

There are a number of tests which aim to establish confidence in the structure of the model. The five tests are: structure-verification, parameter-verification test, extreme-conditions test, boundary-adequacy test and dimensional-consistency test. These tests aim to directly assess the model structure and parameters, without examining causal relationships (Forrester & Senge, 1980).

7.7.1.1 Structure-Verification Test

Verifying structure implies that the model structure should directly compare with the structure of the real system that the model represents (Forrester & Senge, 1980). This is a highly qualitative test and cannot be captured simply by numerical data sets. In order to perform this test, it is necessary to first check whether the CLD resemble the structure of the real system. The dynamic model should correspond with the CLD, and the model logic should agree with the real system.

The structure of the CLD and model were verified by external parties that have a knowledge of SD and the electricity sector, an iterative verification process was followed. In this process, each stage of model conceptualisation and building was verified before a new stage was commenced. Finally, the conceptual and dynamic models were verified holistically to ensure corresponding logic.

7.7.1.2 Parameter-Verification Test

Constant variables in the model can be verified against real life observations, this means that the model parameters should correspond with conceptually and numerically to real life (Forrester & Senge, 1980).

Conceptual correspondence insinuates that parameters correlate with elements of the systems structure. Numerical verification determines if values fall within a plausible range of values over the time period (Forrester & Senge, 1980).

The model's initial variables were inputted from a number of reliable sources and outputs such as electricity demand which is modelled dynamically was compared with a number of existing data sets to establish whether the generated data was within a plausible range. For electricity demand the data was compared to the CSIR electricity demand figures (Mokilane, Makhanya, Koen, *et al.*, 2016).

7.7.1.3 **Extreme-Conditions Test**

Knowledge of real systems relates to the consequences of extreme conditions. For example, if no new capacity is added to the electricity mix and no maintenance is done on the installed capacity, then the existing capacity will be decommissioned and the electricity supply will run to zero (Forrester & Senge, 1980). This is an example of one of the extreme conditions tested during the development of the model. Forrester & Senge (1980) state that, it is unacceptable to assume that if these extreme conditions may never occur in real life they do not need to be incorporated into the model. Therefore, each stock and flow model was analysed individually to determine the implications of the maximum, minimum and zero values.

7.7.1.4 **Boundary-Adequacy Test**

The boundary adequacy test determines whether or not the model aggregation is appropriate and if all necessary structure is included in the model (Forrester & Senge, 1980). The model boundary should correspond with the model's intended purpose and must have the necessary structural relationships. The model's purpose is to determine if the current policy is sufficient to achieve a SET, as defined by a set of criteria.

The model boundary chart, in Table 7.1, states the endogenous, exogenous and excluded variables. For this research, these variables have been modelled as stated in the sub model description and arguments can always be made as to why certain variables were or were not considered, but due to the model being a representation of reality, boundaries need to be established to manage complexity and scope.

7.7.1.5 **Dimensional-Consistency Test**

This test involves analysing dimensional parameters, to ensure correlation between variables. This test is best used with the parameter-verification test (Forrester & Senge, 1980).

This test was conducted by using Vensim's built-in units check function. Vensim DSS displays lookup tables as unit errors and the model does not differentiate between MWh and GWh and thus recognizes these as errors. Therefore, the modeller decided to represent all units in MWh.

7.7.2 Causal Loop Diagram and Model Validation

The CLD was discussed with an electrical engineer who works for the Cape Town municipality and has completed a PhD using the SD methodology. The model structure underwent structural validity tests, and validation was done via a telephonic discussion with electricity sector experts, who have extensive knowledge of SD and work in an SD department within their associated organisation. The experts' comments were considered and the necessary changes were made to the model structure.

The model logic, units and structure was checked by a system dynamic modeller who has completed a postgraduate degree using the SD methodology, as well as by supervisors with extensive knowledge and years of experience in the application of the SD method.

7.7.3 Sensitivity Analysis

To determine the sensitivity of variables to changes, a Monte Carlo simulation was run within Vensim for variables influencing electricity demand. It was through the execution of a sensitivity analysis that electricity demand discrepancies were discovered based on the change in elasticities and changes in GDP growth. The variables that were analysed were the GDP growth of South Africa (within the range of 1-6%) and the elasticity of electricity price, population and GDP on electricity demand, within the range of 1 to -1. The changes in these variables showed unusual outputs for electricity demand, and thus due to these discrepencies a decision was made to change electricity demand from an endogenous variable to an exogenous variable. Therefore this model validation tool, was useful in determining that another approach is necessary in order to improve the model and obtain more accurate results. The alternative approach used input data from the CSIR electricity demand forecasts (Mokilane, Makhanya & Koen, 2016).

Furthermore, other variables that were investigated were: the impact of renewable energy downtime for Wind and Solar PV and CSP on the total cost of unserved energy. The 'electricity lost due to downtime' variable was tested within the ranges of 0-100% of a year of unavailability, or in other words the percentage of time the resource does not generate electricity in a year. Figure 7.13 shows that Solar PV is highly sensitive to the amount of downtime and the amount of electricity in MWh that is 'lost'during this downtime. Likewise, Figure 7.14 shows Solar CSPs sensitivity to the downtime but to a lesser extent than Solar PV. When looking at the sensitivity of wind downtime on the generation of electricity, shown in Figure 7.15, the graphs shows a contined escalation and dispersion of sensitivety. In conclusion, the sensitivity analysis conducted to determine the impact of renewable energy downtime on electricity outputs showed that the effects of longer downtimes translate to decreased ability to meet electricity demand and thus the cost to serve this energy in the form of Dispatchable electricity is greater. Therefore, from the large amount of variation shown by the dispersion in Figure 7. 13-15, it was noted that the time duration of electricity downtime is a highly sensitive variable, and the impact on the outputs of cost of unserved energy, dispatchable costs, and electricity availability are greatly affected and should be considered when analysing the model results.

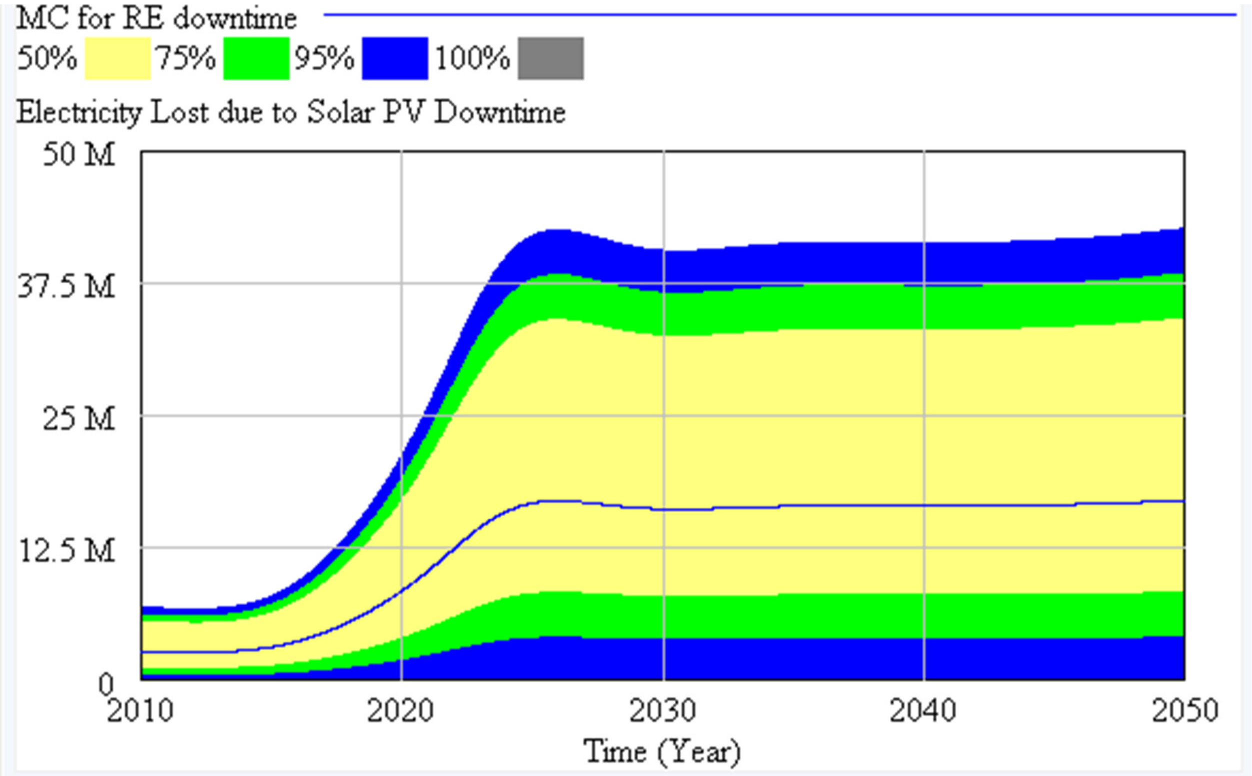

Figure 7.13 The Sensitivity of Solar PV Downtime Variable to Values between 0-100%on the amount of Electricity Lost in MWh.

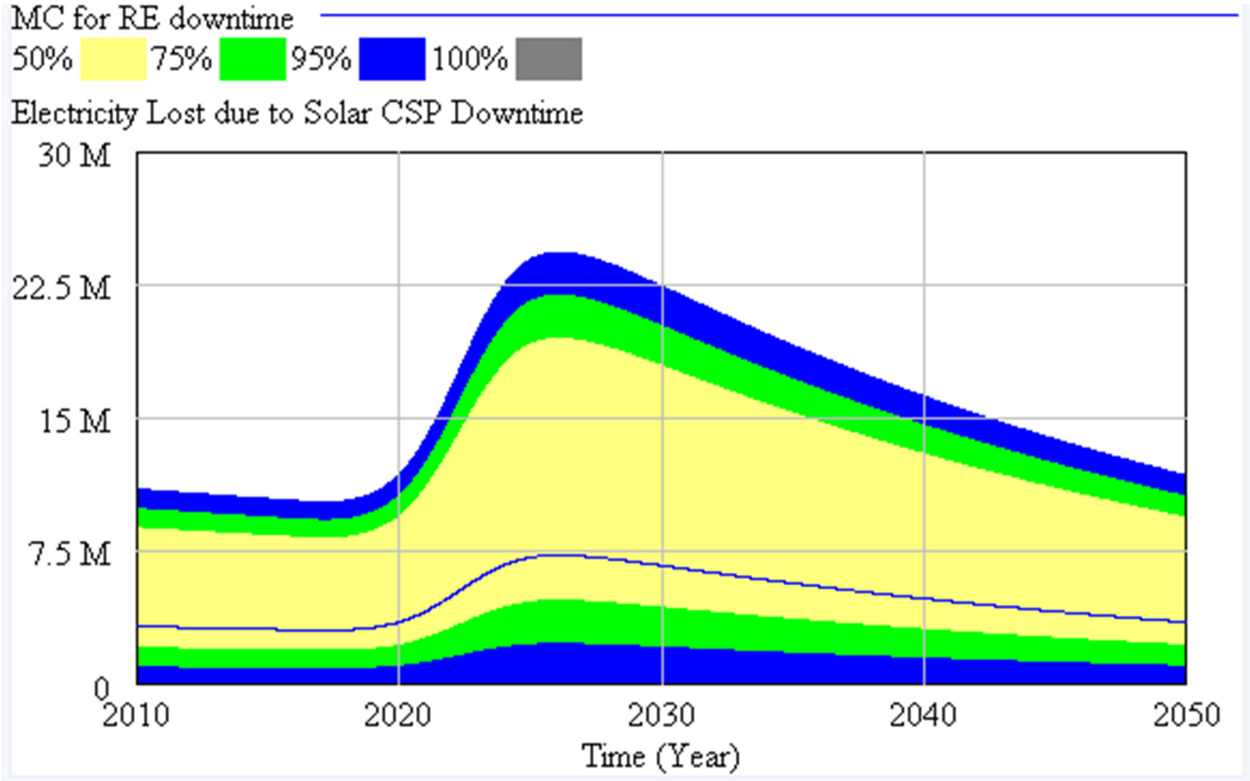

Figure 7.14 The Sensitivity of the Solar CSP Downtime Variable to Values between 0-100% on the amount of Electricity Lost in MWh.

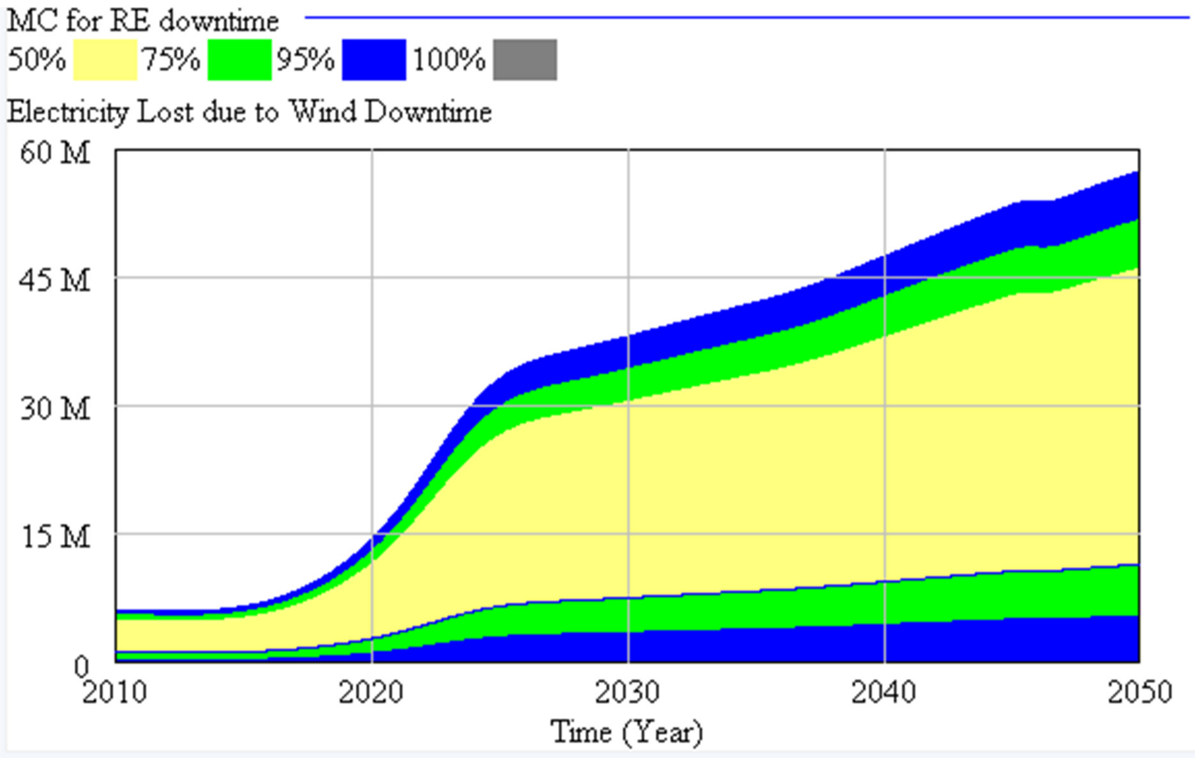

Figure 7.15 The Sensitivity of the Wind Downtime Variable to Values between 0-100% on the amount of Electricity Lost in MWh.

7.8 Scenario Planning and Modelling

The purpose of the SD model is to determine whether South Africa is transitioning at a rate fast enough to achieve a sustainable energy transition and whether the current policies driving the transition are sufficient to achieve sustainability. The first phase of the dual-narrative approach developed the sustainability criteria, by which the transitions status can be measured. Table 7.3 shows the direct outputs of the SD model and its link to the set of criteria. However, 'energy efficiency' and 'innovation and technology' where not addressed as direct model outputs due to the confines of the model boundary, nevertheless these limitations are discussed in Chapter 8, along with the rest of the model results and analysis.

Table 7.3 The set of criteria which are addressed by generating direct outputs in SD model.

Addressed Criteria	Preliminary Model Outputs
CO_2 Emission Reduction	Emissions for CO_2, NO_x, SO_x (kg/MWh)
Economic Competitiveness	Unserved Energy (R/MWh) Levelised Cost of Electricity (R/MWh)
Supply Security and Generation	Demand Supply Ratio: <1= Adequate Supply >1 = Inadequate Supply Blackouts (MWh/Year)
Resilience	Operations and Maintenance Jobs (Jobs/Year) Fuel Supply Jobs (Jobs/Year) Manufacturing Jobs (Jobs/Year) Construction Jobs (Jobs/Year) Water Usage (L/MWh) Land Usage (km^2/MWh)
Policy and Public Acceptance	Graphical output of IRP capacity specifications

Six scenarios were developed to test various electricity mix combinations and their impact on cost, emissions, jobs, water usage and land usage. The scenarios were run for various economic conditions, simulating the effects of a low, medium and high economic growth forecast on the electricity sector. Based on the current economic climate a low economic growth is the most realistic scenario. Table 7.4 shows the breakdown of the scenario's name, conditions, and the supply fraction split for each technology type.

Table 7.4 Scenario Breakdown

Scenario Name	**Scenario Conditions**	**Electricity Mix Percentage Split (%)**							
		Technology Type							
		Coal	***Nuclear***	***Gas***	***Wind***	***Solar PV***	***Solar CSP***	***Hydro***	***Biofuel***
Business as Usual	Input from IRP 2016	Input as specified in IRP2016 and inputted via lookup tables							
Bulk Fossil Fuels	70:30	55	10	5	10	7	3	3	7
All New Fossil Fuels	100:0	60	30	10	0	0	0	0	0
Half and Half (50/50)	50:50	25	20	5	20	12	8	5	5
Bulk Renewable Energy	30:70	15	10	5	30	20	10	5	5
All New Renewable Energy	0:100	0	0	0	45	30	15	5	5

The model was designed to run either the IRP scenario conditions with lookup tables consisting of capacity inputs, or the five scenarios where the user decides on the supply fractions. The Business as Usual (BAU) scenario tests the IRP policy over time, to determine if the policy capacities stipulated for the future, are sufficient to meet demand and determine the impact on employment, emissions, water usage, land requirements and the costs involved. The scenario was named Business as Usual as this is the electricity mix's main policy driving the transition and thus its current trajectory. Therefore, no radical changes are tested in this scenario.

The Bulk Fossil Fuels (BFF) scenario is similar to South Africa's current mix, where most of the electricity is generated from fossil fuels but there are some renewable energy sources that contribute. Thus, this scenario determines the outcome of South Africa's electricity sector if it were to follow its current trajectory with minimal changes until 2050.

The Bulk Renewable Energy (BRE) scenario tests a drastic change in the current electricity mix to one that is comprised of 70% renewables. This scenario will require a fundamental change in the electricity sector, due to the fuel supply industry being a main source of jobs. Thus, to transition it is necessary to reskill workers from one industry to another and ensure that enough jobs are created in the renewable energy industry. This is a complex issue with a number of political, economic and social variables.

The Half and Half (HAH) is the ‘happy medium’ scenario where renewables and fossil fuels are split 50-50. This is the scenario where compromises to achieving sustainability are made – baseload generation is still available but a considerable amount of generation is from renewable sources.

A decision was made to execute two scenarios with extreme conditions, to determine the effects of an electricity mix either fully dependent on fossil fuels (assuming availability of all fuel types until 2050), or a mix that runs off 100% renewable resources. These two scenarios are depicted in the All New Fossil Fuels (ANFF) and All New Renewable Energy (ANRE) scenarios, where all new capacity that is added to the electricity mix is from the relevant fuel type and split in proportions as stated in Table 7.4.

These scenarios imply radical thinking and it is with scenarios such as these, that new insights could possibly be gained from unintended consequences and unpredictable events that emerge from these extreme conditions. Although these scenarios may never become a reality, it is for these reasons that it is important to perform such interventions and ask the ‘what if’ questions.

7.9 Conclusion

The process followed for the development of an SD model was presented and the problem was structured to identify the problem statement, gap, dilemma and boundary. The conceptual model in the form of the CLD and the logic for each feedback loop was discussed in detail. The dynamic model consists of twenty sub-models. The equations used to model the electricity sector, as well as the input data and sources are stated explicitly. The model went through numerous verification and validation tests to ensure that the model is the most accurate representation of real life as possible. Finally, the various interventions that are performed on the model are named and the scenario conditions stated.

In summary, the SD model was developed for South Africa’s electricity sector on a country level to analyse the impact of various energy mixes on achieving an SET, as defined by the set of criteria. To achieve this several direct model outputs are analysed including: emissions, employment, water usage, land usage and costs, and the associated links to the set of criteria were stated.

8 Results and Analysis

8.1 Introduction

The results analysed here are the outcome of executing different strategies, to determine possible insights into fostering a transition to sustainability. The research aimed to determine whether the current policy – the IRP is sufficient to foster a sustainable energy transition the impact that the alternative strategies will have on cost, emissions, water usage, land usage and employment to ultimately determine which route fosters the most sustainable future.

The results of the simulation portray various futures for South Africa's electricity sector for the different pathways South Africa could take when adding new capacity to the grid. Ultimately, the pathway that South Africa seeks, will be the one that measures the most successful against the sustainability criteria. It is possible that there is not one particular pathway to achieve these goals. Therefore, several trade-offs might need to be made in order to achieve long-term sustainable development.

Chapter 8 constitutes the fourth and final phase of the dual narrative approach mentioned in Section 1.6.1, where the model scenario results inform the narrative. As seen in Figure 8.1, the outcomes of each scenario will be presented in terms of the narrative (the set of criteria that was developed).

The model was run for the six scenarios, as explained in Section 7.8, under three economic conditions: low medium and high economic growth. For the results analysis, only the low economic growth graphs will be shown in this chapter, but Appendix D contains the results for the medium and high economic growth scenarios.

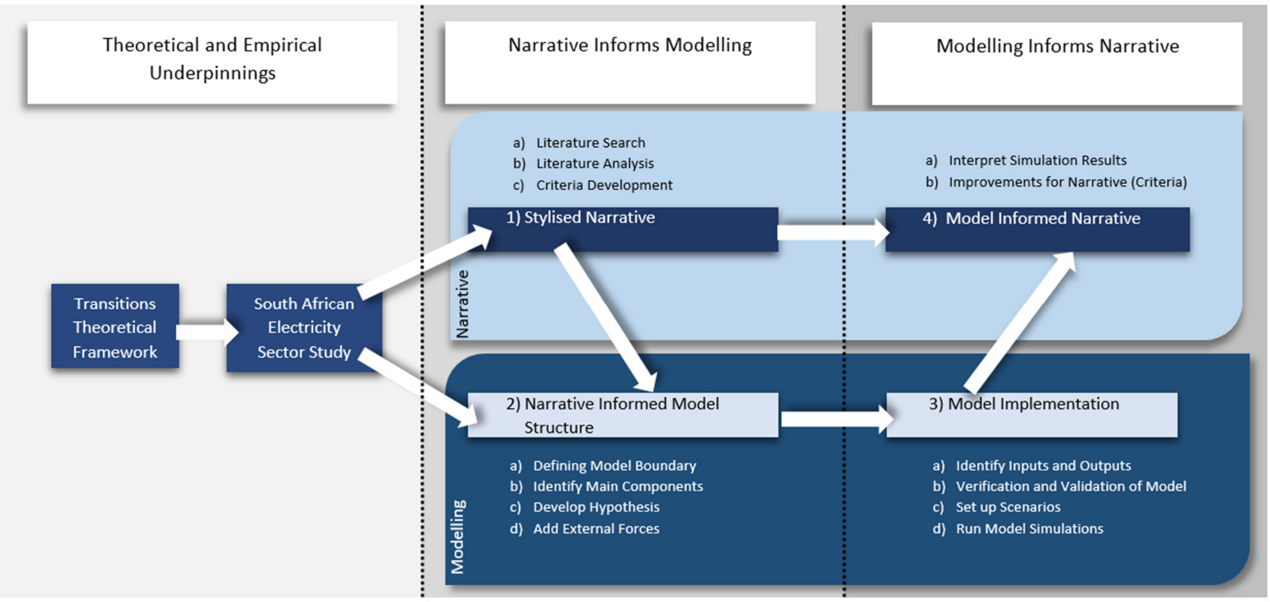

Figure 8.1 The Process followed for the Dual Narrative Approach

8.2 Energy Efficiency

Energy efficiency was not a definitive output of the current model, due to the model boundary only consisting of the electricity sector and excluding liquid fuels, transportation and the mining sector. In order to calculate an accurate indication of energy intensity as defined by Heun (2016), the energy output of all these sectors is necessary in relation to South Africa's Electricity sector. Therefore, it is possible for future research to incorporate energy intensity as a measure of energy efficiency if it is deemed necessary.

Likewise, due to the model simulating the electricity sector on a country level the impact of households or industries becoming more energy efficient, over time, was not modelled. Future research could incorporate these variables, as well as the impact that energy efficient policies could have on the electricity sector.

Electricity demand could be viewed as a possible indicator of energy efficiency, due to appliances becoming more efficient, consumers and industry becoming more aware of energy usage and the implementation of energy efficiency policies and laws could contribute ultimately result in the reduction of demand. For this model however, it was assumed that electricity demand is independent of these factors.

Although this model does not produce outputs for energy efficiency, this is not to suggest that energy efficiency is not a key indicator of a country's transition to more sustainable pathways.

8.3 Emission Reduction

Emission reduction is a key measure of success for sustainability because of the adverse effects of emissions on the environment. Thus, a reducing trend of CO_2 emissions is an essential output for the electricity sector, Figure 8.2 displays the graphical output of the six scenarios. The ANRE scenario achieves the largest reduction in CO_2 emissions, whereas the BFF scenario shows an increase in CO_2 emissions in the future. The results show the positive impact of the addition of renewable energy technologies on $CO_{2,}$ SO_x and NO_x emission trends. Similar trends can be seen in the scenario results for SO_x and NO_x in Appendix D.

In terms of policy goals based on the peak-plateau-decline objective, emissions would be allowed to peak in 2025 at approximately 550 million tonnes per annum, and the upper limit of 428 million tonnes per annum of CO_2 by 2050 (Department of Energy, 2013). These objectives are for South Africa, and thus, the model displays results well under the limits. But, the energy sector constitutes 63.6% of the GHG emissions, which excludes: manufacturing, transportation and other non-specified industries. Therefore, for this analysis, a reducing trend well below the mentioned limits is preferred.

From the results, it is deduced that scenarios with less new fossil fuel and more renewable energy additions are favourable and will foster a transition towards sustainable emission reduction in the future. These scenarios include: BAU, HAH, BRE, and ANRE.

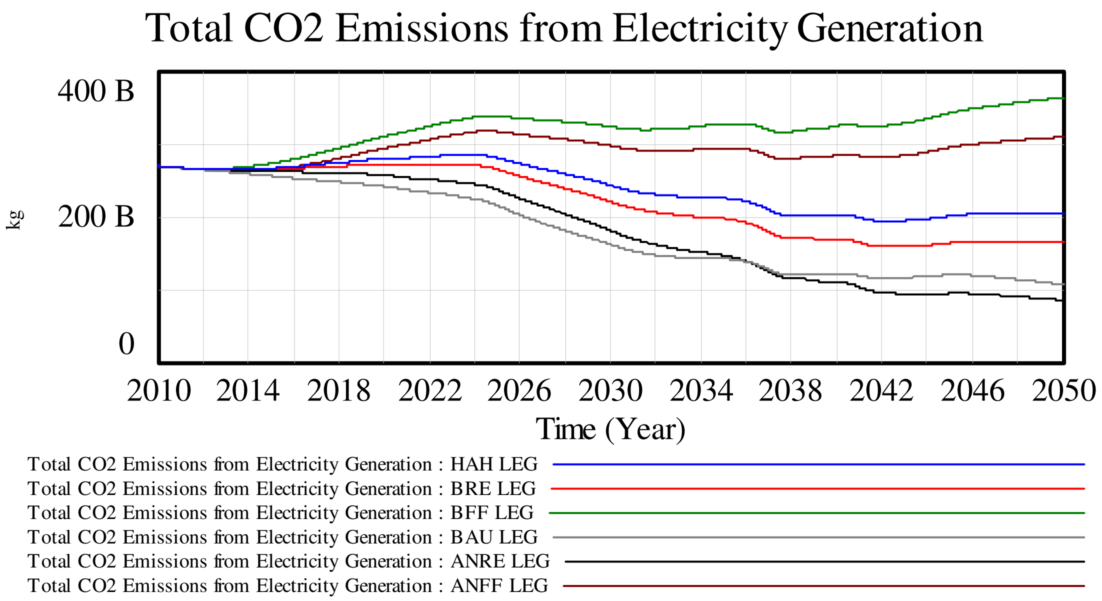

Figure 8.2 CO2 Emission trends for all six scenarios under low economic growth conditions

8.4 Economic Competitiveness

The required investment was calculated from LCOEs of technology types, as stated in Chapter 7. However, reiterated that this amount only includes the technology costs and learning rates for specified technologies and excludes: plant maintenance costs, additional infrastructure development costs, carbon costs and economies of scales. Table 8.1 indicates the total cumulative investment required for all scenarios where the least cost scenario is the BAU scenario (end result in green), followed by the ANFF scenario (end result yellow). The costlier scenarios are the scenarios with higher additions of renewable energy capacity as shown in the ANRE (end result in red) and BRE scenarios. Figure 8.3 shows the low economic growth profile which gives an indication of the cumulative investment required to build the additional capacity for each scenario.

