Investigating the effects of a green economy transition on the electricity sector in the Western Cape Province of South Africa: A system dynamics modelling approach

by

Juan Oosthuizen

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Supervisor: Prof. Alan C. Brent
Co-supervisor: Dr Josephine K. Musango
Department of Industrial Engineering
University of Stellenbosch

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Declaration

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Abstract

Many of the global and regional crises – economic, social, and environmental – that are prevalent today can be attributed to misdirected investments that were made in the past. The current crisis that the electricity sector in South Africa finds itself in can be attributed to such misdirected investments. This current crisis in the electricity sector relates to electricity supply shortages and an increasing carbon footprint. This crisis has to be faced by each of the country's nine provinces. The Western Cape Province in South Africa has identified the green economy concept as a tool to transform the Province's economy to one that is more sustainable from an economic, social, and environmental perspective. This transition would include transforming the Province's electricity sector to one that is more sustainable and more in line with the green economy concept. Three key priorities of this transition include using gas power technologies as a transition fuel, increasing renewable energy capacity, and developing a manufacturing sector that can support the growing renewable energy industry.

The difficulty of obtaining finance and prevalence of financial mismanagement in South Africa requires that such a transition be properly planned and managed in order for it to be carried out successfully. The system dynamics methodology was chosen to develop a better understanding of the impacts of different green economy policies and investments in the electricity sector of the Western Cape Province. This was achieved by developing a system dynamics model of the Province's electricity sector and simulating different green economy investment policies. Five scenarios were simulated over a 40 year simulation period, from 2001 to 2040.

The results suggested that continuing on the current policy path would increase the gap between demand and supply, increase the carbon footprint of the electricity sector, and not provide growth in employment in the sector. Strategic green economy investments are expected to impact positively on a number of indicators across a number of sectors: electricity supply, renewable energy share, employment, and greenhouse gas emissions. A few points of concern for policymakers, regarding renewable energy technologies, were highlighted. These include the short operating life of wind and solar PV technologies, their low capacity factors, and their inability to supply base-load power. Other concerns that were highlighted include the expected growth in electricity demand in the Province, large investments needed for electricity capacity expansion, and the benefit of localising manufacturing activities related to wind and solar PV technologies.

Overall, the study laid the foundation for future research on the topic of a green economy transition of the Western Cape Province's electricity sector. The usefulness of applying the system dynamics methodology to green economy transition research was also demonstrated. The study aims to provide relevant and insightful recommendations to the policymakers and stakeholders that are, and will be, involved in the process of transitioning the Western Cape Province to a green economy hub and the Province with the lowest carbon footprint.

Opsomming

Baie van die globale and plaaslike kriesisse – ekonomiese, sosiale,en omgewings – wat tans ondervind word, kan toegeskryf word aan sleg toegekende beleggings wat in die verlede gemaak is. Die ongewenste omstandighede wat die Suid-Afrikaanse elektrisiteits-sektor hom tans in bevind kan toegeskryf word aan sulke sleg toekende beleggings. Die grootste kommer oor die elektrisiteits-sektor hou verband met die tekort aan verskaffing van elektrisiteit en die sektor se groot koolstofvoetspoor. Al nege van die land se provinsies word tans blootgestel aan hierdie kwessies. Die Wes-Kaapse Provinsie in Suid-Afrika het die konsep van die groen ekonomie geïdentifiseer as ‘n werktuig om die Provinsie se ekonomie te omskep in een wat meer volhoubaar is van ‘n ekonomiese, sosiale, en omgewings perspektief af. Hierdie oorgang na ‘n groen ekonomie vereis die omskepping van die elektrisiteits-sektor in een wat meer volhoubaar is en in lyn is met die konsep van die groen ekonomie. Drie prioriteite van so ‘n oorgang is die gebruik van natuurlike gas tegnologie as ‘n oorgangs-brandstof, uitbreiding van hernubare energie kapasiteit, en die ontwikkeling van ‘n vervaardigings-sektor wat die groeinde hernubare energie sector kan ondersteun.

Die verkryging en wanbestuur van finansiële kapitaal in Suid-Afrika bly ‘n bron van kommer, dus is die sukses van so ‘n oorgang hoogs afhangend van die behoorlike beplanning en bestuur daarvan. Die studie maak gebruik van die stelsel dinamika metode om ‘n beter begrip te ontwikkel van die moontlike voordele en impakte wat verskillende groen ekonomie beleid en beleggings in die elektrisiteits-sektor van die Wes-Kaap kan bewerkstellig. ‘n Stelsel dinamika model van die Wes-Kaapse elektrisiteits-sektor was ontwikkel en simulasies was uitgevoer vir verskillende groen ekonomie beleid gevalle. Vyf gevalle was gesimuleer oor ‘n 40 jaar simulasie tydperk wat strek van 2001 tot 2040.

Die resultate van die simulasie stel voor dat die voortsetting van de huidige beginsels en beleid sal lei tot ‘n groter gaping tussen die aanvrag en die verskaffing van eletriese krag, ‘n groter koolstofvoetspoor van die elektrisiteits-sektor, en geen groei in die werkverskaffing van die sector nie. Daar word verwag dat strategiese groen ekonomie beleggings ‘n positiewe impak sal bewerkstellig in menigde aanwysers: verskaffing van elektrisiteit, aandeel van totale kapasiteit wat hernubare energie uitmaak, werkverskaffing, en kweekhuisgas-vrystellings. ‘n Paar bronne van kommer wat verband hou met die gebruik van hernubare energie tegnologie is uitgewys. Dit verwys na die kort operasionele lewe van wind en sonkrag tegnologie, hulle lae kapasiteit factor, en hulle onbevoegdheid om basisladingskrag te voorsien. Ander bronne van kommer wat bespreek is sluit in die verwagte groei in aanvraag na elektriese krag in die Provinsie, groot beleggings wat benodig word om die sektor te omskep, en die voordeel wat die lokalisering van die vervaardiging van windkrag en sonkrag komponente inhou.

In algeheel het die studie die fondasie gelê vir toekomstige navorsing in die groen ekonomie oorgang van die elektrisiteits-sektor in die Wes-Kaap. Die studie demonstreer verder ook die nuttigheid van die stelsel dinamika metode vir die modellering van groen ekonomie oorgange. Die studie beoog ook om relevante en insiggewende aanbevelings te voorsien aan die beleidsmakers en belanghebbendes wat betrokke is by die oorgang van die Wes-Kaap Provinsie na ‘n groen ekonimie middelpunt en die provinsie met die laagste koolstofvoetspoor.

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Chapter 1

Introduction

The first chapter serves as an introduction to the study that has been carried out. The first three sections provide background information on the study and briefly touch on the problems and issues that motivated the completion of this study. The first section discusses the development of the global energy sector and the issues that have originated from it. These issues include increasing greenhouse gas emissions, degradation of global energy security, and social exclusion. The second chapter discusses the development of the energy sector in South Africa and its accompanying issues. It touches on the plans and policies that have been developed by the South African Government to tackle these energy sector issues. An overview of the Western Cape Province is given in the third section. This includes a discussion of the Province's energy sector, and the policies and regulations that have been introduced by the Provincial Government. The final two sections discuss the research objectives and the research strategy. The research objectives describe what was expected to be achieved by the study and the research outline describes how these objectives were achieved through the completion of this study.

1.1. Global energy sector development and the consequences

Global energy demand is expected to grow by 41% between 2012 and 2035, with emerging economies accounting for 95% of that growth (BP, 2014). Increased energy efficiency in developed countries may partly explain the little growth originating from them. The growth in energy demand is expected to increase CO_2 emissions by 29%, if energy technologies continue on the current path (BP, 2014). It is essential to address energy issues in order to tackle the challenges of the 21st Century. These issues include climate change, economic and social development, human well-being, sustainable development, and global security (GEA, 2012). The WEC (2014) states that secure, reliable, affordable, clean and equitable energy supply presents huge challenges due to its fundamental importance to global economic growth and human development.

Energy is a critical component to any industrial economy and is regarded as vital to economic and social development. It is a potential limiting factor to economic growth, just as labour and capital are limiting factors to economic growth (Ghali & El-Sakka, 2004). Significant increases in global energy consumption can be expected if developing countries are to reach the economic and social prosperity of the OECD countries (Moriarty & Honnery, 2008). It is not only the economic growth in developing economies that is increasing global energy demand. Developed economies are growing every year, albeit slower than developing economies, and also have a significant effect on global energy demand. According to the WEC (2014), global energy demand will continue to be driven by growth in non-OECD economies. The three vulnerabilities that plague many developing economies are lack of power generation capacity, high energy intensity, and rapidly growing energy demand. These three vulnerabilities very often occur simultaneously and are the main contributors to the low penetration of energy services in poorer nations.

Our current methods of energy production and consumption have an undeniable effect on the social and natural environment. Over-reliance on fossil fuels presents four challenges to sustainability (GEA, 2012):

increasing greenhouse gas (GHG) emissions, declining energy security, air pollution and resulting health issues, and lack of universal access to energy services. Massive emissions of CO_2, from the burning of fossil fuels, have become major scientific and political issues because of their impact on the climate (Jean-Baptiste & Ducroux, 2003).

Brown et al. (2014) define energy security as the ability to equitably provide available, affordable, reliable, efficient, environmentally benign, proactively governed, and socially acceptable energy services to end-users. Global competition for resources is growing, partly due to the increasing purchasing power and energy demand of developing countries (Strambo, et al., 2015). Emissions targets for GHGs can pose a threat to the energy security of a country, particularly if the country relies heavily on fossil fuels for energy. Energy governance plays an important role in the achievement of energy security, and refers to the actors, institutions, and processes that determine how decisions are made on energy-related issues (Florini & Sovacool, 2011). A study found that the majority of industrialised countries experienced deterioration in the level of their energy security between 1970 and 2010 (Brown, et al., 2014).

The power sector is an important part of every country's energy sector. Generating electricity from energy sources is the focus of the power sector. Electricity generation in the power sector accounted for 30% of global primary energy use in 1965, and has risen to 42% in 2012 (BP, 2014). It is expected that this value will rise to 46% in 2035. Fossil fuel resources accounted for 68% of power generation in 2012, with the remaining 32% being shared between nuclear, hydro, and renewable energy sources (BP, 2014). The global power sector is believed to be able to make the biggest contribution to GHG emissions reductions in the energy sector, given the rapid growth of carbon-free technologies expected in the future (IEA, 2014b). An analysis of future energy investments found that between USD 48 trillion and USD 53 trillion would be needed before 2035 in order to stay below the 2°C climate change target introduced by the Copenhagen Accord (IEA, 2014a). The same report also highlights how governments need to assume a more active role in shaping energy markets and influencing investment decisions.

Pressing policy concerns and rising public awareness on energy and environmental issues are forcing governments to take a more active role in this sector. Roughly 48% of the world's power generating capacity is state-owned, with the rest owned by the private sector (IEA, 2014a). Many governments, particularly in the OECD, have, in the past, stepped back from direct influence on energy markets by opening them up to competition. These same governments are now taking up a more direct role in the markets in order to promote the development of low-carbon energy technologies (IEA, 2014a). An increasing number of investments are coming from smaller entrepreneurial businesses, as opposed to large multinationals and state-owned enterprises. These smaller businesses rely on external sources of financing to generate the capital they need. This highlights the importance of the financial industry and the role of government to encourage and facilitate investment in the energy sector.

Power sector investments have the potential to generate high economic and social returns by increasing productivity, create jobs, and strengthen economic growth. Investment in the power sector is often the main factor when questions are raised about the affordability, sustainability, and reliability of the global energy system. If governments' interventions are not well directed and consistently implemented, they could deter and obstruct the investment of private capital in the sector (IEA, 2014a).

Conventional energy systems are known to be water intensive and often put pressure on water sources in areas where water is a scarce resource. These systems are also known to have a negative impact on air quality due to emissions of particulate matter and atmospheric pollutants. In 2005, 2.7 million premature deaths globally could be attributed to outdoor air pollution (GEA, 2012). Occupational health impacts from energy systems is a growing concern, with most of the concern focused on coal, oil, and gas extraction and processing. Exposure to collapsing mine shafts, fires and explosions, toxic materials and gases, hazardous dust, and dangerous machinery put workers in this sector at a high risk of injury or death.

The local environmental impacts of energy extraction and power generation have been known for some time. A shift of focus from local to global environmental impacts has taken place, with the growing evidence that energy systems play a huge role in anthropogenic disruptions to the climate, oceans, freshwater, and biosphere. The Stern Review (Stern, 2007) found that 24% of total GHG emissions were from power generation activities, with a total of 65% of GHG emissions being energy-related emissions. Figure 1.1 shows the breakdown of global GHG emissions by for different sectors.

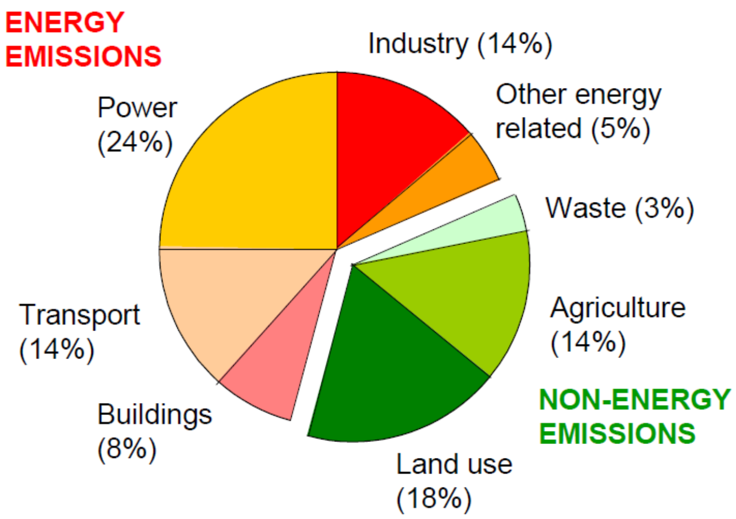

Figure 1.1: Sector share of GHG emissions in 2000 (Stern, 2007)

Energy systems play a critical part in the sustainability of our planet. Over the past two centuries, energy systems have made a significant contribution to the increasing levels of GHGs in the atmosphere. The extent to which fossil fuels have been utilised to generate electricity has pushed anthropogenic levels of GHGs ever higher. This has made a significant contribution to the development of the current global warming problem. In 2000, and estimated 150 000 deaths globally could be attributed to climate change, with the majority of these occurring in the world's poorest nations (GEA, 2012). The number of deaths attributed to climate change and the health impacts of energy systems are expected to keep rising if the current methods of generating and utilising energy are not changed.

A vast increase in the supply of carbon free power would be required in order to stabilise atmospheric CO_2 emissions in a growing world economy (Jean-Baptiste & Ducroux, 2003). Any solution to the global warming problem would require finding energy source alternatives to fossil fuels (Menyah & Wolde-Rufael, 2010). Renewable energy technologies can address many of the pressing issues raised by conventional energy sources: energy security, energy poverty, and GHG emissions. Addressing these issues could contribute to efforts that are aimed at relieving poverty, protecting water sources, industrial development, and developing peace and cooperation between nations.

The use of renewable energy technologies accounted for 13% of global primary energy demand in 2010 (IEA, 2012). Between 2000 and 2010, wind energy grew by 27% per year and solar PV grew by 42% per year (IEA, 2012). The start of the global economic crisis curbed renewable energy growth in developed countries, but strong growth in emerging economies made up for this and pushed up global growth in renewable energy expansion.

Government policies, such as emissions reduction targets, have been an important driver in the growth of renewable energy around the globe. The continued development and implementation of renewable energy technologies could play an important role in stimulating economic growth, strengthening energy security, and diversifying energy supply. Renewable energy technologies are expected to be implemented in, at least, 70 countries by 2017 (IEA, 2012). In September 2011, the 'Sustainable Energy for All' initiative was launched by the UN Secretary-General, Ban Ki-moon. He stated that sustainable development is not possible without sustainable energy, and that human development is dependent on access to modern energy services (Sustainable Energy for All, 2013). The initiative is aimed at mobilising action from all sectors of society in support of three main objectives: universal access to modern energy services, doubling the global rate of improvement in energy efficiency, and doubling the global share of renewable energy technologies in the energy mix (Sustainable Energy for All, 2013).

A transition to a sustainable energy future faces various obstacles and could be hampered by institutions, consumption patterns, vintage capital, vested interests, and investment patterns (GEA, 2012). These factors tend to push developments towards old pathways and often impede transitions. Formulating the most effective energy policies and implementing them successfully is vital in supporting the development and implementation of sustainable energy systems. Formulating adequate energy policies and making effective investment decisions require thorough understanding of the critical drivers and uncertainties related to energy issues. These policies and investments will eventually define the course of our future. The fossil fuel era will be remembered for the considerable impact it had on the planet. The green era, if appropriately implemented in time, will be known for the change it made to our future.

1.2. The South African context

"*No region has done less to contribute to the climate crisis, but no region will pay a higher price for failure to tackle it*" – Kofi Annan (Africa Progress Panel, 2015). Mr Annan is referring to the African continent in this statement. Africa has the potential to play an important role in the global transition towards sustainable energy systems (Africa Progress Panel, 2015). The power gap that exists between Africa and the rest of the world is growing, and the continent cannot afford to stand by and watch. Although Sub-Saharan Africa is home to 12% of the world's population, its share of global power generation capacity stands at only 1.8% (Africa Progress Panel, 2015). The continent has struggled over the past few decades to add significant new electrical power generation capacity, despite having abundant fossil fuel resources and even greater abundance in renewable energy sources. Improper governance of power utilities has made a significant contribution to the energy crisis on the continent (Africa Progress Panel, 2015).

South Africa is the leading electrical power producer and the leading GHG emitter on the continent, thus, making it an important regional leader in the development towards sustainable energy in Africa. Half of Sub-Saharan Africa's 90 GW of electrical power generation capacity is situated in South Africa, even though it's home to only about 7% of this region's population. Nigeria, Africa's biggest economy, consumes nine times less energy than South Africa; despite its population being three times larger (Africa Progress Panel, 2015). Figure 1.2 shows the disproportionate share of the region's electrical power generation capacity.

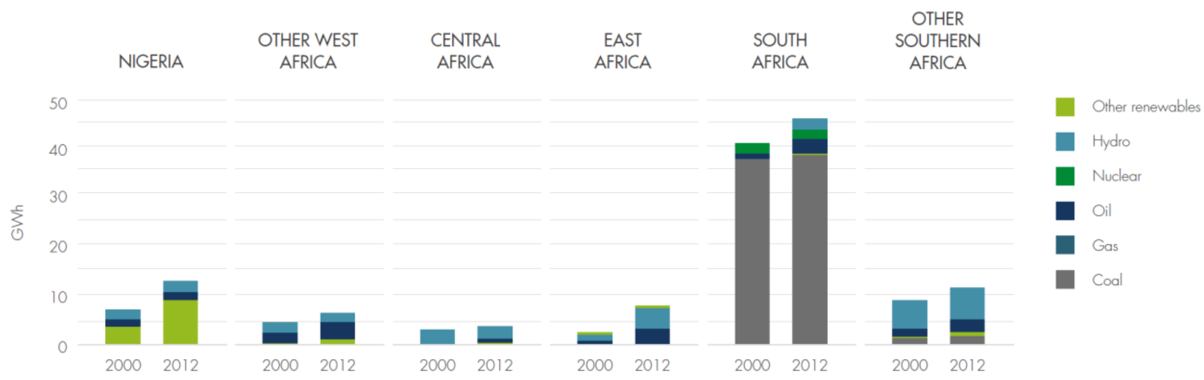

Figure 1.2: Electrical power generation capacity in Sub-Saharan Africa (Africa Progress Panel, 2015)

South Africa has large coal reserves and is under the top ten largest producers and exporters of coal in the world. This relatively cheap source of coal is what has led to South Africa's electrical power sector being dominated by coal-powered technologies. Almost 90% of South Africa's electricity supply originates from coal, with the remaining supply originating from nuclear, hydro, and renewable energy sources.

This also makes South Africa, by far, the biggest GHG emitter on the continent. Its total CO_2 emissions from energy consumption are almost double that of the rest of Sub-Saharan Africa combined. Eskom is the second largest emitter of CO_2 among the world's power utilities (Greenpeace, 2012). Eskom is South Africa's state-owned power utility. Its establishment dates back to 1923, when it was known as the Electricity Supply Commission, or ESCOM (Eskom, 2015a). ESCOM changed its name to Eskom in 1986, and today it is ranked as one of the top 20 power utilities in the world by generation capacity (Eskom, 2015a).

South Africa's power sector has always been dominated by its state utility – Eskom. Eskom is a vertically integrated actor that has a monopoly over the generation, transmission, and distribution of electricity in the country. Before 2011, it generated 96% of the electricity produced in the country, with the remaining 4% coming from off-grid independent producers who produce for their own use. Eskom also owns and controls the country's high voltage transmission grid, and supplies electricity directly to about half of the country's end-users, with the rest being distributed by local authorities.

In the 1970s and 1980s, Eskom made huge investments in its power generation infrastructure because it was experiencing electricity supply shortages. Six large coal-fired power stations, all with a capacity exceeding 3500 MW, were commissioned between 1980 and 1988 (Eskom, 2015b). During this time, Eskom also commissioned the Koeberg nuclear power station, as well as two pumped storage power stations (Eskom, 2015b). Future electricity demand was grossly overestimated, resulting in an overinvestment in infrastructure as a large surplus of power generation capacity was created. By 1983, Eskom had over

22 000 MW of capacity under construction or on order, which effectively doubled its operating capacity (Steyn, 2006). This surplus was assumed to have secured the future of electricity supply for the coming years and no provisions were made for any large investments in the near future. This, combined with the cheap coal supply to the power stations, resulted in South Africa enjoying some of the cheapest electricity prices in the world during this period. By 2006, the tariff for industrial consumers in South Africa was only 20% of the equivalent OECD average tariff (Deloitte, 2012).

No significant additions were made to Eskom's capacity over the next two decades and by the mid-2000s it was evident that a power supply crisis might be on the horizon. Eskom's New Build Programme started in 2005, and includes the construction of two coal-fired power stations (Medupi and Kusile, both exceeding 4 500 MW) and a pumped storage scheme. By 2008, widespread power cuts were being experienced with the introduction of load shedding, as Eskom struggled to match supply to demand. The New Build Programme has attracted a lot of criticism because of the delays and rising costs experienced by the Medupi and Kusile projects. The two projects, which have experienced numerous construction delays, were expected to cost under R100 billion (USD 8 billion), but are now estimated to cost the taxpayers more than R300 billion (USD 25 billion) (Mail and Gaurdian, 2015). The rising costs of new projects have culminated in the rising cost of electricity, with real electricity prices rising by 78% between 2008 and 2011 (Deloitte, 2012). The expectation is that prices will have to continue rising in the near future for Eskom to cover all the new build projects that are currently under construction.

South Africa is a signatory of the Kyoto Protocol. The national government began setting renewable energy targets in 2003, when the government set a target of reaching 10 000 GWh of renewable energy by 2013. During this time, little was done to reach this target and the target itself was ill-defined (Eberhard, et al., 2014). South Africa then became a signatory of the Copenhagen Accord, and announced that it would reduce its CO_2 emissions by 34% below a business-as-usual (BAU) scenario by 2020, and 42% below BAU by 2025 (Eberhard, et al., 2014).

The National Planning Commission (NPC) was appointed, in May 2010, to draw up the National Development Plan (NDP). The goal of the NDP was to set in motion a plan to eliminate poverty and reduce inequality in the country by 2030 (CGTA, 2014). The NDP plans to do this by encouraging development in all sectors of the country's economy and society. Chapter 5 in the NDP is called "Transition to a low-carbon economy". This chapter highlights South Africa's acknowledgement of the current climate crisis and its commitment to reducing its emissions below a baseline of 34% by 2020 and 42% by 2025 (NPC, 2011).

In 2011, the government introduced the Renewable Energy Independent Power Producer Procurement (REIPPP) programme, which is aimed at allowing private capital to fund new sustainable power projects. The programme achieves this through multiple competitive tendering rounds. The programme has succeeded in using private sector investments and expertise to facilitate the development of grid-connected renewable energy projects at highly competitive prices. Projects are not awarded on a price-basis only, with their contribution to social development playing a role in having a successful bid. To date, a total of 64 Independent Power Producer (IPP) projects, with a total capacity of about 4000 MW, have been awarded under the REIPPP programme. The projects have seen close to USD 14 billion being invested by over 100 different shareholder entities, with many shareholder entities being involved in more than one project (Africa

Progress Panel, 2015). The majority of the projects use solar PV and wind technologies, but also include CSP, biomass, biogas, landfill gas, and hydro.

The successful implementation of the REIPPP programme has translated into South Africa having one of the fastest growth rates, globally, for renewable energy investment. Government estimates that over 22 000 jobs have been created so far as a direct result of the programme's implementation, and that local content of goods and services supplied has increased to 53% (Department of Energy, 2014). The plan is to add 17.8 GW of renewable energy capacity by 2030, with competitive tendering rounds being held until this target is reached.

1.3. The Western Cape Province context

South Africa is divided into nine provinces, with each province being governed by its own provincial government. Provincial governments in South Africa form the second layer of government, between the national government and municipalities. The national constitution limits the power of provincial governments to certain functional areas, with exclusive powers limited to only a few areas.

Figure 1.3: Position of South Africa and the Western Cape

As one can see from Figure 1.3, the Western Cape is situated in the south-west corner of South Africa and stretches along parts of the western and southern coast. The Western Cape is the fourth most populated province in South Africa, home to roughly 11% of the country's population – about 6.1 million people (Western Cape Government, 2014a). Its population is expected to grow by almost 11% over the next 10 years, with a large contribution from immigrants from other provinces (Western Cape Government, 2014a). It is also the fourth largest province in the country by surface area. Almost two-thirds of the Province's population live in the metropolitan area of Cape Town, which is the Province's capital and largest city.

The Western Cape forms an important part of the South African economy, being responsible for almost 15% of the country's GDP (Western Cape Government, 2014a). This makes it the third largest contributor to national GDP, compared to the other eight provinces. The Province's economy regularly fares better and experiences higher economic growth rates than the national average. It is one of the most important logistical hubs in the country, with its two major ports; the country's most important international tourism hub; and a major source of professional, business, and educational services for the national economy (City of Cape Town, 2012). The Province is a very important role player in the agricultural industry, responsible for 20% of the country's agricultural production, and between 55% and 60% of the country's agricultural exports (Western Cape Government, 2014c). The Western Cape Province is responsible for 11% of all energy consumed nationally (City of Cape Town, 2011). The Province is heavily dependent on fossil fuels for, both, its non-electricity and electricity energy requirements, leaving a negative footprint on the environment. The majority of its electricity needs are met by Eskom, which generates almost 90% of its electricity from coal.