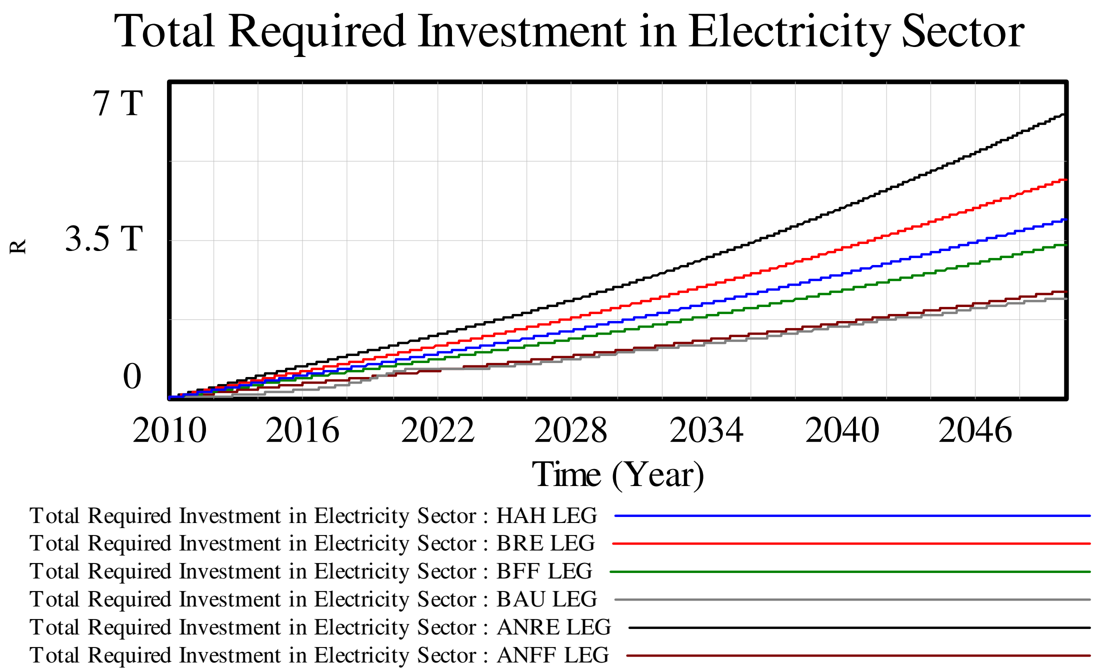

Figure 8.3 Scenario results for the cumulative required investment for a high economic growth strategy.

Table 8.1 The total cumulative investment required for each scenario to add new capacity to the grid

Total Required Investment (Rand in Billions)						
Scenario	**Economic Growth Strategy**	**Year**				
		2010	**2020**	**2030**	**2040**	**2050**
Business as Usual	**Low**	0	556.3	978.1	1574	**2209**
	Medium	0	556.3	978.1	1574	**2209**
	High	0	556.3	978.1	1574	**2209**
Bulk Fossil Fuels	**Low**	0	720.4	1460	2367	3395
	Medium	0	730.8	1601	2822	4317
	High	0	745.5	1724	3225	5125
All New Fossil Fuels	**Low**	0	509	1039	1656	**2353**
	Medium	0	515.9	1142	1970	**2986**
	High	0	526	1229	2216	**3488**
Half and Half	**Low**	0	812.7	1677.5	2727.8	3920
	Medium	0	823.4	1838.6	3284	5071
	High	0	839.6	1985.1	3757	6018
Bulk Renewable Energy	**Low**	0	950.2	1984	3279.5	4818
	Medium	0	963.3	2178.6	4003.7	6276
	High	0	982.1	2366	4576.2	7432
All New Renewable Energy	**Low**	0	1150	2440	4180	**6261**
	Medium	0	1166	2703	5106	**8134**
	High	0	1189	2945	5881	**9723**

8.5 Supply Security and Generation

Supply security and generation is an important model output, due to South Africa's history of supply problems. Thus, the scenarios that generated the lowest supply gap ratios (<1) over time were preferred, due to their improved ability to generated sufficient electricity to meet the various demand profiles. The results showed that the ANFF scenario generated new operational capacity the fastest and ensured that the demand supply ratio remained <1 for all economic growth profiles. The less preferred scenarios were the BAU and ANRE, which struggled to generated sufficient supply, this also resulted in the model calculating this supply shortage as a 'blackout'. Figure 8.4 and Figure 8.5 show the MWh/Year lost due to insufficient supply being generated in both the BAU and ANRE scenarios.

The ANRE scenario recovers over time and the supply deficit returns to zero, whereas, the BAU supply shortage continues to increase. This suggests that the current capacity addition plan for the IRP is insufficient for all three economic growth strategies with the current capacity decommissioning and degradation conditions. Table 8.2 shows the numerical outputs for the demand supply gap for all scenarios, where values in red indicate the insufficient generation of supply at ten-year intervals; the scenario that has the most ease of maintaining supply is the ANFF scenario.

Figure 8.6 shows the total installed renewable energy capacity and Figure 8.7 the total fossil fuel installed capacity. Policy objectives stated in the REI4P aim to added 17.8GW of new renewable energy capacity by 2030, and model results show that BRE and ANRE are well over these targets, however the BAU, ANFF and BFF either barely meet the target or not at all.

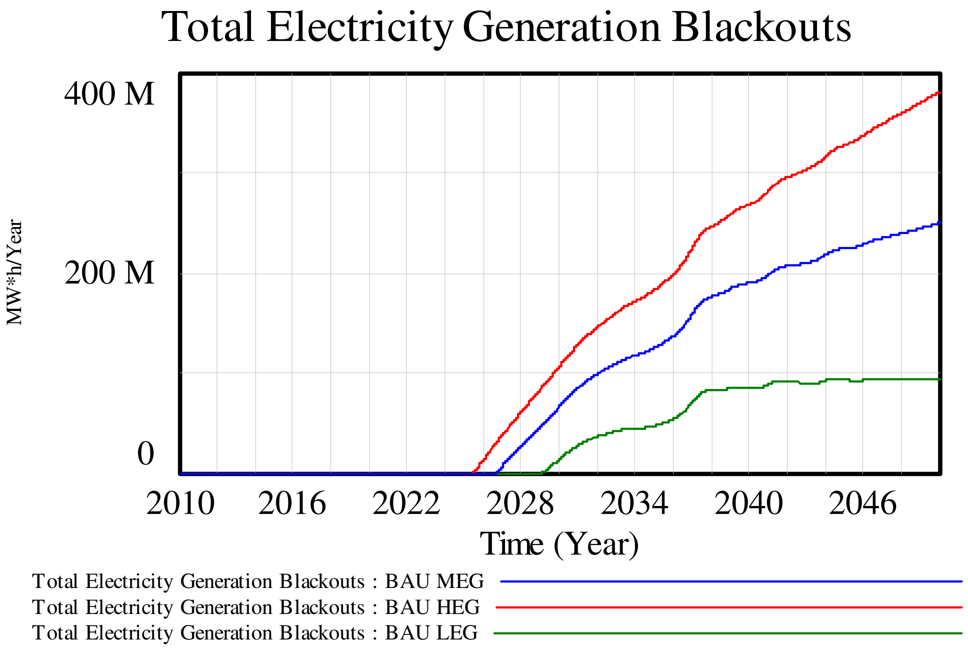

Figure 8.4 BAU Scenario Outputs for Total Electricity Blackouts, simulating the effects of insufficient electricity supply in MWh/Year

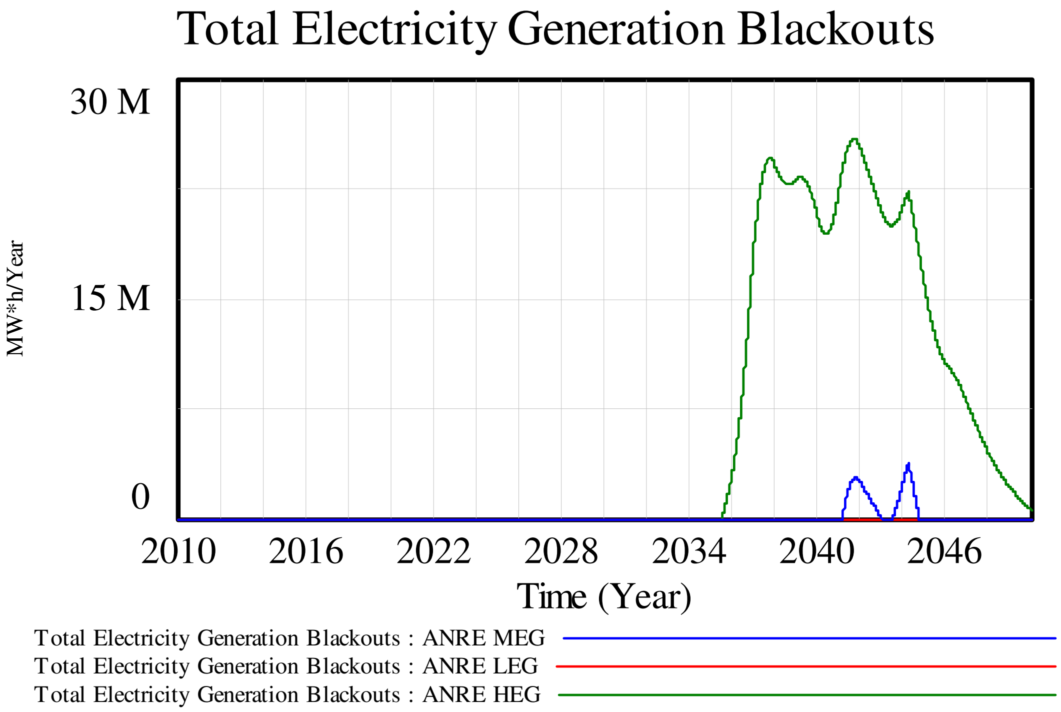

Figure 8.5 Scenario outputs for the ANRE Total Electricity Blackouts, simulating the effects of insufficient electricity supply in MWh/Year

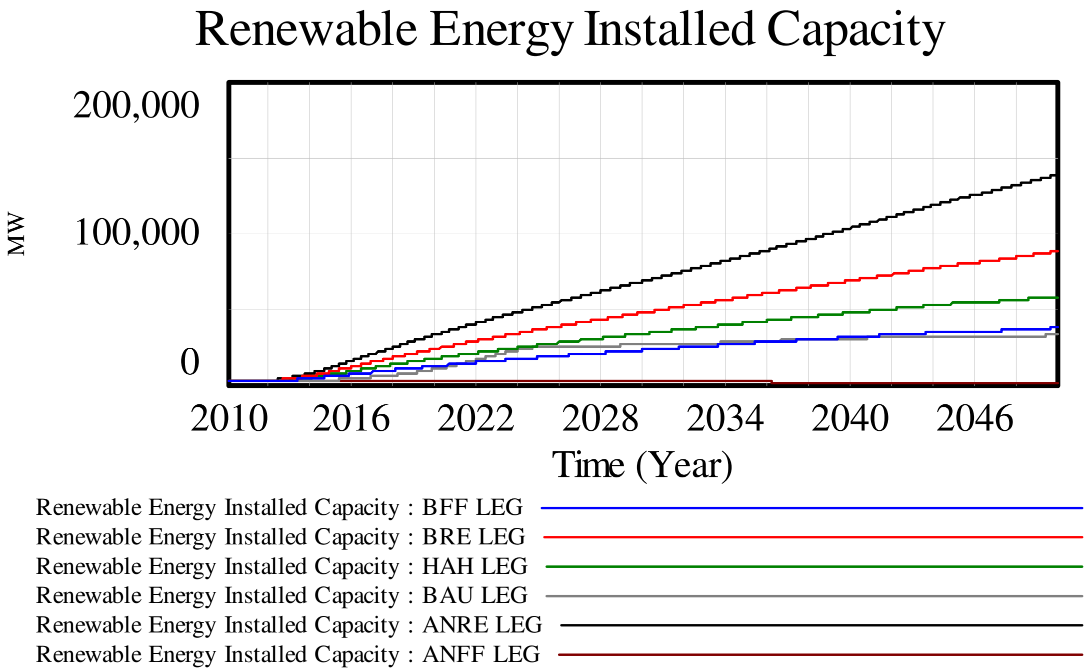

Figure 8.6 The total installed capacity for renewables under low economic growth conditions

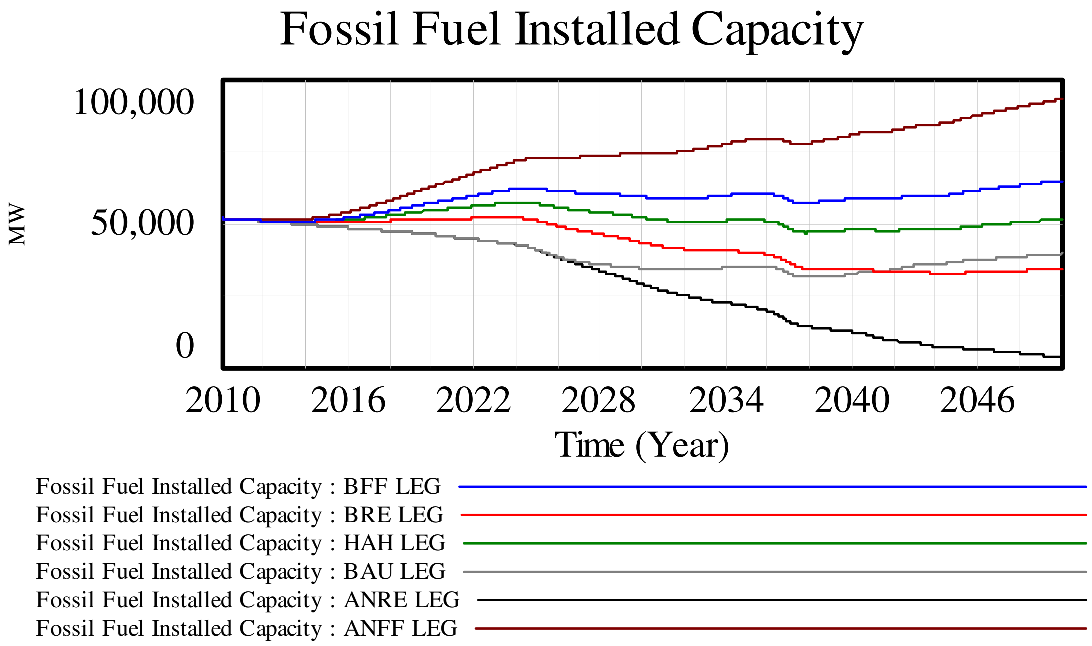

Figure 8.7 The total installed capacity for fossil fuels under low economic growth conditions.

Table 8.2 Scenario Results for Demand Supply Gap Ratio Table

Demand Supply Gap Ratio						
Scenario	Economic Growth Strategy	Year				
		2010	2020	2030	2040	2050
Business as Usual	Low	0.6536	0.7569	1.044	1.319	1.304
	Medium	0.6551	0.7919	1.222	1.71	**1.821**
	High	0.6556	0.8266	1.359	2.004	2.52
Bulk Fossil Fuels	Low	0.6536	0.6085	0.6351	0.6805	0.6844
	Medium	0.6551	0.6372	0.7169	0.7742	0.7462
	High	0.6556	0.663	0.7713	0.8178	0.7762
All New Fossil Fuels	Low	0.6536	0.606	**0.5995**	0.6211	0.6121
	Medium	0.6551	0.6346	0.6775	0.708	0.6757
	High	0.6556	0.6604	0.7294	0.7579	0.7181
Half and Half	Low	0.6536	0.612	0.6609	0.7175	0.7242
	Medium	0.6551	0.6408	0.7462	0.8112	0.7772
	High	0.6556	0.6668	0.8027	0.8538	0.8095
Bulk Renewable Energy	Low	0.6536	0.6208	0.7027	0.7943	0.804
	Medium	0.6551	0.6501	0.7932	0.8842	0.852
	High	0.6556	0.6764	0.8526	0.9291	0.8885
All New Renewable Energy	Low	0.6536	0.6317	0.7639	0.8957	0.9178
	Medium	0.6551	0.6615	0.8617	0.9907	0.9751
	High	0.6556	0.6883	0.9251	1.04	0.9999

8.6 Resilience

Sorrell (2010) mentions the rebound effect and unconventional "what-if" perspectives in his writing, he also mentions that a fundamental shift of how society thinks and operates will need to occur if sustainability is to be achieved. This paradigm shift has the possibility to generate unforeseen events, with unintended consequences of multiple actions and reactions. Therefore, how society deals with these consequences is defined as: resilience, which is listed as the fifth criterion (refer to Section 5.2). The model particularly looks at the effect of changing energy mixes on the amount of new jobs created in the electricity sector, as well as the impact on water and land usage. The preferred outcome in terms of these variables would be the most jobs, least water usage and minimal impact on arable land. Other considerations that were not modelled were, the disposal of radioactive waste and the impact that this has on land and surrounding communities – if this is of interest in the future; further in-depth research is recommended.

With the addition of renewable energy resources to the grid, it is clear that there is a large reduction in fuel supply jobs for the electricity sector. However, there is a large job creation potential in the renewable energy sector. If a pathway consisting of a majority of renewable energy is chosen, then the sector will need to recover these fuel supply jobs by either retraining workers in renewable energy jobs, or; maintain the fuel supply jobs but ensure that the products are exported or sold to new buyers. This is however, a complex dynamic; due to the existing power relations that have had a large influence on the electricity sector and a transition to sustainability will require early mitigation. Likewise, the retraining of workers to work in a new field is a complex and financially intensive process.

Figure 8.8 shows the total electricity sector employment potential for the low economic growth scenarios. The most jobs are created by the ANRE and BRE scenarios and the BAU scenario has the lowest employment output. Figure 8.9 shows the total jobs for the electricity sector fuel supply potential for both local and international job opportunities, where the ANFF and BFF scenarios provide the largest potential of fuel supply jobs.

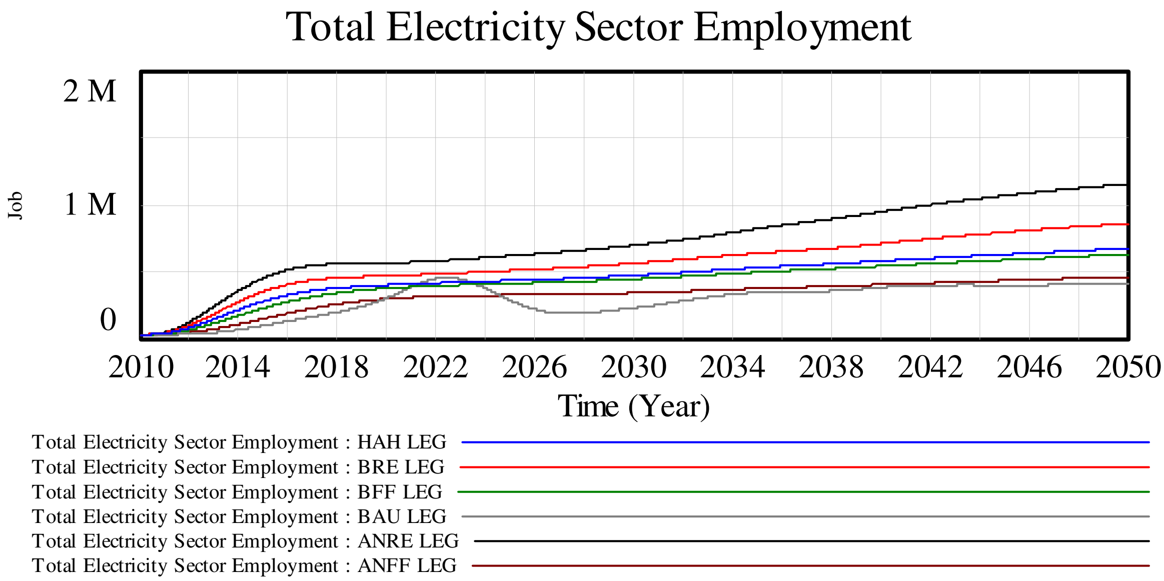

Figure 8.8 The Total Number of Job potential for the Electricity Sector for the Six Scenarios for Low Economic Growth Conditions.

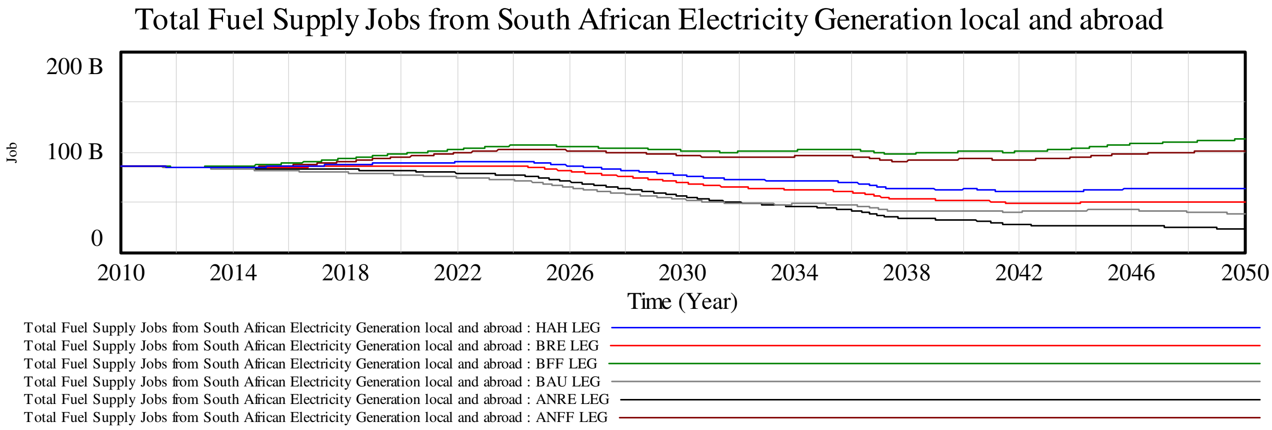

Figure 8.9 The Total Number of Fuel Supply Jobs for the Electricity Sector, showing the Six Scenario results under High Economic Growth Conditions

To determine the amount of land required for the electricity sector additions, the required land area was modelled for each scenario. In terms of fostering sustainability, a scenario that uses the least arable land for electricity generation will be preferred, and if possible; dual-purposing land would be best, for example: wind farms operating on agricultural land. The results in Figure 8.10 show that the scenario that uses the most land is the ANRE, where wind is the largest consumer of land area in terms of its MW output. The land area considers the physical electricity plant area and excludes the land used for mining fossil fuels or growing of bio-fuels.

In terms of water consumption for electricity generation, Figure 8.11 shows that the scenarios that consume the least amount of water are the ANRE, BAU, BRE, and HAH which show reducing water usage trends. Whereas, the BFF and ANFF scenarios show increasing water usage trends over time.

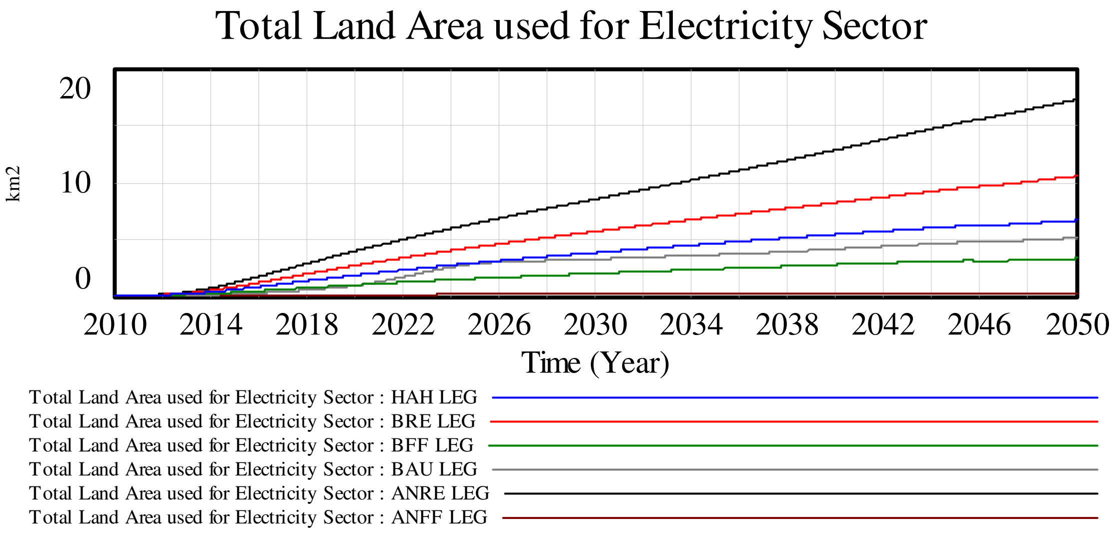

Figure 8.10 The Total Land Area used by the Electricity Sector in square kilometres (km^2)

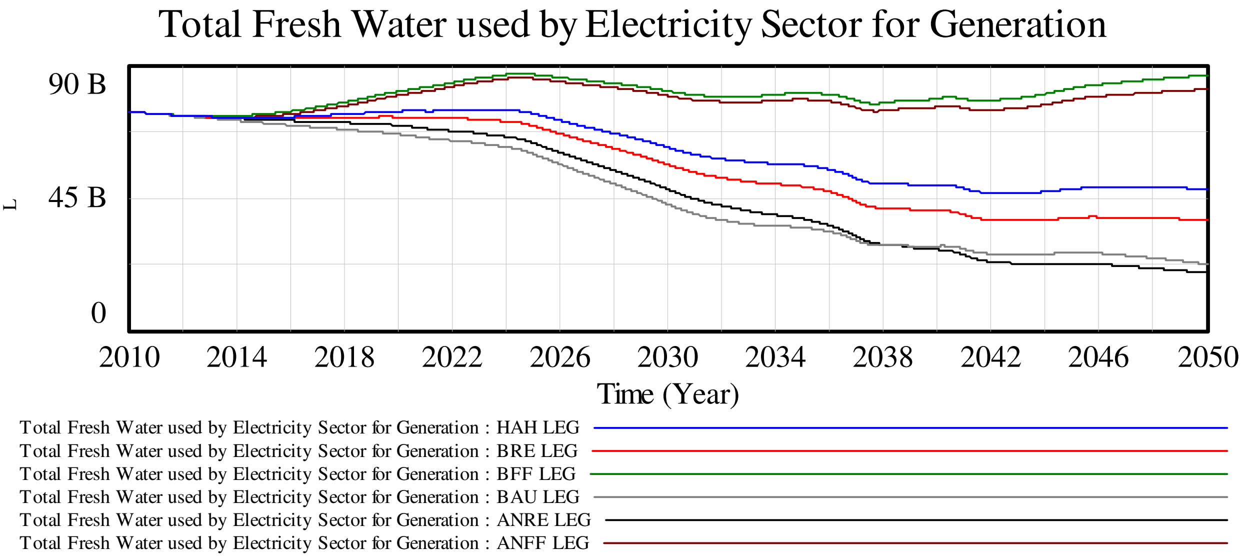

Figure 8.11 The Total Water Usage of the Electricity Sector in Liters (L)

8.7 Innovation and Technology

The impact that new technologies, such as hydrogen fuel cells and improved battery storage, may have on the electricity sector were not considered in this model. Although, these technologies could have a drastic impact on the electricity sector in the future, albeit, Solar and wind energy technologies were considered in the model along with the specified learning rates. Another consideration that was modelled; was the intermittence of these energy technologies. The modelled showed a high sensitivity to the 'maximum downtime' variable, as to be expected. However, this variable was kept constant at 30% for Solar CSP, 40% for Solar PV, and 20% for Wind. It should be noted that these values are a representation of the intermittence of supply, to model the technologies current limitations of electricity supply and to calculate the associated costs of either the unserved energy or the cost to dispatch electricity when these technologies are unavailable.

When comparing the cost of unserved energy and the cost of dispatchable energy outputs as shown in Figure 8.12 and Figure 8.13 respectively. The dispatchable energy was assumed to be gas and the variation in the graph is caused by statistical variation in LCOEs. When comparing the model outputs the results show the detrimental impact of unserved energy on the economy, translating to over R7 trillion in 2050 for the low economic growth scenario. In addition, the cost to serve this energy with gas is less than half the unserved energy cost (R3 Trillion). Thus, when considering renewable energy in large amounts as a source of electricity generation, the intermittence of supply should be taken into account, the ability to service peak loads should also be considered and dispatchable capacity should be available to carry the load during peak times.

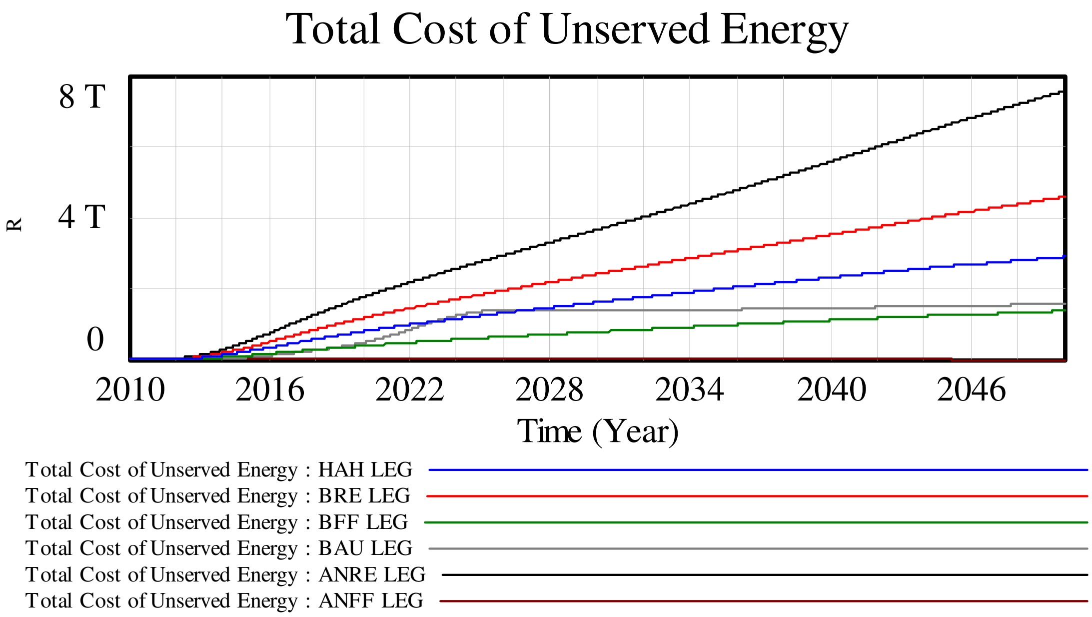

Figure 8.12 The Total cost of Unserved Energy for the Economy in Rands (R) for Wind, Solar PV and Solar CSP yearly unavailability, if the energy went unserved by another source.

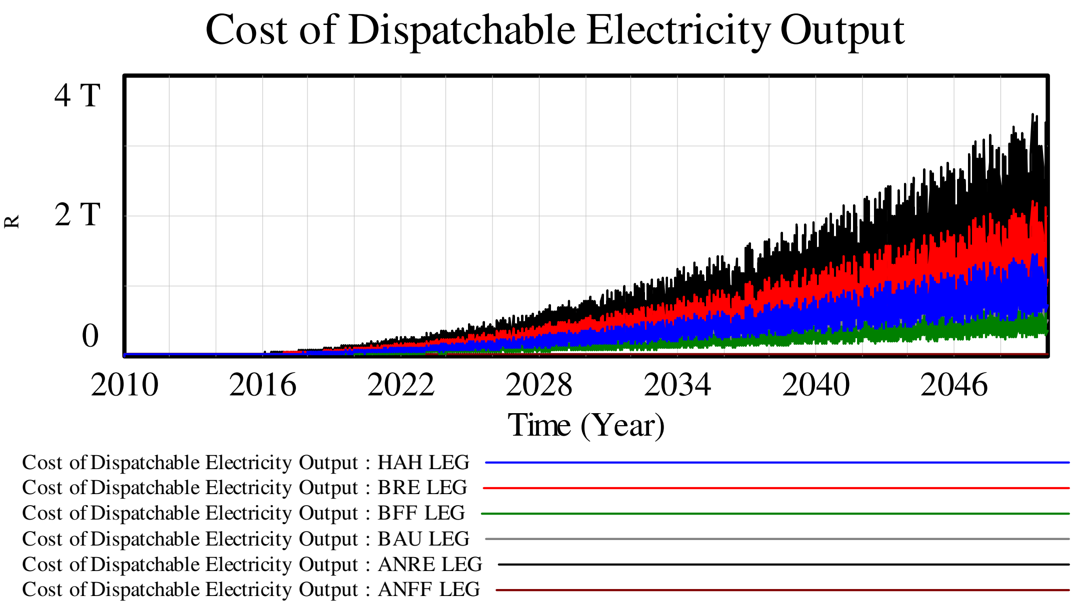

Figure 8.13 The cost of dispatching electricity in Rands (R) for each scenario under low economic growth conditions.

8.8 Policy and Public Acceptance

Consumer demand and the consequences of improved awareness of sustainability from a consumer side was not explicitly modelled by the model. Hence, future research could model the influences of these variables on electricity demand and adoption of more energy efficient technologies. The effect of the adoption of small-scale renewable energy technologies by consumers on the country's electricity demand requirements has not been incorporated into the model. But future research may consider this scenario if it seems there is an accelerated trajectory towards this off-grid solution.

In terms of policy goal fulfilment, the emission reduction goal is one of the most vital and impending goals that needs to be achieved. The goal is driven by a number of polices including the green economy efforts, REI4P, and the Copenhagen Climate Change pledge. From the BAU results the emission reduction targets will not be achieved. The BFF and ANFF scenarios show an increase in CO_2 emissions which will have a detrimental effect on the environment and possible financial penalties may be enforced if carbon tax is inforced in South Africa in future, currently the 2015 Draft Carbon Tax Bill is under revision as announced in the 2017 Budget Speech (Engineering News, 2017).

Therefore, even though BFF and ANFF may seem more cost competitive, the long-term implications may prove costly. Thus, in terms of policy goal fulfilment, the scenario results conclude that the IRP policy is insufficient to foster a sustainable transition for the electricity sector. The policy fails to meet the sustainability criteria in terms of 'supply security and generation' due to the model results showing that insufficient new capacity is added to satisfy all three economic growth strategies.

9 Conclusion and Recommendations

9.1 Conclusion of Results

In summary, if there is sufficient investment, then the BRE is a favourable pathway in terms of the set of criteria. This is especially due to its social and environmental benefits such as: job creation potential, emission reduction trend, and water reduction trend. However, the BRE is not economically competitive due to its required investment and the cost associated with dispatching electricity during peak periods. If technology costs continue to reduce as rapidly as current trends show, and improved energy storage solutions become available in the near future, then a BRE or even an ANRE is a definite alternative.

Conversely, if economic conditions in the electricity sector and the country are deterrent, then the HAH scenario is preferred, due to its favourable scenario results. The results show reducing emission trends that decrease by 2030 in the low and medium economic growth scenarios, also, sufficient capacity is generated ensuring security of supply. There is also the potential to maintain more fuel supply jobs, and create new jobs in the renewable energy sector.

The information in Figure 9.1 is a summary of the set of criteria and the model simulation results for the BRE scenario. This scenario is a preferred solution if sufficient investment is available. Figure 9.2 is a summary of the HAH scenario data, which is the preferred scenario if the economy is deterrent to investment.

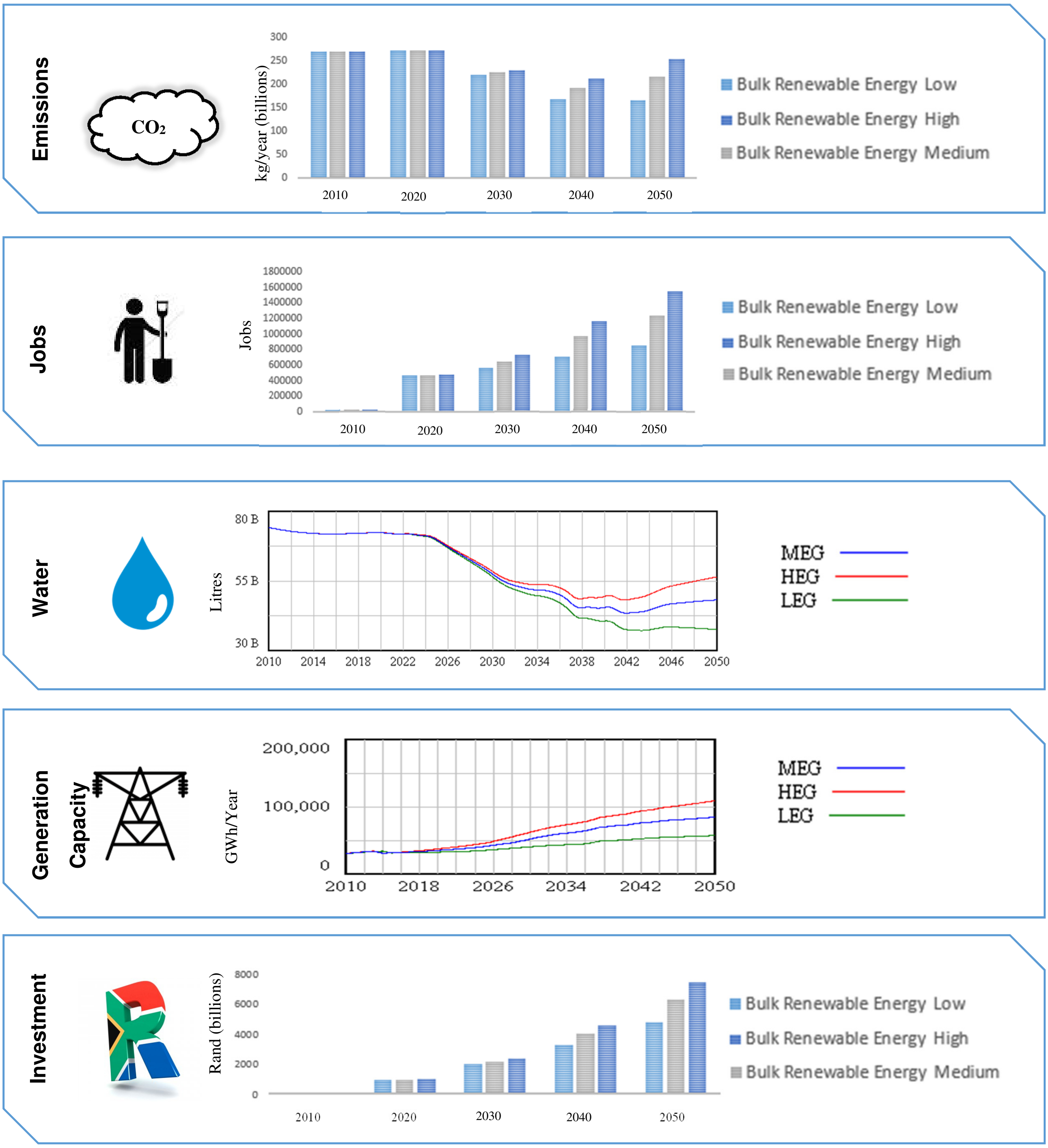

Figure 9.1 Summary of Outputs for the BRE Scenario

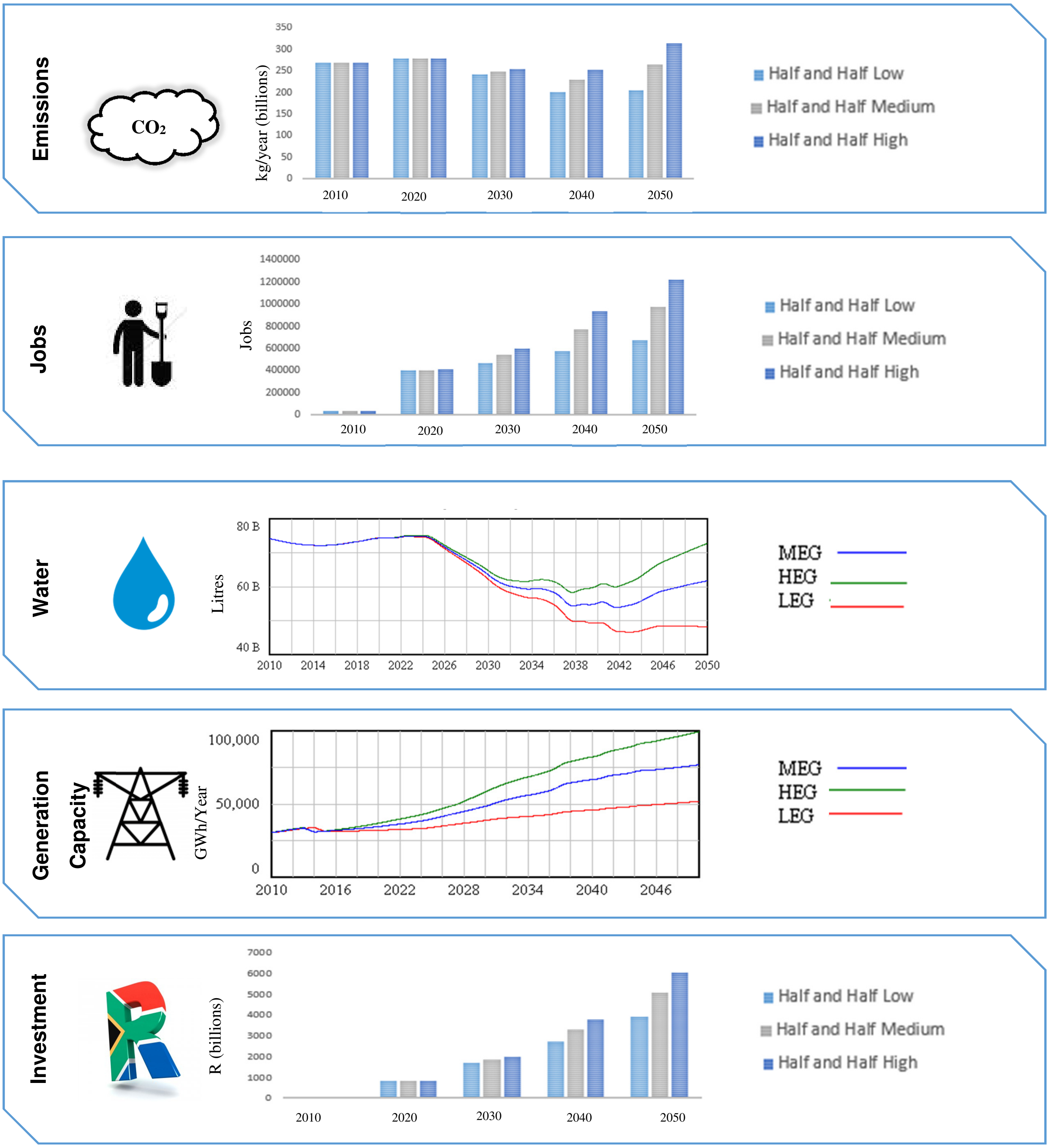

Figure 9.2 Summary of Outputs for the HAH Scenario

9.2 Recommendations

The results conclude that the current BAU scenario is insufficient to achieve the desired electricity capacity requirements in the long-term. This is an indication that, not only is South Africa's current IRP policy insufficient, but it is not fostering a SET. Therefore, the policy should be re-evaluated and the following recommendations should be considered:

Firstly, the dynamics of the system should be considered such as the future decommissioning of installed capacity and possible delays in the additions of new planned capacity. If this is not taken into account history may repeat itself in the form of loadshedding. The model considers a forty year outlook and in the long-term, a number of these new capacity additions will be decommissioned in twenty-five to thirty years, along with a large majority of the current installed baseload capacity also scheduled for decommissioning. Thus, under these circumstances and the possibility of a medium or high economic growth strategy, insufficient capacity is foreseen for future demand and alternative strategies should consider these dynamics.

The second recommendation steams from the model's employment sub-model, which showed that the renewable energy sector could create several jobs. Moreover, additional capacity requirements should be considered from the renewable energy sector. This is on condition that more local manufacturing jobs are created in the renewable energy sector. The results show that an electricity mix consisting of higher percentages of renewable energy are the most favourable solution when compared to the set of criteria for sustainability. Thus, when looking from an employment perspective, the model shows an optimistic outlook on the number of jobs created, and scenarios with a greater percentage contribution (greater than 50 per cent) of renewable energy in the electricity mix are favourable. Conversly, the scenarios containing higher renewable energy capacity additions show a decrease in fuel sector jobs. Thus, it is recommended that the fuel sector jobs – particularly for the coal mining sector, initiate international negotiations to increase their coal exports such that when the local demand for the product diminishes this supply can be exported.

From the model results, it is not recommended that South Africa consider an electricity mix containing more than 70 per cent new capacity additions from fossil fuels. This is due to the associated environmental consequences, where CO_2, SO_x, and NO_x emissions are shown to increase in the future.

9.2.1 Recommendations for Academics

Further recommendations are made to the academic community, for future research opportunities that can be considered. The first of which is the further investigation of energy efficiency as mentioned in Section 8.2. If factors such as the availability of land area and accessibility are of interest, additional modelling could be considered to incorporate factors such as: the total land usage type, ease of access, and ease of connectivity to the grid system. Future research could also consider the impact of factors such as: transmission and distribution infrastructure, necessary weather conditions for renewable technologies, resources availability for fossil fuels, the possibility of decentralised or smart grids, and infrastructure availability (e.g. roads) for the addition of new generation plants. The impact of adding the real grid costs and the costs associated with stabalising the grid should also be considered in the future. Likewise the current LCOE costs should factor in either connecting to the national grid or a decentralised grid depending on the technology type. Finally, future research and model development could include job decline factors and learning rates for the employment sub-model.

9.2.2 **Recommendations for Policy Makers**

Addition variables that could be considered are the impact that weakened States have on the ability of the State to achieve an SET at the desired rate. As well as the impact that factors, such as corruption and poor governance, have on the the selection of technologies for the future electricity mix and the system as a whole. Thus, policy makers should consider these effects when developing and setting policy targets.

It is strongly recommended that South Africa’s current capabilities, in developing local manufacturing potential, is explored. The job creation potential is considerable as shown in the SD model. Thus, the necessary policy measures and associated industry road map development could investigate the opportunities and challenges associated with the development of this capability.

With the transition to sustainability and the resulting reduction in the need for fossil fuels, sufficient mechanisms need to be employed to facilitate the transition and prevent possible social and economic events such as: Strikes due to loss of jobs, increased unemployment rate, and a collapse of an essential commercial sector. These mechanisms could possibly include, but is not limited to, the development of skills and training programmes to transition workers from one sector to another.

9.2.3 **Recommendations for the SET Community**

The study aimed to initiate discussions, and inform and shape strategic decision-making processes in the future, by using the model as a tool to test various futures and their possible outcomes. However, future research endeavours can include a more holistic view of the energy sector and the resulting causalities between the mining sector and the consequences of an SET.

The modelling of stakeholder relationships and the influence these relationships have on an electricity regime is complex and not easy to accurately model. Thus, future considerations could introduce the impact of these relationships on the ability to achieve an SET within the desired scope and at the desired rate of change. Also, a country’s dependence on resources, such as coal or oil, has shown to affect the ease and rate of transition to sustainability, due to vested interests and a certain degree of economic vulnerability.

9.3 Concluding Remarks

This study addressed and successfully achieved the aim of contributing to the knowledge base of fostering SETs within the electricity sector of South Africa. This was achieved using a dual-narrative research approach, comprising of a systematic review of literature to develop a set of criteria, and the use of System Dynamics to model South Africa's electricity sector on a systems level.

The systematic review of literature addressed topics including: sustainable development, the green economy, transitions theory, the South African Electricity Sector and various SET frameworks. The set of criteria and various indicators were developed. These were used to define the scope of the SET and subsequently guided the modelling process. The SD methodology was chosen, due to its ability to handle complexity and various actor levels, and define casual relationships between different variables. The model was used to test and evaluate possible future scenarios that include the IRP policy, and scenarios consisting of varying energy mix compositions between renewable energy and fossil fuel technology types.

From the literature review, it was clear that issues including, but not limited to: decarbonisation, security of supply and the importance of meeting energy demand, are key components of achieving an SET. The model results show that the IRP policy is insufficient in meeting the required electricity demand forecasts and thus, security of supply is a future concern.

Therefore, it can be concluded that the current mechanisms implemented to drive the transition to sustainability, are insufficient and alternative solutions should be investigated to foster the transition. Alternative scenarios, such as additional renewable energy technologies, are increasingly competitive scenarios due to the high job creation potential, decreased water-usage trends and emission-free generation. However, the intermittence of supply remains a challenge and the implications of dispatchable electricity need to be considered. Other considerations include: the affect of skills and training, in terms of the diminishing mining sector need with the transition to renewable technologies, and, the dynamic effects that political circumstances may have on the State, and the electricity sectors overall ability to 'function' and drive an SET.