The Western Cape has been identified as an area that will be very vulnerable to climate change. Climate projections indicate a warming and drying trend for the future, with extreme weather conditions, both floods and droughts, becoming more regular occurrences (Western Cape Government, 2014c). This is a major concern because of the regions importance to the agricultural sector in South Africa. Another concern is the damage that rising sea levels could cause to the Province's 900 km coastline. These climate-related hazards pose a significant risk to the Province's economy, ecosystems, and population. It is estimated that climate-related extreme events in the Western Cape caused approximately R3 billion in damages between 2003 and 2008 (Western Cape Government, 2014c).

In 2008, the Western Cape Government (WCG) developed the Western Cape Climate Change Response Strategy and Action Plan. This strategy is aligned with the National Climate Change Response Strategy, and aimed at addressing climate change through mitigation and adaptation (Western Cape Government, 2014c). It is developed in a way to involve all relevant Provincial departments in a coordinated response strategy for the Province. The strategy aims to facilitate the building of a low-carbon economy and the development of adaptive capacity of the economy (Western Cape Government, 2014c).

In 2013, the WCG launched the Green is Smart roadmap, which is the Western Cape Green Economy Strategy Framework. The purpose of this framework is to encourage collaboration between the public and private sector, in order to steer the Western Cape towards becoming the green economy front-runner on the African continent. The WCG aims to encourage new investments focusing on greening the economy: driving agricultural productivity through conservation and climate smart agriculture; stimulating industries such as aquaculture, renewable energy, sustainable tourism, and the waste economy; and making the living and working environment more resilient (Western Cape Government, 2014a). The Green is Smart roadmap is set to encourage sustainable economic growth, while conserving natural systems and resources, and supporting livelihoods that can lift people out of poverty.

The WCG has committed itself to position the Province as the lowest carbon province, and has identified the potential for the Province to become the green economy hub for Africa (Western Cape Government, 2013b). The focus is on aligning the Province's competitiveness and performance with green economy requirements (Western Cape Government, 2013b). The renewable energy industry is a key area of focus and a fundamental driver in achieving this goal. Developing the renewable energy industry in the Western Cape has become a priority of the WCG, and it has pledged its support to developing this industry. Wind energy and solar PV technologies have enjoyed special attention from the WCG, with the deployment and development of manufacturing opportunities for these technologies in the Province. With the best wind and wave energy resources in the country, and good solar and biofuel energy potential, the Province is set to benefit from the implementation of these technologies. The strong academic and research presence in the Province can play an important role in developing green applications and renewable energy manufacturing capabilities (Western Cape Government, 2013b).

The Western Cape's growing population and its goal to increase economic growth will, undoubtedly, increase demand for electricity. The Province's electricity supply remains dominated by conventional fossil fuel technologies. The WCG has committed to meeting the electricity demand in a sustainable way and developing a sustainable power sector. There is a clear intention to move away from fossil fuel technologies, towards renewable energy technologies, and clear priorities have been identified by the WCG. Renewable energy technologies cannot, at present, supply all of the Province's needs, because base-load electricity is still required. This requires a mix of renewable energy, nuclear, and gas power in order to meet the electricity needs of the Province in a sustainable way. Thorough planning and smart investment is needed if the Province is to meet these goals.

1.4. Research objectives

The main objective of the study is to investigate the effects of green economy investments in the electricity sector in the Western Cape Province, aimed at transitioning the sector to one that is more in line with the green economy. The study then also aims to:

- Explores the potential for a green economy transition in the electricity sector of the Western Cape Province;
- Demonstrates the appropriateness of system dynamics modelling as a tool to analyse green economy policies;
- Demonstrates the key linkages between the different elements making up the electricity sector in the Western Cape Province;
- Explores the effectiveness of different policy interventions aimed at improving the sustainability of the electricity sector in the Western Cape Province; and
- Improves assessment and analysis of green economy policies in the Western Cape Province electricity sector.

1.5. Research strategy

This document is intended to present how the main research objective, as well as the secondary objectives, were carried out in the process of completing the study. Chapter 1 serves as an introduction to the study, giving background information and stating the research objectives. The background information touches on the consequences that have developed from the path along which the global energy sector has developed until now. It also touches on these issues in the context of the energy sector in South Africa and the Western Cape Province. An introduction is also given on the intentions of the WCG to transition the Province to developing into a green economy hub. The information in this chapter is intended to put the study into context by motivating the decision to undertake this study.

Chapters 2, 3, and 4 contain the main body of literature supporting the study. Chapter 2 discusses the concept of the green economy and its relation to the concept of sustainable development. This chapter discusses the literature behind green economy transitions, and provides an overview on the state of the green economy in South Africa and the Western Cape Province. Chapter 2 aims to facilitate an understanding of the green economy concept and also the role it is intended to play in the Province. The literature behind technology transitions is covered in Chapter 3. This includes discussions on the role of technology and energy in green economy transitions. Chapter 3 also describes the state of the energy sectors in South Africa and the Western Cape Province, and discusses the role that financing plays in developing a more sustainable electricity sector. Overall, Chapter 3 is intended to facilitate an understanding of the role that electricity generating technologies play in green economy transitions, and the current state and outlook of these technologies in the Western Cape Province.

Chapter 4 covers the literature on the modelling methodologies used to model green economy transitions. A review of modelling methodologies is given, discussing their implementation and suitability to carrying out green economy modelling. The chapter also discusses the motivation behind using system dynamics modelling for the study and explains the system dynamics methodology. The aim of Chapter 4 is to facilitate an understanding of the modelling methodologies used for green economy modelling, motivate the decision to use system dynamics, and facilitate an understanding of how system dynamics is used to carry out modelling analyses. Chapter 5 details the development of the electricity sector model that was used to carry out the study. The development of the conceptual model is first discussed, before the development of the dynamic model is discussed. Validating the model, which is an important part of the modelling process, is also discussed in this chapter. Chapter 5 aims to facilitate the understanding of the electricity sector model of the Western Cape Province.

Chapters 6 and 7 contain the results and conclusions of the study. The electricity sector model was developed to run simulations of different policies and scenarios regarding investments in electricity capacity in the Province. In Chapter 6, these results were presented in three contexts: (1) techno-economic, (2) environment, and (3) socio-economic. In Chapter 7, the main findings from the simulation results are discussed in the context of the same three contexts. This chapter also covers the limitations of the model, and the recommendations for future research and for policymakers.

Chapter 2

Sustainable development and the green economy

The concept of sustainable development is not a new one and has been discussed and debated by academics, policymakers and political leaders for decades now. A number of global and regional issues – environmental, social and economic – have increasingly brought to light the need for a more sustainable development path for our global society. Understanding the environmental footprint and social effects of our current development path is essential in understanding how policies should be formulated and where future investments should be directed. This chapter shortly discusses the concept of sustainable development, and discusses, in greater detail, the concept of the green economy. This includes a discussion on the state of the green economy in South Africa and the Western Cape Province.

2.1. Transitioning to a more sustainable development path

The 1972 UN Conference on Human Environment in Stockholm can be regarded as the first step towards a universal concept of sustainable development. Although the exact term was not used, the conference did refer to the importance of environmental management and the use of environmental assessment as a management tool (Mebratu, 1998). There were subtle indications that suggested the course of current economic development would have to be re-evaluated, but there was little consensus on the link between development and environmental issues (Mebratu, 1998). A few years earlier, the Club of Rome was established by a group of concerned scientists who shared a common concern for the future of humanity. In 1972, they released the comprehensive report named 'The Limits to Growth', of which the authors included Dennis and Donella Meadows. The report aimed to investigate how the current growth path of humanity would interact with our finite resource base in the future. The report concluded that the industrial growth experienced in the 1960s and 1970s would cause our society to exceed most ecological limits within a few decades.

The term 'sustainable development' and 'sustainability' was made popular by the Brundtland Report (WCED, 1987). The report was named Our Common Future, and stemmed from the recognition that a global agenda for change is needed in order to ensure the preservation of our planet for future generations. Its publication is seen by many as a significant political turning point in the perception of sustainable development, and also having started the global discussion on the subject (Mebratu, 1998). The report states that humanity has the ability to make development sustainable to ensure that it meets the needs of the present generation without compromising the ability of future generations to meet their needs. The concept of sustainable development does not imply absolute limits to development, but rather the limitations of the biosphere's ability to absorb the effects of human activities (WCED, 1987). The report further states that sustainable development should not be seen as a final destination of harmony. It should be regarded as a process of change where decisions regarding resource exploitation, investment strategies, technological development, and institutional reformation should be made with the goal of satisfying future and present needs (WCED, 1987).

It has always been perceived that environmentalists and economists sit on opposite ends of the opinion on future economic development. The environmentalists occupy the no-more-growth side of the argument, and believe that economic and industrial growth should level out and even decline in order to avoid the threat of increasing pollution, protect natural resources, and preserve the environment for future generations (Mitcham, 1995). The opposite end is occupied by the pro-growth economists who argue that economic and industrial growth is critical to societal development. They argue that growth is needed to lift people out of poverty and close the gap between poor and rich nations. According to Mitcham (1995), sustainable development fits between these two opposite views and aims to bridge the gap that exists between them. In this way, sustainable development encourages economic growth that doesn't cause environmental degradation, but still drives social development.

Conventional economics have always tended to assume that there are no limits to economic growth, or that they are too far ahead in the future to be of any relevance. Economic growth, in the conventional sense, depends on growth in physical production and consumption of goods, and the 'bigger is always better' approach is clearly very prevalent. Goodland and Ledec (1987) point to evidence that indicate that the productivity of forests, fish resources, croplands, and grasslands have been on the decline of late. This growing evidence continues to suggest that the limits to economic growth are, in fact, far closer than many have suspected. The point was also raised, suggesting that limiting economic output is not the concern of long-term sustainability, but that the concern lies in stabilising natural resource consumption (Goodland & Ledec, 1987).

Goodland and Ledec (1987) have a very ecologically based concept of sustainability. They stated that sustainability refers to a transition away from economic growth fuelled by the depletion of non-renewable sources and towards growth based on utilising renewable resources. They further stated that contemporary neoclassical economic theories do not promote sustainable development, or even take it into account. Their conclusion was that significant research is needed in the ecology-economics interface, in order to better understand how economic analysis should be used to take environmental concerns into account.

Much of the existing literature on sustainable development is very much environmentally orientated, and focuses on environmental conservation and resource management. The social implications, such as the effects of urbanisation on sustainable development goals, are often completely ignored (Cobbinah, et al., 2015). The concept of sustainability has transformed and evolved from the ecologically based concept of physical sustainability to a broader and more inclusive concept involving the social and economic context of development (Omer, 2008). The environmentally focused view of sustainability has been replaced by one that consists of an integrated social, ecological, and economic system perspective. Thus, the concept of sustainable development consists of three dimensions: economic, environmental, and social. These are seen as the three pillars of sustainable development.

Cobbinah et al. (2015) state that sustainable development is seen by many as being an ideal development approach, but that the lack of a universally accepted and clearly stated meaning has hampered its interpretation and the consistency of its application. Mebratu (1998) argues that the WCED's definition of sustainable development has succeeded in developing a global view of our planet's future, despite being criticised for being vague and ambiguous. The definition's wide acceptance could, however, be seen as a false victory. Mebratu (1998) argues that its wide acceptance could be due to its wide interpretation and everyone being able to fit the definition into their idea of sustainable development. The term has become somewhat of a cliché for some groups and has been twisted by some organisations to fit with whatever agenda they may advocate (Ayres, 2008). Mitcham (1995) argues that 'sustainability' is in danger of becoming a word that can mean almost anything, and end up being an ambivalent cliché approved by all.

The concept of the green economy should be regarded as being consistent with the older and broader concept of sustainable development (Ocampo, 2012). The Brundtland report (WCED, 1987) refers to the importance of managing and improving technological and social organisations in order to garner in a new era of economic growth. UNEP (2011b) states that the concept of sustainable development should not be replaced by that of the green economy. The green economy fits in with the growing recognition that sustainable development cannot be achieved without the current economic system diverting away from its current path of growing resource depletion and social marginalisation.

2.2. Transitioning to a green economy

The majority of the challenges that our society faces now were caused by decisions and actions of the past, made by previous generations. A history of misallocation of capital has made a contribution to the rise of several current crises: climate, biodiversity, energy, food, water, and the global financial and economic crises (Bassi, 2014). The prevalence of global energy, food, water, and financial crises has raised concerns regarding global economic and environmental developments. This is further complicated by the warnings of many academics concerning the danger of transgressing planetary boundaries and ecological limits. The green economy, in its various forms, has been proposed as a means for governments to lead their countries out of these crises, whilst taking into the account these environmental boundaries and limits (UN-DESA, 2012b). The concept of a green economy has recently received attention as a tool to address the recent economic crises and climate change mitigation targets simultaneously. This has led to a rapidly expanding literature on the issue, and increased attention from organisations, governments, experts, and think tanks from around the globe (UN-DESA, 2012b).

Bina (2013) states that a significant proportion of policies and academic literature on green economy and green growth focuses on combining environmental and sustainability discourses with industrial and economic ones, in the pursuit of a viable solution. Many different policies have been suggested to deal with current sustainability crises, and they range from very conservative and weak to very radical and optimistic. Bina (2013) suggests that the current policy options can be categorised into three groups: Almost business-as-usual (BAU), Greening, and All Change.

Almost BAU refers to the stimulus packages, or 'bail-outs', that have been implement by many of the major economies across the globe. These packages include green stimulus measures that are mostly aimed at improving energy efficiency, upgrading physical infrastructure, supporting clean energy markets, and R&D. The main goal of these packages is to stimulate economic growth and increase GDP, with the greening component being the hope that investment and growth will spill into green industries. It is more closely related to contemporary and mainstream economics (Bina, 2013).

Examples of the Greening category are the policy suggestions introduced by UNEP and the OECD. These can be described as more comprehensive strategies aimed at resource-efficient and low-carbon growth, which will serve society and reduce poverty. These measures rely more on scientific and technological development, having their roots in the techno-scientific paradigm. It is closely related to environmental economics and lightly touches on mainstream economics (Bina, 2013).

The All Change category is a more radical and aggressive approach, compared to the previous two. This approach is advocated mainly by NGOs, think tanks, and other non-state actors. Its roots are grounded firmly in the socio-economic paradigm, and draws from natural sciences, social sciences, and humanities. It advocates transformative measures, which downplay economic growth and focuses on progress in well-being and happiness of all individuals, and seeks to end the economic domination of society (Bina, 2013).

Bina (2013) then uses Dryzek's discourse classification in order to explore the relationship between the three categories. From Figure 2.1 one can see where each category fits into the discourse classification.

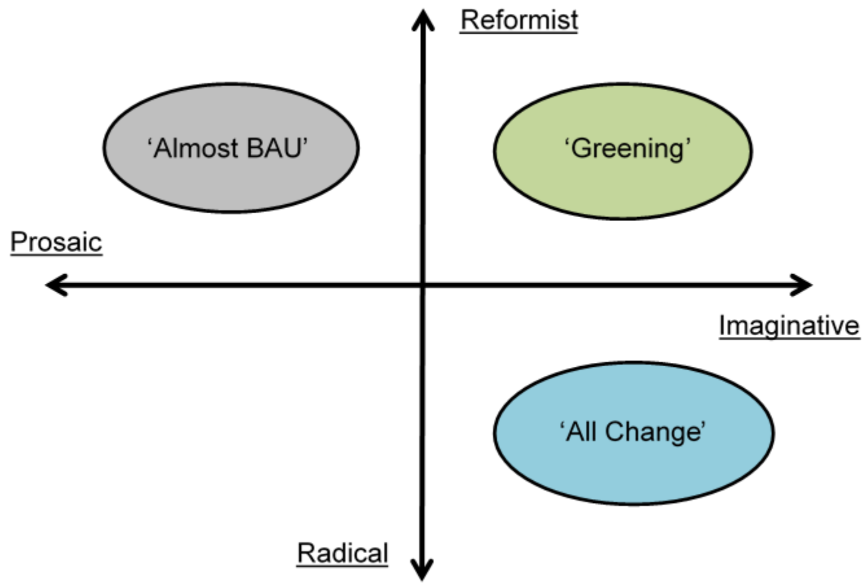

Figure 2.1: Environmental discourse classification of policy options. Adapted from (Bina, 2013)

The Almost BAU category corresponds to reformist-prosiac changes, which gives Almost BAU a classification of 'environmental problem solving'. These changes are characterised as being conservative and gradual. The Greening category is seen as being reformist-imaginative, obtaining a classification of 'sustainability'. The All Change category corresponds to imaginative-radical changes, giving it a classification of 'green radicalism'. These changes are characterised as being rapid and progressive (Bina, 2013).

Cato (2009) states that green economics differs from the conventional dominant economic paradigm in three distinct ways: (1) it is inherently concerned with social justice, and promotes economic equality and justice, instead of only seeing it as an afterthought; (2) it has been introduced by environmental campaigners and green politicians because of a need for it; and (3) it is not yet a mainstream academic discipline with major presence in universities.

Cato (2009) describes the green economy as being a system consisting of the formal, social, and natural economies, where the formal economy is embedded within the social economy and the social economy is embedded in the natural economy. Figure 2.2 illustrates this system of economic spheres.

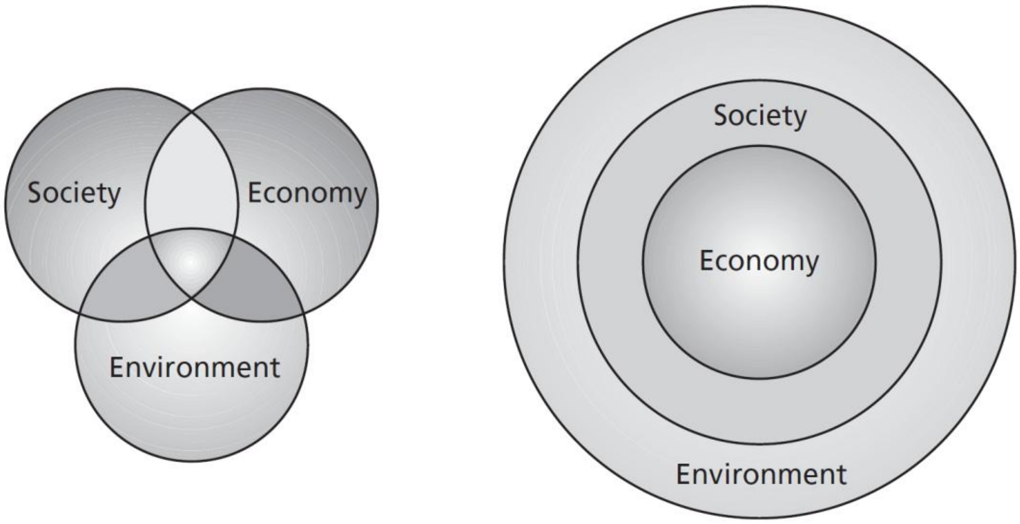

Figure 2.2: Conventional economy and green economy views of the relationship between the economy, environment, and society (Cato, 2009)

The left half of Figure 2.2 shows the conventional economic view of how the three spheres interact. This view states that the three spheres are independent systems, and that sustainability is achieved in the area where all three spheres interact, known as the solution area of integration (Mebratu, 1998). Through this view, the ultimate achievement of sustainability is the full integration of these three spheres. The right half of Figure 2.2 shows the green economics paradigm, which argues that all three spheres are embedded within one another. This view states that these three spheres were never independent and that they never will be. The intersection areas between the spheres consist of millions of systems that interact in conflict or harmony, all in the process of co-evolution of the natural and human universe (Mebratu, 1998). It is when these complex interactions are not taken into consideration that crises start developing. It is easy to forget that these spheres of the economic system are all interconnected and influence one another, and that one cannot be impacted without impacting the others. Conventional economics often see environmental impacts as being externalities that occur outside its boundaries. Cato (2009) explains that the economy is a subsystem of human society, which, in turn, is a subsystem of the biosphere, and that the capacity of any subsystem cannot expand beyond that of the total system. The boundaries of the outer circle are fixed by environmental and ecological limits, which cannot be expanded. Therefore, the expansion and contraction of the inner spheres need to be monitored and any expansion should be kept within certain limits.

There lacks a universally accepted definition and principles for the green economy, which has led to challenges during discussions and negotiations regarding the topic at recent international conferences (UN-DESA, 2012b). The concept of a green economy is still fresh and there are many knowledge gaps and concept ambiguities that need to be addressed. It does not yet enjoy international consensus or widespread agreement (Ocampo, 2012).

There exists confusion on whether green economy is meant to replace the concept of sustainable development, particularly because of their overlapping principles and goals (UN-DESA, 2012a). The green economy should be seen as a means for achieving sustainable development, and should be used to contribute to and progress its broader agenda (UN-DESA, 2012a). Green economy and green growth are used interchangeably, and refer to a set of ideas that are often linked to the concept of low-carbon development (Bina, 2013).

The term ‘green economy’ was first used in a major report in 1989, when a group of leading environmental economists wrote the report for the Government of the United Kingdom. The title of the report was ‘Blueprint for a Green Economy’, but the term ‘green economy’ only appeared in the title, and nowhere else in the report (UN-DESA, 2012b). The main theme was that economics can and should come to the aid of environmental policy (UN-DESA, 2012b). Pearce (1992) argues that most of the global green economy debate is centred around how much of a modification is needed, and to achieve these modifications. Almost a quarter century on and this is still a topic that enjoys a lot of debate. Pearce (1992) also states that sustainability is a common feature of all green economies. Gibbs (1994) refers to ‘greening the local economy’ and ‘the rapid growth of green awareness’. Gibbs (1994) further states that environmental issues cannot be addressed from an economical perspective as long as economic principles are not subject to environmental scrutiny.

The Rio Declaration, conceived at the UN Conference on Environment and Development in 1992, promotes ways of internationalising environmental costs and using economic instruments in order to eliminate unsustainable consumption and production (UN-DESA, 2012b). The global financial crisis of 2008 saw the biggest financial collapse since the Great Depression in the 1930s. The crisis severely affected economic growth, dumping many countries’ economies into recession, and fuelled increasing unemployment around the world. It triggered global discussions on whether our current global financial and economic systems are sustainable in the medium to long term. In 2009, UNEP published the Global Green New Deal (GGND), which referred to a set of globally coordinated large-scale stimulus packages and policy measures (UNEP, 2009). These were developed with the aim of potentially facilitating global economic recovery in the short term, but also laying the foundation for sustained economic growth in the medium and long term (UNEP, 2009). The GGND had three broad objectives: (1) economic recovery and job creation, (2) reducing carbon dependency and ecosystem degradation, and (3) ending extreme poverty by 2015.

Twenty years after the Rio Declaration, at the UN Conference on Sustainable Development, the green economy was chosen as one of the central themes of the conference. By this time, multiple crises were challenging current global policies, and new ideas of how economies should function were emerging. Attended by 191 UN member states, the conference’s overall message was that our current ecological crisis is not subsiding, and that a need for significant transformation exists. An important document that formed a key part of the conference is ‘Towards a Green Economy’ (UNEP, 2011b), which is seen as the United Nations’ version of the green economy and also programme of reform to address environmental and social issues on a global scale (Boehnert, 2013). UNEP’s main message, conveyed through the report, is that the advantages of greening the world’s economies are tangible and considerable, and that the means for achieving this are at hand for both governments and the private sector.

UNEP’s definition of a green economy is one which results in improved human well-being and social equality, while significantly reducing environmental risks and ecological scarcities (UNEP, 2011b). The simpler definition would be to define it as an economy that is low-carbon, resource efficient, and socially inclusive. The green economy approach can be viewed as being socio-economic: aiming to redirect economic investments while taking into regard the possible environmental and policy responses (UNEP, 2014a). The transition and growth of the green economy should be facilitated by investments from the private and public sector. These investments should drive social development by growing employment and raising individual income; whilst also reducing carbon emissions and pollution, improving resource and energy efficiency, and ensuring the preservation of biodiversity and ecosystem services. UNEP (2011b) recognises that these investments may not come easily, and need to be facilitated by changes in regulations, policy reforms, and targeted public expenditure.

UNEP (2011b) argues that one cannot manage something that you do not measure, further claiming that conventional economic indicators, such as GDP, are narrow sighted and do not give a full picture of the state of the wider economy. Green economy indicators should include, apart from GDP, impacts on employment, resource intensity, emissions, and ecological impact. The focus is placed on ten key economic sectors: agriculture, buildings, energy (supply), fisheries, forestry, industry, tourism, transport, waste, and water. These sectors have been identified as playing a critical role in driving the trends of the transition to a green economy, with the goal to increase social equity and reducing environmental risks. UNEP (2011b) also identifies ten indicators that are meant to track the progress of a transition to a green economy: GDP, GDP per capita, total employment, calories per capita, total forest land, water demand, total landfill, footprint/biocapacity ratio, primary energy demand, and renewable energy share of primary energy demand. The indicators proposed by the OECD (2011), include economic and environmental indicators, but lack comprehensive social indicators that can track social development.

The green economy promotes the importance of decoupling economic growth and environmental degradation through improving efficiency in the use of resources and production processes, and through the reduction of resource degradation, pollution, and waste (UN-DESA, 2012b). Although the green economy places emphasis on environmental protection and sustainable consumption of resources, and many people perceive it predominantly in this way, it has a very important social aspect to it as well. It is essential to embrace the multidisciplinary, complex, holistic, and long-term methods to examine in reality what the green economy offers (Kennet & Heineman, 2006). This allows the field of economics to be framed within the natural and social sciences, and brings politics, morals, and ethics back within its borders (Kennet & Heineman, 2006). From a social perspective, it is the intent of the green economy to eradicate the causes of poverty and inequality between nations and within nations. Mainstream economics tend to focus solely on prices, profits, short-term economic growth, and short-term financial success. Kennet and Heineman (2006) argue that green economy logic advocates local production for local needs, reusing, reducing, repairing, and recycling.