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APPENDICES

A. Model Structure

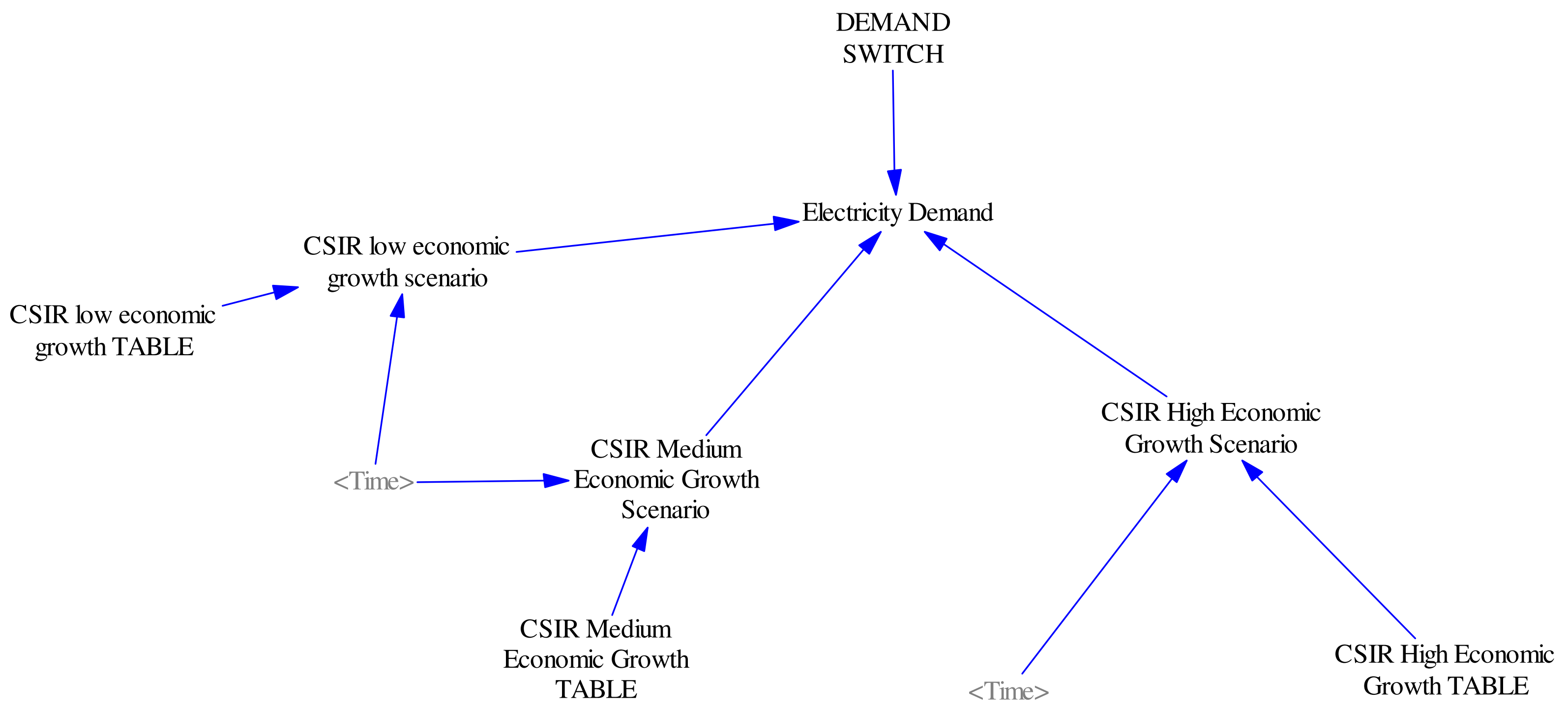


Figure A.1 Electricity Demand Sub-model

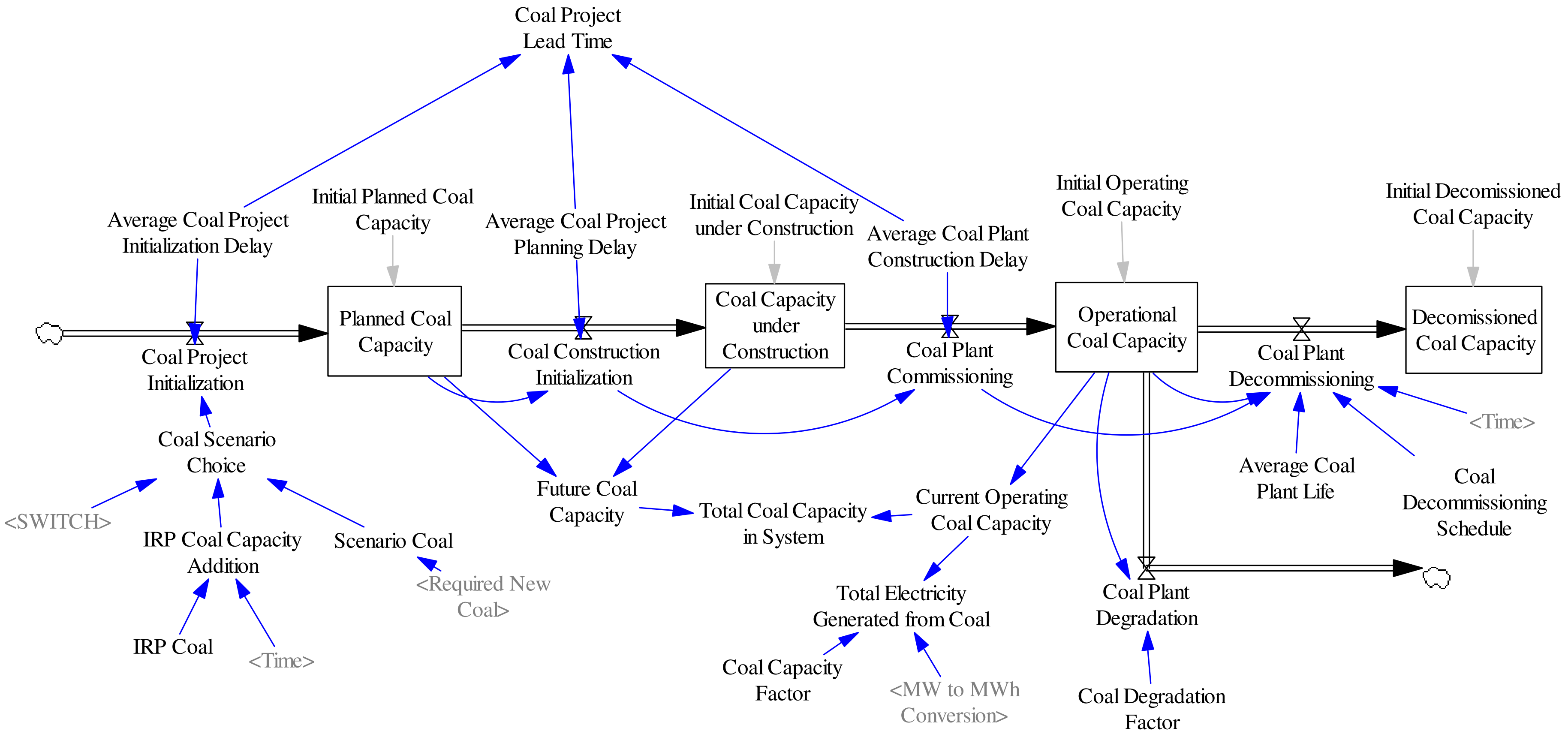


Figure A.2 Coal Generation Sub-model

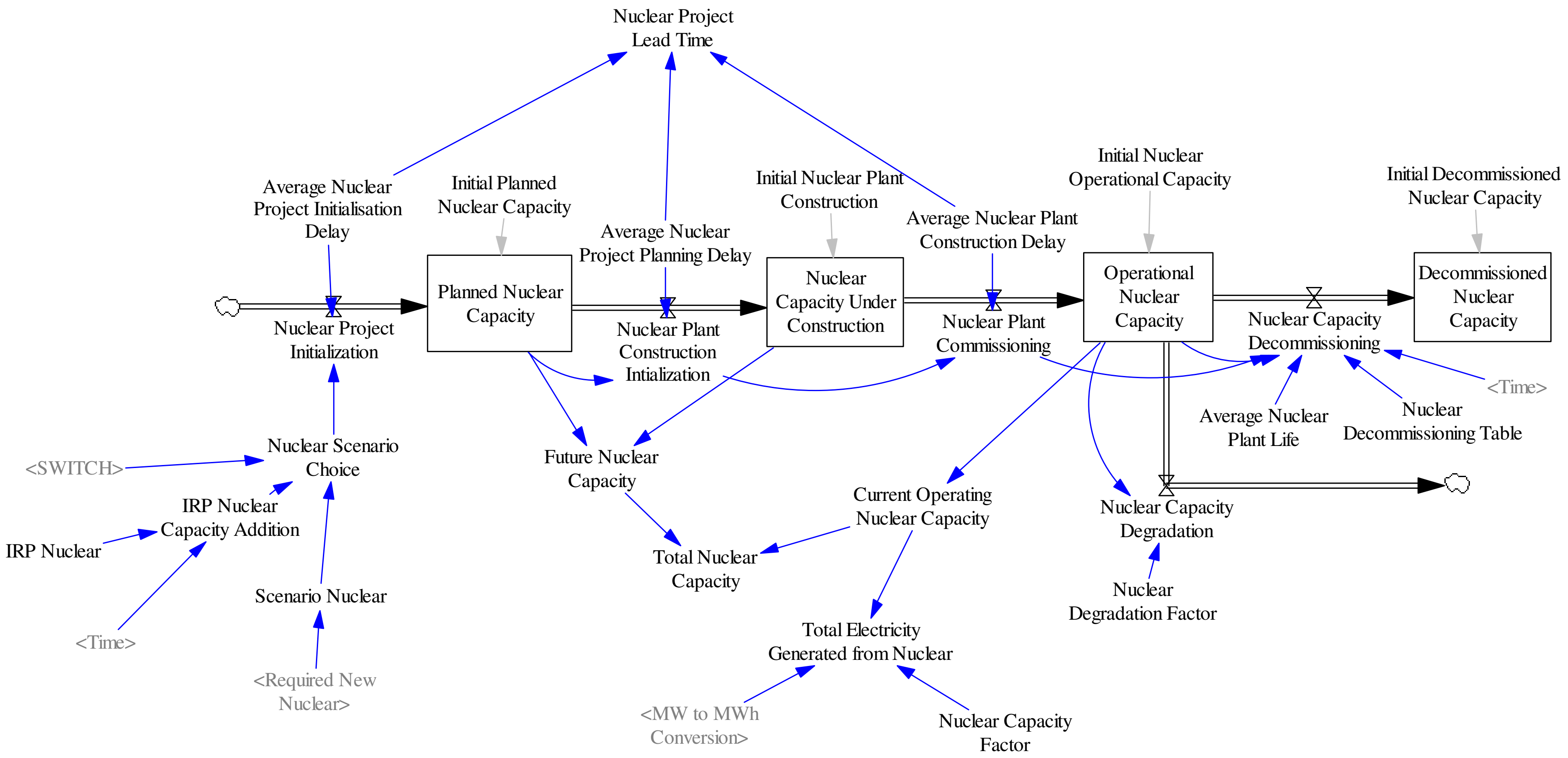


Figure A.3 Nuclear Generation Sub-model

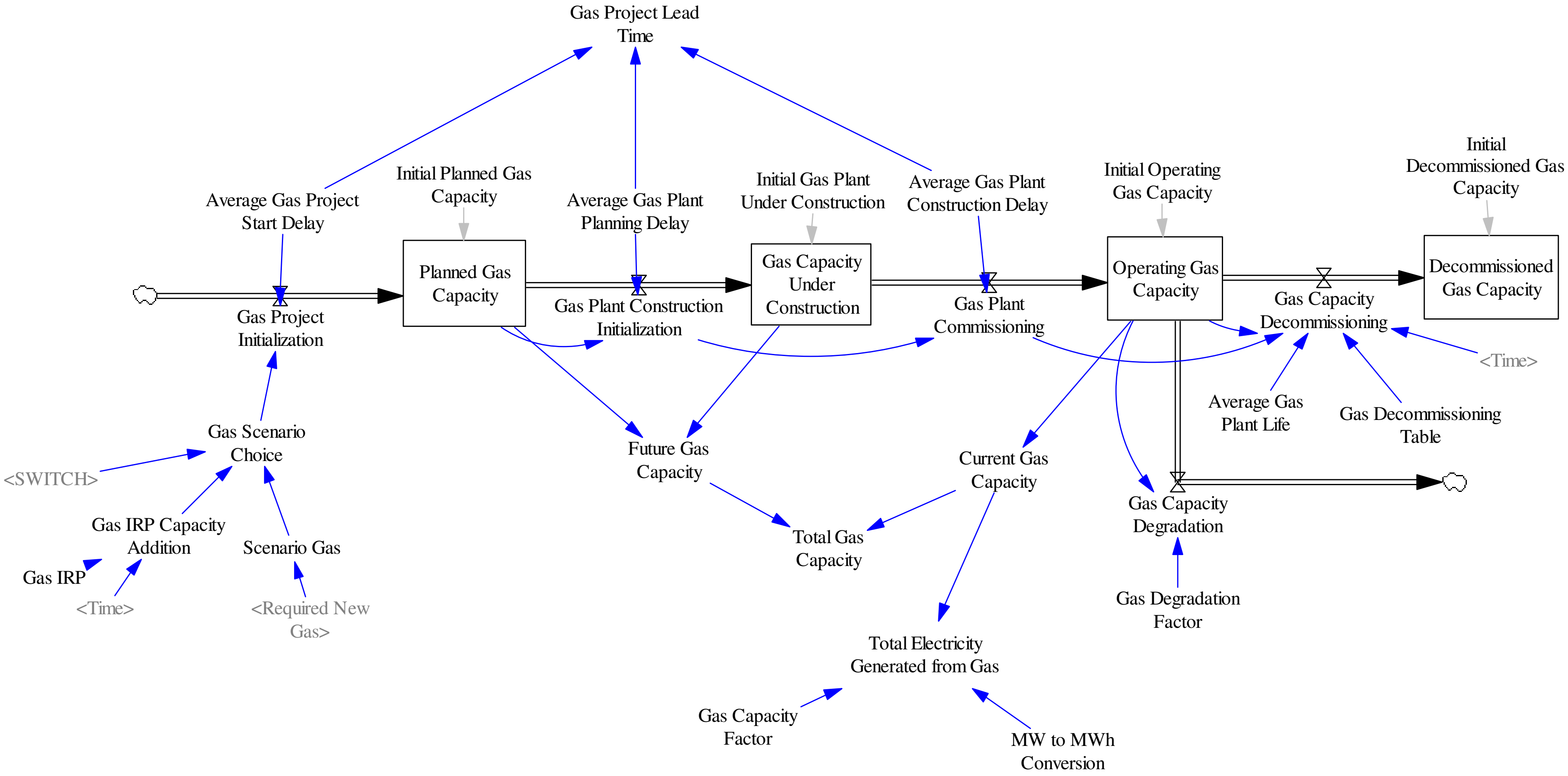


Figure A.4 Gas Generation Sub-model

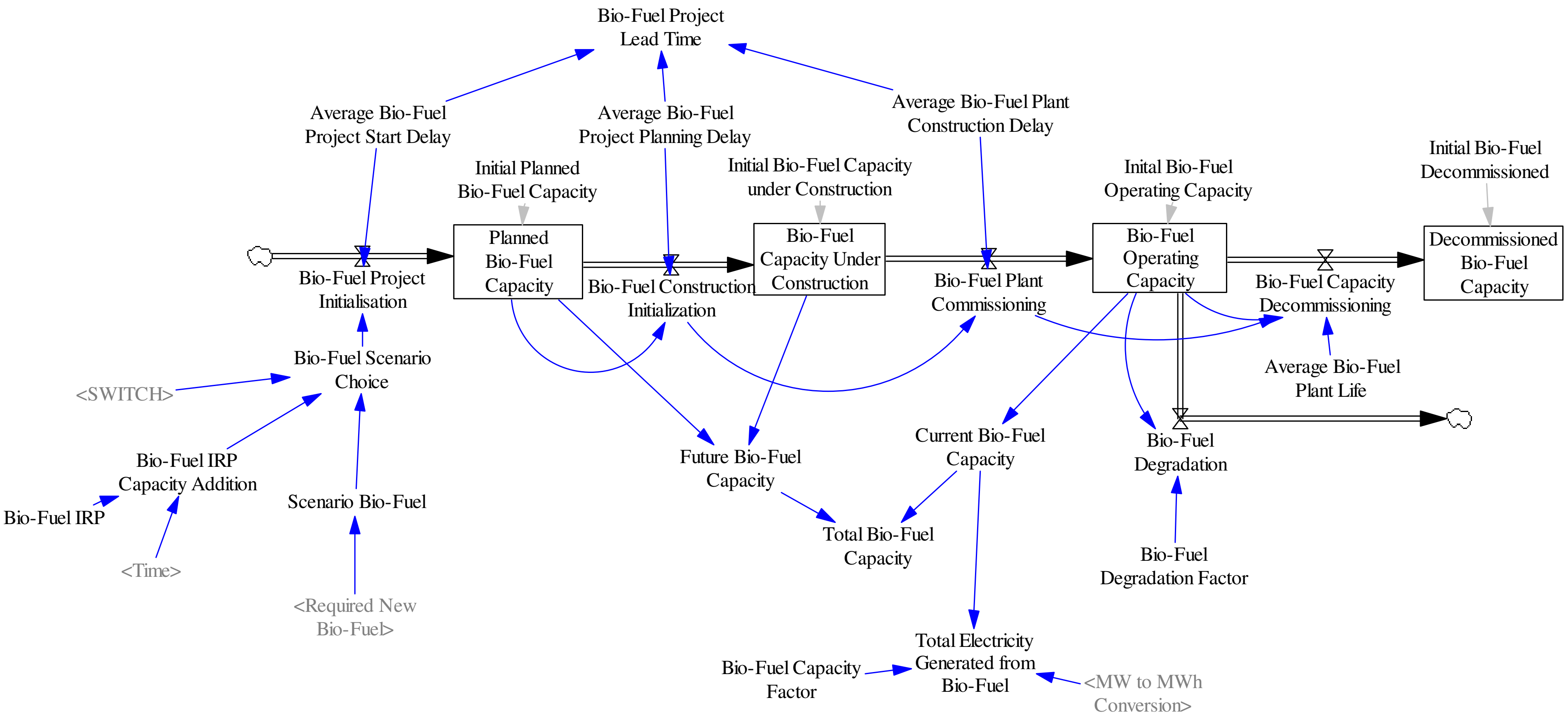


Figure A.5 Bio-Fuel Generation Sub-model

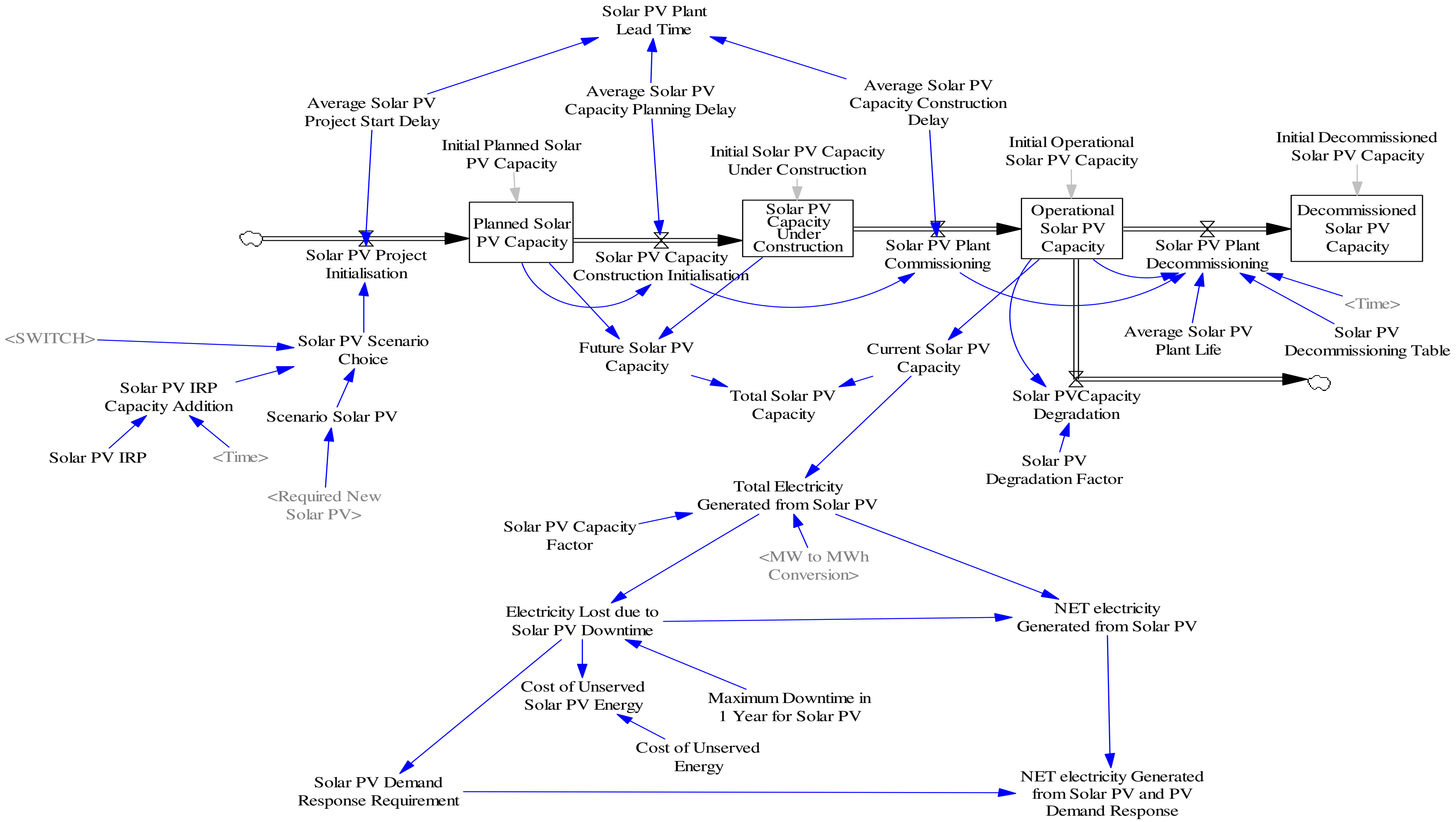


Figure A.6 Solar PV Generation Sub-model

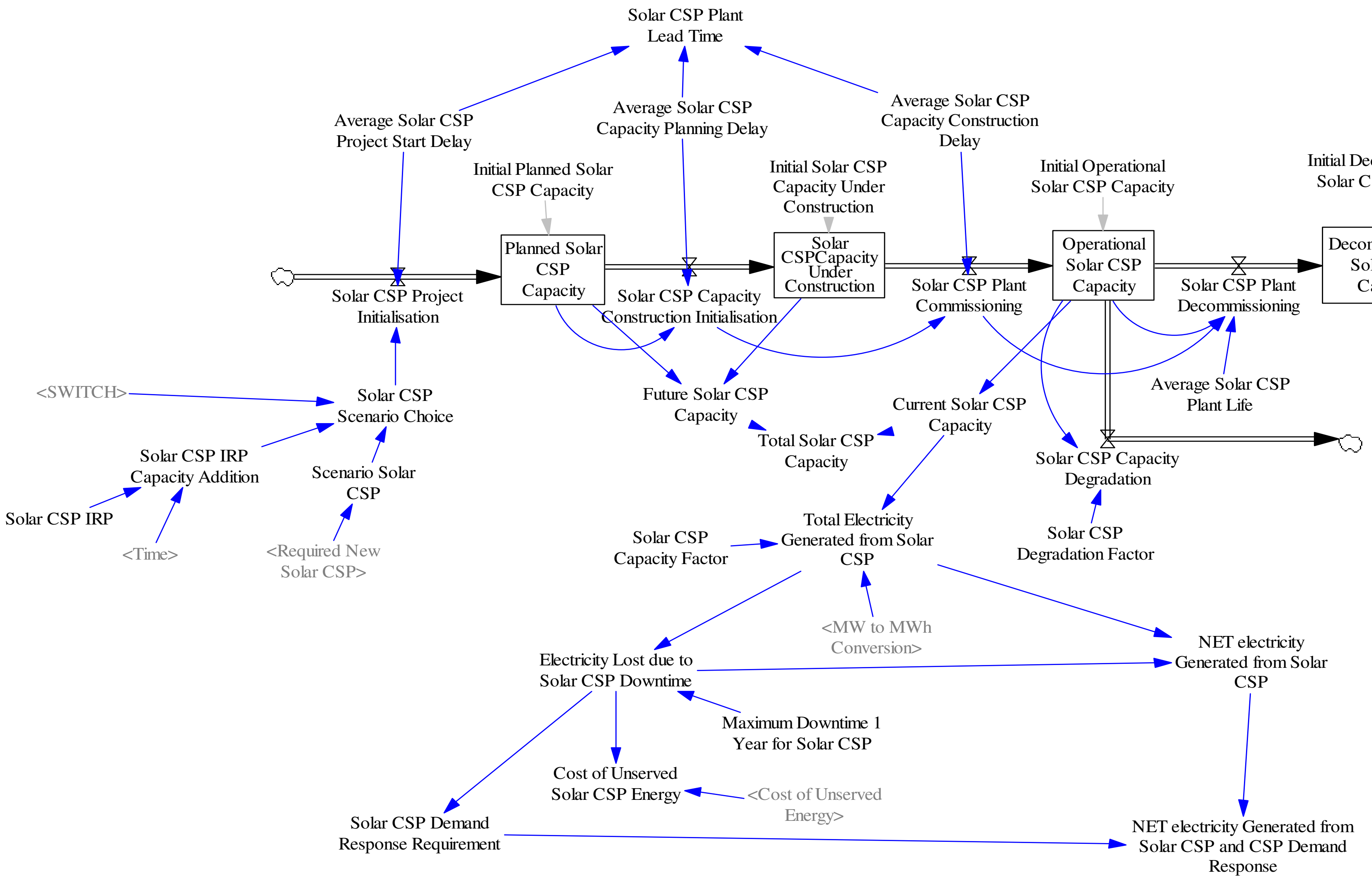


Figure A.7 Solar CSP Generation Sub-model

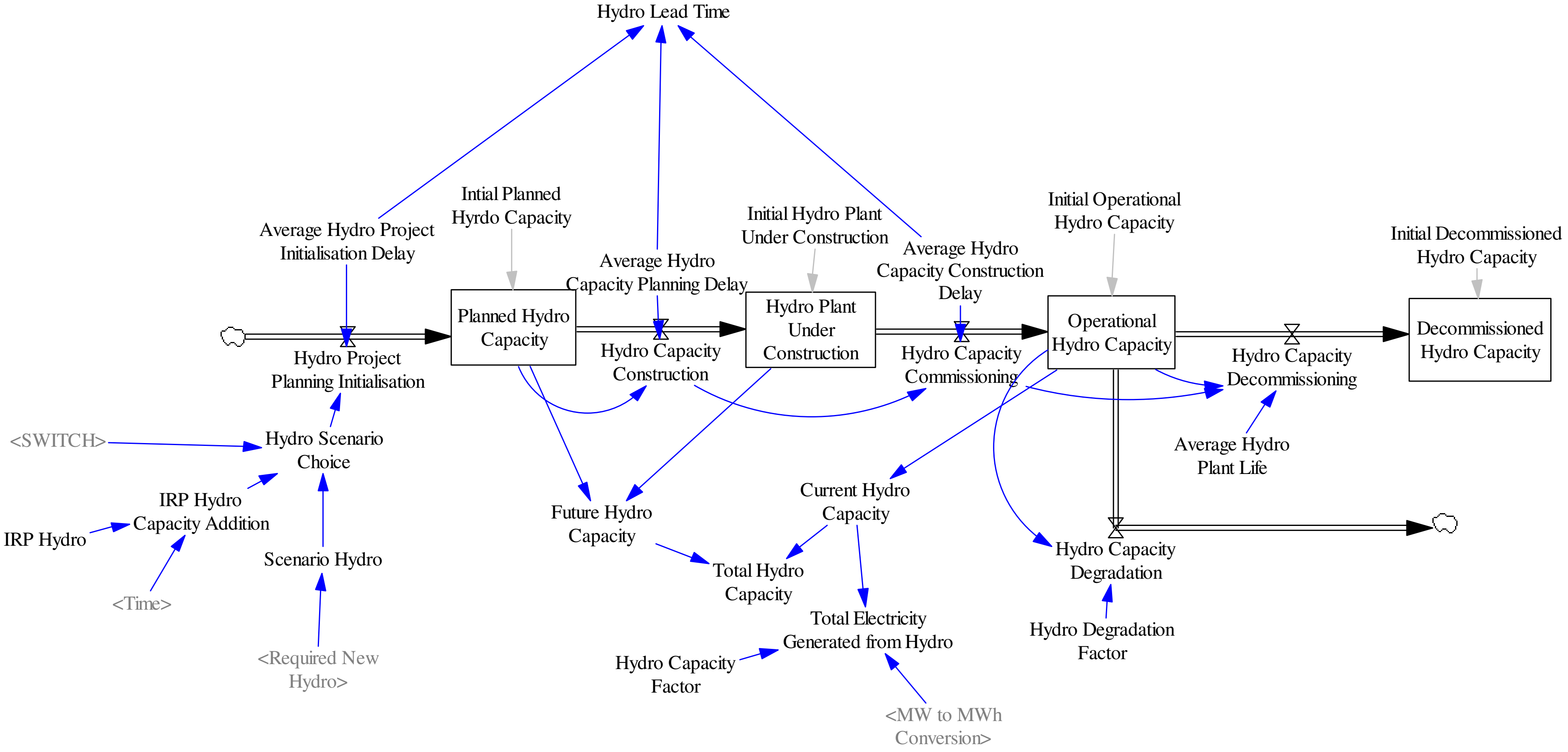


Figure A.8 Hydro Generation Sub-model

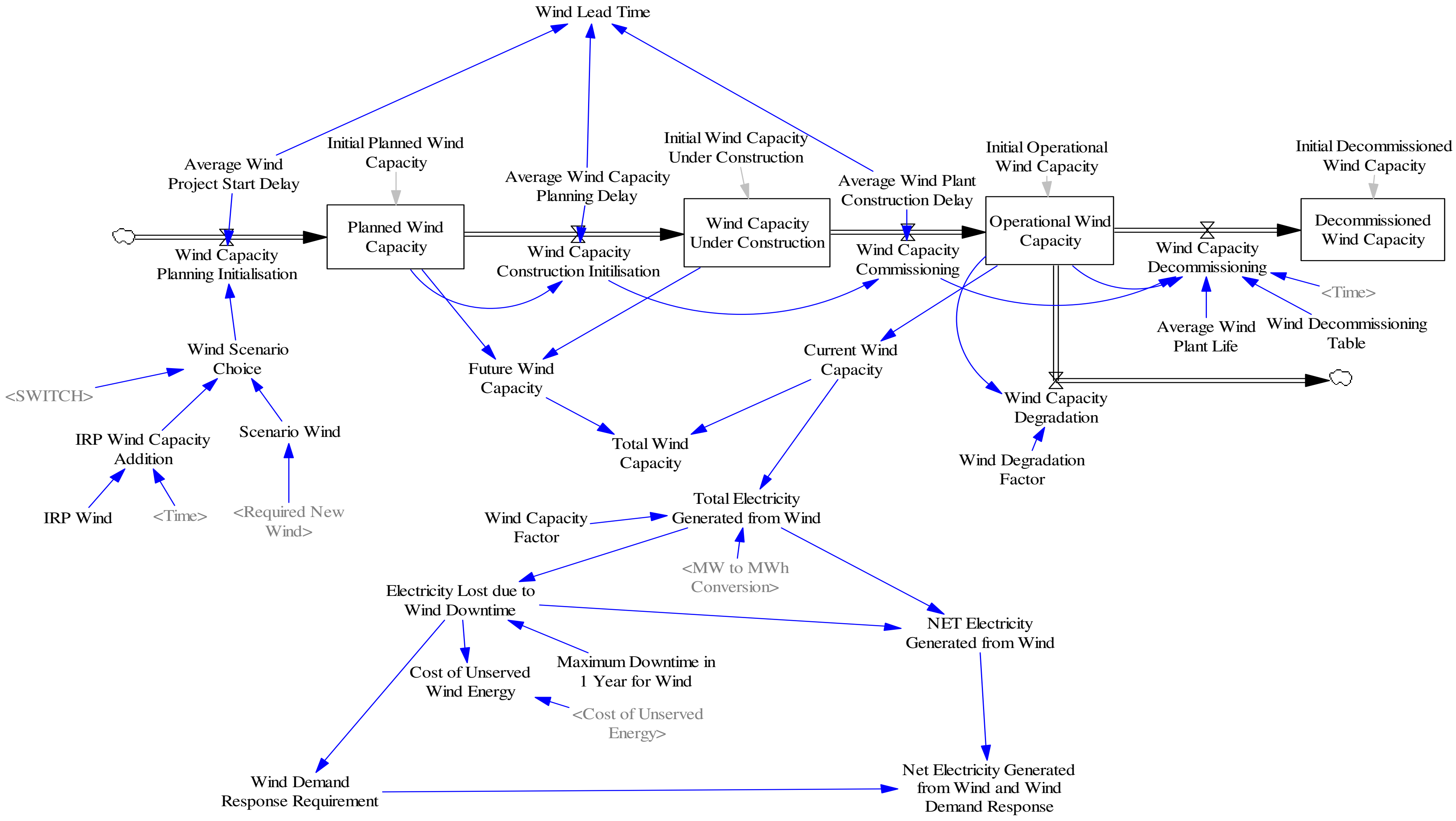


Figure A.9 Wind Generation Sub-model

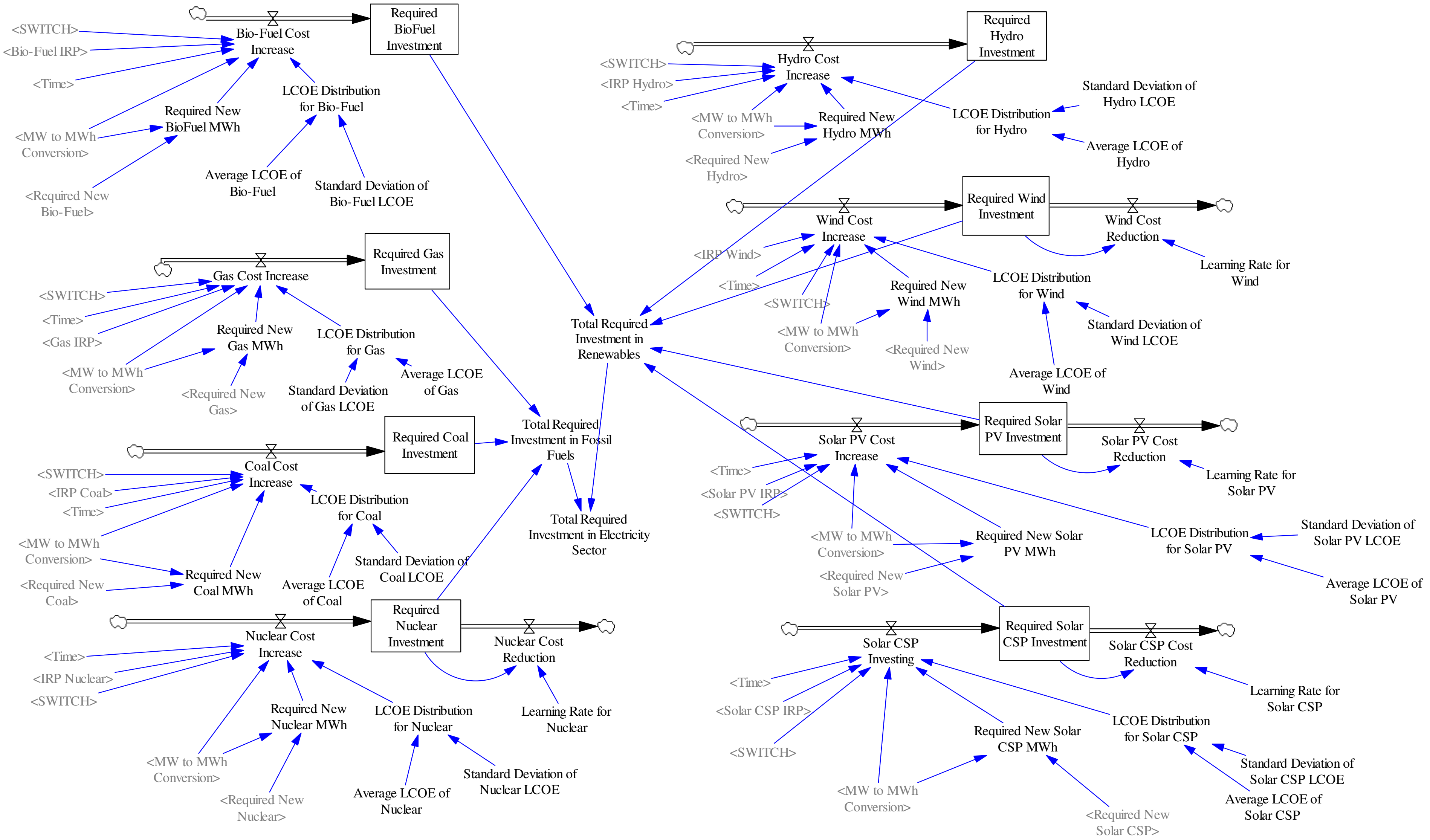


Figure A.10 LCOE Sub-model

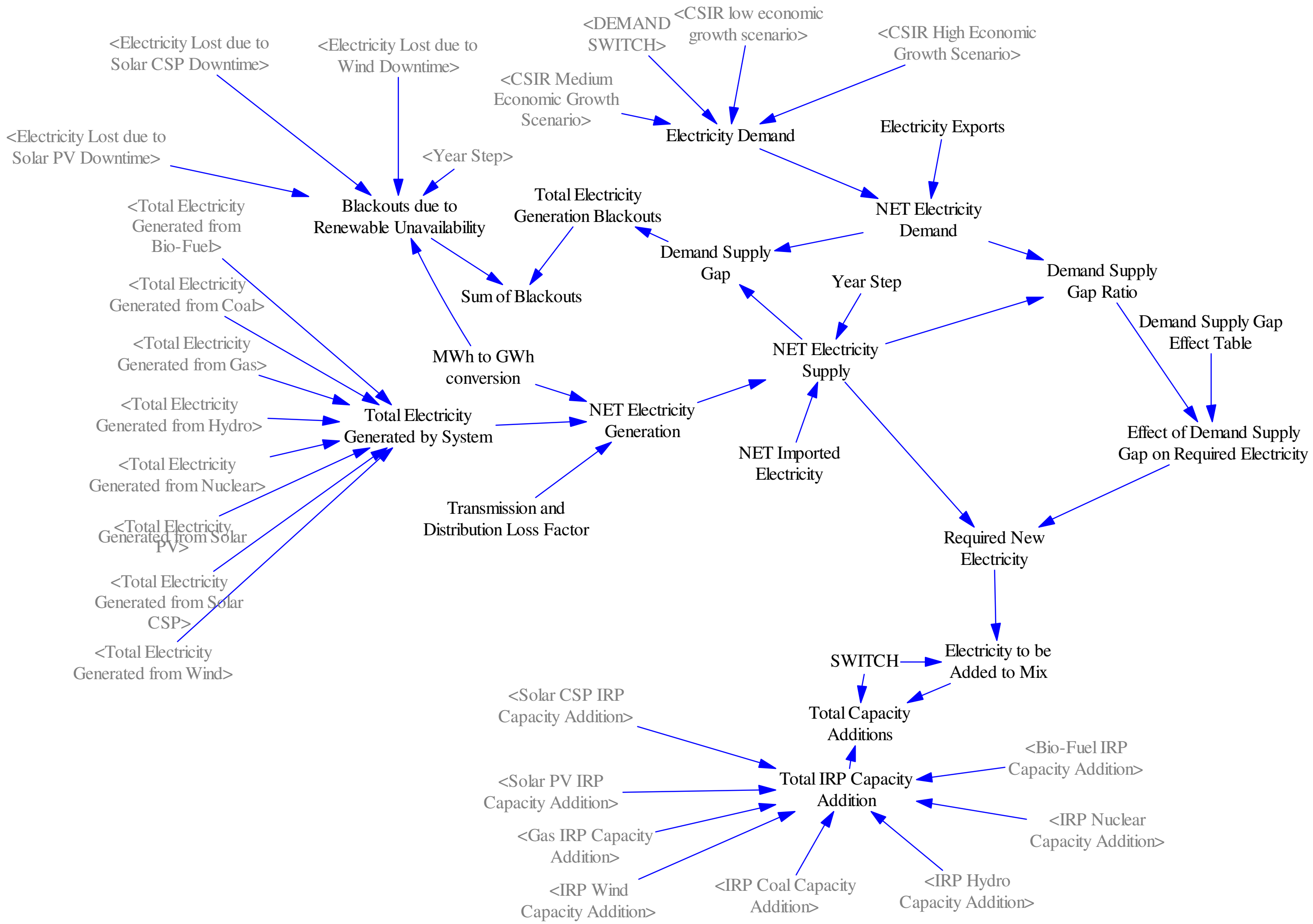


Figure A.11 Demand-Supply Gap Generation Sub-model

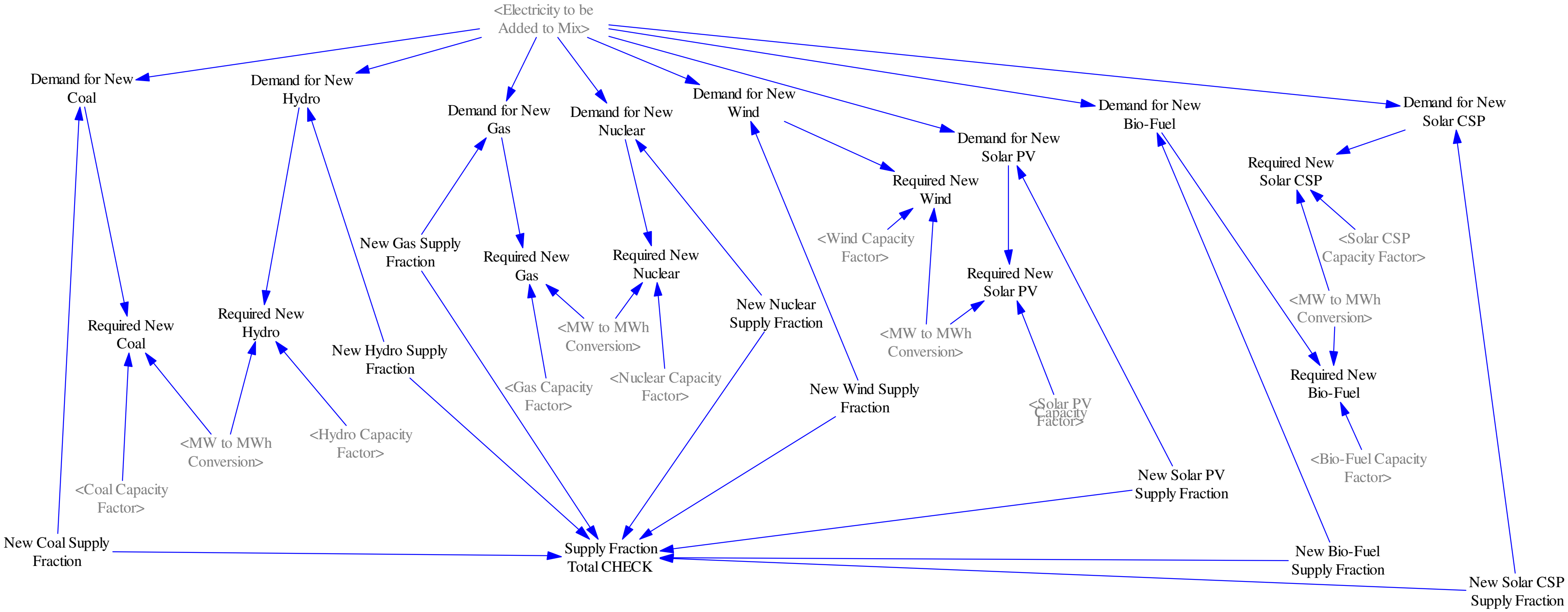


Figure A.12 Supply Fraction Sub-model

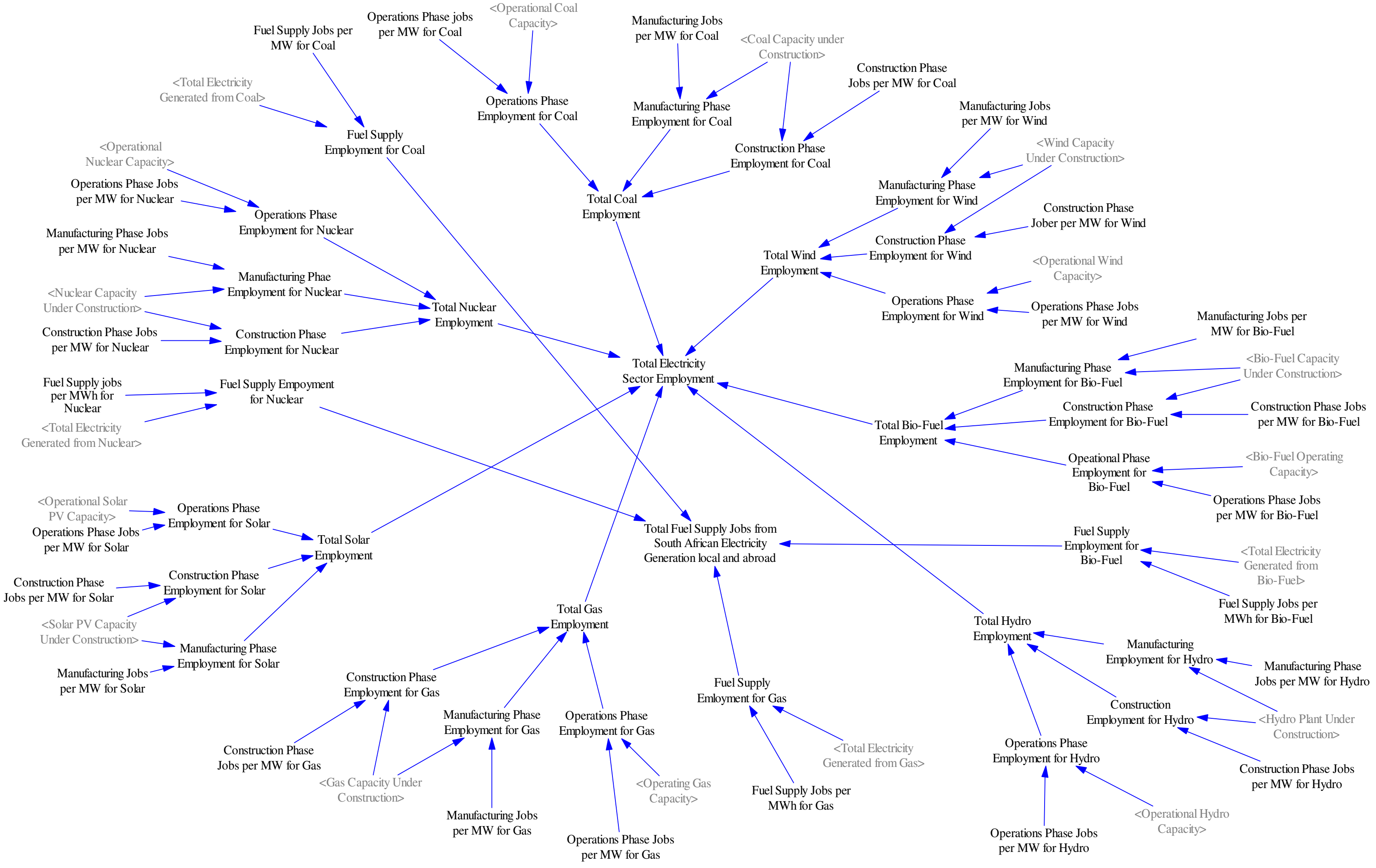


Figure A.13 Employment Sub-model

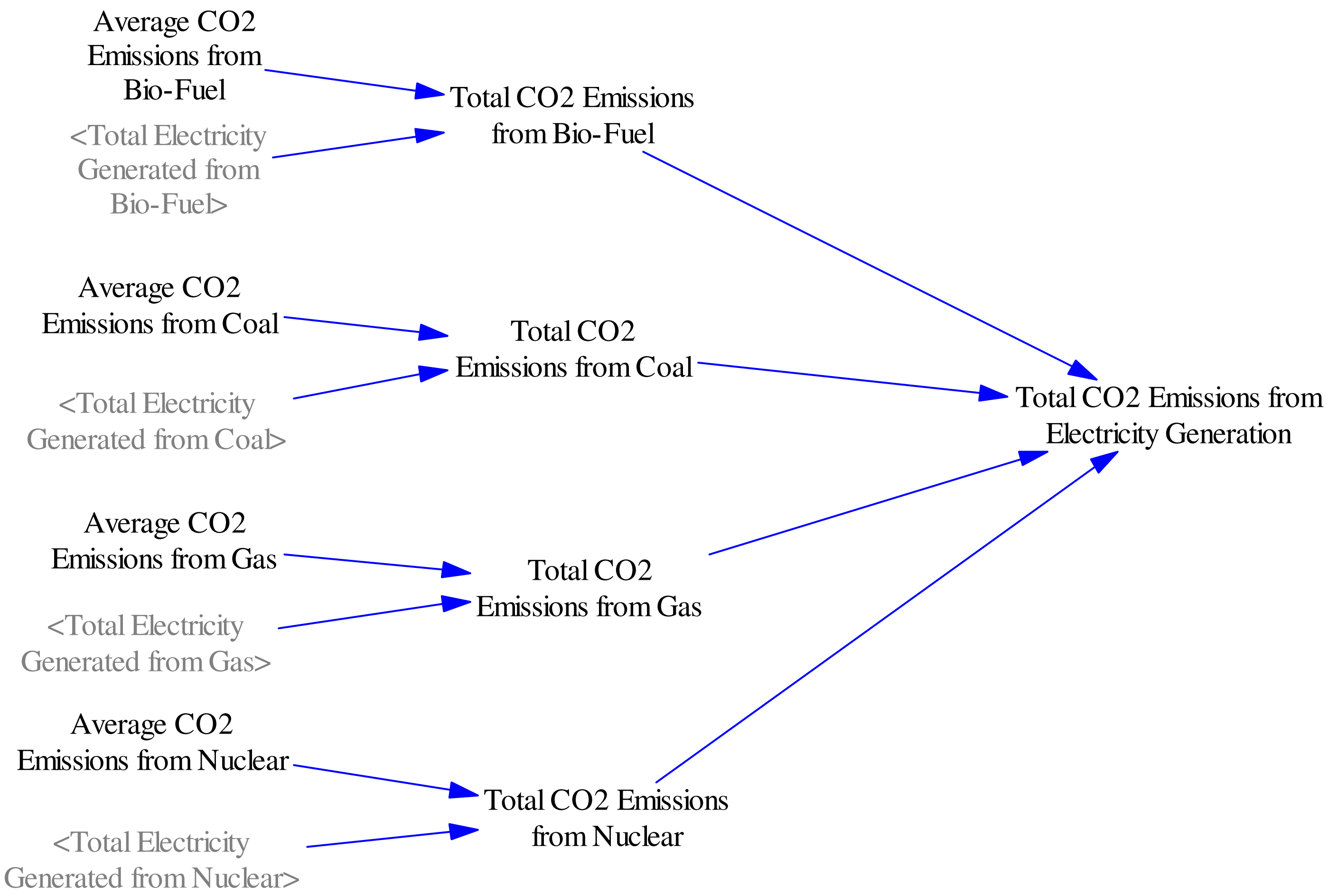


Figure A.14 CO_2 Emissions Sub-model

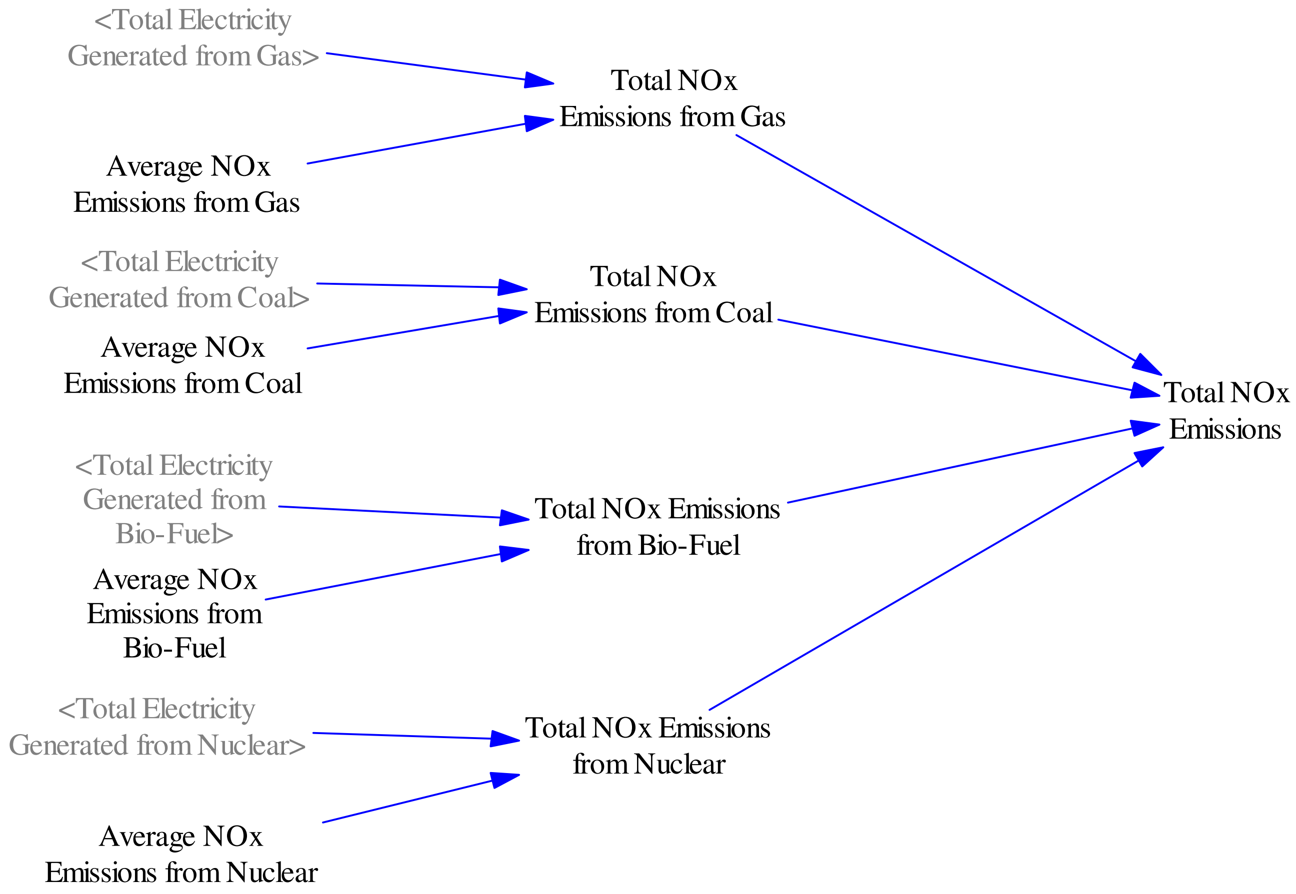


Figure A.15 NO_x Emissions Sub-model

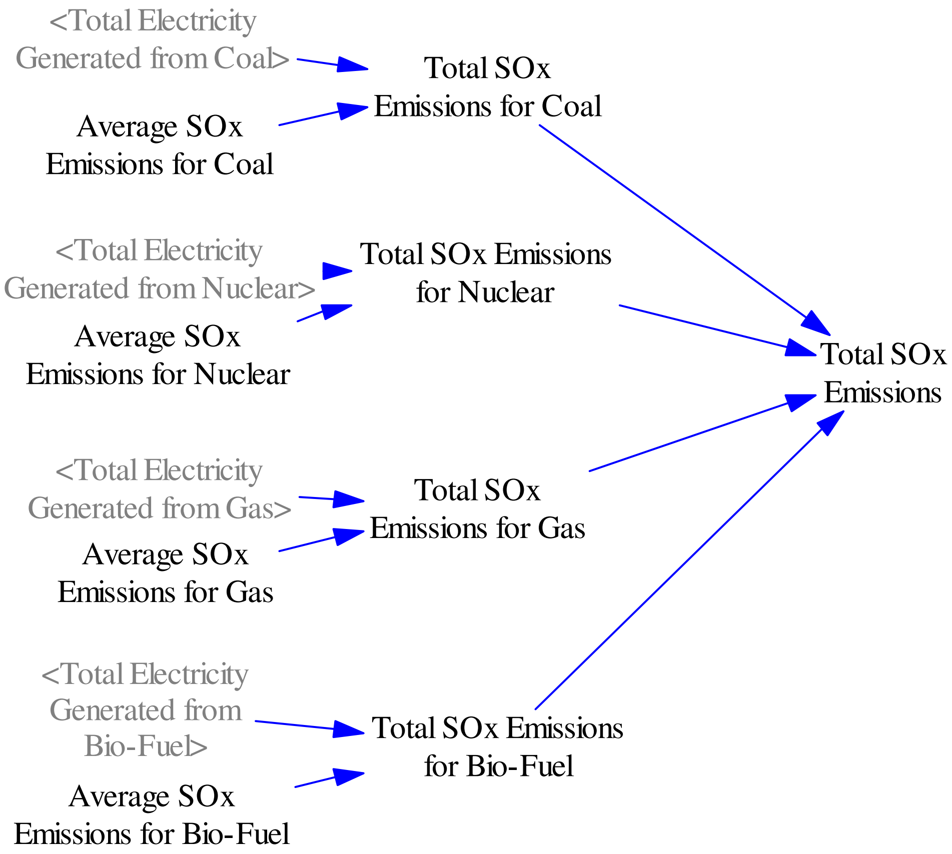


Figure A.16 SO_x Emissions Sub-model

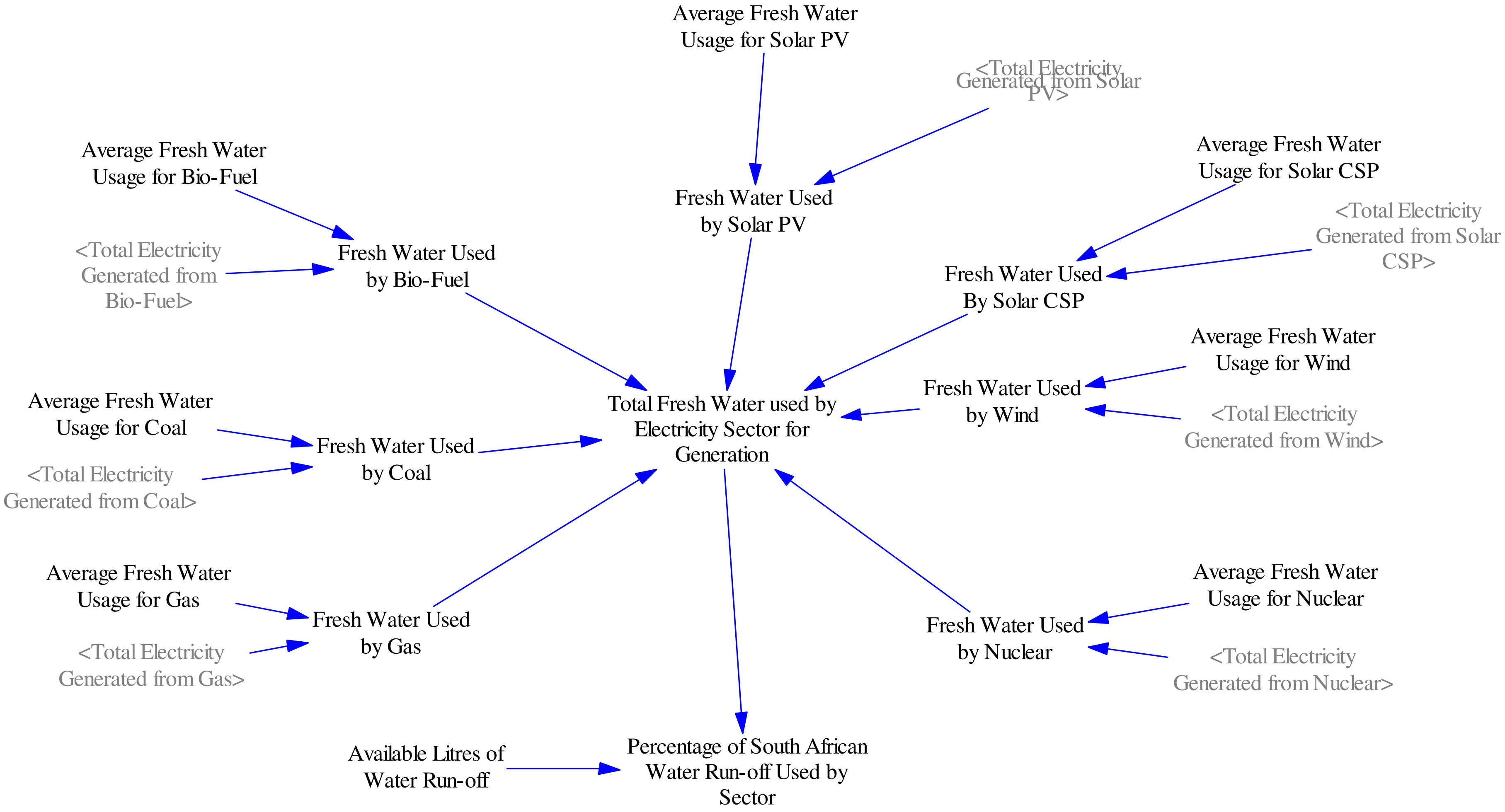


Figure A.17 Fresh Water Usage Sub-model

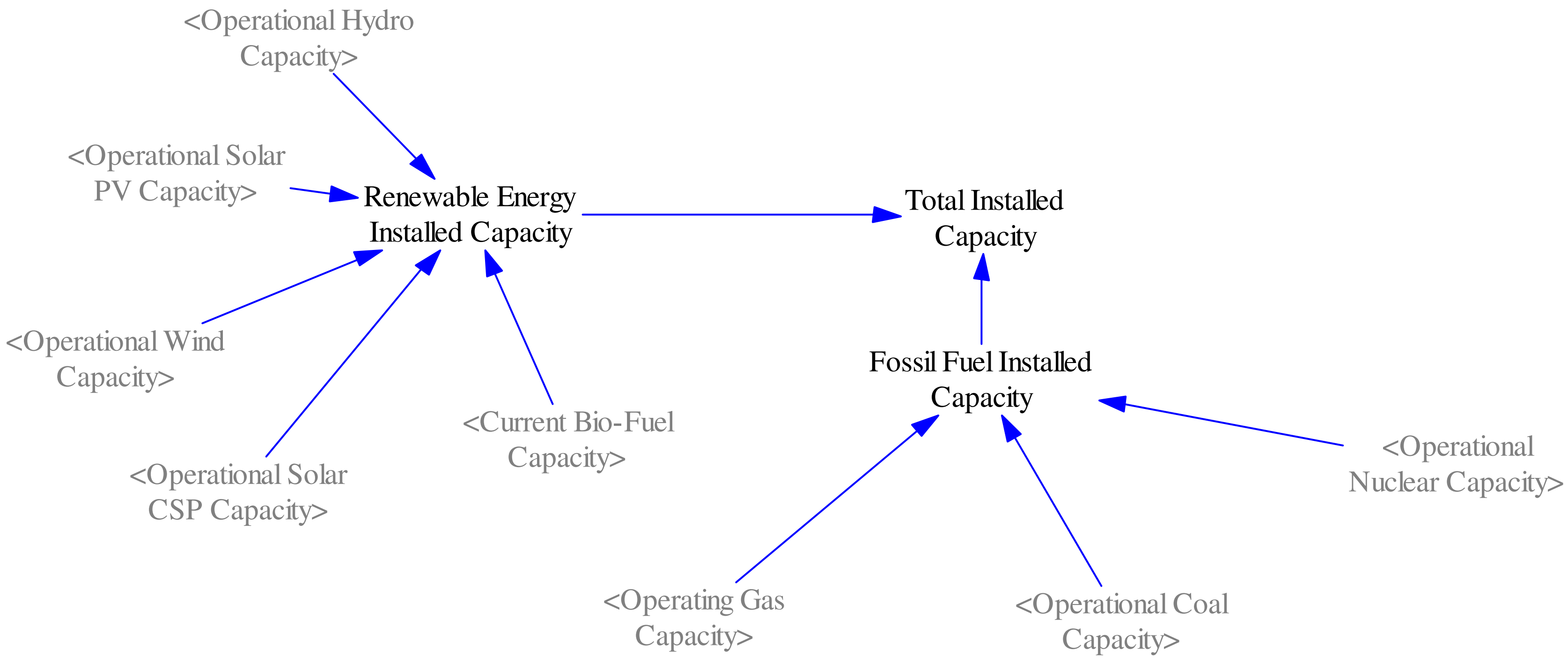


Figure A.18 Installed Capacity Sub-Model

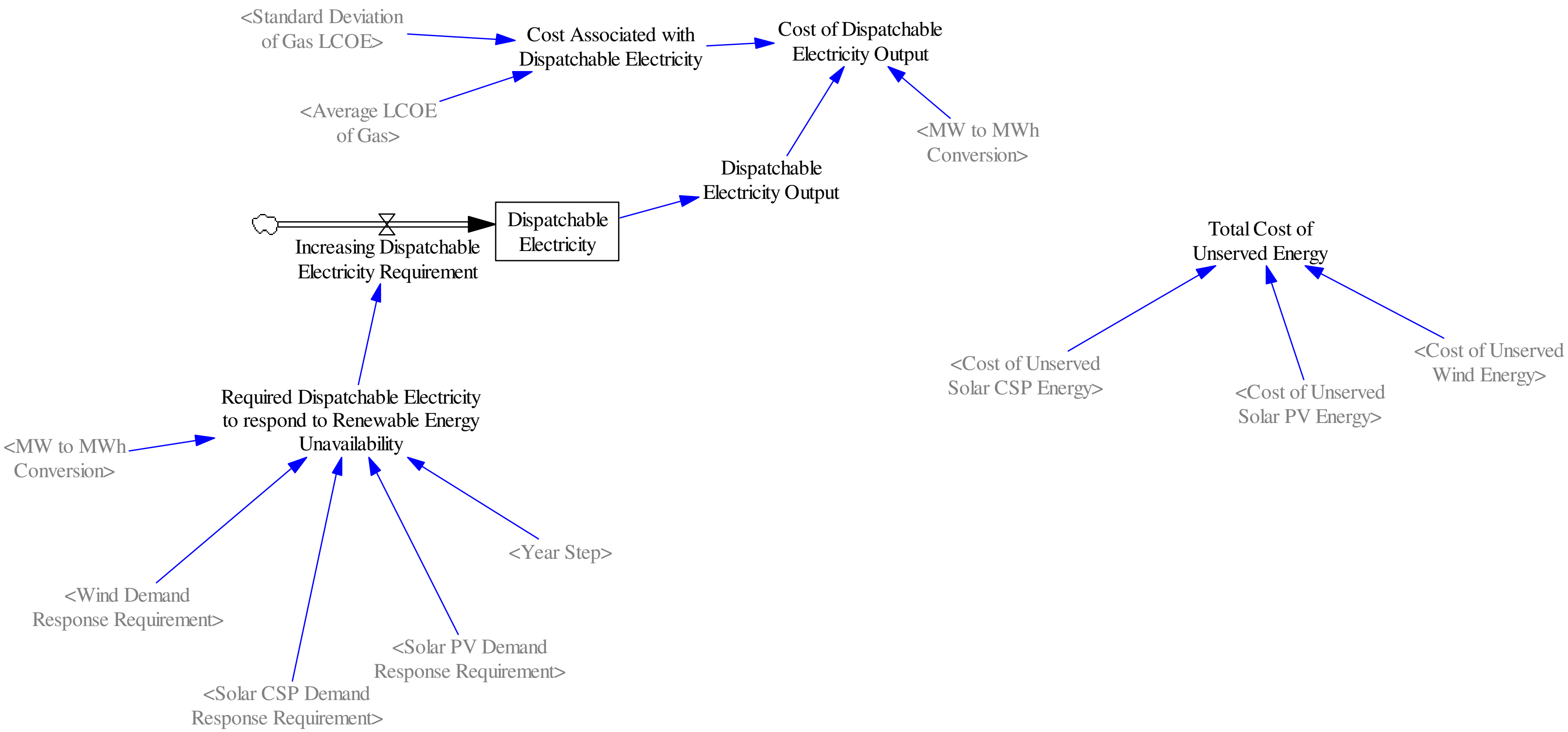


Figure A.19 Dispatchable Electricity Sub-model

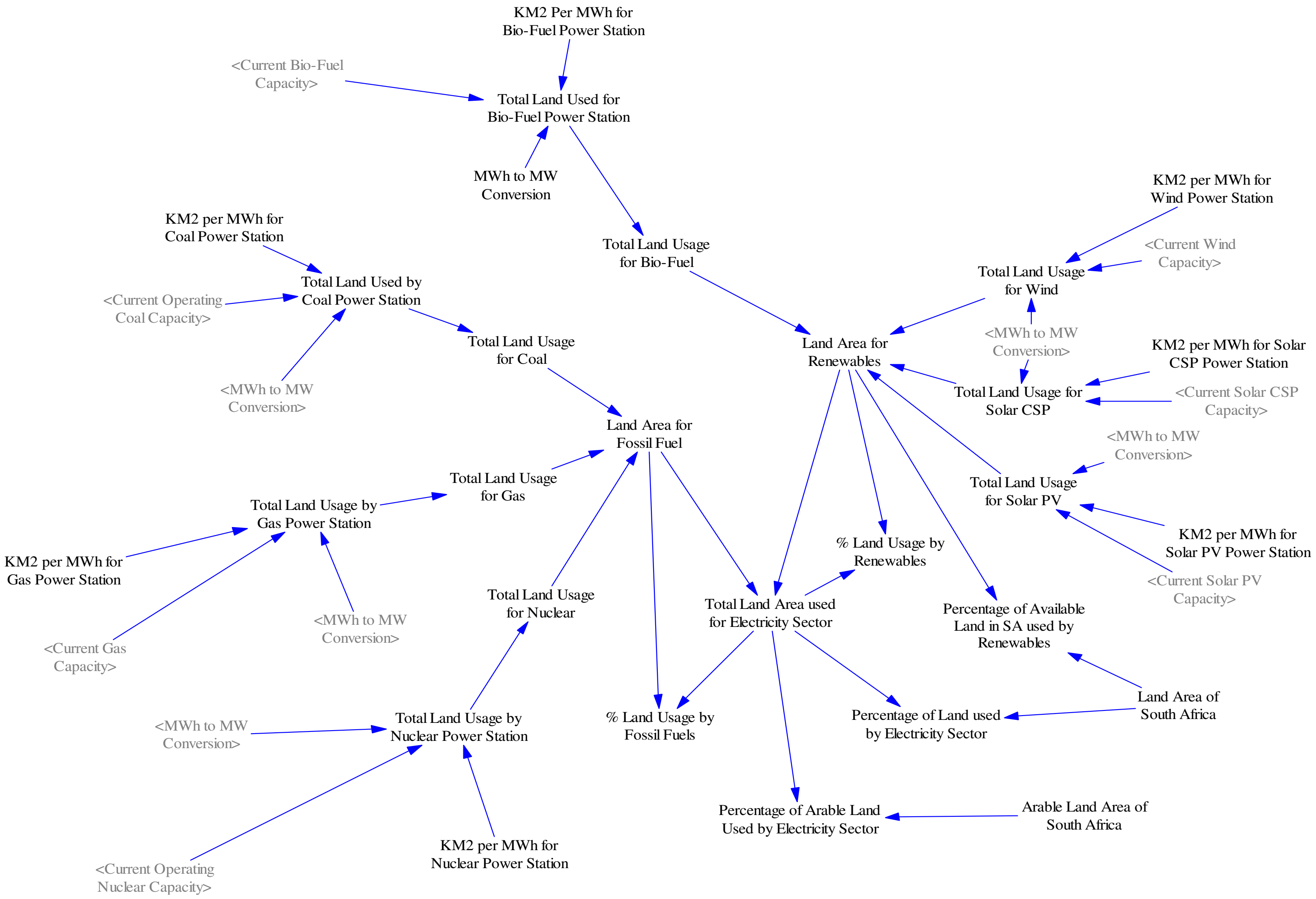


Figure A.20 Land Area Sub-model

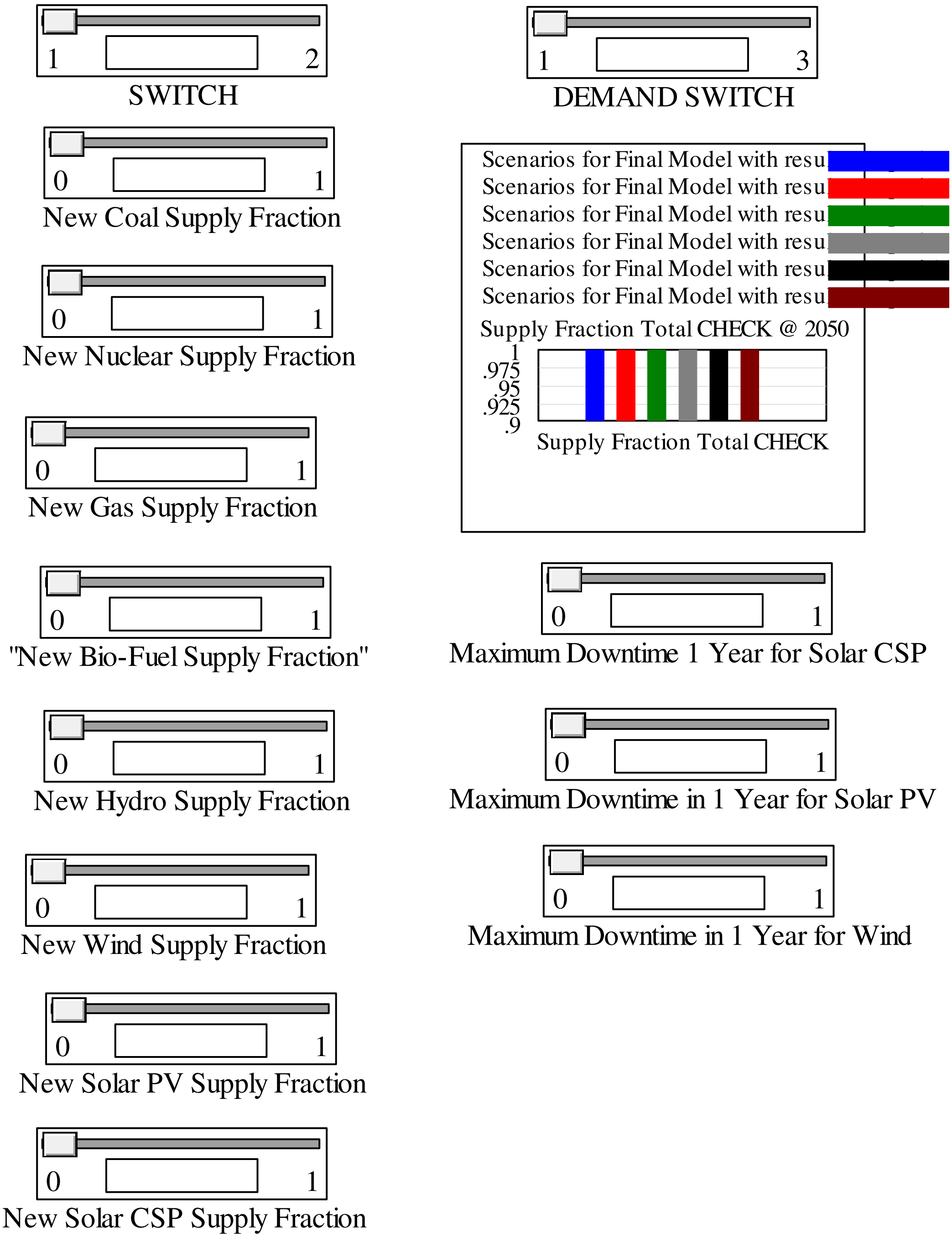


Figure A.21 Control Panel Sub-model

B. Model Data and Sources

Table B.1. Model input data and sources.

Variable Name	Variable Value and Unit		Source
Cost of Unserved Electricity	R77300/MWh		(Department of Energy, 2016b)
Capacity Factors	***Coal***	85%	Calculations based on averages of data (Gross *et al.*, 2015; Department of Energy, 2016b)
	Nuclear	90%	
	Gas	36.6%	
	Bio-Fuel	85%	
	Solar PV	22.12%	
	Solar CSP	49.96%	
	Wind	33.05%	
	Hydro	34%	
Initial Technology Capacities (Installed nominal capacity)	***Coal***	47318MW	(Eskom, 2015; Ngobeni, 2016)
	Nuclear	1940MW	
	Gas	2426MW	
	Bio-Fuel	11.7MW	
	Solar PV	0MW	
	Solar CSP	0MW	
	Wind	8.36MW	
	Hydro	2061MW	
Average Water Usage	***Coal***	210.25L/MWh	(Department of Energy, 2016b)
	Nuclear	0L/MWh	
	Gas	9.9L/MWh	
	Bio-Fuel	148L/MWh	
	Solar PV	4.05L/MWh	
	Solar CSP	82.13L/MWh	
	Wind	0L/MWh	
	Hydro	0L/MWh	
Job Factors for Operations Phase Jobs	***Coal***	0.594jobs/MW	(Rutovit & Letete, 2010)
	Nuclear	0.66jobs/MW	
	Gas	0.09jobs/MW	
	Bio-Fuel	5.51jobs/MW	
	Solar PV	0.73jobs/MW	
	Solar CSP	0.54jobs/MW	
	Wind	0.72jobs/MW	
	Hydro	0.04jobs/MW	
Job Factors for Manufacturing Phase Jobs	***Coal***	3job years/MW	(Rutovit & Letete, 2010)
	Nuclear	1.2job years/MW	
	Gas	0.07job years/MW	
	Bio-Fuel	0.8job years/MW	
	Solar PV	16.8 job years/MW	
	Solar CSP	7.2job years/MW	
	Wind	22.5job years/MW	

	Hydro	0.9job years/MW	
Job Factors for Construction Phase Jobs	***Coal***	15.6 job years/MW	(Rutovit & Letete, 2010)
	Nuclear	10.8 job years /MW	
	Gas	6.2 job years/MW	
	Bio-Fuel	6.9 job years/MW	
	Solar PV	52.3 job years/MW	
	Solar CSP	10.8 job years/MW	
	Wind	4.5job years/MW	
	Hydro	19.4 job years/MW	
Job Factors for Fuel Supply Phase Jobs	***Coal***	240 jobs/MWh	(Rutovit & Letete, 2010)
	Nuclear	2 jobs/MWh	
	Gas	220 jobs/MWh	
	Bio-Fuel	400 Jobs/MWh	
IRP Lookup Tables per Technology Type	Refer to Tables		All IRP Lookup Tables as specified in IRP 2016 and REIPPPP Bid windows 1-4 (Department of Energy, 2016b; Ngobeni, 2016)
NOx Emissions Factor	***Coal***	0.7kg/MWh	(Republic of South Africa Department of Energy, 2016)
	Nuclear	0kg/MWh	
	Bio-Fuel	0kg/MWh	
	Gas	0.25kg/MWh	
SOx Emissions Factor	***Coal***	0.475kg/MWh	(Republic of South Africa Department of Energy, 2016)
	Nuclear	0kg/MWh	
	Bio-Fuel	0.2333kg/MWh	
	Gas	0kg/MWh	
CO2 Emissions Factor	***Coal***	754.125kg/MWh	(Republic of South Africa Department of Energy, 2016)
	Nuclear	0kg/MWh	
	Bio-Fuel	1567.5kg/MWh	
	Gas	470.5kg/MWh	
Coal Land Use Factor	0.0185km^2/MWh		(Fthenakis & Kim, 2009)
Gas Land Use Factor	0.005km^2/MWh		
Nuclear Land Use Factor	0.048 km^2/MWh		
Wind Land Use Factor	2.241666667 km^2/MWh		
Solar PV Land Use Factor	0.367714286 km^2/MWh		

Bio-Fuel Land Use Factor	0.135571429 km^2/MWh	
Solar CSP Land Use Factor	0.459 km^2/MWh	
Average Plant Life	***Coal*** 30 years	(Republic of South Africa Department of Energy, 2016)
	Nuclear 60 years	
	Gas 30 years	
	Bio-Fuel 30 years	
	Solar PV 20 years	
	Solar CSP 30 years	
	Wind 20 years	
	Hydro 20 years	
Electricity Demand	As specified in reports (GWh represented in MWh)	(Statistics South Africa, 2015, 2016; Mokilane, Makhanya, Koen, *et al.*, 2016)
Electricity Imports	Based on average calculations from data (GWh represented in MWh)	(SA Data Portal, 2015a)
Electricity Exports	Based on average calculations from data (GWh represented in MWh)	(SA Data Portal, 2015b)
Transmission and distribution Factor	4%	(StatsSa, 2012)

Table B.2. Model equation abbreviation summary.

Model Equation Abbreviation	**Abbreviation Meaning**
ED	Electricity Demand
PTC	Planned Technology Capacity
TUC	Technology Under Construction
OTC	Operational Technology Capacity
DC	Decommissioned Capacity
PI	Project Initialisation
SC	Scenario Choice
APID	Average Project Initialisation Delay
CI	Construction Initialisation
PC	Planned Capacity
APPD	Average Planned Project Delay
APCD	Average Plant Construction Delay
PC	Project Commissioning
TD	Technology Decommissioning
TDG	Technology Degradation
EG	Electricity Generated
COC	Current Operating Capacity
TCF	Technology Capacity Factor
TEGS	Total Electricity Generated by the System
TDLF	Transmission and Distribution Loss Factor
NEG	NET Electricity Generated