UNEP's definition of a green economy and policy guidelines are strongly focused on economic growth, with the goal of accelerating economic growth and development is very prominent. Some have argued that this view is still too economy-orientated, and that nations should implement far more radical policies and strategies. There are academics who believe that the green economy is not a viable solution to the current crises facing us in recent times. They see the concept as a possible part of the solution, but that it lacks many aspects that are vital to addressing our most pressing issues. There is a fear that the concept will simply become rhetoric used by governments and corporations. Boehnert (2013) states that green economists and social movements are unconvinced by UNEP's proposed policy methods for transitioning to a green economy, as laid out in its Green Economy Programme. The solutions are too market-based and favour the interests of large corporations over those of the environment and society (Boehnert, 2013). Lorek and Spangenberg (2014) argue that the green economy concept, which is set out in the UNEP's Green Economy Programme, cannot provide a complete solution for a transition to a sustainable society. A substantial greening of the global economy could, however, play a critical part in achieving this.

A significant aspect of green economy is its potential to create employment opportunities. This fits into the social and economic sphere of the green economy, as job creation raises living standards for people and also strengthens the economy of a country. A study done on the employment created by China's GHG mitigation policies estimates that the policies resulted in 472 000 net job gains between 2009 and 2010 (Cai, et al., 2011). Another study on the Chinese job market estimates that the same policies had created an estimated 3 million indirect jobs (Wang, et al., 2013). A study done by Frankhauser et al. (2008) concludes that climate change and the mitigation efforts will, in the long term, create more jobs than it destroys. The development and implementation of labour-intensive low-carbon technologies will create jobs in the short term, while a fundamental overhaul of economic systems will trigger job creation in the long term (Frankhauser, et al., 2008). The OECD (2011) argues that some jobs will be at risk because of major changes in economic sectors that are seen as polluting or environmentally threatening. In the long term, however, the expectation is that net employment gains will be experienced due to the expansion of green industries.

Not all studies have been positive about the employment potential of the green economy. A study done by Frondel et al. (2010) concludes that numerous empirical studies have shown zero net employment creation in Germany. The same study states that the German government's renewable energy policies have resulted in massive expenditures, which showed little long-term promise in stimulating the economy (Frondel, et al., 2010). Lesser (2010) argues that the potentially higher electricity prices from renewable energy technologies would hurt the economy and result in job losses. A study done by Furchgott-Roth (2012) also states that there is much confusion about what green jobs really are and whether green energy policies, in the United States, have created or destroyed jobs. It should be noted that not all jobs in a green industry are green jobs, and not all green jobs are in the green industry (Yi & Liu, 2015). This makes it a tricky and, often, complicated task to accurately calculate the number of green jobs that have been created. Green jobs can be defined as jobs in business that produce goods and provide services that benefit the environment or conserve natural resources, according to the U.S. Bureau of Labor Statistics (2011).

Green businesses have been described as those who utilise renewable energy technologies and employ green labour forces, in order to provide clean energy services and goods (Yi, 2014). These businesses are said to play a critical role in a clean energy or green economy. It is essential to understand the forces and factors that affect green businesses, such as the policy, economic, and political environment, in order to support the growth of these businesses.

When it comes to green economy, there is no one-size-fits-all solution for every government, as different countries have different levels of development, governance frameworks, and resource reserves.

Governments should identify priority sectors and select the most appropriate policy instruments to successfully green their economies. According to UNEP (2011b), transitioning to a green economy requires specific conditions to be met. These conditions relate to current positions of national regulations, policies, subsidies, incentives, international market and legal infrastructures, and trade and aid protocols. These conditions have previously caused the global economy to be locked into an unsustainable path. The specifics of human and natural capital and the level of development between different countries hold many disparities. Therefore, the path that needs to be taken, in order to successfully transition towards a green economy, will differ greatly from country to country. In most countries, the majority of investments will have to come from the private sector, but public investment will have to play a major role in jump-starting the green economy movement. Public policy will have to play a critical role in guiding investments down the right channels in order to promote green economic growth (UNEP, 2011b).

UNEP (2011b) lists six priorities that need to be addressed, by the public sector, in order to establish conditions that will enable a transition to a green economy: (1) establishing effective regulatory frameworks; (2) focusing government investment on areas that will stimulate the greening of the economy; (3) reducing spending in areas that diminish natural capital; (4) introducing taxes and market-based instruments that promote green investment and innovation; (5) investing in capacity building and training; and (6) strengthen international governance.

An effective regulatory framework should be designed to create incentives and remove barriers to green investments. The OECD (2011) states that the objective of a green growth framework is to establish incentives and institutions that build well-being. This can be achieved in a number of ways: improving resource management and increasing productivity; facilitating economic activity in areas where it is of most advantage to society over the long-term; and leading to innovative ways of achieving the previous two objectives. The OECD (2011) agrees with UNEP, acknowledging that policy and institutional settings, level of development, and resource endowment play a critical role in the path that a country needs to take in order to green its economy. The group's green growth policies are divided into two broad sets. The first establishes broad framework policies that reinforce economic growth and conserve natural capital; the second consists of incentives to use natural resources efficiently and discourage pollution.

Any transition faces barriers, and a transition to a green economy will be no different. Certain constraints to green growth have been identified by the OECD (2011): inadequate infrastructure, poor institutional quality, regulatory uncertainty, low returns on R&D, and barriers to competition. The public sector would, in most cases, implement policies and institutional reforms in order to negate the effects of these barriers. Innovation also plays a critical part in overcoming these barriers, creating the need for policies and reforms to encourage green innovation (OECD, 2011).

Certain risks have been identified with regard to the misuse of the concept of green economy. The first risk is that it could be defined and implemented in a very one-dimensional manner – purely in an environmental manner (Ocampo, 2012). The second risk is that it will be interpreted as a one-size-fits-all solution, and that developing countries will try and follow the same strategy as developed countries (Ocampo, 2012). The third risk is that corporations will misuse the concept to gain market access or to grow their own market share (Ocampo, 2012).

2.3. The green economy in South Africa

South Africa is a water-scarce country with little arable land and an overreliance on coal-fired power and oil imports (Von Bormann & Gulati, 2014). The current view is that the South African economy is pushing the limits of its resource constraints. A secure supply of food, energy, and water is the basis for a resilient economy (Von Bormann & Gulati, 2014). The large size of the country adds a factor of spatial complexity and makes effective resource management a difficult task; this creates one of the biggest challenges for sustainable development. The National Development Plan (NDP) of South Africa sets out to eliminate poverty by 2030, deliver environmental protection, and promote economic development.

South Africa holds the unwanted claim of being one of the most carbon-intensive economies in the world, but the national government has shown commitment to unleashing the potential of the green economy (Maia, et al., 2011). The New Growth Path (Economic Development Department, 2010), a framework designed to encourage sustainable economic growth and create employment, states that the green economy is one of the main drivers of employment potential in the country. An estimated 300 000 direct jobs are expected to be added by 2020 as a result of the transition to a green economy, rising to well over 400 000 by 2030 (Economic Development Department, 2010). The energy sector has been identified as the sector supporting the most of these additional jobs. Research conducted by Maia et al. (2011) suggest that up to 460 000 direct employment opportunities could be created by the green economy by 2025, with almost one-third of these being contributed by the expanding energy generation segment. The New Growth Path framework contains a document called the Green Economy Accord (Economic Development Department, 2010), which is aimed at promoting the green economy in the country as a platform for employment creation. Some of the commitments that the national government have made through this accord include increasing public investment in the green economy, procurement of renewable energy, promoting energy efficiency, and reducing carbon-emissions.

A clear long-term national industrialisation strategy is needed in order to maximise localisation benefits of an expanding green economy (Maia, et al., 2011). Two broad areas of investment are required for green economy growth. The first is investment in infrastructure and the second is investment in information and industry (Western Cape Government, 2013a). Infrastructure investment needs are increasingly being met by private capital, but public finances are critical in filling gaps and covering the risks associated with new and alternative technologies. The risks associated with green investments in South Africa have given rise to the need for government and development finance institutions to play a catalytic role in providing financing facilities (Western Cape Government, 2013a). The Industrial Policy Action Plan (Department of Trade and Industry, 2013) highlights the development of financing support mechanisms for green industries as a key objective. In 2011, the Development Bank of Southern Africa (DBSA) and the Department of Environmental Affairs set up the Green Fund to support the transition to a low-carbon, resource efficient, and climate resilient economic development path. An amount of R800 million was set aside to support investments in green initiatives that will support projects that promote poverty reduction and job creation (Department of Environmental Affairs, 2015).

Government policy has been seen as the main driver behind the shift to greener energy technologies. The past few years have seen the rising costs of conventional energy, rising demand for energy, and the decreasing costs of renewable energies contribute greatly to the rise of renewable energy technologies in South Africa (Department of Trade and Industry, 2013). The systematic introduction of renewable energy is seen as a key contributor to unlocking the country's green growth potential, and the government has shown a clear intention to support it. The government aims to stimulate the local industrial sector with this program by encouraging localisation of manufacturing. Manufacturing operations supplying equipment, parts, and components, particularly for the renewable energy sector, could grow substantially in the future with an expanding green economy.

The National Climate Change Response Strategy (Department of Environmental Affairs, 2010) lists the promotion and expansion of the green economy sectors, together with the promotion of investment in human and productive resources that will grow the green economy, as one of its main objectives. It also aims to promote job creation, through the implementation of climate change response strategies, during the shift to a green economy. These goals all need effective policies that will mobilise labour and capital out of carbon intensive sectors and redirect them to greener production sectors.

Overall, the South African government views the green economy as a mechanism that involves new economic activities that will be socially inclusive, protect the environment, and promote economic growth. The government's definition of social inclusivity covers the development of broad-based black economic empowerment and addresses the needs of women and the youth, as well as lifting the significant share of the population out of poverty. The economic growth goal is to promote employment creation and also to grow key sectors in the economy, which would lead to an annual economic growth rate of above 5%. The green economy is seen as an effective investment in climate change response and a secure resource to support climate change interventions.

2.4. The green economy in the Western Cape Province

Maia et al. (2011) point to the important role that local governments need to adopt in the implementation, coordination, and support of green projects. In 2013, the Western Cape Government (WCG) developed the Western Cape Green Economy Strategy Framework, also known as the Green is Smart document (Western Cape Government, 2013a). Green is Smart is the Western Cape Province's roadmap to becoming the green economy leader on the African continent. Its core ambition is to turn the Western Cape Province into the lowest carbon province in South Africa and the leading green economic hub of the African continent. It aims to also steer the country, as a whole, down a greener growth path and further places emphasis on achieving the dual goal of optimising green economic opportunities and enhancing environmental performance. The Province considers private enterprises to be the driver behind the green economy, with government assisting as a responsive partner (Western Cape Government, 2013a). The Green is Smart document highlights the responsibilities of the local government, in a green economy transition, as streamlining regulations as much as possible, ensuring sufficient and resilient infrastructure, and educating and training local people for a different future. The roadmap is seen as a living document that is expected to transform and change as increasing stakeholder engagement takes place over time. This allows the strategy to take a more dynamic form, being allowed to change as priorities change.

The Province's Green Economy Report states that the role of the green economy is to reconfigure the relationship between the economy and the natural systems and resources on which it depends (Western Cape Government, 2014a). It further states that the green economy should create an environment that would simultaneously facilitate economic growth, social development, and the protection of environmental resources and systems. According to the Western Cape Government (2014a), the green economy consists of two components; the first involves existing economic sectors, and the second involves new economic activities. Applying green economy thinking to existing economic sectors would mean mitigating environmental risks and increasing the efficiency of these sectors. On the other hand, the green economy should also ensure that new economic activities, businesses, and industries are established in a way that protects and enhances natural systems and resources, and properly utilise the value generated by natural systems.

The WCG defines 'green growth' as a component of the green economy, which focuses on economic efficiency and the protection of the environment (Western Cape Government, 2014a). According to the WCG, Green growth is not seen as being inherently beneficial towards social progress, even though green growth projects may often generate significant social co-benefits. Green growth should only be considered as one of the components of the green economy. With social inequality and a number of social challenges facing the Western Cape Province, it is critical to include social issues and opportunities within any green growth strategy for the Province (Western Cape Government, 2014a). Three significant trends have emerged in the Western Cape Province: (1) declining natural systems and resources, (2) increasing and unsustainable consumption patterns, and (3) growing disparities in and competition for access to natural resources (Western Cape Government, 2014a). These three trends have convinced the WCG to adopt a green economy approach.

The Western Cape Province is rather exposed to high energy costs, carbon trade barriers, and water shortages because of its resource intensive nature (Western Cape Government, 2013a). The economy in the Province is considered to be resource intensive. This means that in order to ensure the province's climate resilience and environmental integrity, a serious transformation is required (Western Cape Government, 2014a). Five categories of green economy indicators have been identified (Western Cape Government, 2014a): (1) natural asset based; (2) resource productivity; (3) socio-economic; (4) environmental health and inclusivity; and (5) policy and investment. The indicators included in these categories are intended to monitor and evaluate the state of the green economy and the progress that has been achieved, and whether the desired shifts are occurring. They are designed and developed in order to support and compliment strategy and policy, and to identify emerging risks and opportunities related to the green economy.

The WCG has identified three 'high level priorities for green growth' in the Province (Western Cape Government, 2013a). The first priority is the pursuit of green jobs; a green growth path is not sustainable unless it drives job growth. These jobs are expected to realise in the rehabilitation of natural assets, responsible tourism, and in the waste sector. The second priority is the establishment of the necessary financial infrastructure. Green investments have a unique risk profile, raising the need for financial innovation and the availability of capital for investors (Western Cape Government, 2013a). The third priority is the role that natural gas and renewable energy technologies have to play in reducing the carbon footprint of the province. Renewable energy technologies are expected to supplement gas base-load power, with these developments also contributing to significant investments in the manufacturing sector.

The drivers of the green economy are market focused and private sector driven. The enablers that support the drivers are either in the domain of the public sector or a collaborative effort between the private and public sector. The enablers are identified as finance, rules and regulation, knowledge management, capabilities, and infrastructure (Western Cape Government, 2013a). The Green is Smart document states that enterprises, large and small, will be the driving force behind green growth. Small and medium sized enterprises will play a very important role because they make up a large portion of the economy, and also employ the most people. It also states that innovation should be at the centre of any green economy strategy, and highlights the importance of establishing institutions and systems that promote, support, and stimulate innovation and knowledge. The inability to transform information into knowledge is a barrier to innovation and green transition. The Green is Smart document suggests that creating a coordinated knowledge hub could support innovation in the Province, where information is currently not consolidated in a central hub or networked in a structured manner.

The GreenCape Special Purpose Vehicle (SPV) was established by the WCG in 2010. It is a government-funded and industry-led initiative, with the main goal of supporting investors in the renewable energy industry and assisting them with strategy development. GreenCape is also tasked with supporting the development of local manufacturing capabilities and to facilitate opportunities for local manufacturers (WCG Provincial Treasury, 2013). It plays a supporting role in assisting firms to partake in the rolling out of renewable energy projects, mainly through the REIPPP programme. GreenCape is an example of the government playing a collaborative role in supporting the private sector with driving green economy initiatives.

Transitioning to a green economy requires significant investments in technology and system design in order to reposition societies towards a transition to a more climate resilient and green future. Apart from this, the proper management of environmental and financial-related risks is vital. The Western Cape Province, much like South Africa and other emerging economies, lack the financial resources, but it does boast a foundation supporting knowledge, design, and innovation on which solutions for emerging markets can be developed (Western Cape Government, 2013a). The establishment of innovation districts in Cape Town and Stellenbosch, and the awarding of Cape Town as the World Design Capital in 2014 are testament to the effort put into positioning the Western Cape Province as a leading knowledge, design, and innovation centre for emerging markets. Partnerships have been developed with international institutions, such as the Fraunhofer Institute and MIT, in order to further this agenda. The Green is Smart document highlights the need for improved indicators, which measure activities and desired impacts, as a basis for benchmarking the Western Cape Province internationally and guiding the green economy transition. It also points to the need to coordinate knowledge management and cooperation between universities, government, agencies, and the private sector in order to provide information and knowledge that can be adapted to meet the needs of the region (Western Cape Government, 2013a).

Concerns have very often been raised regarding the ability of local governments and municipalities to finance their infrastructure requirements. The WCG is constrained in offering financial incentives and investments in many regards. Therefore, it must be innovative in finding new channels to leverage financial resources and investments (Western Cape Government, 2013a). The Western Cape Province is well established as a financial asset management centre in the country. The opportunity certainly exists to establish the Province as a green finance centre, to facilitate green financial innovation and risk management, and to drive the emergent green private equity presence. The Green is Smart document states that the Province should investigate potential financial mechanisms that would make investment accessible to enterprises that want to start up and scale up green production activities.

According to the Green is Smart document, the private sector has an important role to play in the green economy. The private sector is the producer of goods and services and, thus, is the driver of the green economy. Its responsibility is to produce goods and services that are less resource intensive, which requires investments in research, development, and innovation. The private sector is also a major consumer of goods and services, and is responsible for driving the green economy through the procurement of greener goods and services. A study done by the Western Cape Government (2014b), on whether to set up a green fund, found that there were very few green economy companies struggling to acquire finance. Instead, it found financiers and investors with unallocated funds, struggling to find enough green economy investment opportunities.

The WCG's view of transitioning to a green economy is defined as a planned and progressive transition towards an economy that is more productive, more competitive, and less environmentally damaging (Western Cape Government, 2014b). Adding to this, it will only be socially and politically tenable if these efforts simultaneously address the Province's social needs, such as unemployment, poverty, lack of housing, and social inclusion (Western Cape Government, 2014b). An economy that is more productive and competitive is in the best interest of private companies, but the Provincial Government will ultimately have to play a critical role in guiding financial resources towards the socio-ecological priorities of the green economy.

2.5. Conclusion: Sustainable development and green economy

The concept of sustainable development has been discussed and debated for a number of decades. It highlights the importance of preserving our planet for future generations by ensuring that economic growth does not negatively impact on our social and environmental wellbeing. The concept of the green economy fits in with the recognition that sustainable development is not possible without a change in the current global and regional economic systems. It has also been recognised as a tool to achieve economic growth and climate change mitigation simultaneously. South Africa is a country struggling with economic, environmental, and social issues. The South African Government has identified the need to tackle these issues simultaneously and has made commitments to steering the economic down a more sustainable path. A number of government policies have been drawn up and implemented. This is also the case for the Western Cape Province; the Provincial Government has identified the need for a shift to a green economy, and has developed policies and regulations in order to tackle this issue. Infrastructure and technology have been recognised as playing a critical part in any economic transition. Thus, the need exists for the proper understanding and management of such technology transitions.

Chapter 3

Technology transitions in the electricity sector

The electricity sector is critical to the economic and social development of any country or region. The lack of electricity supply can have detrimental effects on economic growth and the standard of living for the citizens it is meant to serve. Any green economy transition will need to be supported by the transition of the electricity sector supporting that economy. Electricity sectors are technology-intensive and, therefore, any transition of the electricity sector would be a technology transition. This chapter discusses the concept of technology transitions by looking at the role that technology and energy plays in the green economy. The chapter then discusses the state of the energy sectors in South Africa and the Western Cape Province, before discussing the different electricity generating technologies used in South Africa. A discussion on the role that financing plays in an electricity sector transition concludes the chapter.

3.1. The role of technology in a green economy transition

According to Smith and Stirling (2008), the purpose of transition research is to gain a better understanding of how sustainable technology systems might become established over time, and how incumbent systems may become unsettled and displaced by more sustainable alternatives. The focus of analysts and policy makers is the possibility of accelerating transitions away from current unsustainable regimes and towards more sustainable pathways (Smith & Stirling, 2008). Transitions generally involve a broad range of actors, occur over several decades, and involve significant changes across different dimensions: technological, organisational, political, institutional, material, economic, and social (Markard, et al., 2012). The results of such a transition include new products, services, organisations, and business models.

Socio-technical transitions are similar to technical transitions: both involve technical dimensions. What sets the former apart from the latter, according to Markard et al. (2012), is the fact that it additionally includes transitions in user practices and institutional structures. According to the Brundtland Report (WCED, 1987), technology transitions involve developing alternative technologies, upgrading current technologies, and importing technologies. Yi (2014) states that ensuring the robustness of a green economy is essential in order for the use of sustainable and renewable technologies to bring about stable economic growth. Technologies make use of natural resources and are responsible for stress on the natural environment, meaning that the correct utilisation of technologies could result in more efficient use of resources and decreased stress on environmental systems. When technologies do the latter, instead of the former, they can be referred to as sustainable technologies. Sustainable technology development is not an autonomous process, thus its management is critical (Musango & Brent, 2011). Green growth and green economy transitions have been linked to promising changes in the use of technologies. There has been a shift from downstream environmental protection technologies to resource saving technologies, with the focus on implementing these technologies across all sectors and industries (Janicke, 2012).

Socio-technical systems refer to the conceptualisation of sectors such as energy supply, water supply, and transportation (Markard, et al., 2012). The constituents of such systems include networks of actors, institutions, material artefacts, and knowledge. These constituents of the system interact and provide services for society. The dynamics of these systems are heavily influenced by the fact that the constituents are significantly interrelated and interdependent on each other (Markard, et al., 2012). Socio-ecological and socio-technical systems have each been understood to display complex, multi-scale, and adaptive properties, with the associated sustainable governance recommendations emphasising approaches focusing on learning, experimentation, and iteration (Smith & Stirling, 2008). Smith and Stirling (2008) argue that strong parallels exist between the challenges facing current research in these two systems, but that socio-ecological systems literature rarely considers the dynamics of technology transitions in any detail. Studying technological systems form a socio-technical perspective allows one to understand technological development and use in terms of the complex adaptive processes constituting the interdependencies between the social and material spheres (Smith & Stirling, 2008).

According to Markard et al. (2012), the shift of established socio-technical systems towards more sustainable modes of consumption and production can be referred to as sustainability transitions. These shifts are characterised as being long term, multidimensional, and fundamental in nature. Therefore, any policy decisions aimed at facilitating transitions should incorporate long time horizons. Patterns of growth and technological change are long term in nature and build on one another, creating path dependency and leading to technological and institutional lock-in (OECD, 2011). Grubler (2012) points to three factors that can explain the slow technology transition rates: (1) technology interrelatedness plays a role, because technology systems experience slower transitions the more complex they get; (2) infrastructure needs is a factor, because increasing infrastructure intensiveness increases transition time of the system; and (3) scale, or market size, is a factor, as larger systems take more time to change than smaller systems. This last factor partly explains why developing and emerging economies will have an increasing influence on the future of the global energy systems. According to Grubler (2012), countries on the energy periphery, with smaller and less developed energy systems, might find it easier to transition away from fossil fuels. The countries already ‘locked-in’ into larger fossil fuel energy systems, mainly OECD countries, might face higher hurdles and have to wait longer for their next energy transition. Geels (2002) states that technological reconfigurations are a difficult process, because the elements in a socio-technical system are all linked and aligned to each other.

Smith and Stirling (2008) point to the fact that incumbent technology regimes have an advantage over more sustainable socio-technical practices. Geels (2002) states that radical new technologies are mismatched against established technologies, because of the established socio-institutional frameworks. Existing and established technologies are better aligned with regulations, infrastructure, user practices, and maintenance networks. The mismatch can be attributed to distinct structural disadvantage of sustainable systems related to the fact that incumbent systems are more established, and thus seem economically more attractive and politically stronger (Smith & Stirling, 2008). Incumbent systems can be considered as being more structurally resilient, but they may become destabilised when they can no longer resist and tolerate shocks and stresses. This could lead to their decline and make them vulnerable to transitions towards more novel systems. Innovation plays an important role in shifting technological transitions. The ease with which societies and economies become dependent on established technologies makes transitions an often slow and difficult process, even when the shift holds great advantages. Innovation plays a key role in breaking these dependencies and facilitating technological transitions (OECD, 2011).

There are also factors that can speed up transitions, according to Grubler (2012). A major factor is the comparative advantage of the technology system compared to incumbent technologies; the higher the comparative advantage – comprising multiple dimensions – the faster the transition toward the new technology system. Another factor is the existence of niche markets that could act as testing beds for scaling up novel technologies: it is easier to displace an existing technology with one that has been tried and tested, than to create a new one from scratch. Grubler (2012) states that the process of scaling-up technological solutions drives the technological energy transitions, but that successful scaling-up requires prolonged periods of experimentation and learning.

Smith and Stirling (2008) agrees that niche markets provide an environment that is less susceptible to market pressures, and where sustainable systems can develop, improve, and gain support. The identification of transition pathways is essential in providing a framework for the support and development of socio-technical practices and systems. Transition management is responsible for governing transitions towards more sustainable socio-technical systems, and is critical in supporting the above mentioned developments. Another aim of transitions management is to execute socio-technical transitions that improve performance in the desired sustainability functions. What transition management proposes includes new governance arrangements informed by socio-technical transitions theory (Smith & Stirling, 2008). A prevalent problem is how this interacts with prevailing policy institutions and political processes. The basis for its authority, legitimacy, and accountability will ultimately depend on how it engages with other political processes and institutions (Smith & Stirling, 2008). Markard et al. (2012) describes transitions management as a discipline that combines the work on technical transitions with insights from complex systems theory and governance approaches. The guiding principles for transition management have evolved from conceptualising existing sectors as complex, adaptive societal systems (Markard, et al., 2012).

The developing transition towards the implementation green technologies will be far more of a global process than any technological transition that has ever taken place (Ocampo, 2012). International institutions will have to play a critical role in developing cooperation between different nations. Most of the technological development is expected to take place in countries with developed industrial sectors. International inequality related to technology capacities is of great concern, and effective technology transfers will have to take place for these technologies to be implemented in less developed parts of the world. Growing local capacity for technology development in these less developed nations could also be a possible solution (Ocampo, 2012). International cooperation is essential for narrowing the gap between developed and developing countries. Cooperation is required for the transfer of technological knowledge, but also in order to build up economic, technical, and managerial capabilities to use the transferred technology and to further develop it (Khor, 2012).

Grubler (2012) points to three characteristics of successful energy systems and policies driving transitions. Firstly, persistence and continuity of policies are key factors to facilitating energy transitions, mainly due to the fact that energy transitions take a long time and that technological knowledge needs to be continuously nurtured. Secondly, the alignment of these policies is critical to the success of a technology transition, with actors and mechanisms involved in transitions requiring consistent and contradiction free policy signals. Lastly, balance is required in portfolios and policies due to the need for diversification in order to hedge against technology uncertainties and risks.

Technology uncertainty is experienced when there are a number of solutions for a certain problem. This gives rise to uncertainty relating to which solution is the best suited when all economic, social, technical, and environmental factors are taken into account (Musango & Brent, 2011). Musango and Brent (2011) state that the development of technology is systemic and cannot be treated as a single isolated event; technology change should be considered as being cumulative, building on previous experience and knowledge. Large scale changes in technological systems are often very challenging because of the interdependence of technologies.