NES	NET Electricity Supply
NED	NET Electricity Demand
DSGR	Demand Supply Gap Ratio
RNE	Required New Electricity
ND	New Demand
SF	Supply Fraction
RNT	Required New Technology

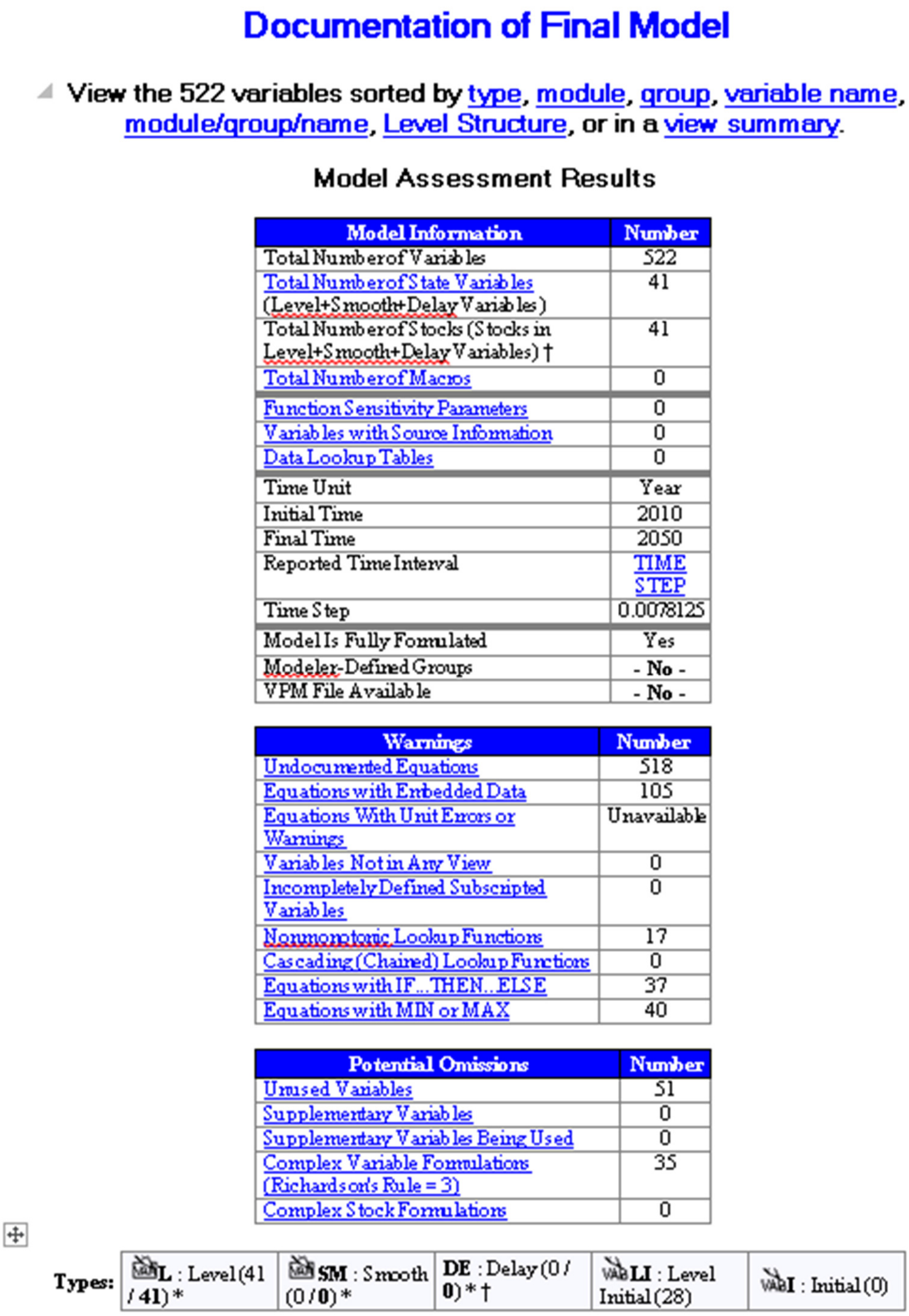
TE	Total Emissions
AE	Average Emissions
NTE	NET Total Emissions
WU	Water Usage
AWU	Average Water Usage
TWU	Total Water Usage
TLU	Total Land Usage
LA	Land Area
TLUE	Total Land Used for Electricity
IDER	Increasing Dispatchable Electricity Required
DE	Dispatchable Electricity
UE	Unserved Electricity
CDEO	Cost of Dispatched Electricity Output
CDE	Cost of Dispatched Electricity
A	Amount
LCOED	Levelised Cost of Electricity Distribution
I	Investing
RI	Required Investment
TRI	Total Required Investment
CR	Cost Reduction
CMI	Construction and Manufacturing Installed
OJ	Operations Jobs
MJ	Manufacturing Jobs
CJ	Construction Jobs
OJF	Operations Job Factor
MJF	Manufacturing Job Factor
CJF	Construction Job Factor
FSJ	Fuel Supply Jobs
FSJF	Fuel Supply Jobs Factor
TFE	Total Fuel Employment

TESE	Total Electricity Sector Employment
E	Employment
REIC	Renewable Energy Installed Capacity
FFIC	Fossil Fuel Installed Capacity

C. Model Validation

SDM Document

An SDM Document was generated but due to the length of the document only a screenshot is shown here. The complete document is included with the electronic files.



Documentation of Final Model

View the 522 variables sorted by type, module, group, variable name, module/group/name, Level Structure, or in a view summary.

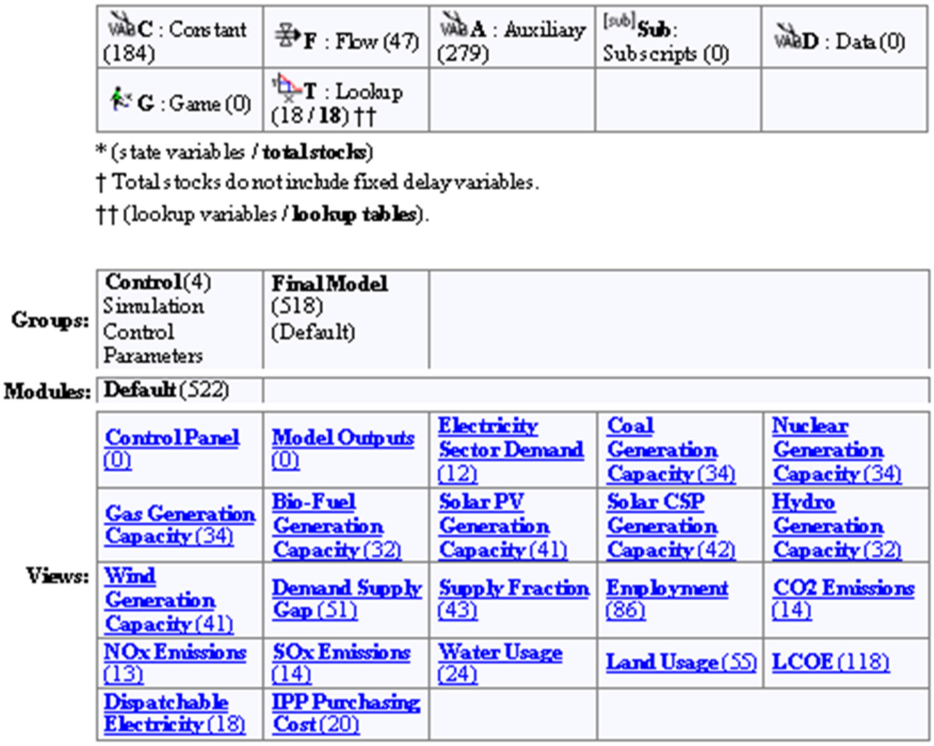
Model Assessment Results

Model Information	Number
Total Number of Variables	522
Total Number of State Variables (Level+Smooth+Delay Variables)	41
Total Number of Stocks (Stocks in Level+Smooth+Delay Variables) †	41
Total Number of Macros	0
Function Sensitivity Parameters	0
Variables with Source Information	0
Data Lookup Tables	0
Time Unit	Year
Initial Time	2010
Final Time	2050
Reported Time Interval	TIME STEP
Time Step	0.0078125
Model Is Fully Formulated	Yes
Modeler-Defined Groups	**- No -**
VPM File Available	**- No -**

Warnings	Number
Undocumented Equations	518
Equations with Embedded Data	105
Equations With Unit Errors or Warnings	Unavailable
Variables Not in Any View	0
Incompletely Defined Subscripted Variables	0
Nonmonotonic Lookup Functions	17
Cascading (Chained) Lookup Functions	0
Equations with IF...THEN...ELSE	37
Equations with MIN or MAX	40

Potential Omissions	Number
Unused Variables	51
Supplementary Variables	0
Supplementary Variables Being Used	0
Complex Variable Formulations (Richardson's Rule = 3)	35
Complex Stock Formulations	0

Types:	**L** : Level (41 / **41**) *	**SM** : Smooth (0 / **0**) *	**DE** : Delay (0 / **0**) * †	**LI** : Level Initial (28)	**I** : Initial (0)



C : Constant (184)	**F** : Flow (47)	**A** : Auxiliary (279)	[sub] **Sub**: Subscripts (0)	**D** : Data (0)
G : Game (0)	**T** : Lookup (18 / **18**) ††			

* (state variables / **total stocks**)

† Total stocks do not include fixed delay variables.

†† (lookup variables / **lookup tables**).

Groups:	**Control** (4) Simulation Control Parameters	**Final Model** (518) (Default)			
Modules:	**Default** (522)				
Views:	**Control Panel** (0)	**Model Outputs** (0)	**Electricity Sector Demand** (12)	**Coal Generation Capacity** (34)	**Nuclear Generation Capacity** (34)
	Gas Generation Capacity (34)	**Bio-Fuel Generation Capacity** (32)	**Solar PV Generation Capacity** (41)	**Solar CSP Generation Capacity** (42)	**Hydro Generation Capacity** (32)
	Wind Generation Capacity (41)	**Demand Supply Gap** (51)	**Supply Fraction** (43)	**Employment** (86)	**CO2 Emissions** (14)
	NOx Emissions (13)	**SOx Emissions** (14)	**Water Usage** (24)	**Land Usage** (55)	**LCOE** (118)
	Dispatchable Electricity (18)	**IPP Purchasing Cost** (20)			

D. Simulation Results

Table D.1 Results for the cumulative total required investment for fossil fuel technologies in billion Rands based on LCOE.

Total Required Investment in Fossil Fuels (Rand billions)						
Scenario	Economic Growth Strategy	Year				
		2010	2020	2030	2040	2050
Business as Usual	Low	0	0	172	487.2	805.8
	Medium	0	0	172	487.2	805.8
	High	0	0	172	487.2	805.8
Bulk Fossil Fuels	Low	0.2876	356.6	737.4	1198	1725
	Medium	1.089	361.4	808.5	1427	2191
	High	1.091	368.5	870.2	1629	2599
All New Fossil Fuels	Low	0	509	1039	1656	2358
	Medium	0	515.9	1142	1970	2986
	High	0	526	1229	2216	3488
Half and Half	Low	0.2	250.8	522.5	854.8	1237
	Medium	0.2007	254.2	572.6	1027	1592
	High	0.2009	259.2	618.1	1174	1887
Bulk Renewable Energy	Low	0	154.2	325	541.5	801.4
	Medium	0	156.3	356.6	659.7	1039
	High	0	159.4	387	753.2	1228
All New Renewable Energy	Low	0	0	0	0	0
	Medium	0	0	0	0	0
	High	0	0	0	0	0

Table D.2 Results for the cumulative total required investment for Renewable Energy Technologies in billion Rands, based on LCOE.

Total Required Investment in Renewables (Rand billions)						
Scenario	**Economic Growth Strategy**	**Year**				
		2010	**2020**	**2030**	**2040**	**2050**
Business as Usual	**Low**	0	577	808	1087	1403
	Medium	0	577	808	1087	1403
	High	0	577	808	1087	1403
Bulk Fossil Fuels	**Low**	0.2123	354.4	721.9	1.164	1.67
	Medium	1.049	359.2	791.9	1.387	2.126
	High	1.05	366.2	852.4	1.586	2.526
All New Fossil Fuels	**Low**	0	0	0	0	0
	Medium	0	0	0	0	0
	High	0	0	0	0	0
Half and Half	**Low**	0	561.9	1155	1873	2693
	Medium	0	569.2	1266	2257	3479
	High	0	580.4	1367	2583	4131
Bulk Renewable Energy	**Low**	0	796	1659	2738	4026
	Medium	0	807	1822	3344	5237
	High	0	822.7	1979	3823	6204
All New Renewable Energy	**Low**	0	1150	2440	4180	6274
	Medium	0	1166	2703	5106	8134
	High	0	1189	2945	5881	9723

Table D.3 Results for the total amount of blackouts calculated by summing the possible electricity sector blackouts and renewable energy technology unavailability.

Sum of Blackouts (GWh/Year)						
Scenario	Economic Growth Strategy	Year				
		2010	2020	2030	2040	2050
Business as Usual	Low	4.839	6155	31510	103800	112400
	Medium	4.839	6155	84100	208200	269200
	High	4.839	6155	124100	286700	400100
Bulk Fossil Fuels	Low	4.839	4958	10130	14360	17680
	Medium	4.839	4940	10920	17240	23620
	High	4.839	4977	11630	19820	28720
All New Fossil Fuels	Low	4.839	4.38	3.962	3.586	0
	Medium	4.839	4.38	3.962	3.586	0
	High	4.839	4.38	3.962	3.586	0
Half and Half	Low	4.839	10250	20830	29890	37470
	Medium	4.839	10210	22430	36170	50810
	High	4.839	10290	23890	41690	61530
Bulk Renewable Energy	Low	4.839	15070	31080	45410	59270
	Medium	4.839	15000	33440	55950	80620
	High	4.839	15110	35660	64420	97110
All New Renewable Energy	Low	4.839	22640	47240	72080	97770
	Medium	4.839	22560	50870	89040	131600
	High	4.839	22730	54430	122990	160800

Table D.4 Results for the total blackouts due to renewable energy technology unavailability (Includes: Wind, Solar PV and Solar CSP.)

Blackouts due to Renewable Energy Unavailability (GWh/Year)						
Scenario	Economic Growth Strategy	Year				
		2010	2020	2030	2040	2050
Business as Usual	Low	4.81	6141	17860	18790	20400
	Medium	4.81	6141	17860	18790	20400
	High	4.81	6141	17860	18790	20400
Bulk Fossil Fuels	Low	4.84	4958	10130	14360	17680
	Medium	4.84	4940	10920	17240	23620
	High	4.84	4977	11630	19820	28720
All New Fossil Fuels	Low	4.839	4.38	3.962	3.586	0
	Medium	4.839	4.38	3.962	3.586	0
	High	4.839	4.38	3.962	3.586	0
Half and Half	Low	4.84	10250	20830	29890	37470
	Medium	4.84	10210	22430	36170	50810
	High	4.84	10290	23890	41690	61530
Bulk Renewable Energy	Low	4.839	15070	31080	45410	59270
	Medium	4.839	15000	33440	55950	80620
	High	4.839	15110	35660	64420	97110
All New Renewable Energy	Low	4.84	22640	47240	72080	97770
	Medium	4.84	22560	50870	89040	131600
	High	4.84	22730	54430	102400	160800

Table D.5 Results for CO2 Emissions in kg/year.

CO2 Emissions kg/Year (billions)						
Scenario	Economic Growth Strategy	Year				
		2010	2020	2030	2040	2050
Business as Usual	Low	269.4	241.4	161.6	121.2	106.3
	Medium	269.4	241.4	161.6	121.2	106.3
	High	269.4	241.4	161.6	121.2	106.3
Bulk Fossil Fuels	Low	269.4	310.3	322.4	324.2	363.6
	Medium	269.4	310.1	334.2	371	467.5
	High	269.4	310.6	345.1	412.7	557.1
All New Fossil Fuels	Low	269.4	293.6	296.7	284.2	309.1
	Medium	269.4	293.4	305.4	322.4	392.5
	High	269.4	293.8	313.5	352.4	457.6
Half and Half	Low	269.4	279.4	242.7	202.1	204.6
	Medium	269.4	279.3	249.1	229.2	265.3
	High	269.4	279.7	255	253.1	314.5
Bulk Renewable Energy	Low	269.4	271.4	220.7	168.7	165.1
	Medium	269.4	271.4	225.9	192.3	215.1
	High	269.4	271.6	230.7	211.5	253.7
All New Renewable Energy	Low	269.4	256.8	180.9	109.4	85.41
	Medium	269.4	256.8	183.7	121.5	108.3
	High	269.4	256.8	186.6	131	128.1

Table D.6 Results for NOx Emissions in kg/year.

NOX Emissions (kg/Year) millions						
Scenario	**Economic Growth Strategy**	**Year**				
		2010	**2020**	**2030**	**2040**	**2050**
Business as Usual	**Low**	248.5	221.7	141.4	101.4	85.69
	Medium	248.5	221.7	141.4	101.4	85.69
	High	248.5	221.7	141.4	101.4	85.69
Bulk Fossil Fuels	**Low**	248.5	263.8	257.6	242.2	263.6
	Medium	248.5	263.6	264.3	273	335
	High	248.5	263.9	270.7	300.4	396.6
All New Fossil Fuels	**Low**	248.5	269.1	270.3	258.8	280
	Medium	248.5	268.9	277.9	293.3	355
	High	248.5	269.2	285.2	320.4	413.6
Half and Half	**Low**	248.5	241.6	193.7	144	134.8
	Medium	248.5	241.5	196.9	159.3	171.2
	High	248.5	241.7	199.9	172.8	200.8
Bulk Renewable Energy	**Low**	248.5	234.2	172.9	111.7	94.21
	Medium	248.5	234.2	174.9	122.4	119
	High	248.5	234.3	176.8	131.2	138
All New Renewable Energy	**Low**	248.5	221.6	137.6	56.6	18.37
	Medium	248.5	221.6	137.6	56.6	18.37
	High	248.5	221.6	137.6	56.6	18.37

Table D.7 Results for SOx Emissions in kg/year.

SOX Emissions (kg/year) Millions						
Scenario	Economic Growth Strategy	Year				
		2010	2020	2030	2040	2050
Business as Usual	Low	167.4	149.8	93.07	61.92	48.43
	Medium	167.4	149.8	93.07	61.92	48.43
	High	167.4	149.8	93.07	61.92	48.43
Bulk Fossil Fuels	Low	167.4	180.4	178.5	171.4	187.3
	Medium	167.4	180.3	183.5	193.9	238.3
	High	167.4	180.5	188.2	213.8	282.4
All New Fossil Fuels	Low	167.4	179.5	178.8	170.5	183.9
	Medium	167.4	179.4	183.7	192.6	232.5
	High	167.4	179.6	188.4	209.9	270.6
Half and Half	Low	167.4	164.3	133.2	102	96.73
	Medium	167.4	164.3	135.7	113.2	123.1
	High	167.4	164.4	138	123.1	144.6
Bulk Renewable Energy	Low	167.4	159.3	119.4	80.26	69.54
	Medium	167.4	159.3	121	88.49	88.16
	High	167.4	159.3	122.5	95.31	102.5
All New Renewable Energy	Low	167.4	151.8	97.55	45.63	22.23
	Medium	167.4	151.7	97.98	47.41	25.64
	High	167.4	151.8	98.4	48.83	28.57

Table D.8 Results for the total job potential of the electricity sector.

Total Electricity Sector Employment (Jobs)						
Scenario	Economic Growth Strategy	Year				
		2010	2020	2030	2040	2050
Business as Usual	Low	29760	307200	226500	380600	412700
	Medium	29760	307200	226500	380600	412700
	High	29760	307200	226500	380600	412700
Bulk Fossil Fuels	Low	29750	375100	443700	540400	627400
	Medium	29750	376900	508500	703200	892300
	High	29750	381700	562000	850700	1120000
All New Fossil Fuels	Low	29750	296000	339800	402600	459900
	Medium	29750	296300	387200	522100	649600
	High	29750	296400	426700	612000	800600
Half and Half	Low	29750	399600	471300	578200	672000
	Medium	29750	402700	543100	773900	976800
	High	29750	408500	603300	935600	1224000
Bulk Renewable Energy	Low	29750	467500	561800	707600	857300
	Medium	29750	472100	649700	975200	1237000
	High	29750	479400	731600	1170000	1543000
All New Renewable Energy	Low	29750	564400	696200	949500	1152000
	Medium	29750	570800	817100	1287000	1643000
	High	29750	580400	932700	1564000	2064000

Table D.9 Results for the potential fuel supply jobs created by the electricity sector.

Total Electricity Sector Fuel Supply Employment created (jobs in billions)						
Scenario	Economic Growth Strategy	Year				
		2010	2020	2030	2040	2050
Business as Usual	Low	86.2	77.26	52.22	41.61	37.97
	Medium	86.2	77.26	52.22	41.61	37.97
	High	86.2	77.26	52.22	41.61	37.97
Bulk Fossil Fuels	Low	86.2	98.21	101.3	100.5	112.3
	Medium	86.2	98.15	104.8	114.9	144.3
	High	86.2	98.31	108	127.7	171.9
All New Fossil Fuels	Low	86.2	94.86	96.53	92.83	101.4
	Medium	86.2	94.8	99.42	105.5	129
	High	86.2	94.92	102.1	115.5	150.5
Half and Half	Low	86.2	88.85	76.49	62.7	63.17
	Medium	86.2	88.83	78.44	70.96	81.86
	High	86.2	88.92	80.23	78.26	97.01
Bulk Renewable Energy	Low	86.2	86.26	69.41	51.95	50.32
	Medium	86.2	86.25	70.94	59.06	65.47
	High	86.2	86.33	72.41	64.85	77.2
All New Renewable Energy	Low	86.2	81.18	55.82	31.79	23.04
	Medium	86.2	81.18	56.56	34.87	28.89
	High	86.2	81.22	57.27	37.31	33.93

Low Economic Growth Scenario Results

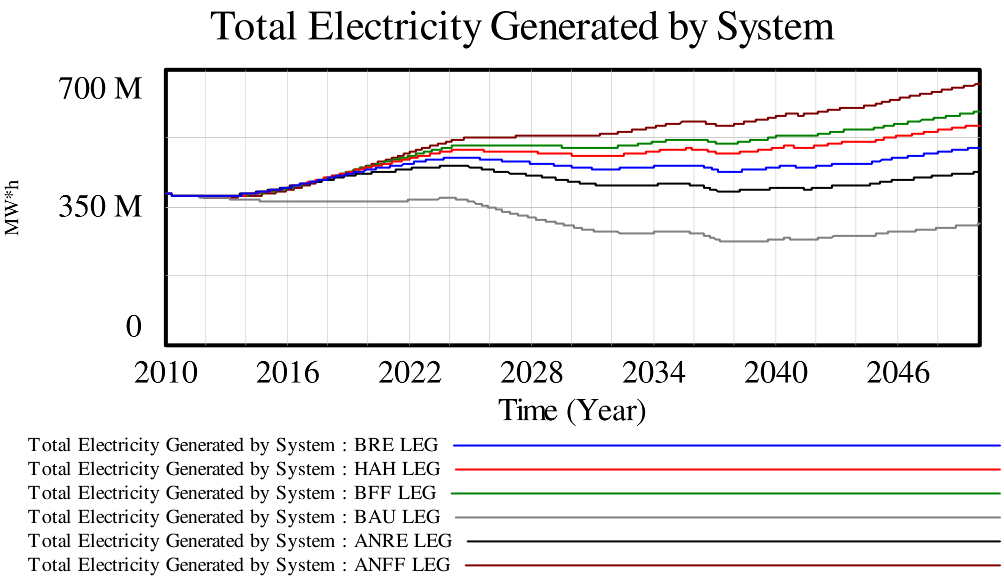


Figure D.1 Results for the total amount of electricity generated by the system over time for low economic growth demand conditions.

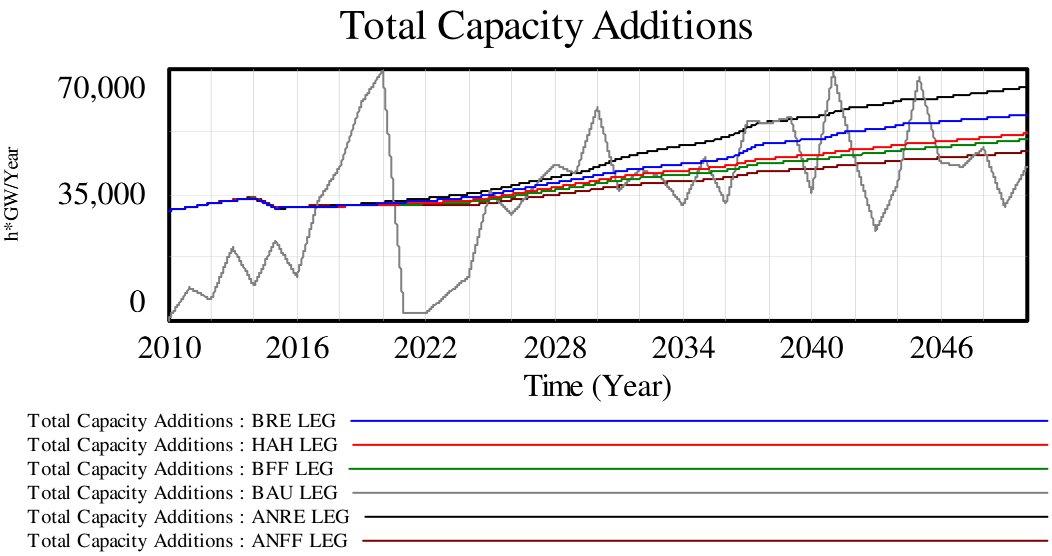


Figure D.2 Results for the total new capacity added on a yearly basis for each scenario under low economic growth demand conditions.

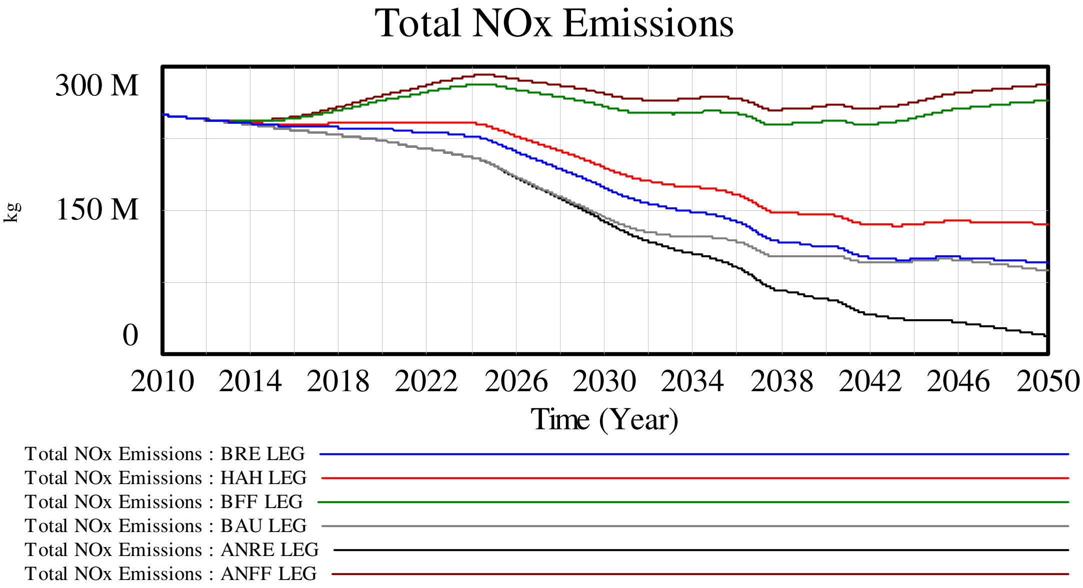


Figure D.3 Results for the total NOx emissions generated by the various scenarios under low economic growth demand profiles.

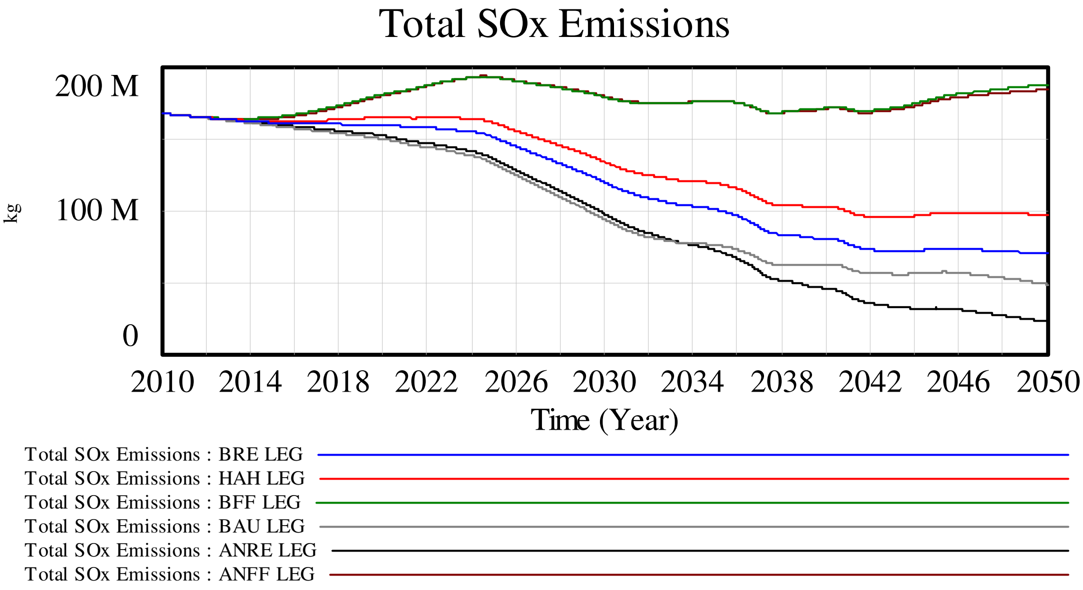


Figure D.4 Results for the total SOx emissions generated by the various scenarios under low economic growth demand profiles.

Medium Economic Growth Scenario Results

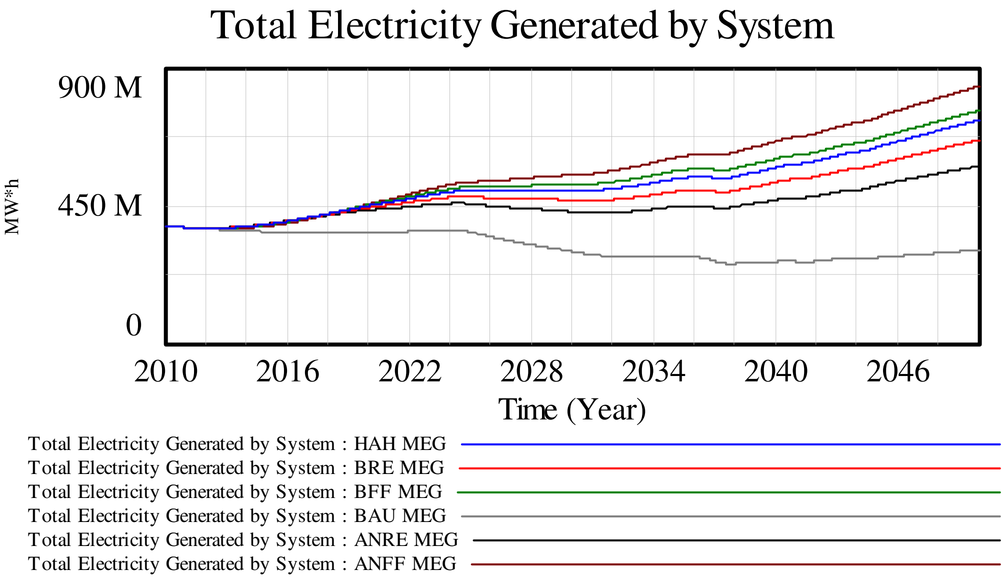


Figure D.5 Results for the total amount of electricity generated by the system over time for medium economic growth demand conditions.

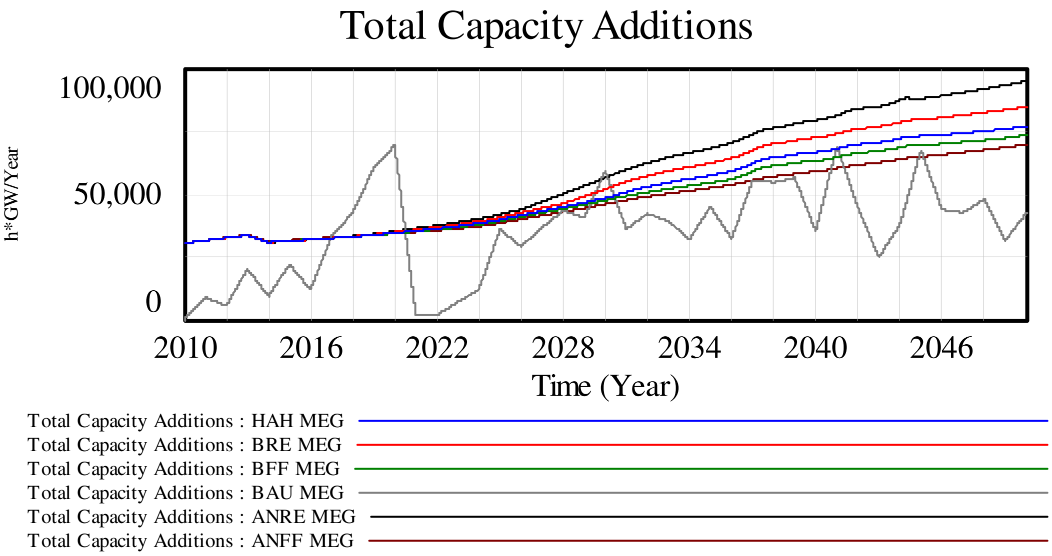


Figure D.6 Results for the total new capacity added on a yearly basis for each scenario under medium economic growth demand conditions.

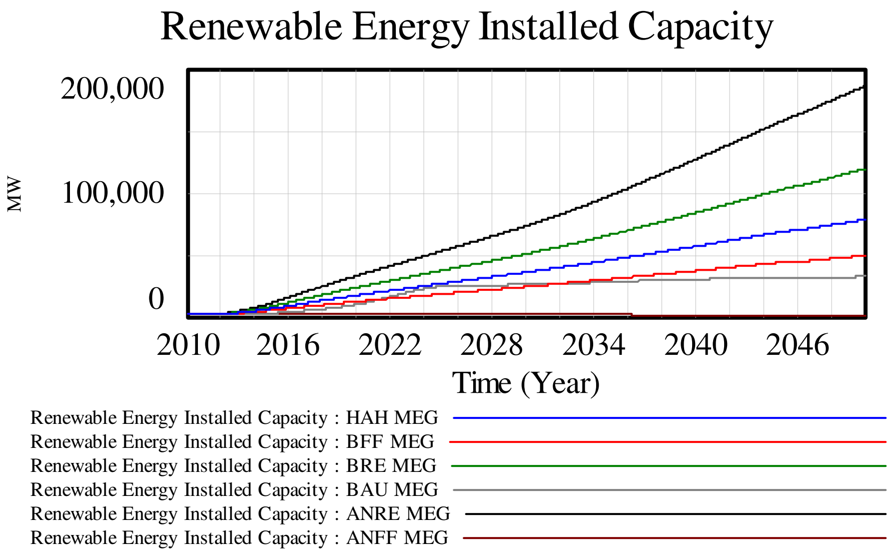


Figure D.7 Scenario results for the renewable energy installed capacity for the medium economic growth strategy.

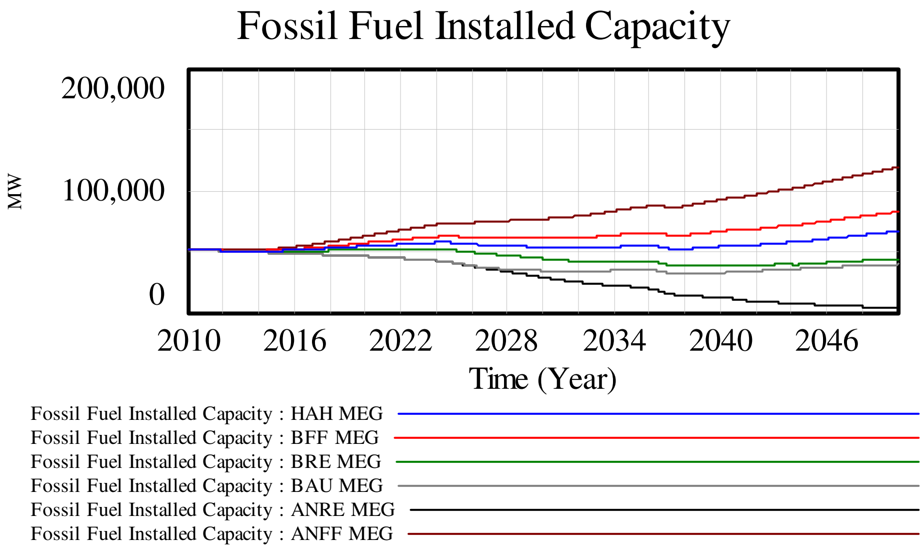


Figure D.8 Scenario results for the fossil fuel installed capacity for the medium economic growth strategy.