The report that brought sustainable development into the global spotlight - the Brundtland Report (WCED, 1987) - recognises the importance of realigning technology as the key link between humans and nature. The report outlines the need to enhance the capacity for technological innovation in developing countries, in order to give them the means to effectively respond to the challenges of sustainable development. It also discusses the need for technological development to take environmental factors into consideration by managing the orientation of technological development. Musango and Brent (2011) state that technology systems – throughout their entire life cycle – have an impact on the three dimensions of sustainable development: economic, ecological, and social.

According to Musango and Brent (2011), technology is embedded in the sub-system of the economic, societal, and environmental spheres, as related to sustainable development, see Figure 3.1 below.

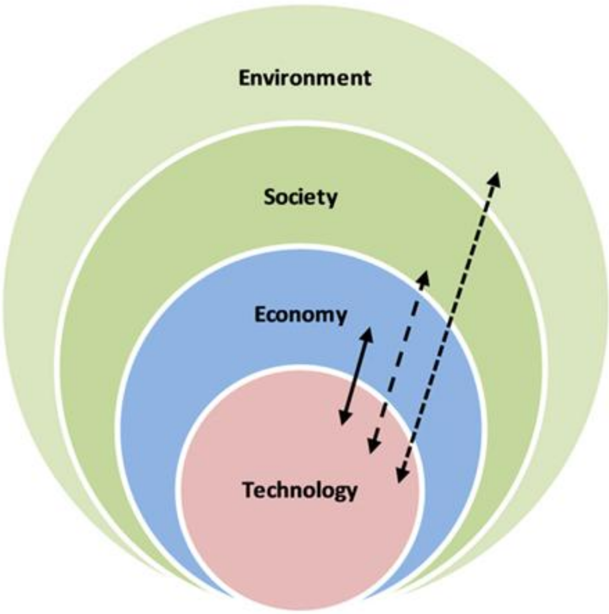

Figure 3.1: Technology as a sustainable development sub-system (Musango & Brent, 2011)

Transformation must be driven towards new dynamic green activities by active development strategies. These strategies should have effective technology policies at their core, with a focus on adaptation and dissemination of green technologies (Ocampo, 2012). The public sector needs to implement policies to encourage green innovation. These policies, however, are often subject to certain challenges and barriers that counter their effectiveness: insufficient demand for green growth; lack of innovation capability; technological roadblocks; research and investment bias to incumbent technologies; lack of finance; and SMEs lacking capabilities to adopt green innovation (OECD, 2011).

3.2. The role of energy in a green economy transition

Grubler (2012) states that current energy systems are unsustainable on all accounts of social, economic, and environmental criteria, and that the urgency for an energy transition is widely apparent. Energy services are a basic human need, but impacts caused by the extraction, conversion, and use of energy form a major component of global environmental and social problems. This makes it clear that the character of energy systems plays a critical role in the human condition and the prospect of improving it (Sagar & Holdren, 2002).

A sustainable society cannot be created without the design and implementation of a sustainable energy sector (Omer, 2008). Dincer (2000) argues that energy is one of the most important factors to take into consideration when discussing sustainable development. He further states that the development of energy supply from fully sustainable resources is critical to achieving sustainable development. Sustainable supply of energy does not only refer to environmentally friendly or renewable sources of energy. Sustainable energy sources must also be readily available at a reasonable economic cost and be utilised without having any negative impacts on society (Dincer, 2000). This highlights the connection between renewable energy technologies and the concept of sustainable development. Araujo (2014) states that the costs related to global energy entail more than just finance: political, environmental, security and societal effects are difficult to monetise. Understanding the relationships between these effects, the trade-offs they present, and understanding how to effectively address them is an underlying concern for decision-makers (Araujo, 2014).

The energy sector has experienced a long evolution, with technological advancements being the key driver behind it (Sagar & Holdren, 2002). These advancements have managed to increase the usefulness of energy, while reducing costs and risks. Other advancements have contributed to expanded energy supplies, increasing efficiencies, improving energy availability, improving energy quality, and reducing dangerous environmental impacts (Sagar & Holdren, 2002). Grubler (2012) argues that the fundamental drivers of historical energy transitions originate from transformations in energy end-use. Grubler (2012) also argues that energy demand and supply systems co-evolve, with their transformations mutually enhancing one another. Long-term planning is an intrinsic demand of sustainable energy technology development. The complex nature of the interaction of energy systems with the sustainable development sub-system leads to required changes in these systems to be of a long-term nature (Musango & Brent, 2011). Figure 3.2 illustrates the role and interaction of energy technology systems within the sustainable development sub-system.

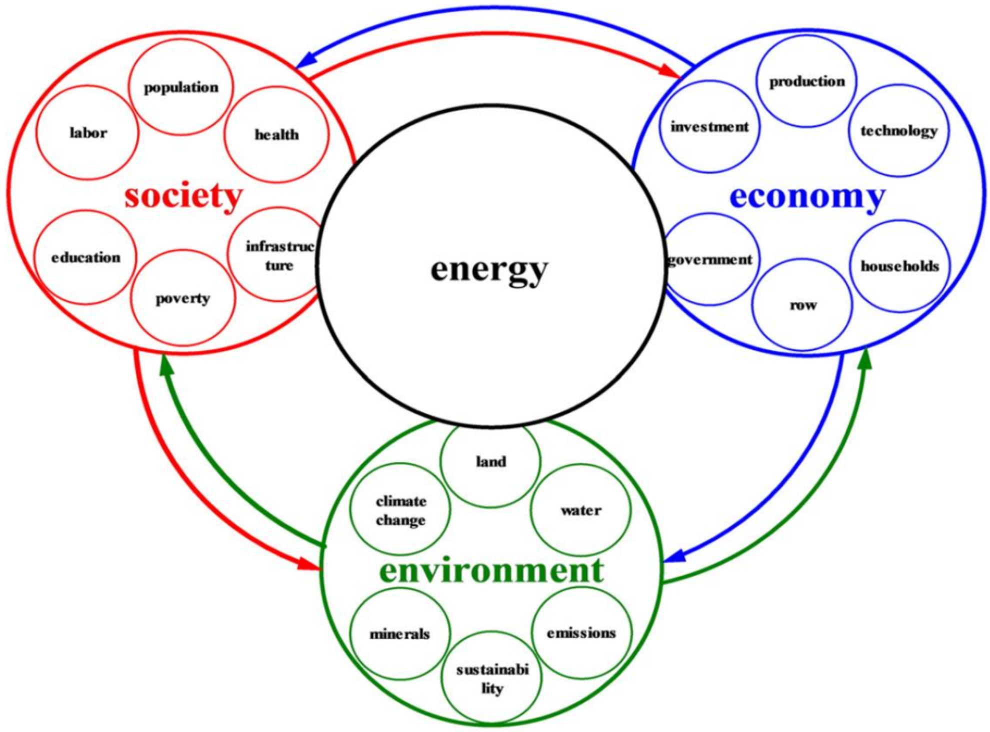

Figure 3.2: Interrelationship between energy systems and the sustainable development sub-systems (Bassi, 2009)

Economic growth is very closely linked to energy development, particularly in developed countries. The clean energy economy should not be defined as a single industry, but comprises all businesses that contribute to the conservation of energy and the development of alternative energy sources (Li, et al., 2010). The Pew Charitable Trust (2009) gives the following definition to the clean energy economy: "*An economy that generates jobs, business and investments while expanding clean energy production, increasing energy efficiency, reducing greenhouse gas emissions, waste and pollution, and conserving water and other natural resources*". Business establishments and jobs are the two pillars of the clean energy economy, and the growth of green jobs and green businesses are essential to clean energy development (Yi, 2014). The OECD (2011) states that transitioning to a cleaner energy sector has the potential to generate large net employment gains, estimating that the renewable energy industry could create up to 20 million jobs by 2030.

UNEP (2011b) identifies energy efficiency and renewable energy as sectors that have strategic importance in successfully transitioning to a green economy. Therefore, these sectors should receive special attention when investment and policy decisions are made. UNEP (2011b) also identifies these sectors as ones where responsible investment could lead to new sectors and technologies acting as the main sources of economic development and growth in the future.

A critical component to poverty alleviation is making basic infrastructure and services accessible to everyone, including the most marginalised sectors of the population (UNEP, 2011b). Access to energy is a basic need, and addressing energy poverty makes a significant contribution to eradicating poverty in a broader sense. Renewable energy technologies have far greater potential to address energy poverty issues, compared to their fossil fuel counterparts. They can play a cost-effective role in reversing global energy poverty (UNEP, 2011b).

The environmental sustainability of renewable energy systems is seen by many as being undisputable. The concern with renewable energy technologies is whether they can be economically sustainable without the support of government subsidies and investments. The private sector is likely to shy away from renewable energy technologies if their economic sustainability is still in question. Public sector support for renewable energy technologies has jump-started the growth of the industry, and has contributed to the falling price of electricity generated by these technologies. It remains to be seen if the private sector can find enough potential for profit creation, which is needed to propel them into widespread and large-scale implementation. Many experts argue that the cost of renewable energy will be far lower than those of fossil fuels, if the environmental and social costs of using fossil fuels are taken into account.

The culmination of improved technology and greater efficiency should reduce the price of renewable energy technologies and make them more competitive against conventional energy sources. Dincer (2000) identifies four activities that should be given priority in order to realise the benefits of renewable energy sources: (1) Research and development (R&D) should be conducted in close consultation with public departments and private industry, in order to ensure inclusion of stakeholder needs; (2) technology assessment should be conducted on cost benefit, reliability, environmental impact, safety, and opportunities for improvement; (3) the development of standards is required in order to promote acceptance of new technologies into the marketplace; and (4) technology transfer should be encouraged through sharing R&D methodologies and results.

The direct contribution of the energy sector, in South Africa and the Western Cape, to GDP is relatively small. The sector does, however, play a significant role in serving as a critical input for all other sectors of the economy. Those sectors of the economy that are the most energy intensive, and thus most reliant on energy supply, are often also the ones that are most labour intensive (Deloitte, 2012). This is true for the mining and manufacturing sectors in the country, which also make the biggest contribution to South Africa’s exported trade.

3.3. Sustainability indicators for energy technologies

It is well known that the earth’s supply of renewable energy sources dwarfs its reserves of fossil fuel resources. The sun is ultimately the biggest supplier of energy to earth, with solar energy being converted into other forms of energy that fuel many of the earth’s natural processes. Solar energy allows crops to grow through the process of photosynthesis. Solar energy also heats up our atmosphere and causes disparities in air pressure, leading to wind energy. Wind energy causes waves to form, from which wave energy can be obtained. The hydrologic cycle is also driven by solar energy, leading to rainfall and the ability to harness hydro energy. Together with the moon, the sun is also responsible for tidal rise and fall. With all these sources of energy, the energy supply we need to sustain ourselves is readily available. The challenge lies in solving problems related to the dispersed nature, accessibility, and regional variability of renewable energy sources (Dincer, 2000). What we require is research and technological advancement to harness and utilise these sources of energy. Dincer (2000) argues that the scientific understanding of the processes is the easy part; it is the engineering part that is difficult to conduct.

Omer (2008) describes absolute sustainability of electricity supply as no depletion of world resources and no ongoing accumulation of residues. A technology must be absolutely sustainable in order to be considered as being a renewable energy technology; nuclear energy is seen as not being absolutely sustainable, but being more sustainable than fossil fuel technologies (Omer, 2008). Coal-based power generation has the highest carbon dioxide emissions per kWh, and is also a major contributor to pollution through sulphur oxides and nitrogen oxides (Evans, et al., 2009). Global warming is not the only concern connected to energy supply and power generation. Other environmental concerns include air pollution, acid rain, ozone depletion, forest destruction, and the release of radioactive substances (Omer, 2008).

Renewable energy technologies are considered as being environmentally sustainable, but their implementation should never decrease the quality or reliability of electricity supply. Renewable energy sources and their electricity output can easily be predicted, but can very seldom be controlled. Therefore, renewable energy technologies are often difficult to implement in the form of base-load electricity supply. The intermittent nature of renewable energy supply will require these technologies to be used in conjunction with large-scale energy storage, and other sources that are capable of constant and controllable electricity supply (Omer, 2008). The operating and financial attributes of traditional fossil fuel based power technologies include large capital investments, long construction lead times, and operating cost uncertainties caused by the fluctuation of fossil fuel prices (Dincer, 2000). Renewable energy technologies, on the other hand, can be described as possessing modularity and flexibility, and having low operating costs.

Sustainability indicators for energy systems should always take into account the environmental, social, and economic aspects of the energy technology. Any energy system will have an impact on each of these three spheres, and the impact on each should be considered and measured. Communication on energy issues by policy makers and the public are mostly carried out with the use of indicators. The purpose of an indicator or set of indicators is to convert basic statistical information in order to provide a more comprehensive understanding of an issue or dimension (Iddrisu & Bhattacharyya, 2015). It helps to develop an overview of the entire system, including its inter-linkages and trade-offs. The wide range of sustainable energy indicators that exists points to the concern that there is uncertainty and ambiguity concerning the sustainability components, their inter-linkages, and the indicators (Iddrisu & Bhattacharyya, 2015). This is due to a knowledge gap that can be attributed to the lack of a systematic focus and incomplete coverage on sustainability components (Iddrisu & Bhattacharyya, 2015).

Iddrisu and Bhattacharyya (2015) suggest a Sustainable Energy Development Index (SEDI) to evaluate the sustainability of existing energy supply systems. This index makes use of five different dimensions of sustainability: technical, economic, social, environmental, and institutional sustainability. The technical dimension involves the supply side of the energy system and its ability to meet the present and future energy demands reliably, efficiently, and from a clean source (Iddrisu & Bhattacharyya, 2015). The combination of the availability of resource inputs and the ability of the installed physical infrastructure to produce outputs is what defines the ability of the system to meet energy demand. The economic dimension evaluates the affordability and cost effectiveness of the system. Affordability relates to the ability of society to afford and access the energy supply, and cost effectiveness relates to whether the system is economically viable enough to attract reinvestment from the private sector. Another important aspect of economic sustainability is observing how much of total energy supply is used for productive purposes – activities that contribute to GDP – and also the energy efficiency of these activities.

The social dimension looks at the accessibility and acceptability of the energy system by society (Iddrisu & Bhattacharyya, 2015). Accessibility involves wealth distribution and access to basic energy services, while acceptability looks at the fact that society will accept what they perceive to be fair and offering equal opportunities to all. The environmental dimension looks at the impacts that the physical disruption and release of waste from the energy systems have on the environment and biodiversity. The institutional dimension involves the institutions defining the structure of the energy industry. These institutions are required to manage and control the other four dimensions, and are the link between the energy system and the external world. The institutions are subject to, and significantly influenced by, political stability and foreign policy. The system structure and the framework of processes are defined by this dimension, which then influences the policy decisions that are taken. Local ownership and participation, local skills base, and local regulation and protection of investors and consumers are all aspects that are defined by this dimension.

Sustainability indicators for energy technologies should account for the entire energy chain life-cycle: from mining and processing all the way through to disposal or recycling (Evans, et al., 2009). Evans et al. (2009) suggest seven key indicators that should be used when assessing the sustainability of energy technologies: price of electricity; GHG emissions; availability of the energy technology; efficiency of the energy technology; land use; water consumption; and social impacts.

Sustainable energy is a fairly complex issue and includes dimensions that are often regarded as being intangible. This makes it challenging to capture the state of these dimensions with simple indicators, leading to a trade-off being required between complexity and ease of use (Iddrisu & Bhattacharyya, 2015). Based on a sustainability assessment, conducted by Evans et al. (2009), wind energy was found to be the most sustainable form of electricity generation, followed by hydropower, geothermal, and solar PV.

3.4. The state of the energy sector in South Africa

South Africa's National Development Plan (NDP) aims to ensure that the country has an energy sector that promotes economic growth and development, social equity through expanded access to energy services, and environmental sustainability through efforts to reduce pollution and mitigate the effects of climate change (Department of Energy, 2014). Significant investments in the energy sector are required in order to ensure security of supply and adequate infrastructure, which supports and facilitates economic development. This requires the support of effective policies, institutions, governance systems, regulations, and competitive markets.

There are numerous socio-economic benefits related to increasing the local content factor of renewable energy projects in South Africa. It will boost economic growth and increase employment, which will lead to improved standards of living. Careful consideration should be taken of the current capabilities and capacities, and also the timeframes that will be required for the expansion of existing capacities or the building of new ones. Ahlfeldt (2013) suggests four factors that need to be addressed in order to facilitate localisation efforts and encourage investments in developing local capabilities: (1) break down administrative barriers that inhibit international companies from establishing local manufacturing facilities; (2) create incentives by offering guarantees or preferential financing for projects involving local companies; (3) some technology risks of unproven components should be carried by government; and (4) encourage scaling up of existing manufacturing facilities, as it is more expensive to build new ones. There are fears that the overarching goal of the current REIPPP programme – to ensure the security of electricity supply – could undermine the secondary goal of employment creation through localisation strategies.

The Integrated Resource Plan (IRP2010) (Department of Energy, 2013b) states the intention to add 17.8 GW of new renewable energy generation capacity by 2030. This new capacity will consist of 8400 MW wind power generation, 8400 MW solar PV generation, and 1000 MW Concentrated Solar Power (CSP) generation. The majority of these projects are expected to be situated in the Northern, Eastern, and Western Cape Provinces; these areas have the best renewable energy resources in the country. Most of this capacity will be added through the REIPPP programme, and is expected to attract annual direct investments in the order of R20 billion (Western Cape Government, 2013a).

The IRP suggests large investments in nuclear and coal energy technologies, apart from the investments in renewable energy technology (Department of Energy, 2013b). New coal is expected to rapidly increase the generating capacity of Eskom, with the parastatal having committed to building over 10 000 MW of generating capacity from coal by 2020. Medupi and Kusile are expected to provide the bulk of this expansion, but their commissioning dates have been significantly delayed. Nuclear energy is expected to add 9600 MW of new capacity between 2023 and 2029, but the government has not signed any deals yet and these goals are set to be missed. Apart from the 10 00 MW committed build capacity, the IRP also predicts over 6000 MW of new build coal power between 2014 and 2030. A total of 2600 MW is expected to come from new hydro projects. Nuclear and coal energy have the disadvantage of long lead times, with some projects taking as long as ten years from signing the deal to delivering power at full capacity. New gas power projects are expected to add just over 6000 MW of power between 2019 and 2030.

3.5. The state of the energy sector in the Western Cape Province

An important factor to keep in mind is that primary electricity supply in South Africa is a mandate of the National Government (under the National Energy Act, Act 34 of 2008). Not all the electricity generated in the Western Cape Province is used within its borders, and not all electricity consumed in the Province originates from within its borders. The role played by Eskom in electricity generation is expected to change in the future. The parastatal is expected to occupy a declining role, as IPPs are set to develop a growing share of the national electricity generation capacity (Palmer & Graham, 2013). The Western Cape Government (WCG) is expected to play a critical role in assisting these IPPs to develop projects within the region.

Local municipalities manage and are responsible for about 60% of the electricity distribution system in the province, with Eskom being responsible for the remaining 40% (Palmer & Graham, 2013). In the past, infrastructure planning has been hampered by the lack of cooperation between national, provincial, and local governments. The success of large infrastructure initiatives is crucially dependent on cooperation between the different tiers of government. The ability of the WCG to finance large infrastructure projects depends on economic growth, in the form of tax revenue.

The ‘Energy Vision’ of the WCG is: ‘*To ensure that the WC has a secure supply of quality, reliable, clean energy, which delivers social, economic, and environmental benefits to the Province’s citizens, while also addressing the climate change challenges facing the region and eradicating energy poverty*’ (Western Cape Government, 2007).

The WCG’s future energy plans do not quite line up with those proposed in the national government’s IRP of 2010. Both the national and provincial governments acknowledge the importance that renewable energies will play in the expansion of power generating capacity, but the WCG places more emphasis on the use of natural gas, as opposed to nuclear and coal. The use of natural gas is expected to function as a transition from a carbon intensive energy mix to a truly renewable energy future (Western Cape Government, 2013a). It is seen as a ‘game changer’ needed to increase power capacity, but still reduce the Province’s carbon footprint. Saldanha Bay has been identified as a possible concentration point for the future gas industry.

The Western Cape Infrastructure Framework (WCIF) (Palmer & Graham, 2013) was developed with the goal of aligning planning, delivery, and management of infrastructure in the Western Cape Province to the strategic agenda and vision for the Province. An expected R850 billion will be required between 2012 and 2040 in order to cover the required infrastructure investments in the Western Cape Province, with the national government remaining a primary financier. The report divided infrastructure in the province into five major systems: energy, water, transport, settlement, and information and communication technology (ICT). It states that the energy focus is on reducing the carbon footprint in the province, with the priority of increasing renewable and locally generated energy. The WCIF states that the energy goals of the IRP are not sustainable, due to the high reliance on coal and nuclear power sources. Two key transitions in the energy sector of the province have been identified by the WCIF: (1) making gas available as a transition fuel by developing natural gas processing and transport infrastructure; and (2) ensuring the development of renewable energy infrastructure and manufacturing capabilities.

The Western Cape Province has the potential to become a major research and servicing hub for the renewable and gas energy sectors in South Africa and the African continent (Western Cape Government, 2013a). The first two rounds of the REIPPP programme saw eight wind and solar projects being approved in the Province. These projects are estimated to contribute a direct investment of just under R8 billion (Western Cape Government, 2013a). Some of the world’s leading solar PV manufacturers have opened facilities in the Western Cape. Two solar PV manufacturing facilities were opened in the province in 2012, with three more having opened in 2014. The town of Atlantis, 40 km North of Cape Town, has been developed as a Special Economic Zone (SEZ) with the goal of concentrating renewable energy and advanced manufacturing industries in this area. Gestamp Wind opened a wind-tower manufacturing facility, worth R300 million, in this zone in 2014 (Creamer, 2014).

From an innovation perspective, the expansion of gas and renewable energies in the region would offer R&D and design opportunities to universities and industry, further encouraging investment in this sector. This does require an enabling environment brought on by lobbying and collaboration between national government departments, provincial government departments, agencies, and the private sector.

3.6. The state of electricity technologies in the Western Cape Province

The majority of the Western Cape Province's electricity supply originates from the Koeberg Nuclear Power Station. This supply is supplemented with electricity from a number of gas power plants, which currently run on diesel fuel, and two pumped storage power plants. Renewable energy supply has only recently begun to supply any significant amounts of electricity to the grid. Wind and solar PV technologies make up the majority of the renewable energy capacity that has been added over the past three years, predominantly through the REIPPP programme. These two renewable energy technologies will most likely continue to make up the majority of new renewable energy capacity over the next few decades. Gas power technologies, together with renewable energy technologies, are earmarked to transition the Province's electricity sector to one that is more in line with a green economy.

3.6.1. Electricity from wind power

'Bigger is better' is often a phrase that is synonymous with wind energy. The capability of a wind turbine to generate electricity increases by the square of its blade length, and increases by the cube of the wind speed (Welch & Venkateswaran, 2009). The largest wind farms in the world are operating at capacities above 1000 MW, with a 20 000 MW wind farm planned in China. Wind energy has moved ever closer to being competitive with conventional energy sources, mainly due to continuing advancements in technologies and improvements in efficiencies (Maia, et al., 2011).

The price of electricity supplied by wind farms in South Africa has dropped by 43% between 2011 and 2014 (Eberhard, et al., 2014), and some wind farms are expected to produce electricity at costs that are lower than that of Eskom's coal-power fleet. The average price per kWh for wind energy projects under the first bid window of the REIPPP programme was R1.14, with average prices decreasing to R0.74 in bid window 3 (Eberhard, et al., 2014). All the large wind farms in operation or under construction in South Africa have been started under the REIPPP programme. A total of 34 wind energy projects were approved during the first four rounds of the programme. This amounts to total installed wind capacity, commissioned under the REIPPP programme, of 3343 MW, and a total investment of over R50 billion. Six of these projects are being developed within the Western Cape Province.

South Africa, and particularly the Western Cape Province, has significant wind energy potential. Figure 3.3 shows the wind atlas for the country, with the red and yellow areas showing high and medium mean wind speeds. A large portion of these areas are situated within the Western Cape, making it ideally suited to become the wind energy hub in the country. The South African Wind Energy Association (SAWEA) estimates the national wind power capacity to be as high as 30 000 MW.

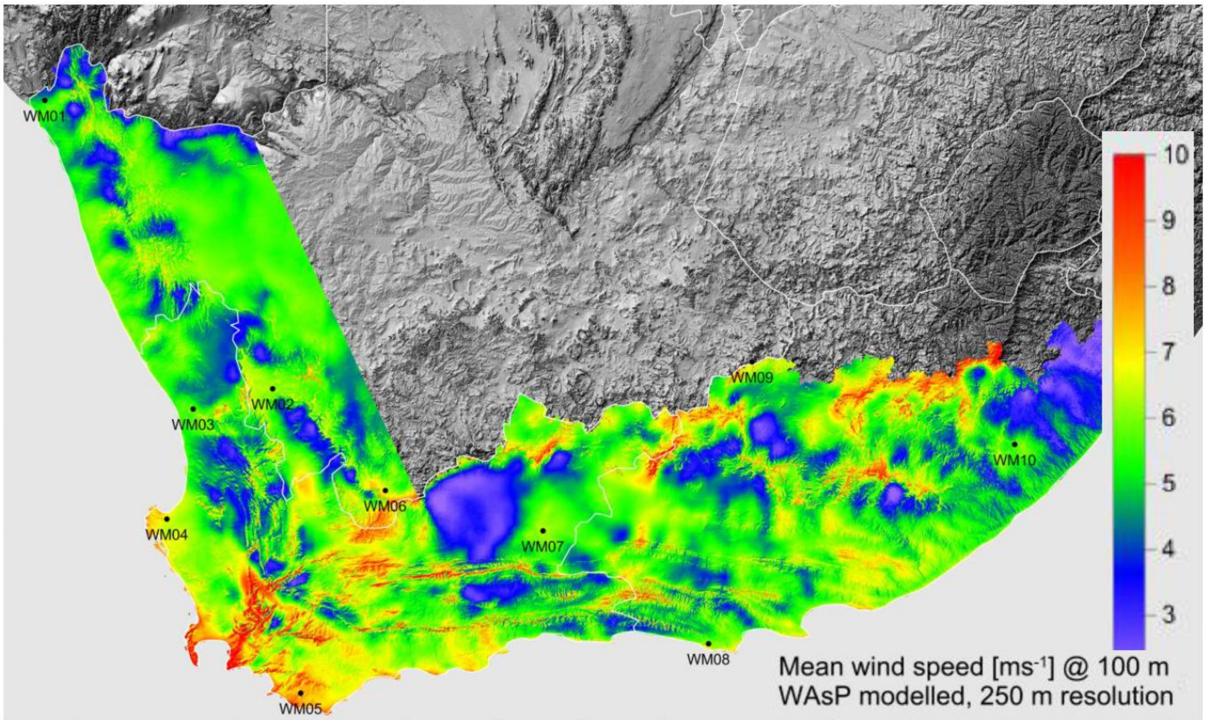

Figure 3.3: Wind atlas of South Africa (WASA, 2013)

Wind energy technologies have short construction periods and need less time for overall plant completion when compared to conventional power stations. Very low lifecycle emissions are another advantage of wind energy technologies (Maia, et al., 2011). Wind farms have the potential to be completed in a modular manner, with individual turbines coming online and generating electricity while the others are still being erected. Wind energy, in its operational phase, has many advantages related to the conservation of the environment and ecology (Maia, et al., 2011). It has no reliance on water sources and does not put pressure on water supply, as is often the case with many conventional power stations. It has minor degrading effects on the land, very little pollution risk, and very little health risk to people (Maia, et al., 2011). The general consensus is that wind energy is a very clean and safe form of power generation.

As with any form of technology, there are a number of social and environmental concerns related to the use of wind energy technologies. A major concern is the possibility that wind turbines could negatively affect bird life. One wind farm in the United States has recorded an annual body count of up to 4700 birds, some of which are endangered species (Ritter, 2005). This wind farm is, however, situated on a well-known migratory path for birds. A better understanding of the interaction between birds and wind turbines could, in the future, prevent such situations. Wind farms are large and prominent and often regarded as visual pollution. This could affect tourism and even the housing market. These concerns should be addressed by conducting environmental impact assessments before a wind farm is approved. A further concern for onshore wind farms is the possibility of them interfering with military and civilian radar systems (Welch & Venkateswaran, 2009). This could pose a threat to the safety of individuals in areas where onshore wind farms are operational. Concerns also exist regarding the interference of offshore wind farms with boating, fishing, and shipping activities (Welch & Venkateswaran, 2009).

Natural variation in wind power on a daily and seasonal basis means that wind strength and patterns can be predicted, but never controlled. Wind farms are generally built in areas where the power generation capacity factor is at a maximum, but even the best positioned wind farms cannot produce electricity on a continuous basis. Intermittent power supply is inherent to wind energy and makes it necessary to use it in combination with other sources of power generation.

Vestas, a company headquartered in Denmark, has been the largest wind turbine manufacturer for the past few years, with just over 13% of the global market share in 2014 (Energy Digital, 2015). The market has always been dominated by European manufacturers such as Siemens, Enercon, Gamesa, and Nordex. General Electricity is headquartered in the USA and has competed very well with the European manufacturers. Chinese manufacturers, such as Goldwind, United Power, and Ming Yang, have also gained significant market share over the past few years. So too has Sulzon Group, which is an Indian manufacturer. In South Africa, Vestas secured the highest number of wind energy projects under the REIPPP programme – a total of eight – with Nordex and Siemens each securing four projects (UEDE and EScience Associates, 2015). The other manufacturers with projects are United Power, Sinovel, Acciona, and Suzlon.

A big challenge for wind energy expansion in South Africa is the shortage of skills in some professional fields, which means that skills would have to be imported. This would happen by, firstly, attracting professionals from abroad to work in the country, and, secondly, by getting these individuals to transfer these skills to local professionals. Another challenge is the isolated nature of some potential sites, requiring expansion of transmission infrastructure and raising transmission costs.

Significant potential exists in South Africa for the manufacturing of wind energy components, particularly the blades and towers that could be manufactured by adapting existing steel manufacturing facilities (Maia, et al., 2011). The number of manufacturing jobs created by the wind energy sector is dependent on the degree of localisation that will take place. Localisation, in this regard, refers to the degree to which parts and components will be manufactured locally. The construction and operation phases will create definite jobs, as local labour is needed to construct the facilities and then also to operate and maintain them. The growth of wind energy sectors in other African countries could offer opportunities for South African companies involved in supplying components and parts, construction and installation, and operation and maintenance of wind farms. It is estimated that about two-thirds of the total jobs in a wind power value chain can be attributed to manufacturing activities (Maia, et al., 2011), thus highlighting the importance of encouraging localisation of manufacturing activities.

The manufacturing of the towers, on which the turbines are mounted, tends to be the first activity to be localised. Towers are large, and expensive and difficult to transport over large distances. Three local firms – DCD Wind Towers, Gestamp Renewable Industries, and Concrete Units – are currently involved in the manufacturing of these components (UEDE and EScience Associates, 2015). No blade manufacturing facilities currently exist in South Africa. The main reasons for this is that the manufacturing process is investment intensive, labour intensive, and requires a skilled labour force. It is also a precision process to manufacture the blades and the market size is perceived to be too small for now. A single blade manufacturing facility could cost up to R500 million to set up and would take 12 months to be constructed (UEDE and EScience Associates, 2015). The nacelle unit – housing most of the rotating mechanical parts and electronics – is the least likely component to see localisation, but assembly facilities could possibly be set up. These facilities would procure the parts from reputable suppliers and then assembly the nacelle units locally. No local companies are currently involved in manufacturing or assembling of these units and the potential to do so is limited by the complexity of the manufacturing process. The need for highly specialised labour and high input costs further hamper the possibility of this expansion. If local manufacturers can expand into markets beyond South Africa, then the potential exists for up to five new tower manufacturers and four blade manufacturers to be established in South Africa (UEDE and EScience Associates, 2015).

3.6.2. Electricity from solar power

The dominant renewable energy source for the foreseeable future is considered by many to be solar power. South Africa's solar energy resource is amongst the highest in the world, with the country having almost 300 days of sunshine per year. Germany, France, and the United Kingdom all produce significantly more power from solar resources, yet they possess far less of the resource than South Africa does.

The map in Figure 3.4 shows the distribution of solar resources across the country.

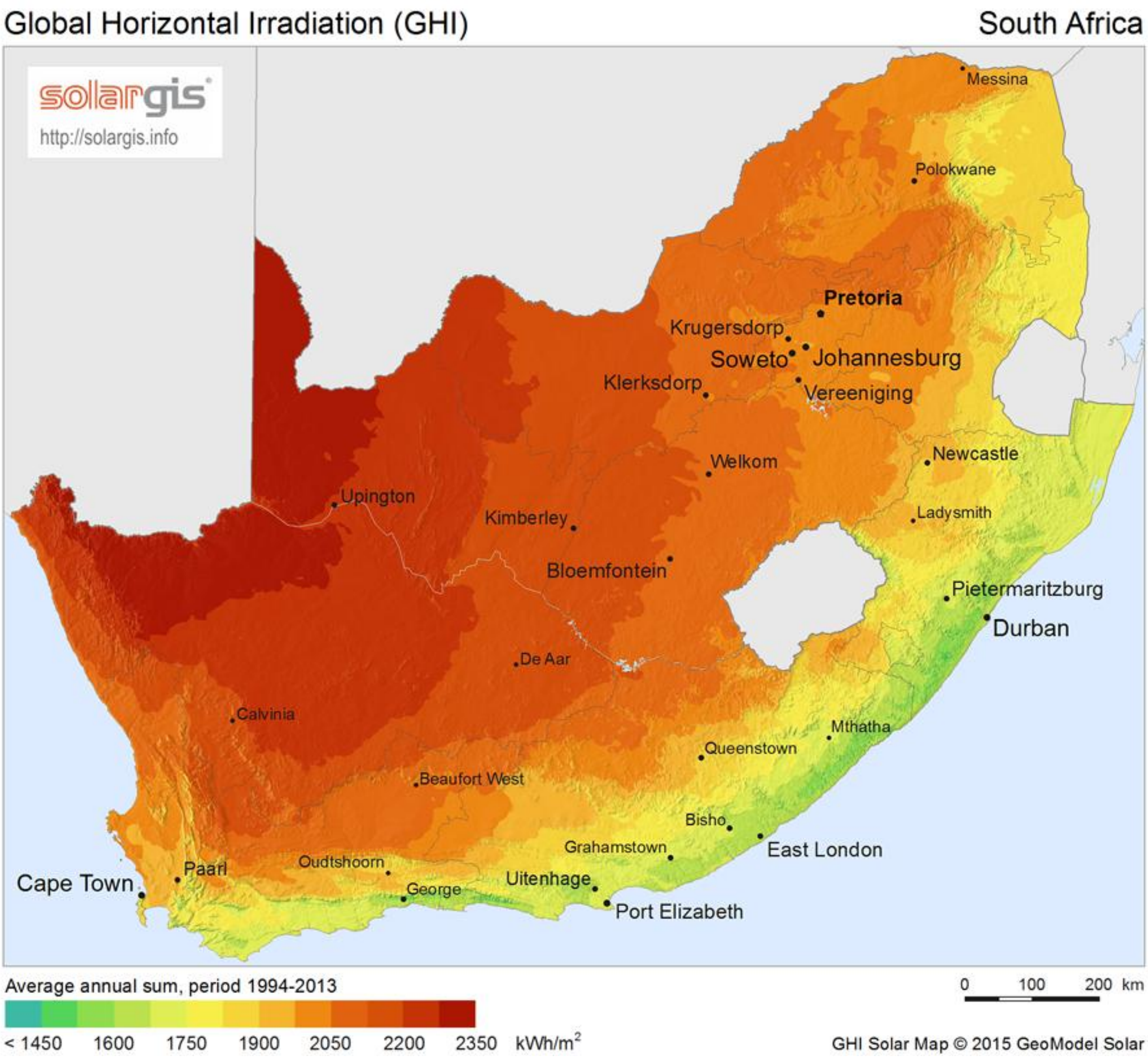

Figure 3.4: Annual solar radiation for South Africa (SolarGIS, 2015)

Utility scale solar power technologies can be grouped into two main categories: solar PV and concentrated solar power (CSP). The Northern parts of the country receive the highest annual solar radiation, making them ideally suited for CSP plants. PV plants can operate in areas with less solar radiation, making the majority of the country suitable for PV applications. Only very small areas of the Western Cape Province are suitable for CSP plants, but the province is ideally suited to generate power from PV applications. The size of CSP plants usually range from 50 MW to 300 MW, with most plants being located in Spain, the USA, North Africa, and the Middle East.

A CSP plant generates heat by making use of solar power, allowing it to be used in hybrid configurations with fuel or steam based power systems and industrial heat applications (Maia, et al., 2011). A big advantage of CSP is that it can solve the intermittency problem, experienced by many renewable energy sources, by making use of integrated heat storage systems. Other advantages include short construction periods, fixed operational costs, and the fact that the plants use fairly familiar and established technologies (Maia, et al., 2011). The use of CSP plants has a few disadvantages: high initial capital costs and substantial water requirements for wet-cooled plants (dry-cooling uses less water, but decreases plant efficiency). The average cost per kWh for CSP projects under the first bid window of the REIPPP programme was R2.69, decreasing to R1.64 under the third bid window (Eberhard, et al., 2014).

CSP technologies are very well suited to South African conditions, and there is significant potential for the development of utility-sized power plants. A total of seven CSP plants are operating or under construction in South Africa, with all of them being developed under the REIPPP programme and all located in the Northern Cape Province. This represents a total installed capacity of 600 MW, and a total investment of over R40 billion (Eberhard, et al., 2014). The development of CSP plants in South Africa, and the rest of Africa, is a great opportunity for local industries to expand their manufacturing capacities and capabilities, and to supply this growing sector with parts and components. The Western Cape Province is not an ideal location for the use of CSP technologies, but it is ideally positioned to become an important hub for the manufacturing of parts and components for the CSP market. Many of the CSP components can be manufactured in already existing production facilities, with minimal modification to the facilities. The Province also has strong research capabilities in this field, with two major universities in the area. These factors increase the potential for commercialisation in the area.

PV systems consist of cells, made up of layers of semi-conducting material, which convert solar radiation directly into electrical power. The amount of electricity generated by each cell is proportional to the intensity of solar radiation reaching the cell. Cost reduction and electrical efficiency improvements are the main focus of current advancements in the technology, with these factors determining which products become the technology leaders.

The costs of solar PV systems have decreased substantially over the last decade, with costs expected to reduce further until 2020 (Ahlfeldt, 2013). Between 2011 and 2014, the bid prices for solar PV projects in the REIPPP programme fell by 68% (Yuen & Luciani, 2014). The IHS, a global information company, rated South Africa as the most attractive emerging market for PV technologies (Woods, 2014). The company praised the country for cultivating a policy environment stable enough to attract financing from commercial banks. The average cost per kWh for solar PV projects under the first bid window of the REIPPP programme was R2.76, decreasing to R0.99 under the third bid window (Eberhard, et al., 2014). A total of 45 solar PV projects are operating or under construction – all being developed under the REIPPP programme – for a total of 2297 MW of installed capacity, and representing close to R60 billion in investments. Five of these projects are located in the Western Cape.

A major barrier for the widespread adoption of solar PV technologies remains the large initial upfront investments that are needed; such projects are characterised by high start-up costs. Large utility-scale PV plants require large areas of land on which to lay out the thousands of panels. They operate on lower costs, because there are no fuel costs and they require minimal maintenance, and these costs tend to show very little variation throughout the life of the plant. Unlike CSP technologies, PV cells do not require direct sunlight to produce power. They can operate on cloudy days, albeit at a lower power output, making the Western Cape Province a very suitable area to utilise them.

The solar PV industry is expected to be one of the major contributors to direct employment within the country's emerging renewable energy industry (Maia, et al., 2011). As is the case with most renewable energy technologies, the manufacturing industry is where the most employment opportunities will come from. This industry is still in its early development stages in South Africa, but is expected to grow rapidly with the majority of the REIPPP programme's allocated 8 400 MW of Solar PV projects still to be filled. Bid Window 2 saw an average of close to 48% for local content. Manufacturing employment will be concentrated in the production of solar cell modules, which requires combining manufactured solar cells to form modules and then assembling the modules into larger units called arrays (Maia, et al., 2011). Apart from the PV modules, manufacturing opportunities also lie in the production of inverters, mounting structures, and trackers, with these components accounting for up to 70% of total project costs (Ahlfeldt, 2013) The Western Cape Province, once again, is an ideal location to grow this manufacturing capability, because of its existing manufacturing industry, international ports, and close proximity to the areas where solar PV projects are being planned.

The biggest challenges facing the development of this market segment are market certainty and government commitments (Ahlfeldt, 2013). The capabilities and capacities of the local manufacturing industry, coupled with requirements in terms of bankability of projects, are two factors determining the level of participation of local companies in the supply value chain of these projects (Ahlfeldt, 2013). The local utility-scale market is dominated by international companies with extensive experience and expertise. The local PV industry is concentrated towards downstream activities such as project developers, EPC contractors, installers, and operators. Currently, only a small number of local manufacturers produce components such as PV modules, inverters, mounting structures, and trackers (Ahlfeldt, 2013). The dumping of heavily subsidised products, mostly from some Asian countries, onto the South African market provides a significant barrier to the competitiveness of local manufacturers.

The current local content ability of the industry in South Africa is between 55% and 65%, with further increases being possible with the establishment of certain capabilities: solar float glass manufacturing; magnetic parts and transformer manufacturing; wiring/cabling manufacturing; and the manufacturing of printed circuit boards and miscellaneous parts for inverters (Ahlfeldt, 2013). The development of local silicon cell manufacturing capabilities would be critical in order to achieve a local content of closer to 90%. These manufacturers would then supply the local PV module assembler with the silicon cells.

The country has always played a minor role in the global PV industry, but it is well positioned to become a key player in the industry. The rapid increase in local solar PV projects is set to make South Africa one of the largest contributors to installed solar PV capacity globally, and also one of leading players in the solar PV industry (Ahlfeldt, 2013).

3.6.3. Electricity from natural gas

All of South Africa's gas power stations are located within the Western Cape Province. They all make use of Open Cycle Gas Turbine (OCGT) technology, with two of them running on diesel fuel and the other two on natural gas. These four plants are part of Eskom's Peaking Power Capacity strategy, as they have the advantage of being able to supply electricity to the grid within 30 minutes of starting up (Western Cape Government, 2013c). This means that they are currently not intended to supply base-load power to the grid, but only supply power in times of high demand. The Roggebaai and Athlone Gas Power Stations have installed capacities of 40 MW and 36 MW respectively. Both these power stations run on expensive jet fuel, but are mostly used for load regulation of the electricity grid. Another power station running on jet fuel, Acacia power station, is located close to the City of Cape Town and is primarily intended as a back-up power supply to the Koeberg nuclear power station. The power station consists of three OCGT units and has a total capacity of 171 MW. Apart from supplying back-up power to Koeberg, it also functions as a peaking power station in the national grid.

Gourikwa OCGT power station is situated in Mossel Bay and has a capacity of 746 MW. It is supplied with diesel fuel, directly with a pipeline, from the PetroSA fuel refinery. Ankerlig is the largest OCGT power station out of the four. It has a capacity of 1338 MW and is situated in Atlantis, close to Cape Town. These two power stations were built after the government realised that a power crisis is imminent, with both being constructed in just over two years. The two larger power stations presently run on diesel fuel as an energy source, with both being situated in close proximity to fuel refineries. Both these power stations were built with the intention to only supply peak power, but the country's electricity supply crises have forced Eskom to often use them in more of a base-load role. They are well suited to supply base-load power, but the fact that they use diesel fuel as an energy source means that they are very expensive to run. This forces Eskom to generate electricity from them at a cost per kWh of more than R3/kWh, which is much higher than consumers pay for electricity.

The OCGT technology has a proven track record and has been extensively implemented across the world, with numerous suppliers offering different options for power solutions. Gas power plants burn a cleaner fuel than oil or coal-fired power plants, thus release less carbon, nitrogen, and sulphur oxides. This makes them more environmentally friendly than other fossil fuel power plants. Like coal and oil-fired power stations, they can effectively be used to provide base-load power to the grid. They also operate at higher efficiency rates than coal and oil power stations. Gas power plants have very good load-following capabilities, making them ideal in supporting a roll-out of more intermittent renewable energy options (Western Cape Government, 2013a).

Ankerlig and Gourikwa were designed and built in a way that would allow them to be converted to Combined Cycle Gas Turbines (CCGT). In CCGTs, the exhaust gasses are used to heat steam which turns a second turbine, as opposed to just being released into the atmosphere. This makes them more efficient, but they require higher capital costs and use slightly more complicated technology. Ankerlig and Gourikwa would have to be modified to run on natural gas in order to make use of CCGT technology, requiring the establishment of natural gas infrastructure (Eskom, 2012). A Deloitte analysis (2015) estimated that converting the Ankerlig Power Station to CCGT technology would allow the cost of electricity production to drop from above R3/kWh to just above R1/kWh. This is very dependent on the natural gas price that can be obtained and the establishment of natural gas infrastructure in the area. The conversion would also increase the load factor of the power station from the current 20% to around 50%.

The rapidly expanding natural gas sector is of significant importance to the Western Cape's energy sector. In addition to the large natural gas discoveries that have been made in Mozambique and Tanzania, the Western Coast of Africa has also seen smaller discoveries of late. The use of gas in electricity generation would require the development of greenfield gas infrastructure in the region, stimulating industrial growth and development, and creating employment opportunities for thousands of the Province's residents. The development of natural gas infrastructure will dramatically change the energy picture in the Province and in South Africa, making the Province a major player in the energy sector. Very limited Liquefied Natural Gas (LNG) import infrastructure currently exists in South Africa. The lack of government investment in gas infrastructure can be attributed to the challenge of large, capital-intensive investments in infrastructure that would be needed along the supply chain (Department of Energy, 2013a). The government has, however, stated the significant potential for use in power generation, and that this would be the main driver behind the expansion of gas infrastructure.

3.6.4. Electricity from coal power

South Africa's electricity supply is dominated by coal-based electricity, due to the vast coal reserves that are situated within the country's borders. No significant amounts of coal are mined in the Western Cape Province and there are no known deposits large enough to supply a coal power station. Cape Town was home to the only coal-fired power station in the Province when the Athlone power station was still in use. The Athlone Power Station was commissioned in 1962, and had an installed capacity of 120 MW when it was decommissioned in 2003. Most of South Africa's coal deposits are situated in Mpumalanga and KwaZulu-Natal. Apart from the environmental implications, coal-based power is not considered not to be a viable option for the Province because of the large distances between the Province and the country's coal deposits. Transporting coal from these deposits would not be economically feasible or sustainable and would necessitate further increases in the price of electricity (Eskom, 2015b).

3.6.5. Electricity from nuclear power

The only two nuclear power reactors in Africa are at Koeberg Nuclear Power Station, located north of Cape Town. Koeberg is owned and operated by Eskom and has an installed capacity of 1800 MW, generating about 4% of the national electricity supply. It has been in operation since 1984 and has a Pressurised Water Reactor (PWR) design. High level nuclear waste is stored on site in specially designed pools, while low and intermediate level waste is transported to a special disposal site at Vaalputs in the Northern Cape Province (Western Cape Government, 2013c). Koeberg's electricity costs are comparable with those of the coal-fired power stations (Department of Energy, 2013a), but newly built nuclear power stations are expected to produce electricity at a considerably higher cost.

Nuclear power plant projects are known for their long development lead times, with estimates suggesting up to eight or ten years from project start to plant commissioning. Nuclear power could present a solution to electricity supply problems in the long-term, but does little to solve short-term electricity shortages. Nuclear power is seen as a very controversial power source because of the dangers of high radioactivity, but it is still regarded as being a cleaner power source than coal (Western Cape Government, 2007). The Department of Energy (2013b) has stated that nuclear power generation could play an important role in reducing South Africa's carbon footprint. Nuclear power has the ability to generate large amounts of base-load power from small amounts of fuel and release very little GHGs in its operation. The country's significant uranium resources have been used by the government as one of the reasons to pursue nuclear power projects, but no facilities exist for the enrichment of uranium and nuclear fuel would have to be imported.

3.6.6. Electricity from hydropower

The Western Cape Province has no significant potential for large hydropower projects. There exists reasonable potential for small scale hydro, but these projects are unlikely to offer significant power generation capacity to the Province (Western Cape Government, 2013c). Two hydropower projects do exist just east of Cape Town. The Palmiet and Steenbras Pumped Storage Schemes play a dual role of providing water for Cape Town and providing peak power to the electricity grid. Pumped storage schemes act more as energy storage facilities than power generation facilities. They do not supply the grid with net power input, but are used to store energy to be used during peak electricity demand periods. There are no immediate plans to build any new pumped storage schemes in the Province, and no intention has been shown to do so in the future. The number of suitable locations is also very limited.

3.6.7. Electricity from other power sources

There exists potential for bulk biomass power production in the Western Cape Province, but it requires extensive dedicated farming and forestry activities (Western Cape Government, 2013c). Some environmental fears do exist in the form of over-exploitation of natural woodlands or irresponsible harvesting practices. Socio-economic fears also exist due to the possibility of land degradation and compromised food security, but these could be avoided if fuel inputs are drawn from existing agricultural waste products.

3.7. Financing a more sustainable electricity sector

According to Grubler (2012), investments are the mechanism for increases and replacements of the capital stock of an economy. According to Smith and Stirling (2008), the process of enhancing and maintaining socio-technical systems (e.g. infrastructure additions and maintenance, training personnel, regulatory institutions) requires considerable investments. Securing long-term affordable finance is often a greater barrier than the technology costs, inhibiting the full-scale transition towards renewable energy in developing countries. Fuel expenses are the primary costs associated with conventional fossil fuel power stations, making it the primary determinant of generation costs. Renewable energy technologies, apart from biomass and biofuel, have no fuel costs, but their high upfront investment requirements result in financing costs being the primary determinant of total operational costs.

Accessing the large amounts of upfront financing needed to invest in infrastructure is often the main concern for project developers in developing countries (Glemarec, et al., 2013). Removing the barriers related to infrastructure investment is critical for policymakers seeking to facility renewable energy implementation in developing countries. Public finance will play an important role in achieving cleaner energy production, but the most effective and efficient financing mechanisms must be identified. Sullivan (2011) states that constraints on government finances in South Africa could threaten the credibility and effectiveness of policy measures. Eskom has, traditionally, been the only player in the power generation market in South Africa, with the significant majority of investment coming from the state owned enterprise. The recently introduced REIPPP programme has changed this; IPPs have become the main developers of renewable energy projects, and will continue to do so. Thus, financing from the private sector will also play a significant role in greening electricity generation. Private investment institutions have an obligation towards their clients to be prudent in their investment decisions and to maximise risk-adjusted returns on their investments. This means that institutional investors will only invest in energy projects if they are certain of the financial merit of the investment.

The willingness of the private sector to sponsor or invest in renewable energy projects increases if the procurement process is well designed and transparent, projects show reasonable levels of profitability, and critical risks are mitigated by government (Eberhard, et al., 2014). Sullivan (2011) points to five issues that affect investors in the clean and renewable energy industry: (1) government support or other support that exists; (2) financial attractiveness of the investment; (3) expected duration of the policy frameworks that are in place; (4) maturity of the technologies that are involved; and (5) the likelihood of governments to change the policies and incentives that currently exist.

The competitiveness of renewable energy technologies in developing countries, versus fossil fuel technologies, can be severely affected by the difference in debt and equity financing costs (Glemarec, et al., 2013). Renewable energy technologies can greatly benefit from lower financing costs in developed countries, and can compete financially with fossil fuel technologies. Figure 3.5 illistrates the comparison (2012 average levelised costs of electricity) between wind and gas projects in developed and developing countries. It shows the advantage enjoyed by wind energy technologies in developed countries, making them financially competitive with gas energy technologies. One can see that the same wind energy project would be 40% more expensive in a developing country, mainly due to the greater investment costs. A gas power project would require roughly the same investment. These figures are calculated from average costs for developed and developing countries.