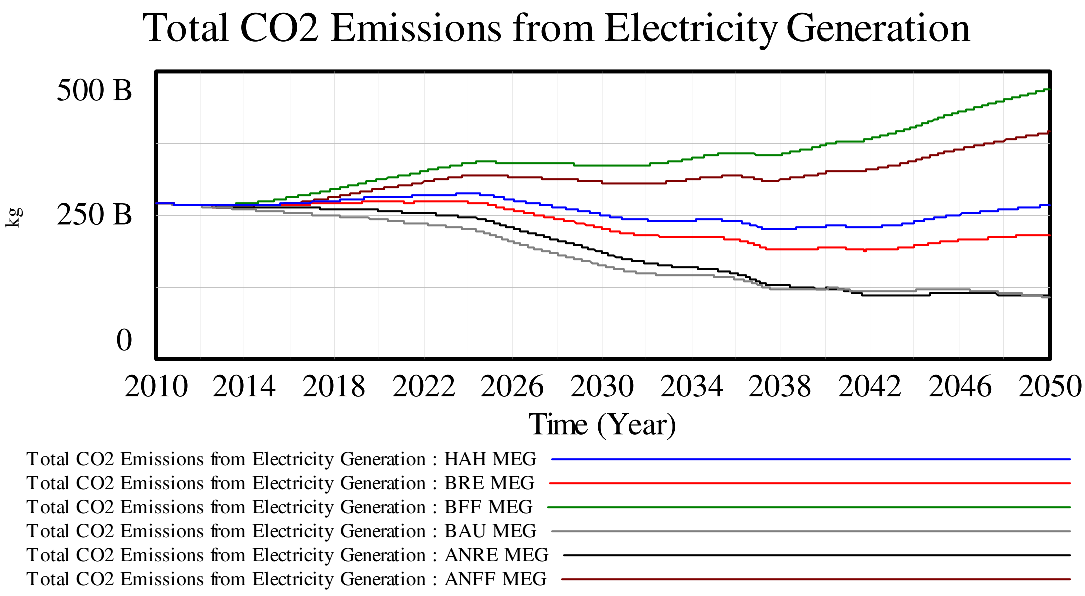


Figure D.9 Results for the total CO2 emissions generated by the various scenarios under medium economic growth demand profiles.

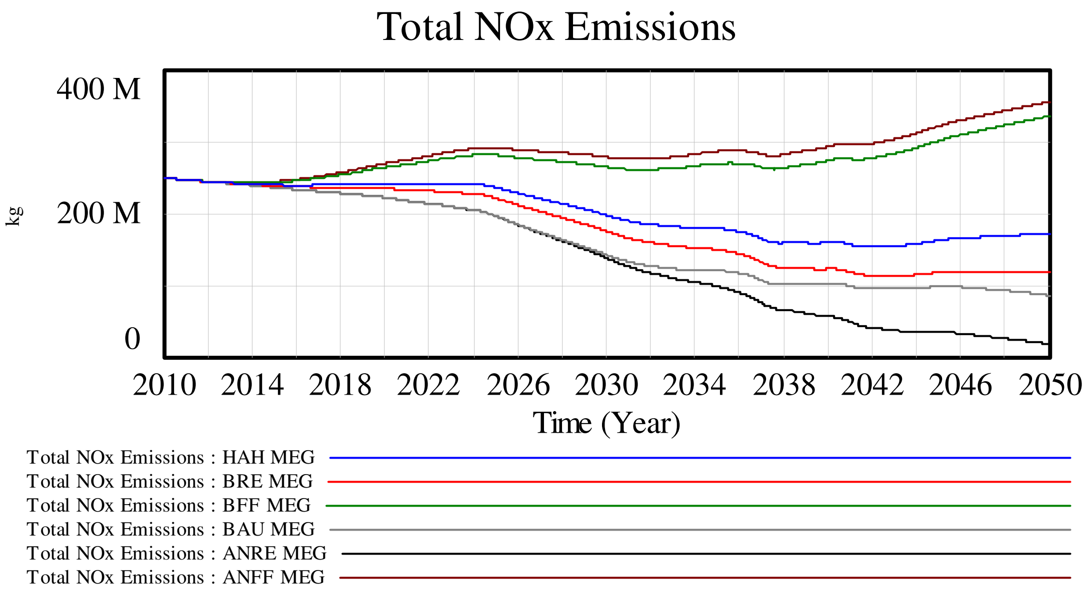


Figure D.10 Results for the total NOx emissions generated by the various scenarios under Medium economic growth demand profiles.

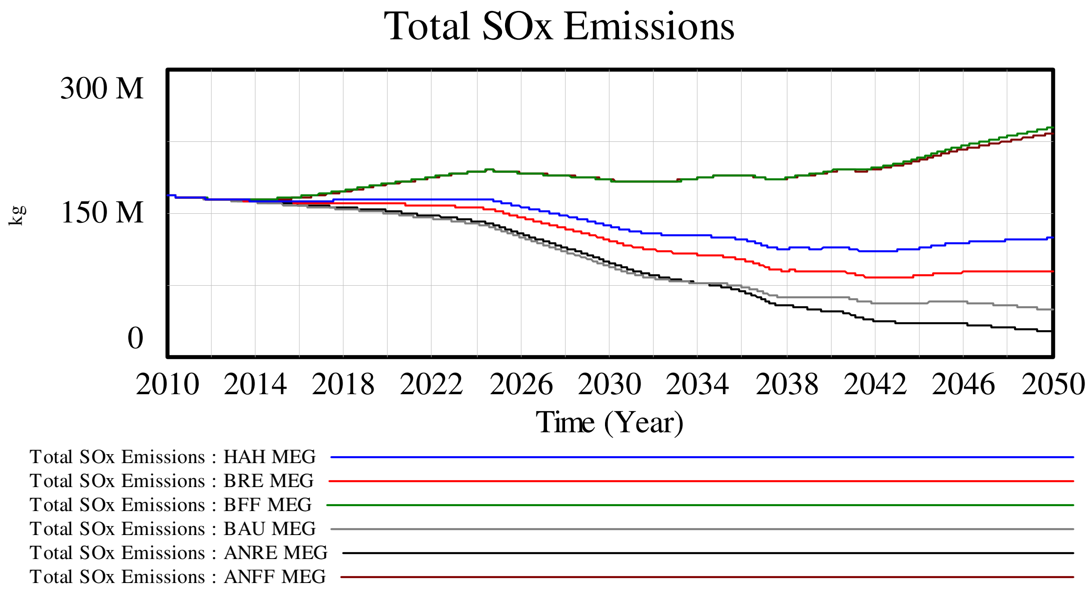


Figure D.11 Results for the total SOx emissions generated by the various scenarios under medium economic growth demand profiles.

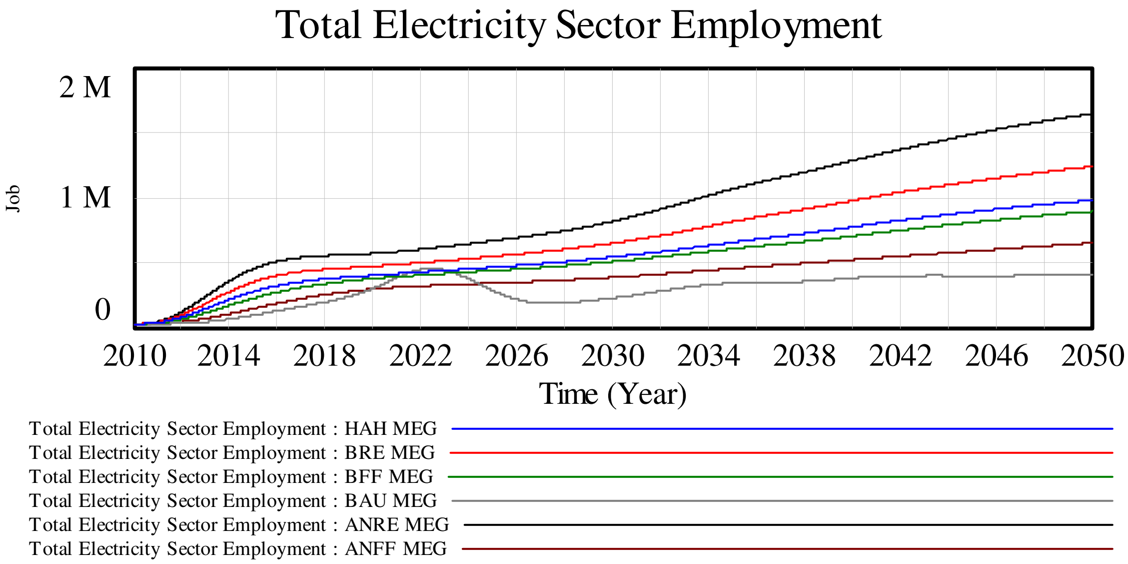


Figure D.12 Results for the total electricity sector employment potential for a medium economic growth demand conditions.

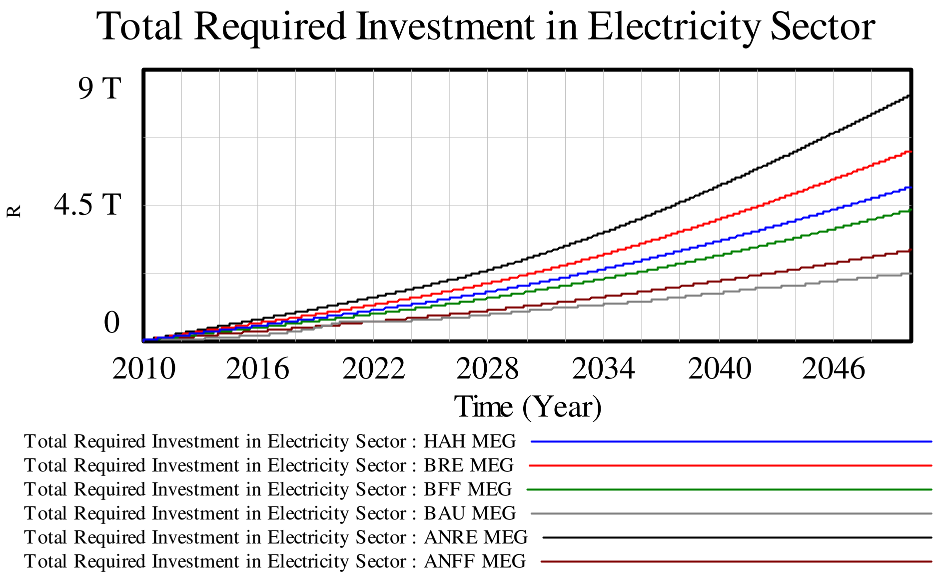


Figure D.13 Results for the cumulative total amount of required investment necessary for the various scenarios under high economic growth demand conditions.

High Economic Growth Scenario Results

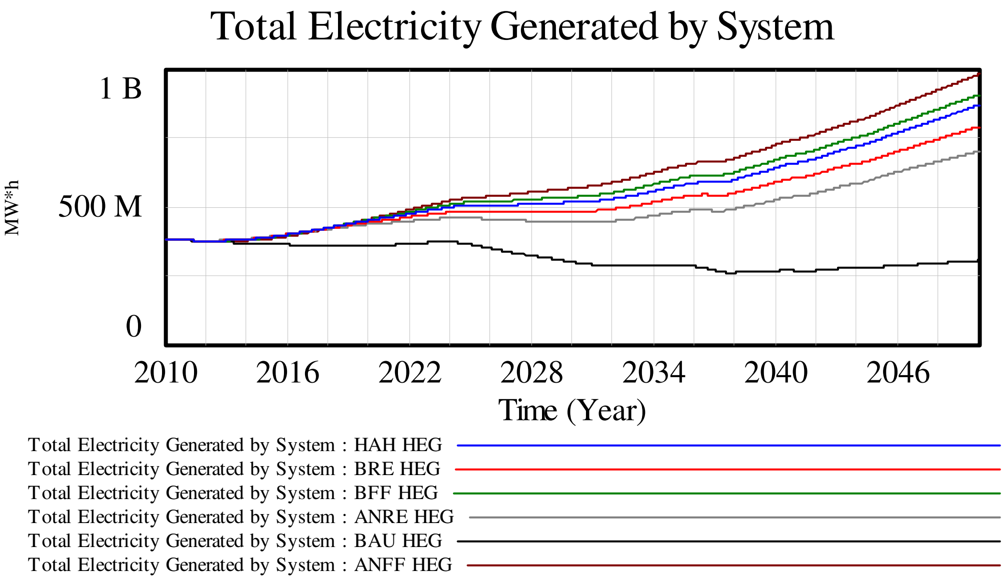


Figure D.14 Results for the total amount of electricity generated by the system over time for high economic growth demand conditions.

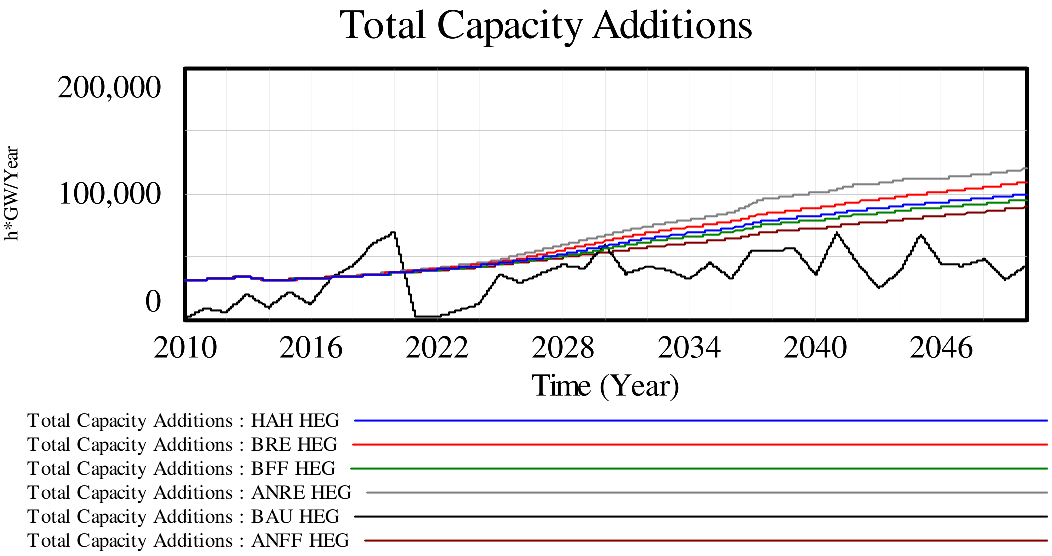


Figure D.15 Results for the total new capacity added on a yearly basis for each scenario under high economic growth demand conditions.

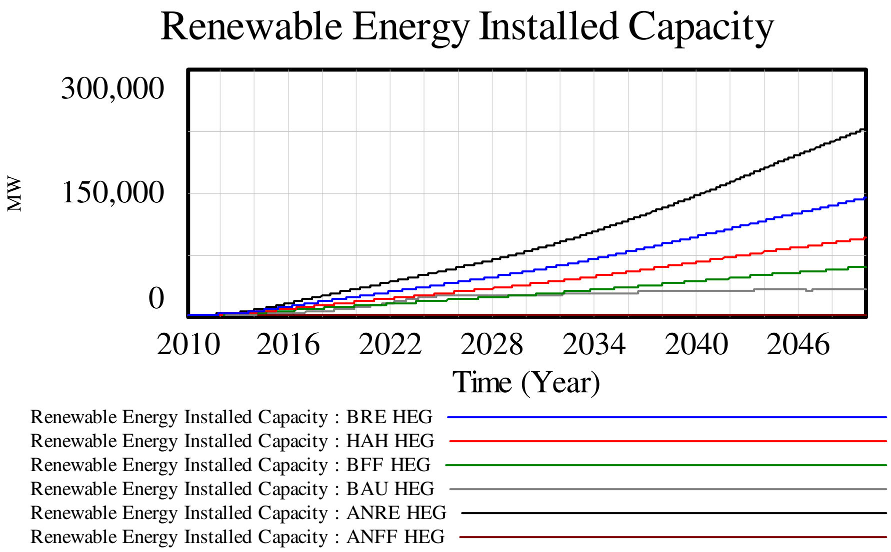


Figure D.16 Scenario results for the renewable energy installed capacity for the high economic growth strategy.

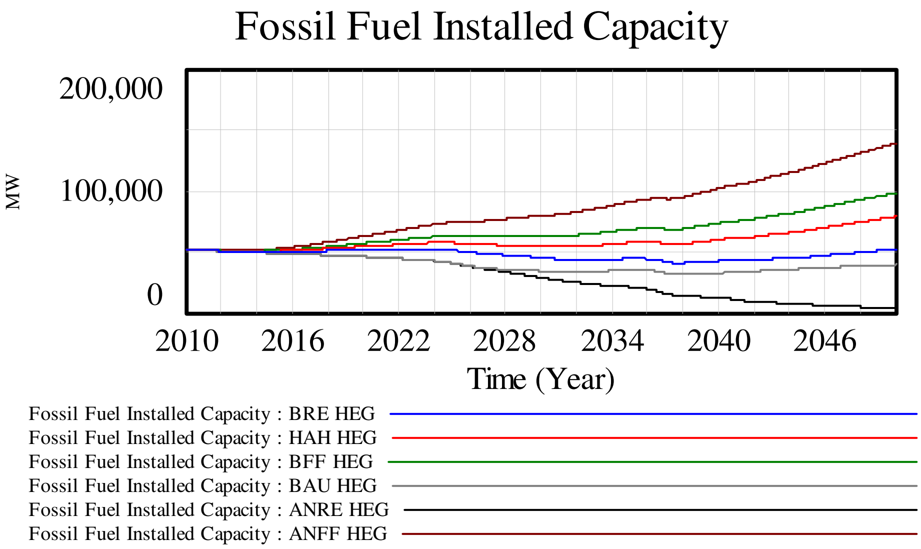


Figure D.17 Scenario results for the fossil fuel installed capacity for the high economic growth strategy.

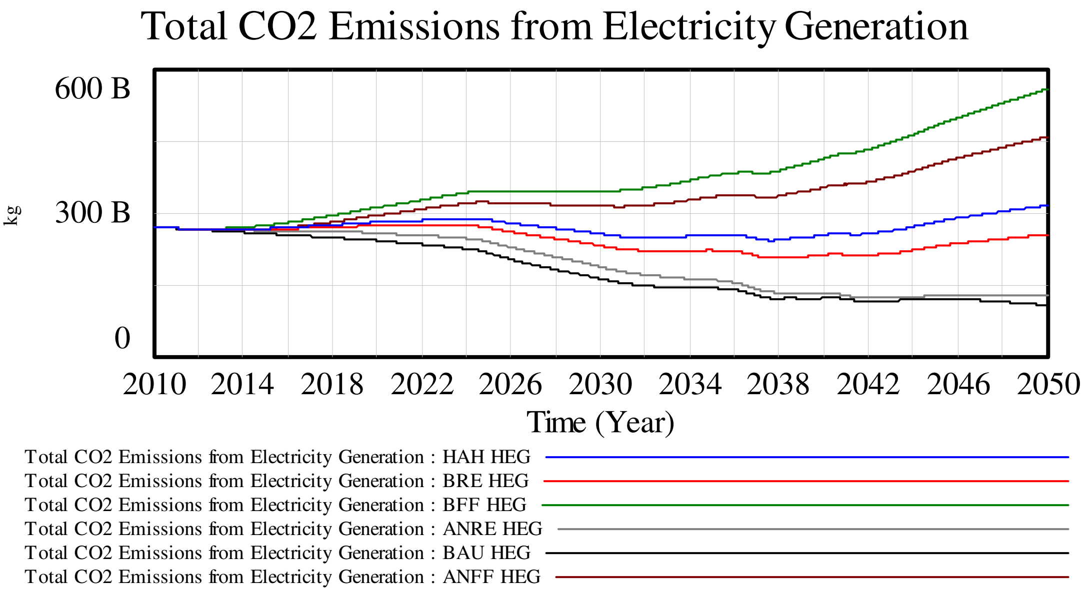


Figure D.18 Results for the total CO2 emissions generated by the various scenarios under high economic growth demand profiles

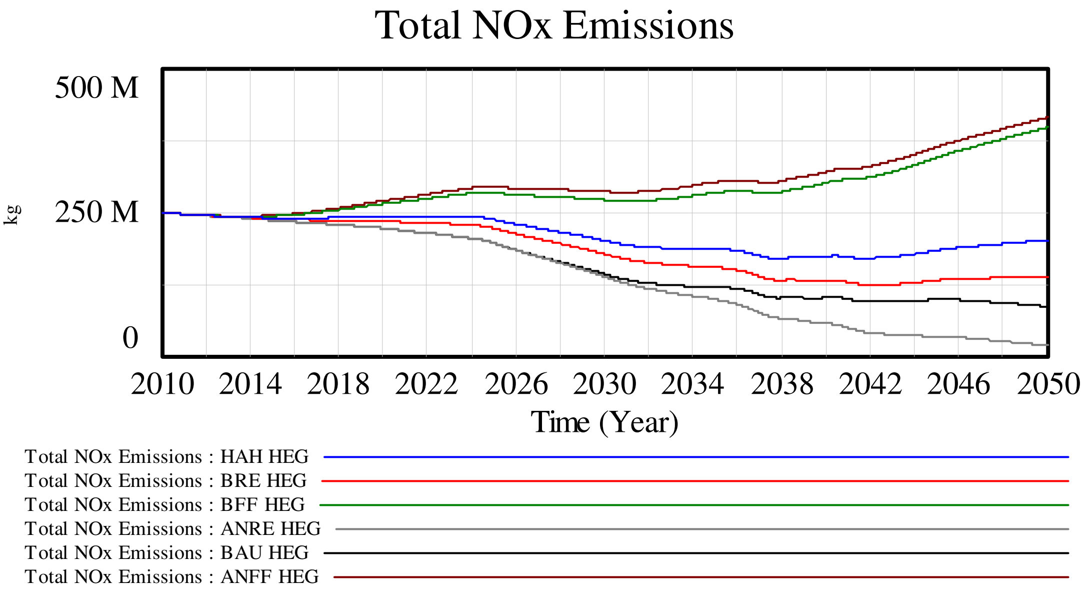


Figure D.19 Results for the total NOx emissions generated by the various scenarios under high economic growth demand profiles

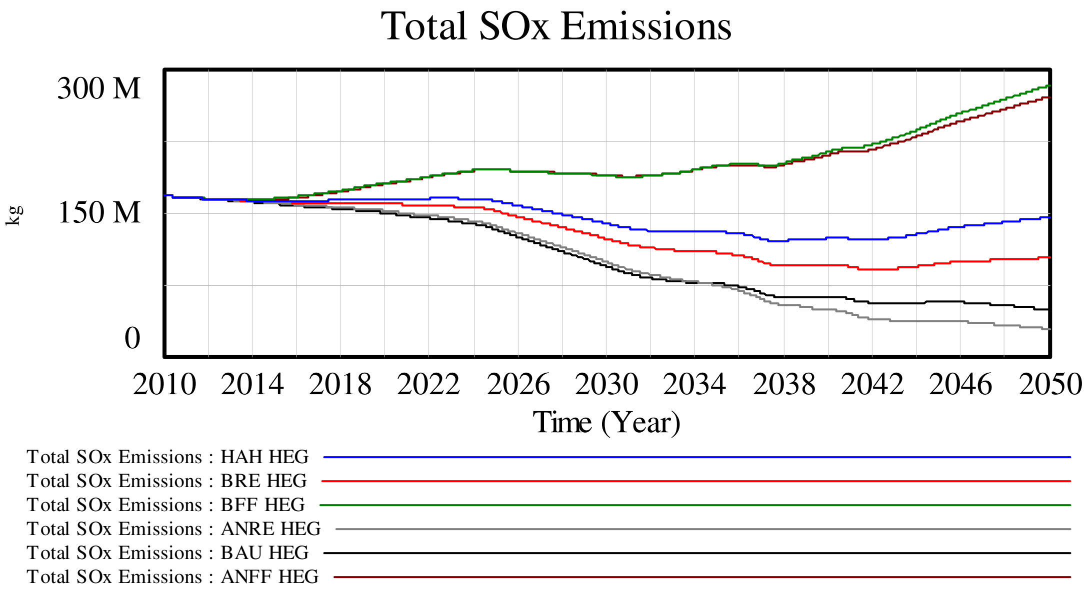


Figure D.20 Results for the total SOx emissions generated by the various scenarios under high economic growth demand profiles

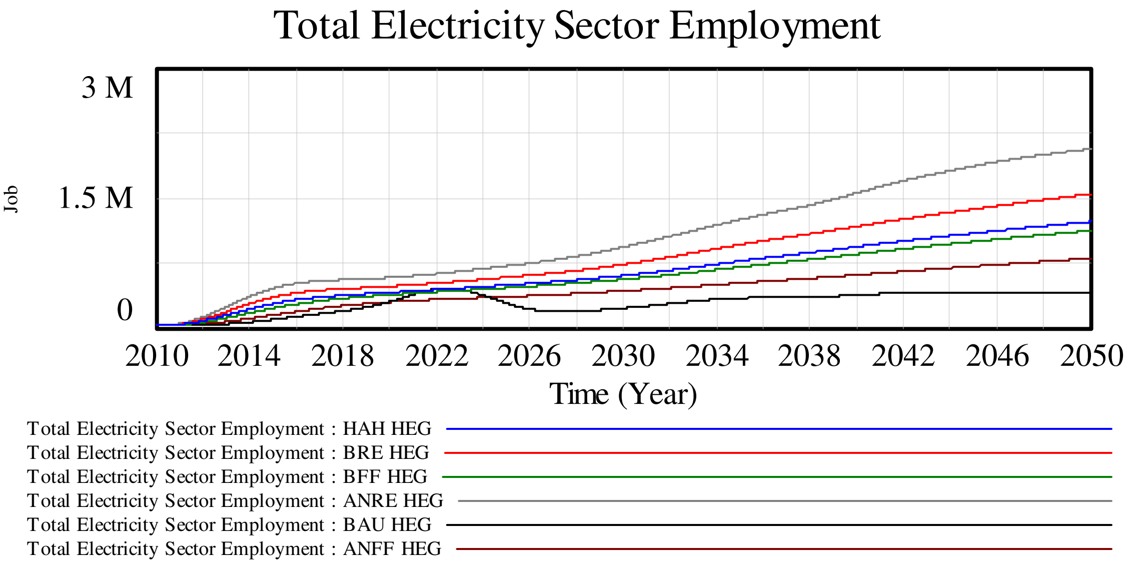


Figure D.21 Results for the total electricity sector employment potential for a high economic growth demand conditions.

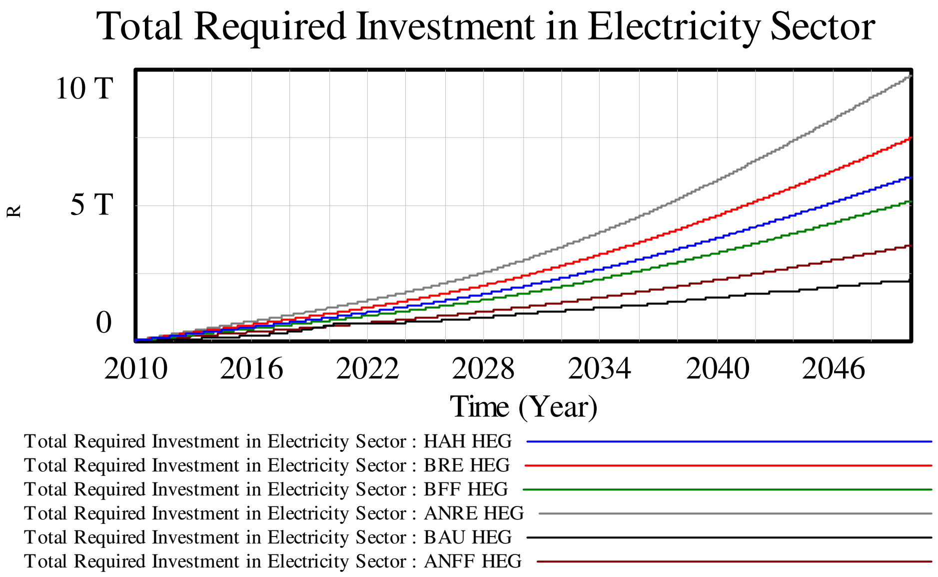


Figure D.22 Results for the cumulative total amount of required investment necessary for the various scenarios under medium economic growth demand conditions.