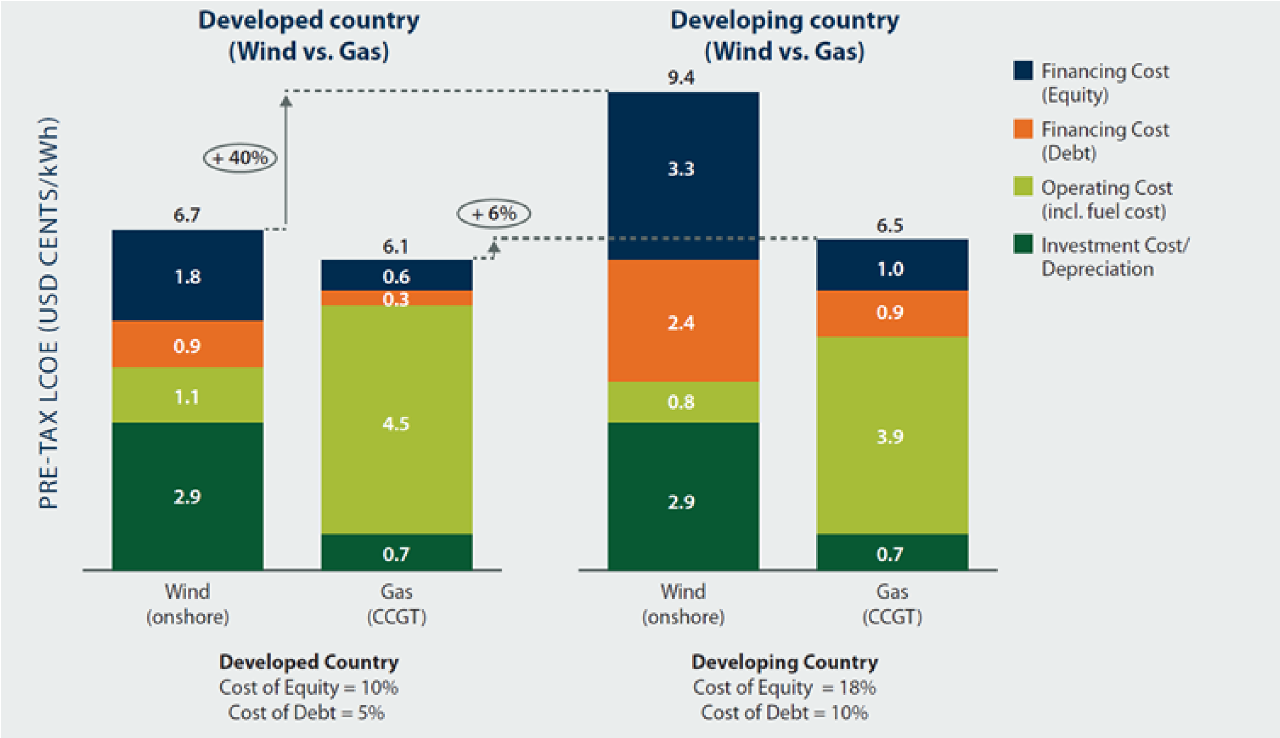

Figure 3.5: The effect of financing costs on wind and gas power projects (Glemarec, et al., 2013).

These higher financing costs require higher potential return rates in order to attract private investors. The higher financing costs in developing countries can be attributed to perceived and actual informational, technical, regulatory, and administrative barriers and associated risks (Glemarec, et al., 2013). In terms of funding a transition to greener electricity production, capital generation is not as big an issue as the need to address the risks affecting financing costs and competitiveness of clean energy technologies in developing countries. Public instruments are essential in addressing these risks, highlighting the critical role played by public sector policymakers.

A report written by Glemarec (2013), for the UNDP, defines all risks relating to renewable energy projects into nine categories: (1) power market risk; (2) permits risk; (3) social acceptance risk; (4) resource and technology risk; (5) grid and transmissions risk; (6) counterparty risk; (7) financial sector risk; (8) political risk; and (9) currency and macro-economic risk. Governments not only need to implement the appropriate policies, but should also make sure that these policies are well designed and that the institutions assigned to implement these policies are effective in their execution.

The goal of policies should be to achieve a risk/return profile that is attractive enough to encourage private sector investment in renewable energy projects. Figure 3.6 conceptually illustrates the risk-reward profile for renewable energy projects. The two goals are to decrease investment risks while increasing financial returns. Investment risks can be decreased through specific regulatory policies such as guaranteeing grid access to IPPs and signing long-term contracts with them. Financial returns can be increased by creating financial incentives such as guaranteeing a premium price for renewable energy and offering tax incentives (Glemarec, et al., 2013).

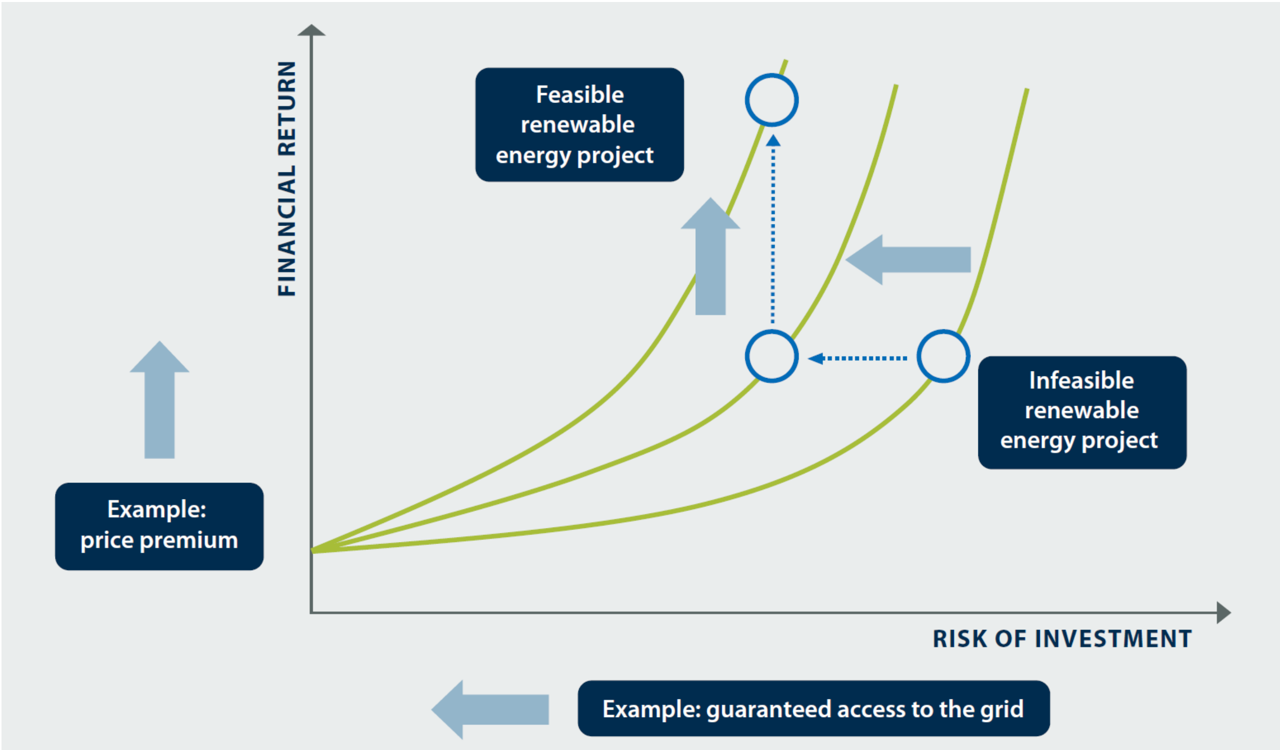

Figure 3.6: Conceptual risk-reward profile for renewable energy projects (Glemarec, et al., 2013)

An effective instrument for decreasing risks is a power purchase agreement (PPA). PPAs give IPPs the guarantee of a fixed long-term price for power supplied, and also guaranteed access to the electricity grid. This instrument acts, both, as a policy instrument, by guaranteeing access to the grid, and as a financial instrument, by guaranteeing a premium price for a long-term period. Different countries have different resource endowments, market conditions, and national goals. Therefore, different countries would need different sets of policy instruments - no one-size-fits-all policy solution exists. Glemarec (2013) argues that implementing a single risk-decreasing instrument will not guarantee investments, as a number of residual risks exist on the periphery, which need to be addressed by complementary risk instruments. Glemarec (2013) further states that renewable energy market transformations are long-term endeavours hampered by deeply embedded barriers, such as practices centred on fossil-fuel dominated monopolistic market structures.

The most significant risks facing investors in South Africa, in terms of impacting on financing costs, are power market risk and currency/macro-economic risk (Glemarec, et al., 2013). Power market risks relate to investors' scepticism over Eskom's monopoly of the electricity sector, and the question of whether current bidding practices are sustainable. Delays in tender processes are another concern for investors. Although many investors show confidence in the country's regulatory framework, others believe that government should continue to closely monitor the development of the energy sector in order to maintain an effective regulatory framework (Glemarec, et al., 2013). Currency and macro-economic risks relate to the historic volatility of the Rand. PPAs are Rand-denominated and, therefore, exposed to currency fluctuations.

Renewable energy transitions are often blamed for rising energy costs for end-users in countries that pursue ambitious clean energy transitions. The declining costs of renewable energy technologies will, in fact, contribute to reducing end-user energy costs in countries with rising fossil-fuel energy costs. South Africa is an example of such a country, with some renewable energy project's feed-in tariffs dropping below Eskom's average cost of producing electricity.

Traditionally, large infrastructure projects have been financed by means of public sector debt. This has changed in the energy sector lately due to the privatisation of public sector capital investments and the internationalisation of investment in large infrastructure (Baker, 2015). The financial structure and financial model used by project developers play a significant role in the approval of utility-scale projects. The two main sources of funds for any investment are debt and equity. Equity financing bestows ownership of the project on the financier, while debt financing involves burrowing money without giving up ownership of the project. The two main debt financing structures, which are generally used for infrastructure projects, are either corporate financing or project financing. Corporate financing structures are general employed by large institution. Lenders would assess credit risks on the strength of the institution's entire balance sheet, allowing the cost of debt to be hedged against the financial strength of the institution and not by the risks involved with the project itself. This structure is often favoured by large, financially sound businesses. It is not favourable for smaller businesses looking to enter the renewable energy market to use corporate financing, as these businesses do not have the strong asset base needed to get favourable credit rates.

Since the 1980s, project finance has increasingly been used as a mechanism for long-term, capital-intensive financing of privately owned energy projects (Baker, 2015). Project financing structures make it possible for these smaller businesses to become developers in the renewable energy market. These structures consider the overall risk profile of the project: a function of factors including track record and guarantees of technology providers, profile of sponsors, as well as the experience and financial strength of EPC and O&M companies involved in the project (Ahlfeldt, 2013). Project financing allows only for the underlying assets of the project to serve as the collateral for lenders to have recourse to. Only the risks of the project itself are taken into consideration when calculating credit rates. Policies that decrease the risks and barriers involved in renewable energy policies are critical for the competitiveness of project financing structures. This has allowed for the participation of many smaller local firms to partake in South Africa's REIPPP programme, as they could compete with larger companies, especially in the early phases of the programme. Over 85% of the projects approved under the REIPPP programme's first three bidding windows were project financed (Baker, 2015). Rounds three and four saw a shift away from project financing coming from the four large local banks, and instead saw large multinationals win a number of projects backed by corporate financing structures.

Projects in the first two rounds of the REIPPP programme were typically structured according to 70:30 or 75:25 debt/equity ratios, with debt financing coming from the commercial banks and development finance institutions (Ahlfeldt, 2013). Some projects even used 80:20 debt/equity ratios, as a higher ratio decreased the cost of funding (Baker, 2015). A higher debt/equity ratio lowers the cost of capital, making the overall project cheaper. This can be attributed to the lower risk held by debt financiers because of their lack of liability for any losses generated by the project, and them being first in line to receive the financial revenues generated by the project. On the other hand, equity investors have greater dependency on the success of a project in generating returns on capital. They, therefore, have to cover the majority of the project's risk, and expect to be rewarded for this with higher returns on their investments.

Commercial banks and development financial institutions play a critical role in providing finance for utility-scale power projects in South Africa. Some of the major development financial institutions involved include the Industrial Development Corporation (IDC), the Development Bank of Southern Africa (DBSA), the Public Investment Corporation (PIC), and the National Empowerment Fund (NEF). Apart from private investors and asset managers, the development finance institutions also made contributions to equity finance in a number of the projects. During the first two rounds of the REIPPP programme, the biggest providers of debt finance were the four largest commercial banks (Standard Bank, ABSA, FirstRand Bank, and Nedbank), with Investec – a private bank – also providing considerable debt finance (Baker, 2015).

Local manufacturing of renewable energy components can reduce the cost of installing renewable energy technologies, increase foreign direct investment (FDI), and contribute to creating green jobs (Glemarec, et al., 2013). In an attempt to boost the local manufacturing industry, some of the development finance institutions have announced plans to attach criteria for minimum local content on projects planning to acquire financing from them. The plan could succeed in growing the local manufacturing industry, but there are also some concerns connected to these plans. The fact that the country's solar PV industry is not yet well established, coupled with the increasing local content, could lead to a greater risk profile of projects. The greater risk profile would then lead to greater financing costs (Ahlfeldt, 2013). This will pose a barrier for obtaining finance for such manufacturing industries until the country's solar PV industry is better established.

3.8. Conclusion: Technology transitions in the electricity sector

Transitioning to a green economy requires transitions in technologies and the way technologies are used. These transitions in technologies predominantly apply to technologies in energy supply, water supply, and transportation. Such technology transitions tend to be long term and complex, and involve a broad range of actors. They also involve the economic, environmental, and social sectors and are embedded within these sectors. The energy sector, especially the electricity sector, will play a critical role in any green economy transitions. The high technology-intensiveness of the electricity sector gives rise to the importance of technology transitions in any green economy transition. The South African Government has made commitments to transform its electricity sector to one that promotes economic growth, social equity, and environmental sustainability. Included in these commitments are plans to expand renewable energy capacity in the country through the REIPPP programme. The Western Cape Government has developed its own green economy goals and has set infrastructure priorities that target the transitioning of the electricity sector in the Province. These priorities include the expansion of renewable energy capacity, and the use of natural gas power stations as a transition towards a greener electricity sector. Wind and solar PV power technologies are very well suited to the conditions within the Western Cape Province, and are expected to contribute the majority of new renewable energy capacity. Establishing supportive manufacturing industries is essential in order to exploit the employment creation potential of expanding renewable energy capacity in the Province, as well as in South Africa and the rest of Africa. Financing such technology transitions remains one of the biggest hurdles. Financing must come from provincial and national governments, private investors, and institutional investors. Governments not only play a role in financing electricity sector transitions, but also play an important role as regulators and policymakers.

Chapter 4

Modelling green economy transitions

Computer-based modelling has developed as a very useful tool for assessing green economy transitions. A number of modelling methodologies exist, each with their own advantages and disadvantages. This chapter serves as a review of the modelling methodologies that were considered for this study. These modelling methodologies include, among others, data frameworks, econometrics, optimisation, and system dynamics. The chapter then discusses why system dynamics was chosen as the modelling methodology and gives a description of this modelling methodology. A review is then given of a number of system dynamics models that have been developed for the purpose of modelling energy sectors, electricity sectors, and green economy transitions.

4.1. Review of modelling methodologies

Hofkes (1996) states that the interactions between economic activities and the environment have to be modelled in order to investigate what the correct conditions are for sustainable development to take place successfully. According to Bassi (2014), an important criterion for such models is their ability to carry out investment and policy analysis. Their ease of use and customisation, are also important criteria (Bassi, 2014). Models should be capable of supporting issue identification and agenda setting, policy formulation and assessment, and policy monitoring and evaluation. The ability to involve a variety of stakeholders in a model's development and use is essential when modelling the green economy (Bassi, 2014). This allows for the multi-sector and multi-stakeholder approaches that are needed in the green economy. Bassi (2014) states that models used for green economy applications should show relevance to the concept and definition of the green economy in three ways: (1) representing the social, environmental, and economic dimensions of problems and opportunities, with the ability to incorporate human, economic, and natural capital in a single framework of analysis; (2) address the issue of climate change by forecasting impacts, and analysing mitigation and adaption options; and (3) make a contribution to green economy investment and policy analysis.

In order to model the green economy, one must identify the specific impact, or dimensions of the transition, which need to be estimated and evaluated in order to assist policymaking (UNEP, 2014b). Many definitions of a green economy exist, thus each case must be uniquely tailored to fit the relevant country. Any assessment of a green economy transition should be multi-layered, and dynamically and systematically integrate social, environmental, and economic spheres (UNEP, 2014b). Furthermore, it should be able to account for social, economic, and natural capital in the estimation paths over the next 25 to 50 years. Green economy models should be able to analyse the impact and effectiveness of capital investments, and should be able to support policy analysis before and after implementation (UNEP, 2014b).

UNEP (2014b) identifies seven criteria related to model creation and customisation: (1) applicability to country context; (2) ease of customisation; (3) multi-stakeholder consultation; (4) transparency; (5) data intensity/needs; (6) time required for implementation; and (7) sectoral coverage. Five criteria were identified for model use and policymaking support: (1) time horizon for the analysis; (2) effort for maintenance and use; (3) complementarity with other models and methodologies; (4) multi-stakeholder involvement; and (5) support in the policymaking process.

Bassi (2014) carried out a study to assess the green economy transition methodologies and models that are most commonly used in developing countries. Simulation model methodologies can be considered as static or dynamic. Static methodologies are generally data frameworks, while dynamics methodologies are modelling approaches. Both methodology types are used in order to create and simulate quantitative models. Data frameworks may form part of modelling approaches, and often function as the backbone of these models. They can be utilised in two main ways. The first use is in isolation, functioning as a means of investigating historic and current states of systems. The second use is embedding them in simulation models, in order to generate simulations of future trends for each indicator in the framework. Data frameworks can exist in a number of forms: Indicators, Input-Output Frameworks (I-O), Social Accounting Matrices (SAM), and Geographical Information Systems (GIS). Modelling methodologies are considered to be dynamic because of their use of underlying mathematical theories and frameworks to generate future projections by creating and solving quantitative simulation models (Bassi, 2014). Modelling methodologies can exist in a number of forms: Econometrics, Optimisation, and System Dynamics.

Indicators are used to describe and give an order of magnitude to a given condition, and can be used to analyse whether progress is being made in reaching certain policy targets. They are used to define the historic and current state of a system, and to expose trends that can contribute in identifying causal relations among the elements composing a system (UNEP, 2014b). Indicators can support entire policy cycles, but are limited to quantitatively measurable variables. The purpose of Input-Output (I-O) frameworks is to characterise inter-industry relationships within or across economies, estimating how outputs from a certain sector may become inputs to another sector. I-O frameworks are often used to estimate the impacts of investments and policies on the value chain of industries (Bassi, 2014). I-O frameworks are often data intensive and the needed material flows are not always readily available. A Social Accounting Matrix (SAM) can be defined as an accounting framework that records the transactions and transfers between the main sectors in an economy. A SAM is concerned with information on monetary flows, with all inflows being equal to the number of outflows. They often act as a backbone for Computable General Equilibrium (CGE) and other macroeconomic models, which carry out analyses that concern the whole economy (Bassi, 2014). SAM frameworks only cover monetary flows and lack system feedback. GIS frameworks are intended to capture, store, manipulate, analyse, manage, and present different types of geographical data. It is used to analyse land use changes and can be described as a combination of cartography, statistical analysis, and computer science technology (UNEP, 2014b). GIS frameworks can fully account for natural resources and ecosystem services, but are also data intensive and may lack the economic dimension.

Econometrics incorporates three stages: (1) specification, (2) estimation, and (3) forecasting. It runs statistical analyses of historical data in order to find correlations between certain variables, measuring the relation between variables (Bassi, 2014). A set of equations describe the physical relation and behaviour that define the system. Forecasts arise from simulating changes in exogenous input parameters used to calculate multiple variables defining the structure of the system. Historical developments and exogenous assumptions determine the reliability of forecasts, making the validation of projections troublesome (Bassi, 2014). The soundness of the theory used to define the structure of the model determines the quality and validation of the projections (Bassi, 2009). Econometrics benefits from quick implementation, but is unable to capture emerging dynamics within a system, and lacks representation of system feedbacks. Econometric theories make three major assumptions: (1) human behaviour is fully rational; (2) perfect information is available; and (3) market equilibrium exists (Bassi, 2009). The inclusion of these three assumptions lead to the major limitations associated with econometrics. The three assumptions have raised concerns regarding the validation and reliability of models that are based on historical developments and exogenous assumptions.

Optimisation produces models that are normative or prescriptive. Optimisation models generally have three inputs: (1) specific goals, (2) areas of intervention, and (3) specified constraints. The CGE models use optimisation to estimate the impact of external shocks. These models only provide snapshots of the optimal state, and give very limited insight into the means to achieve it. They can be useful when applied to issues that are static and free of feedback, which usually occur over a short time frames. In this regard, they can be applied to situations where it is necessary to define optimum solutions given a specific situation, on top of which specific policy proposals are developed (Bassi, 2009). Thus, they are not suited to analysing the impacts of policies over long time frames. They cover the economic sphere of sustainability, but are not viable for highly dynamic and cross-sectoral systems (UNEP, 2014b). There are three main challenges related to optimisation models (Bassi, 2009): (1) the correct definition of the objective function; (2) the extensive use of linearity; (3) and the lack of feedback and dynamics.

The World Input-Output Model (WIOM) is an example of an I-O model. It was developed as a long-term, global economic forecasting model. It was first developed in the 1970s and it aims to capture the future of the world economy within the constraints of resources, energy, and the environment under different policy scenarios for the UN International Development Strategy (UNESCO-EOLSS, 2015). The EnergyPLAN model is a deterministic I-O simulation model, and was designed with the purpose of analysing alternative regulation strategies of complex energy systems (Lund, et al., 2007). It has been used to investigate new operation strategies and investments in renewable energy technologies. Other I-O models include the MIS and MEPA models, which both function on a national scale (Nakata, 2004).

Project LINK was started in 1968 with the objective of developing an econometric model of the world economy. The main objective was to model the transition mechanism among major industrial countries. It produces short-term and medium-term projections of the world economy for policy simulations. It has been adapted to incorporate the political, environmental, social, and economic events that are of importance for sustainable development (UNESCO-EOLSS, 2015). The 3E COMPASS is an econometric simulation model developed to capture the interaction between the 3E spheres: energy, economy, and environment. It can be described as being multi-sector and multi-country orientated, and uses empirically based econometric methods throughout (UNESCO-EOLSS, 2015). Other econometric models include the WORLDSCAN and POLES models, both functioning on a global scale. The PANTA RHEI macro econometric model was used to depict the dependency of resource consumption and emissions from the development of the economy (Meyer, et al., 2012).

The Dynamic New Earth 21 (DNE21) model is a multi-period, inter-temporal, nonlinear optimisation model. The model is able to assess different energy technology options. It is divided into three sub-models: (1) an energy systems model, (2) a macro-economic model, and (3) a climate change model (UNESCO-EOLSS, 2015). The MARKAL family of models are multi-period linear optimisation models, and can further be described as vertically integrated models of a country's entire energy system (Loulou, et al., 2004). They are applied to national contexts, and seek to find an optimised energy portfolio allowing for the smallest energy production and energy costs. They cannot be used for forecasting purposes, but, instead, offer a tool to investigate the trade-offs and tipping points between different energy systems pathways (Anandarajah, et al., 2009). A drawback of these models is the exogenous nature of energy demand and price inputs, leading to a lack of dynamic analysis of simulated scenarios (Freedman, et al., 1983).

Other modelling methodologies have also been used in the green economy context. Carfi and Schiliro (2012) developed a coopetitive model for the green economy. The model, which is based on Game Theory, addresses the issue of climate change policy and diffusion of low-carbon technologies. It is applied at a macroeconomic level and assumes coopetition – a combination of cooperation and competition – between countries. The main aim of the model is to demonstrate the benefit for countries to participate actively to a program of low-carbon technologies within a cooperative framework to address a policy of climate change. It examines a range of possible economic outcomes along a dynamic path. Another game-theoretic model was developed by Carraro et al. (2012): the World Induced Technical Change Hybrid (WITCH). The WITCH is a regional integrated assessment model developed to provide information on optimal responses of world economies on climate change and climate change policies. It combines features of top-down and bottom-up modelling approaches, and is designed to produce scenarios instead of forecasts. A downside to the model is the fact that it does not include feedback from climate change on the economy.

The Futures of Global Interdependence (FUGI) modelling system was first developed by three Japanese universities in 1976 (Onishi, 2006). It is intended to function as a scientific policy simulation tool. Its main purpose is to investigate the possibility of policy coordination among countries in order to achieve sustainable development of the global economy within the boundaries of a rapidly changing global environment. International Futures (IF) is a large-scale, long-term, integrated global modelling system. It serves as a thinking tool for long-term and country-specific projections in areas such as social change, human development, and environmental sustainability. It is a structure-based, agent-class driven, and dynamic modelling system that is aimed at scenario development and policy analysis (Hughes, 2009).

Thiam et al. (2012) uses the PowerPlan model to analyse the role of renewable energy technologies in providing an energy transition in the electricity sector of South Africa. The impacts of the transition were captured in terms of costs, electricity supply mix, and environmental reduction advantages. PowerPlan is an end-orientated, bottom-up simulation model intended to assess economic and environmental impacts of the introduction of renewable energy technologies into the electricity sector. UNEP (2014b) states that energy and other system engineering models are well suited to support green economy investment and policymaking. These models focus on a limited number of sectors, and track built up capital and climate change mitigation (limited to energy applications).

According to Nakata et al. (2011), energy models have been used to aid decision-making in energy planning, analyse energy policies, and analyse the implications arising from introducing new energy technologies. Connolly et al. (2010) reviewed 37 models used for renewable energy integration, and found that only eleven of these can be used to account for all technologies in the electricity sectors. Energy contexts differ from country to country, with a wide range of properties characterising these contexts; from political environments to endowment of natural resources. These contexts need to be understood in order to set the boundaries of simulation models. Customisation becomes an important aspect of a simulation model when such diverse properties need to be taken into consideration (Bassi, 2009). Reality is unavoidably complex due to two reasons (Bassi, 2009): (1) a high level of detail exists in every real system, and (2) dynamic relationships exist among the elements forming the system analysed and those surrounding it.

Conventional modelling tools are able to represent the details of the linear processes active in a real system, but lack the ability to investigate the dynamic relationships contributing to the behaviour of the system itself. Dynamic systems are characterised by feedbacks, non-linearity, and delays. Linking the energy sector to other dimensions of society, environment, and economy, contributes to the representation of the context in which different energy issues are analysed (Bassi, 2009).

4.2. System dynamics as a modelling tool

The system dynamics modelling methodology was chosen for this project because of its suitability to carry out policy and investment analyses. Another advantage it has is its ability to carry out these analyses in the context of economic, environmental and social factors. The rest of this chapter describe the suitability of system dynamics to modelling complex systems and also further describe the system dynamics methodology in greater detail.

4.2.1. Modelling complex systems

Meadows (1980) states that complex systems are characterised by non-linear relationships – between elements in the system – which cause feedback loops to vary in strength, subject to the state of the system. UNEP (2014b) defines a complex system as one that is dominated by dynamics, which are often beyond control, resulting from the multiple interactions between variables that do not follow a regular pattern. According to Norman (2011), a complex system is one that is open to the outside world and is continuously exchanging energy with its surroundings; one that affects its environment and is affected by its environment. Complex systems consist of indefinable variables interacting in indefinable ways in such a way that no combination of linear equations can represent the reality (Norman, 2011).

The causes of complexity, according to Chan (2001), include the inter-relationship, inter-action, and inter-connectivity of the elements making up a system and between the system and its environment. Complexity theory is used to describe how unpredictability can be caused if these relationships are non-linear (Norman, 2011). Chan (2001) describes Complex Adaptive Systems (CAS) as dynamic systems that are able to adapt in and evolve with a changing environment, and are closely linked with, and co-evolve with, all other systems making up their ecosystem. According to Bassi (2009), a clearer interpretation and understanding of the context of analysis is created when considering non-linearity in a system. Rotmans and Loorbach (2009) argue that a greater insight into the dynamics of CAS can lead to improved insight into the feasibility of managing these systems towards a more sustainable direction. Gaining insight into the behaviour of complex systems can greatly improve the effectiveness of transition management (Rotmans & Loorbach, 2009).

Mei et al. (2015) state that studying complex systems is essential for understanding and predicting the behaviour of these systems and can have a significant impact on understanding the complex world around us. Constanza et al. (2009) argue that the analysis of complex systems could potentially offer significant insight into the behaviour of linked ecological-economic systems. Linear models are often unable to provide insights on the potential medium to long-term impacts of policies (Bassi, 2009), thus dynamic models should be used for this purpose. According to Bassi (2014), an important criterion for such models is their ability to carry out investment and policy analysis.

4.2.2. The system dynamics modelling methodology

A complex system cannot be described by a linear equation or a combination of linear equations (Norman, 2011). According to Bassi (2009), conventional modelling tools are able to represent the details of the linear processes active in a real system, but lack the ability to investigate the dynamic relationships contributing to the behaviour of the system itself. Sterman (2000) states that system dynamics should be seen as a perspective and a set of conceptual tools enabling us to better understand the structure and dynamics of complex systems. System dynamics builds on control theory, organisational theory, and decision theory, and is utilised to model interactions within and between systems. It places emphasis on the relationships between different elements that cause a system to be dynamic, instead of analysing details involving individual elements (Botterud, 2003).

The system dynamics methodology was first conceived in the late 1950s by Jay Forrester at the Massachusetts Institute of Technology (MIT). It has evolved over the past 25 years and is used to analyse the relations between structure and behaviour of complex, dynamic systems. System dynamics models analyse causal relationships and formalise them into different equations, and then simulate and analyse them using computer software (UNEP, 2011a). According to Sterman (2000), these formal computer simulations of complex systems can be utilised to design more effective organisations and policies. The system dynamics method represents systems using stocks and flows, and is ideally suited to represent the economic, social, and environmental aspects of development processes.

Bassi (2014), describes system dynamics as a methodology focused on creating descriptive models aimed at identifying causal relations within a system. System dynamics models aim to understand the main drivers behind a system’s behaviour by identifying the properties of real systems, such as feedback loops, nonlinearities, and delays (UNEP, 2014b). It provides flexibility, making it relevant for all stages of policy analysis. It allows for the incorporation of different fields of knowledge and cross-sectoral factors into a single framework. An important aspect of system dynamics is its ability to investigate how structure and decision making principles embedded within a system generate the eventual behaviour of the system in the midst of feedback between the components in the system (Ahmed & bin Mat Tahar, 2014). System dynamics models endogenously represent the economic, human, and environmental spheres, and can be used for green economy investment and policy analysis. They are particularly suited to representing long-term problems involving a large number of variables and parameters (Pereira & Saraiva, 2013).

UNEP (2014b) describes system dynamics as a flexible methodology that can be utilised to develop sector models that represent key causal relations and their cross-sectoral linkages. The models explicitly account for feedbacks, delays, and non-linearity through the representation of stocks and flows. Their ability to support multi-stakeholder participation and consensus-building, and their ease of customisation make them ideally suited to supporting green economy assessment. Table 4.1 provides a summary of the assessment of system dynamics models according to the criteria set out by UNEP (2014b).

Table 4.1: Assessment of system dynamics as a modelling tool (UNEP, 2014b)

Model creation and customisation	Country applicability	Fully tailored to analysed country
	Ease of customisation	Easy customisation, subject to good understanding of the system
	Multi-stakeholder consultation	Broad, captures cross sectoral driver and effects
	Transparency	Highly transparent
	Data needs	Medium, does not require full-time series and large sets of data
	Time of implementation	In the order of weeks
	Sectoral coverage	Often focused on one sector, but with cross-sectoral links
Model use and policymaking support	Time horizon	Medium to long term
	Effort for maintenance	Medium, if structural drivers of the system stay constant over time
	Complementarity	High, other methodologies can be incorporated and can be coupled with other models
	Multi-stakeholder involvement	Broad, captures cross-sectoral drivers and effects
	Policymaking support	Capable of supporting all policymaking stages

A weakness of system dynamics models is their reliance on knowledge of different fields, and the long implementation time for large models (Bassi, 2014). System dynamics models lack extensive reliance on historical data, requiring that such models be exposed to two layers of validation: structural and behavioural. Structural validation relates to assessing the accuracy and effectiveness of the equations that make up the model, while behavioural validation relates to the accuracy of the projections produced by the model (UNEP, 2014b). The validity of the internal structure of the model should enjoy preference over the accurate output behaviour. This means that the system dynamics model should generate the correct output behaviour for the right reasons. Decision strategies based on optimisation are difficult to include because the ability of system dynamics models to include optimisation is very limited (Botterud, 2003). Ultimately, the purpose of system dynamics modelling should be mainly focused on improving policy makers' qualitative understanding of complex systems and their associated problems (Botterud, 2003).

According to Maani and Cavana (2007), there exist five major phases in the development of a systems thinking and modelling intervention: (1) problem structuring, (2) causal loop modelling, (3) dynamic modelling, (4) scenario planning, and (5) implementation and organisational learning. Figure 4.1 illustrates these five phases.

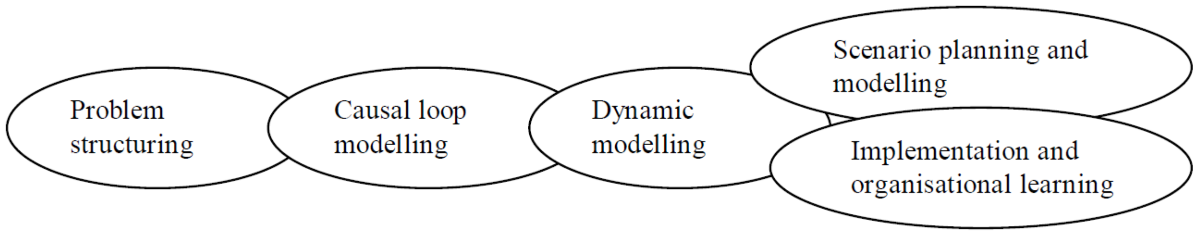

Figure 4.1: Five phases of the systems thinking and modelling methodology (Maani & Cavana, 2007)

The first phase – problem structuring – involves defining the scope and boundaries of the study. This phase identifies the policy issue and main problem that is being investigated. It also involves collecting the relevant information and data on the system under investigation (Maani & Cavana, 2007). Botterud (2003) states that time must be taken to develop an understanding of the problem/issue being analysed. An in-depth understanding of the model is required in order to identify the model boundaries, time horizons, variables, and parameters (Pereira & Saraiva, 2013). The second phase – causal loop modelling – involves developing the conceptual model of the problem and is key to enhancing the conceptual understanding and learning power of the systems approach (Maani & Cavana, 2007). A CLD also plays the role of conceptually visualising the system. Causal loop diagrams (CLDs) assist in identifying the main variables involved in the system. CLDs represent the feedback structures of a system and have three key functions (Sterman, 2000): (1) capturing the hypothesis about the causes of the system's dynamics; (2) capturing mental models; and (3) identifying important feedback loops responsible for a system's behaviour. Figure 4.2 illustrates a simple example of a CLD for a given population.

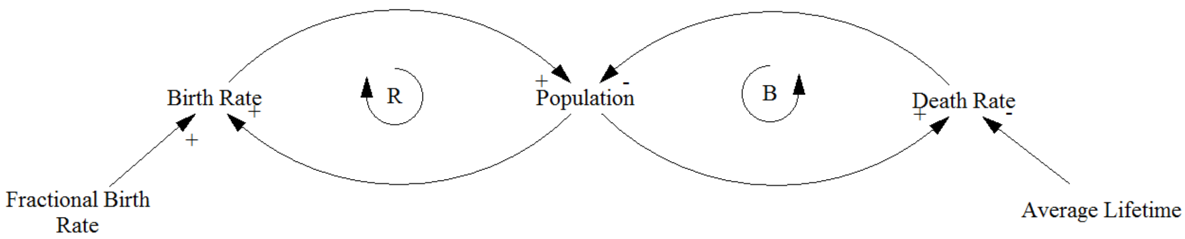

Figure 4.2: CLD for a given population

A CLD consists of variables connected by causal links (arrows). The polarity of a causal link, either positive (+) or negative (–), indicates how the dependent variable reacts when the independent variable changes. In Figure 4.2, an increase in Fractional Birth Rate will increase Birth Rate above what it normally would have been, and an increase in Average Lifetime would decrease Death Rate below what it normally would have been. The two links connecting Birth Rate and Population form a loop. A loop is positive/reinforcing (denoted by an 'R') when the sum of the polarities is positive, as is the case in the left loop, and a loop is negative/balancing (denoted by a 'B') when the sum of the polarities is negative, as is the case in the right loop. CLDs are qualitative models; they described what would happen if there were a change in a variable and do not describe what actually happens (Sterman, 2000).

The third phase – dynamic modelling – involves constructing stock and flow diagrams (SFDs) based on the CLDs (Maani & Cavana, 2007). These models are quantitative models – mathematical representations of the qualitative models – which need values for initial conditions and parameters. During this phase, SFDs for the different sectors of the model are developed as a computer simulation model. The process of developing SFDs promotes model transparency in three ways: (1) making explicit statements about assumptions involving the model; (2) determining uncertainties involving the system structure; and (3) outlining underlying gaps in the availability of data (Musango & Brent, 2011). Figure 4.3 illustrates the same population model, as used in Figure 4.2, but in the form of a SFD.

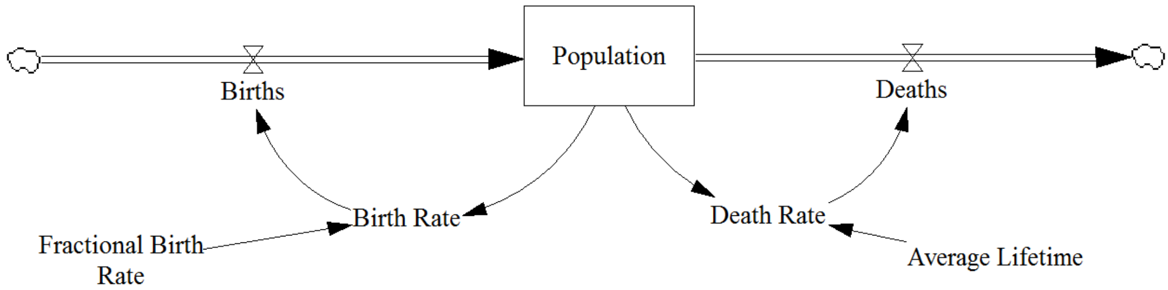

Figure 4.3: SFD example for a population model

SFDs generally consist of four building blocks: stocks, flows, constants, and auxiliaries. In Figure 4.3, Population is the stock. Stocks characterise the state of the system, provide systems with inertia and memory, and are the source of delays in systems (Sterman, 2000). The value of a number of values usually depend on the value of the stocks in the system, thus the state of the system is characterised by the stocks (Pereira & Saraiva, 2011). Stocks also decouple inflows from outflows; flows represent the primary activity of the system. The behaviour of a dynamic system over time is strongly dictated on the behaviour of the stocks (Pereira & Saraiva, 2011). The behaviour of the stocks are determined by a set of differential equations, given below by Equations (1) and (2), which represent the value of a stock at time *t* and the rate of change of a stock respectively (Sterman, 2000).

$$Stock(t) = \int_{t_0}^{t} [Inflow(t) - Outflow(t)]dt + Stock(t_0) \quad (1)$$

$$\frac{\delta Stock(t)}{\delta t} = Inflow(t) - Outflow(t) \quad (2)$$

The two flows are Births and Deaths. The Births flow is the inflow to the stock and increases the level of the stock over time, while the Deaths flow is the outflow from the stock and decreases the level of the stock over time. Flows represent the activity of the system and increase or decrease the level of stocks over a period of time. Auxiliary variables consist of functions of stocks and/or constants. The auxiliaries are Birth Rate and Death Rate, and represent an instantaneous effect. The constants are Fractional Birth Rate and Average Lifetime, and are exogenous parameters. Constants represent parameters that define certain characteristics of the system. These parameters are not endogenously determined by the system, but are rather exogenously determined by the user of the system dynamics model.

The fourth phase – scenario planning and modelling – involves postulating and testing various scenarios and policies. Scenario modelling refers to the act of testing these different strategies under varying external conditions (Maani & Cavana, 2007). This allows for the investigation and visualisation of the effects resulting from different intervention strategies and policies. In the context of this paper, the effects resulting from green economy policies, often developed in isolation in different governmental departments, are investigated and analysed. Implementation and organisational learning is the fifth, and final, phase and is meant to enhancing the model through interaction with stakeholders. Communication between stakeholders is facilitated through the structural transparency of the system dynamics methodology, thus organising discussions that develop constructive criticism (Musango, et al., 2014b). Ultimately, this leads to the system dynamics model being able to offer learning and decision support in scenario planning and policy design (Botterud, 2003).

Botterud (2003) describes electrical power systems as large-scale, integrated, and complex engineering systems. When addressing the problem of expanding electricity capacity, two important dimensions should be taken into consideration (Botterud, 2003): (1) the type of project must be identified, that is, which technology to use and what capacity the new plant should be; and (2) the timing of the investment must be investigated and evaluated. System dynamics modelling allows for the use of feedback information by investing agents. This information is used to evaluate the impact of past and current decisions – strategies and policies – and then utilised to make future decisions. In the model of an electricity sector, this information would be the effect of investment decisions on electricity capacity, electricity supply, air emissions, employment etc (Botterud, 2003). Delays exist between the moment an investment decision is made and the moment when the electric power station is commissioned. It is critical to take these delays into account when modelling the electricity sector in order to capture the true evolution of the sector in the long term. Botterud (2003) highlights the importance of taking into account uncertainties, construction delays, investment timing, and investor foresight when investment decisions are being modelled. The ability of system dynamics modelling to capture and model the feedback loops present in the electricity sector makes it a very appropriate tool to use for such electricity sector applications (Ford, 1997). Pereira and Saraiva (2011) argue that system dynamics is particularly suited to modelling the electricity sector due to the interdependencies between the long-term evolution of electricity prices, electricity demand, and the development of new electricity generation capacity.

4.3. Review of system dynamics models

A number of studies have utilised the system dynamics methodology in the context of the energy sector. Shin et al. (2013) use the system dynamics methodology to develop an energy security management model. The goal of the model is to assist policymakers in managing national energy security in a more effective manner. Musango and Brent (2011) describe the development of the system approach to technology sustainability assessment (SATSA), which makes use of system dynamics modelling and acts as a framework that integrates energy technology development, sustainable development, and the dynamics systems approach. Its aim is to demonstrate the linkages between proposed elements that are considered as being important in improving energy technology sustainability assessment practices. Musango et al. (2012) apply the SATSA framework to assess the sustainability of biodiesel development in South Africa, calling the model the bioenergy technology sustainability assessment (BIOTSA). Movilla et al. (2013) describes the development of a system dynamics model of the solar PV market in Spain. This model aims to facilitate a better understanding of the sector's behaviour under certain policy decisions by analysing the sensitivity of a number of variables on the development of the solar PV market in Spain.

A number of system dynamics models have been developed exclusively for the analysis of national electricity sectors. Dyner et al. (2011) use system dynamics modelling to assess the effects of integrating national electricity markets on electricity system expansion and security of supply. A system dynamics model developed by Olsina et al. (2006) analyses the effects of supply-side policies on the ability of electricity generation capacity to keep up with demand. Pereira and Saraiva (2013) describe the development of a long-term expansion planning model using system dynamics. Its main function was to estimate the long-term evolution of electricity demand and price, and the effects of these on generation expansion plans of the Portuguese/Spanish electricity system. Qudrat-Ullah (2013) describes the development of a system dynamics model of the electricity sector in Canada. This model was developed with the purpose of explaining the dynamics of variables acting within the electricity system in Canada, with a focus on variables within the generation capacity system. Ultimately, the model was used as a policy design and analysis tool, analysing policy decisions and providing policy insight on the electricity dynamics in Canada. Ahmed and bin Mat Tahar (2014) describe the development of a system dynamics model that is used to evaluate the effect of electricity sector policies on the expansion of renewable energy capacity in Malaysia. Qudrat-Ullah and Davidsen (2001) describe the development a system dynamics model that assesses the effect of different electricity policies on electricity supply, resource import dependency, and the evolution of CO_2 emissions in Pakistan.

The majority of these studies fail to account for the interdependencies between the electricity sector and the different spheres of economy, environment, and society. Linking the energy sector to other dimensions of society, environment, and economy, contributes to the representation of the context in which different energy issues are analysed (Bassi, 2009). The ability of system dynamics modelling to offer a holistic method of analysing the electricity sector and its impact on these spheres makes it a very appropriate tool for modelling the electricity sector in its totality. There are currently a limited number of studies using system dynamics to analyse how green economy investments in the electricity sector could benefit green economic agendas, such as job creation, emissions reductions, and economic growth (Musango, et al., 2014b).

The Threshold 21 (T21) system dynamics model was developed to contribute to national planning policies and to function as a tool for conducting stakeholder consultations (Millennium Institute, 2015). It aims to provide insight into potential impacts of development policies across a wide range of sectors, including the electricity sector, revealing how desired goals and objectives can be achieved using different strategies (UNEP, 2014b). The T21 is most often used as a country model, and can be customised to capture the specific issues of the country being analysed. The South African Green Economy Model (SAGEM) utilises the same framework as the T21 model, meaning it also makes use of the system dynamics modelling approach. Its primary aim is to assess the impacts of green economy investments in selected sectors, including the electricity sector, of the South African economy. It was developed to explore the transition to a green economy for South Africa, focusing on its ability to facilitate low carbon growth, resource efficiency, and employment development targets. SAGEM is used to investigate target-specific scenarios aimed at identifying certain policies can achieve the medium and long term goals after green economy interventions have been implemented (UNEP, 2013). It was modelled on a national level and does not provide for disaggregation on a provincial level. This allows for it to be utilised for planning and policy testing on a national level, but not on a provincial level.

4.4. Conclusion: Modelling green economy transitions

Modelling methodologies used to asses green economy transitions include data frameworks, econometrics, optimisation, and system dynamics. These methodologies were reviewed and discussed. A number of models used for energy and electricity sector modelling were also reviewed. It was decided that system dynamics is the most suited methodology for modelling the electricity sector of the Western Cape Province from a green economy perspective. The chapter then discussed the suitability of system dynamics to modelling complex systems and gave a description of the system dynamics methodology. This explanation included the five stages of the systems thinking and modelling methodology, and a description of how CLDs and SFDs function. A review was then provided of a number of system dynamics models that have been utilised to model energy sectors, electricity sectors, and green economy transitions. SAGEM was used to investigate the transition to a green economy in South Africa. It, however, does not allow for these investigations on a provincial level.

Chapter 5

Modelling the electricity sector of the Western Cape Province

The development of the WeCaGEM followed the same conceptual framework used for the SAGEM, with the WeCaGEM being implemented on a provincial level, instead of on a national level like the SAGEM. The SAGEM analysed green economy investment interventions undertaken at a national level, but, in reality, the majority of these interventions are required to take place at a provincial or local government level. Policymakers at provincial and local government level need insight into what level of investment is needed to achieve their planned targets, or whether planned investments would be able to achieve their planned targets. The WCG has stated its vision for the Province to transition towards a green economy and become a leading green economy hub on the African continent. The involvement and commitment of a number of key sectors would be required if such a transition is to be successful. Such a transition would require a trans-disciplinary and integrated approach to design and manage these key sectors. The WeCaGEM was developed by Musango et al. (2015), using the system dynamics approach, with the purpose of examining the complexities and implications of a green economy transition in the Western Cape Province of South Africa. Integrating the concept of the green economy into a formal model, calls for the amalgamation of the social, economic, and environmental systems being analysed. Such an analysis must occur across the different sectors of the Province due to the dynamic nature of the green economy concept. The WeCaGEM specifically focused on five green economy investment areas: (1) biofuels, (2) water infrastructure, (3) agriculture, (4) transport infrastructure, and (5) renewable energy generation.

This chapter discusses the development of the electricity sector model of WeCGEM. The sector model was first developed as a conceptual model, before the dynamic model was developed, both of which are discussed and explained. The validation and verification of the model is then discussed. Validation was carried out in the form of model structure validity tests and model behaviour validity tests. The different scenarios that were run are then discussed, as well as the policies and how they were formulated.

5.1. The conceptual model of the electricity sector

The WeCaGEM model consists of a number of sector models, but this study only focuses on the electricity sector. In reality, the electricity grids of the different South African provinces cannot be separated, as they are all part of one large national grid. Consumers in any other province can use electricity produced by power stations in one province, and the electricity demand in a province can be supplied by a combination of power stations in the other provinces. Nevertheless, for the purpose of analysing the Western Cape Province in isolation, the Province was assumed to have its own electricity grid. This is done in order to look at the Province's electricity sector as a single system separate from the electricity sector of the other eight provinces. The assumption then dictates that all the electricity that then is generated by power stations within the Western Cape Province is utilised to supply only the electricity demand of the Province; all electricity generated in the Province stays within its borders and is used within its borders. When the Province's electricity demand exceeds the supply, the needed electricity is imported from outside the Province, and surplus electricity is exported when supply exceeds demand. Although the assumption states that the Province has its own independent electricity sector, the fact that the electricity price is regulated on a national level still applies. Assuming that the Province's electricity sector is based in a free market, where prices are determined by market forces, would remove it too far from its position in reality. The assumption is made that price regulation takes place on a national level in order to maintain the fact that the Province's electricity sector is still part of a larger national network.

In order to model the electricity sector of the Western Cape Province, one has to first understand the major components it consists of. Electricity needs to be generated because demand for it exists. Businesses, residents, and government require it in order to be able to perform many of their basic daily functions. Electricity is generated by the installed electricity generation capacity that is present in the Province. When demand exceeds the electricity supply generated by the installed capacity, the gap must be covered by electricity imports from other Provinces. Importing electricity is a necessary short-term option, but can often be expensive and compromises the Province's electricity security, making it dependent on the policies and agendas of other governments and policymakers. The gap between electricity demand and supply can also be covered by increasing the local electricity generation capacity. This requires investments in electricity generation infrastructure in order to fund the capacity expansion. Investments in capacity do not immediately yield increases in capacity. Due to the lengthy planning and building processes of power stations, time delays exist between the investment being made and the expanded capacity supplying electricity to the grid. The links between these components of the electricity sector form the main feedback loop of the model. Figure 5.1 illustrates the causal relationships between the electricity sector components that have been discussed, forming the causal loop – named B1 – for electricity generation capacity expansion.

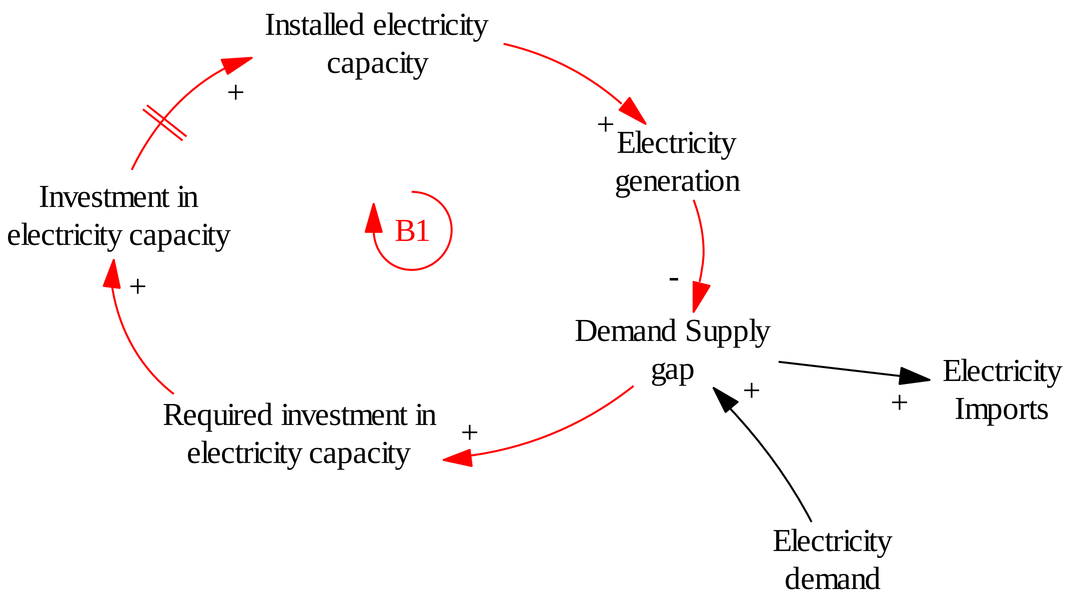

Figure 5.1: CLD for electricity generation capacity expansion

The causal loop for electricity generation capacity expansion can be identified as a negative feedback, or balancing, loop. As demand for electricity increases, the requirement for new electricity generation capacity increases. This increase is delayed, but eventually increases the amount of electricity that is generated, consequently decreasing the gap between demand and supply. An increase in demand-supply gap also increases electricity imports until new electricity generation capacity is commissioned. The double parallel lines through the link denote the time delay between investments in electricity capacity and installed electricity capacity expansion. Installed electricity generation capacity does not have an infinite life, thus there exists a process that decreases the capacity over time. Figure 5.2 illustrates the causal relationships between the factors in the capacity decommissioning loop – B2 – in the form of a CLD.

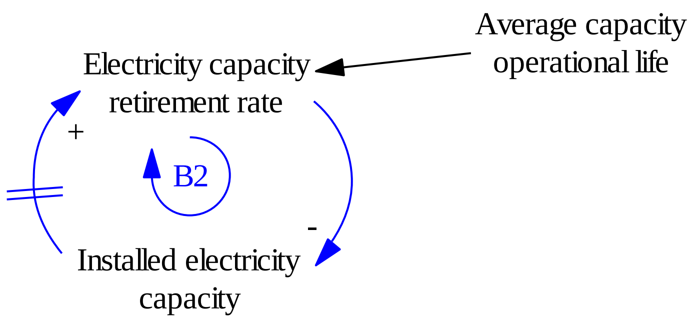

Figure 5.2: CLD for capacity decommissioning

The causal loop B2 is a negative feedback, or balancing, loop. An increase in capacity will, after a time delay, increase the capacity retirement rate, increasing the amount of capacity that is decommissioned. This retirement rate is subject to the installed capacity and the length of the operational life of the installed capacity. The length of the operational life is what determines the length of the delay.

The three main drivers behind electricity demand in South Africa are population, gross domestic product (GDP), and electricity price (Inglesi, 2010; Musango, et al., 2014b). A number of studies have shown the effects of population (Debba, et al., 2010; Inglesi, 2010; Inglesi & Pouris, 2010), electricity price (Debba, et al., 2010; Inglesi, 2010; Inglesi-Lotz, 2011) and GDP (Debba, et al., 2010; Deloitte, 2012; Inglesi & Pouris, 2010) on electricity demand in South Africa. In a study on the residential electricity demand in South Africa, Ziramba (2008) states that personal income and electricity price are the main drivers behind residential electricity demand. In this study, GDP per capita was used as a proxy indicator for personal income. GDP is also a proxy variable for a driver of electricity demand. It is not GDP that is the underlying driver of electricity demand, but, rather, factors such as business productivity and profitability. Specific data are not always available for these factors. Therefore, such proxy variables are used with the assumption that their patterns roughly correspond with the patterns of the underlying drivers of electricity demand (Debba, et al., 2010). Population and GDP are sub-models in the WeCaGEM, while electricity price is an exogenous variable. This assumption arises from the fact that the Province has no control over the price of electricity, which is currently regulated by the National Energy Regulator of South Africa (NERSA). Figure 5.3 illustrates the causal relationships affecting electricity demand.

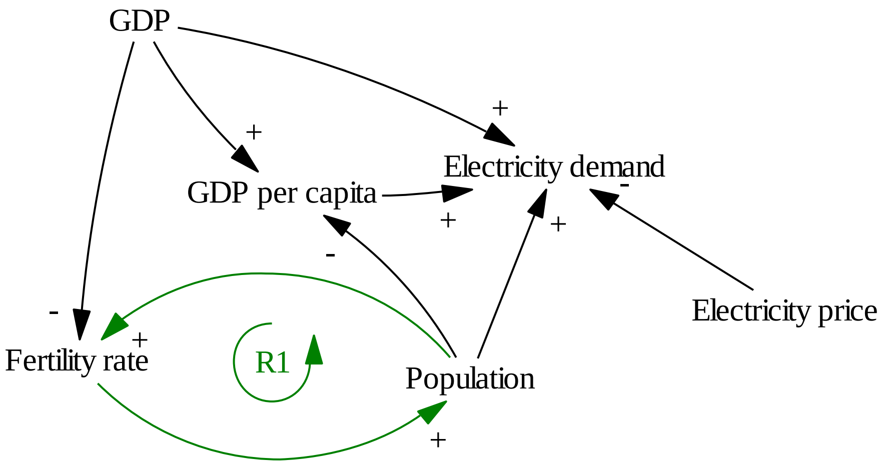

Figure 5.3: CLD for electricity demand

Figure 5.3 shows the links from GDP, GDP per capita, population, and electricity price to electricity demand. Increasing electricity prices decrease demand for electricity. An increasing in the electricity price increases personal and business expenditure, leading to the possibility of electricity consumption being reduced by consumers in order to decrease their overall expenditure. Increasing GDP increases electricity demand as businesses and industries expand and require larger amounts of electricity. An increase in GDP per capita is an indicator that personal income is on the rise, allowing residents to, possibly, increase their electricity usage and allowing them to cover larger electricity bills. An increasing population increases electricity demand because of the larger number of residents who need electricity for their everyday requirements. Population is affected by the fertility rate of the population. The fertility rate, in turn, is affected by the size of the population and the value of GDP. Loop R1 is a positive feedback, or reinforcing, loop involving population and the fertility rate of the population. It is a reinforcing loop because an increasing population will have an increasing effect on the fertility rate, which then has an increasing effect on the population, causing a reinforcing effect. Increases in GDP will decrease the fertility rate. This study focuses on the electricity sector and discusses the development of the electricity sector model. Therefore, the population, education, and GDP models will not be discussed in great detail. Another reason for this is that the same individual who developed the electricity sector model did not develop these three models, thus the author's knowledge of the development process of these three models is limited.

The conceptual model describing the electricity sector of the Western Cape Province is created by combining the above mentioned causal relationships for electricity generation expansion, electricity capacity decommissioning, and electricity demand. This model is then capable of conceptually describing the dynamic interactions and feedbacks that exist between the different components of the provincial electricity sector. Figure 5.4 illustrates this conceptual model in the form of a CLD.

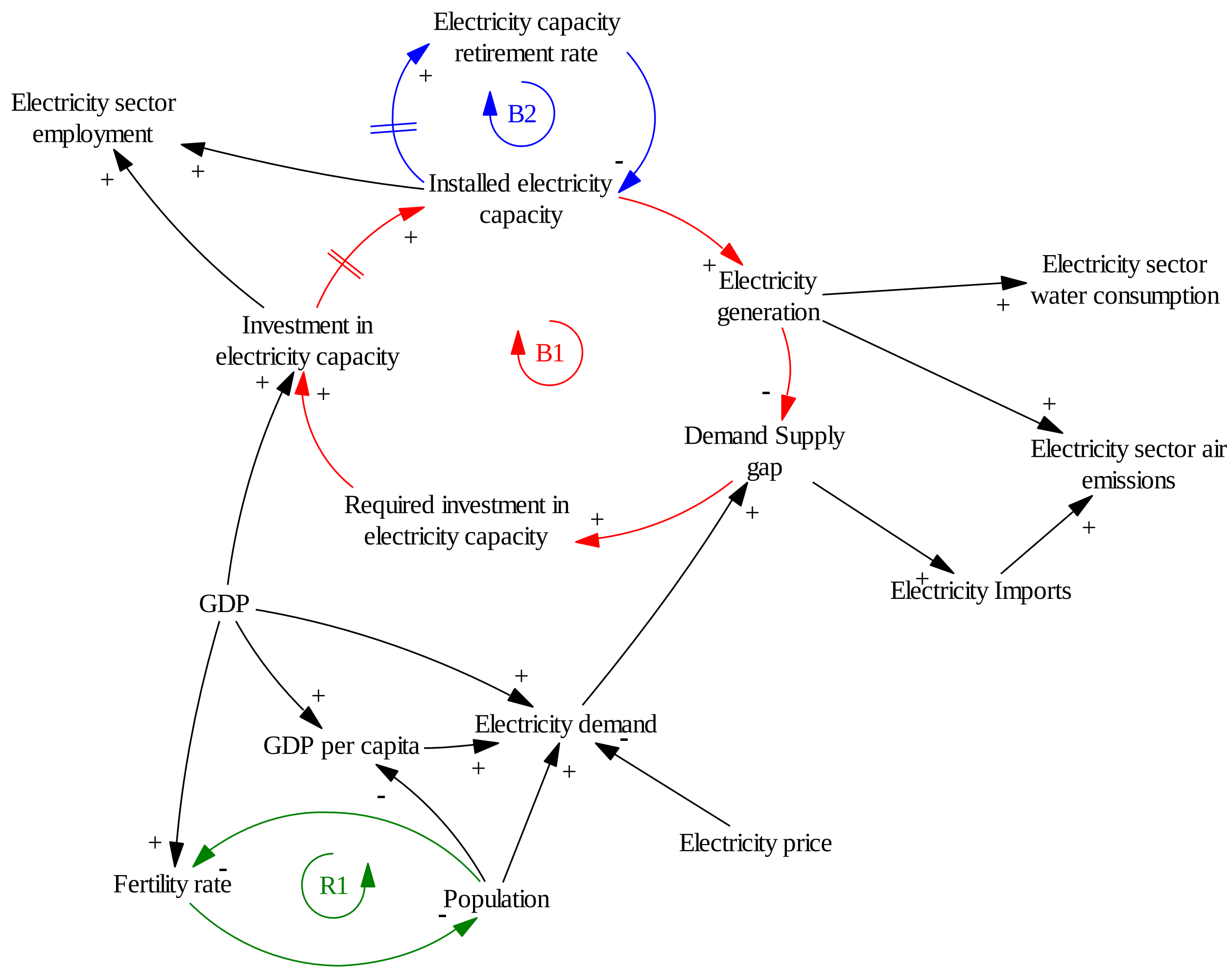

Figure 5.4: CLD for the electricity sector of the Western Cape

From Figure 5.4, one can see the effects of the capacity expansion loop – B1 – on employment, water consumption, and air emissions. Investments in electricity capacity increase employment in the electricity sector because jobs are created in construction, manufacturing, and installation activities related to the electricity sector during the construction phases of power plants. An increase in installed electricity capacity will increase employment in the electricity sector as more jobs are created in the operation and maintenance activities involving power plants. An increase in electricity sector employment will have an increasing effect, although very minute, on the GDP of the Province. This effect is, however, not taken into account in this model because it will have no significant effect on the GDP of the entire Province, and will not provide any significant feedback to GDP.

Including water demand and air emissions for the electricity generation technologies is essential in order to assess the environmental impact of investments in electricity generation technologies and also the impact of the entire electricity sector. As electricity generation capacity increases, the total water consumption of the electricity sector will increase; all power plants, to some extent, require water to function. Some electricity generation technologies require more water during operation than others, with the investment in different technologies determining the extent to which water consumption will increase. The water demand of the electricity sector has the potential to affect the ability of other sectors in the economy to satisfy their water needs. An increasing water demand from the electricity sector could potentially place constraints on water supply, affecting industries that occupy a lower priority position for water supply than the electricity sector, especially in times of draught.

An increase in electricity generation capacity will increase the amount of air emissions; all operating power stations release, to some extent, greenhouse gases. The Province must account for all the air emissions resulting from its electricity consumption, and not only from its electricity generation. A region that consumes electricity and produces none is still responsible for greenhouse gas emissions; they are still responsible for greenhouse gases originating from their use of electricity. Therefore, the air emissions from electricity imports are also taken into account. The effects of greenhouse gas emissions are not concentrated locally and can have an effect on areas far away from its source. Therefore, the CO_2 equivalent air emissions of these electricity imports need to be taken into account in order to assess the full environmental impact of the Province's electricity sector. This gives a more holistic view of the impact of investments in the electricity sector on air emissions.

The causal link between GDP and investment in electricity capacity can be seen in Figure 5.4. Capital cannot be designated for electricity capacity expansion if the capital does not exist. The GDP is a limiting factor affecting the investment in new capacity, and determines to what extent required investments in electricity capacity can be met by available capital. Figure 5.4 does not cover all the relationships present in the sector, nor does it include all the parts and feedback loops that make up the sector. It, rather, illustrates the most important relationships and feedback loops defining the dynamic behaviour of the electricity sector. These are the dominant relationships that define how the system responds to changes in its environment.

5.2. The dynamic model of the electricity sector

The dynamic model of the electricity sector is divided into seven sub-models: (1) electricity demand, (2) electricity supply, (3) electricity technology share, (4) electricity sector employment, (5) electricity sector water requirements, (6) electricity sector air emissions, and (7) electricity sector investments. These sub-models allow for the analysis of the electricity sector within the framework of the green economy, inclusive of social, economic, and environmental issues. The conceptual model included the population, education, and GDP sectors, as these models provide inputs that are necessary to evaluate the electricity sector. The development of these three sector models was not part of the modelling effort of this author and, therefore, they will not be covered in the description of the dynamic model of the electricity sector. Illustrations of the SFDs for the sub-models can be seen in Appendix A.

5.2.1. Electricity demand

Electricity demand is a very important sub-model in the electricity sector; it estimates the future dynamics of electricity demand in the medium and long term for different electricity consumers in the economy. The development of the demand for electricity over time is the driver in determining to what extent new electricity generation capacity must be added to the existing operational capacity. The different consumers are divided into 5 sectors: (1) industry, (2) residential, (3) transport, (4) commercial, and (5) agriculture. The various drivers of electricity demand affect the different consumers in different ways. The total electricity demand (TED) in the Western Cape Province is the sum of the sectoral electricity demand (SED) for the five sector consumers and is represented by Equation (3):

$$TED(t) = \sum SED_i(t) \tag{3}$$

The subscript i denotes the consumer sector and t is time. The reason for splitting the electricity demand into the five sectors is the fact that different drivers affect these sectors, and it is necessary to distinguish between these in order to get a better understanding of the evolution of electricity demand over time. It also provides a more accurate and detailed method of predicting electricity demand than an aggregate demand method would provide. The demand for each sector is calculated using the initial demand for that sector and the total effect of the drivers of demand on that sector. Table 5.1 lists the driver of electricity demand for each of the five sectors of electricity consumers.

Table 5.1: Drivers of electricity demand per consumer sector

Consumer sectors	Drivers affecting demand
Industry	Electricity price; GDP
Residential	Electricity price; GDP per capita; Population
Transport	Electricity price; GDP per capita; Population
Commercial	Electricity price; GDP
Agriculture	Electricity price; GDP

The electricity demand for each sector is calculated by multiplying the initial demand for that sector with the effects of the electricity demand drivers for that sector. The electricity demand (ED) for the industry, residential, and commercial sectors are calculated by multiplying the initial electricity demand (IED) by the electricity price effect (EPE) and the GDP effect (GDPE), see Equation (4). The SED for the residential and transport sectors are calculated by multiplying the IED by the EPE, the GDP per capita effect (GPCE), and the population effect (PE), and is given by Equation (5).

$$SED_i(t) = IED_i * EPE(t)_i * GDPE(t)_i \tag{4}$$

$$SED_i(t) = IED_i * EPE(t)_i * GPCE(t)_i * PE(t)_i \tag{5}$$

The IED for the Province was obtained from electricity consumption data provided by Stats SA, with the sector share of consumption for each sector in the Province obtained from Kowalik and Coetzee (2005). The effect that a driver has on the demand for electricity is dependent on the change in value of the driver itself. In order to determine the effect of a driver on demand, it is necessary to determine the change in the driver from its initial value to the value at the relevant point in time. This change can then be used to determine a change in the variable that it is influencing; thus, the change in the driver is expressed in the form of its relative value, which is its current value divided by its initial value. The relative change of the driver is very rarely equal to the change in the variable it is influencing. The elasticity of a driver determines to what extent a change in the driver causes a change in the affected variable. The elasticity determines the responsiveness of the affected variable to the change in the driver. It measures the sensitivity of the affected variable to the driver, and determines how the affected variable will change with a certain change in the relative value of the driver. Figure 5.5 gives an illustration of the drivers affecting electricity demand in the electricity sector model.

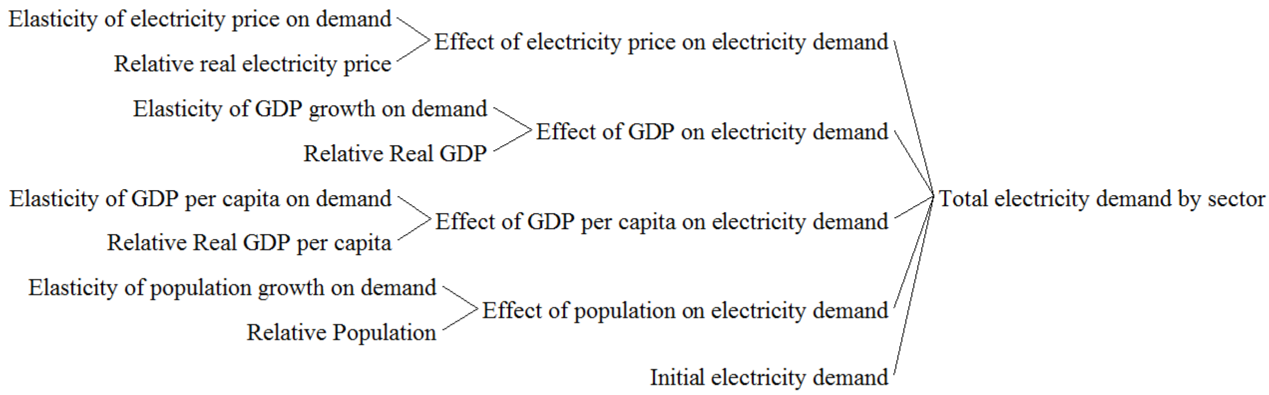

Figure 5.5: Causal tree for electricity demand

Changes in GDP affect three of the five consumer sectors, with the residential and transport sectors not being directly affected by it. Economic growth will be reflected in growth in GDP. As economic production increases the economy grows and the demand for electricity increases. The elasticity of GDP on demand determines the responsiveness of electricity demand to a change in the GDP, and determines how demand will change with a change in GDP. The GDPE, used in Equation (4), for the industry, commercial, and agriculture sectors is calculated by taking the relative real GDP (RRGDP) to the exponent elasticity of GDP (EGDP). This is shown below in Equation (6). The EGDP for industry, commercial, and agriculture are 0.8, 0.42, and 0.42 respectively. These values were obtained from Deloitte (2012) and Inglesi (2010).

$$GDPE(t)_i = RRGDP(t)\hat{}EGDP_i \qquad (6)$$

The transport and residential sectors are affected by GDP in the form of GDP per capita, which is a more robust reflection of the growth in income for individuals than GDP is. An increase in GDP per capita is expected to indicate that individuals have more money to spend, leading to increased demand for residential electricity and increased demand for passenger rail. Thus, GDP per capita is used as a proxy variable for the average personal income of residents. Electricity demand in the transport sector comes mainly from passenger trains. Therefore, increased personal income is expected to lead to more residents earning enough money to be able to use public transport, including passenger rail. The possibility does exist that people may switch to personal transport with increasing income, but this is not taken into account; the assumption is made that people who use public transport will continue to do so after their incomes rise. The GPCE, used in Equation (5), for the residential and transport sectors is calculated by taking the relative real GDP per capita (RRGPC) to the exponent elasticity of GDP per capita (EGPC). This is shown in Equation (7). The EGPC for residential and transport is 0.31, and was obtained from Ziramba (2008).

$$GPCE(t)_i = RRGPC(t)\hat{}EGPC_i \qquad (7)$$

Population also affects electricity demand from the residential and transport sectors. It is expected that an increase in population will drive electricity demand from the residential sector as the number of homes increases. It is also expected that it will increase passenger rail transport, as there will be a greater demand for passenger rail, consequently having an increasing effect on electricity demand from the transport sector. The PE, used in Equation (5), for the residential and transport sectors is calculated by taking relative population (RP) to the exponent elasticity of population (EP). This is shown in Equation (8). Very little credible data could be found for the EP, thus it was assumed that EP is unit elastic – equal to 1.

$$PE(t)_i = RP(t)^\wedge EP_i \quad (8)$$

The electricity price has an effect on all five consumer sectors. It is expected that an increase in electricity price has a negative effect on electricity demand, and will decrease electricity demand. This is, in most cases, due to consumers cutting down on electricity consumption or utilising efficiency improvements in electricity use in order to decrease their electricity costs. The EPE, used in Equation (4) and (5), is calculated by taking the relative real electricity price (RREP) to the exponent elasticity of electricity price (EEP). This is shown in Equation (9). The EPE is equal to -0.04 for residential and transport, -0.3 for industry, and -0.045 for commercial and agriculture. These values were obtained from Ziramba (2008), Deloitte (2012) and Inglesi-Lotz (2011).

$$EPE(t)_i = RREP(t)^\wedge EEP_i \quad (9)$$

The relative real electricity price is calculated by dividing the real electricity price with the initial price. The real price of electricity is used in order to negate the effect of consumer price inflation (CPI). Price inflation/deflation has an effect on monetary values, therefore, using real values over nominal values allows for a more robust comparison of monetary values over a period of time. This also holds true for the use of real GDP and real GDP per capita, as was used above. The price that was used is the average price of electricity across all sectors. The assumption is made that any price increase would occur, and be equal, across the full range of sectors.

As was mentioned previously, the electricity sector in South Africa is highly regulated, with the price of electricity being totally dependent on NERSA. Therefore, the price of electricity is considered an exogenous variable. Electricity price data, for the period 2000 – 2040, was imported to the model. Historical data was used for the period 2000 – 2013, with the values for 2014 – 2040 being forecasted. The average nominal year-on-year price increase between 2000 and 2007 was 5.3%, with the average nominal year-on-year price increase between 2008 and 2011 climbing to 27.4%. This sudden increase was due to required funding for the new build coal projects. A 16% increase was approved for 2012, with year-on-year increases of 8% being approved for the period 2013 – 2017. During the period 2000 – 2012, consumer price inflation was averaging 5.3% per year. The assumption was made that the nominal year-on-year price increase over the period 2018 – 2040 would be equal to the consumer price inflation, giving a real price increase over this period of 0%. This assumption was made because of the fact that the average year-on-year price increase, before the big spike in price between 2008 and 2011, was roughly equal to inflation. It is difficult to determine what Eskom’s exact future capacity expansion plans are and what effect this would have on price increases, thus the decision was taken to assume that real price increases will be 0%.

5.2.2. Electricity supply

The total electricity supply is determined by the total installed electricity generation capacity from the different electricity generation technologies in the Province. Electricity generation technologies are categorised into nuclear, gas, pumped storage, wind, and solar PV. These are the technologies that already have a presence in the Province or are seen as being in a position to make a significant contribution to the Province's electricity supply in the future. Only wind and solar PV are classified as renewable energy technologies, with the remaining three being classified as conventional technologies. Nuclear and gas technologies have the largest presence, with pumped storage also contributing to the Province's electricity supply over the past few decades. The two pumped storage power stations in the Province are mainly used as power sources during peak demand periods. The contribution made by renewable energy technologies has been negligible up until 2010, but this has been changing over the past few years with these technologies set to significantly increase their contribution in the next few decades. The five electricity generation technologies were modelled separately in different sub-models and have their own capacity development processes. These capacity development processes include important parameters, such as time delays, capacity factors, and costs, which differ for each of the technologies and need to be explicitly accounted for. Figure 5.6 illustrates an example of an SFD for the capacity development process of an electricity generation technology, as used in the electricity model.

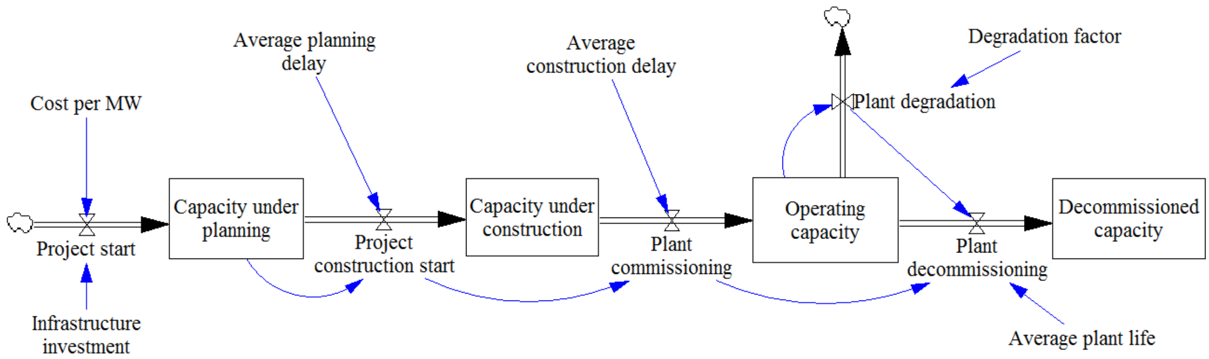

Figure 5.6: Example SFD for an electricity generation technology

The SFDs for the five electricity generation technologies include the same basic stocks, flows, and parameters as the example in Figure 5.6. There are four stocks: (1) capacity in planning, (2) capacity under construction, (3) operating capacity, and (4) decommissioned capacity. Investments in electricity generation infrastructure determine the capacity of new projects being approved. New projects originate from green economy investment or from projects already committed to by the National or Provincial Governments, usually through the Integrated Resource Plan. The project start rate (PSR) is calculated by dividing the investment in new capacity (INC) by the cost per MW (CPMW), and then adding the integrated resource plan commitments (IRPC), shown in Equation (10). The subscript j denotes the different energy generation technologies.

$$PSR(t)_j = \frac{INC(t)_j}{CPMW(t)_j} + IRPC(t)_j \qquad (10)$$

The assumption is made that no green economy investments will be made towards nuclear energy projects. Nuclear energy projects are expensive and nuclear energy capacity expansion does not coincide with green economy principles. The capacities (in MW) of the new projects are determined by the magnitude of the investments and the cost per MW for the specific technology. The PSR increases capacity under planning (CUP), which is decreased by project construction start rate (PCSR). The project construction start rate (PCSR) is CUP divided by the average planning delay (APD). The average planning delay accounts for the time delay between the approval of a new project and the start of construction for that project. Nuclear and pumped storage projects have longer planning delays because these projects are generally larger and more complicated than gas and renewable projects. A first order material delay is used for PCSR due to the fact that the planning phase of the project does not take place at a set rate and the sequence at which projects enter the planning phase is not necessarily the sequence at which they exit it. The equations defining CUP and PCSR are given by Equations (11) and (12) respectively.

$$CUP(t)_j = CUP(0)_j + \int [PSR_j - PCSR_j]dt \tag{11}$$

$$PCSR(t)_j = \frac{CUP(t)_j}{APD_j} \tag{12}$$

The PCSR increases capacity under construction (CUC), which is decreased by the plant commissioning rate (PCR). The PCR is calculated by shifting the PCSR by the average construction delay (ACD). A fixed delay function, or pipeline delay is used to do this, with the delay equal to the ACD. This allows the PCR to be equal to the PCSR, but with a time delay equal to the time it would take to complete the power plant. This assumes that every project takes exactly the ACD to be completed and commissioned, and that the sequence of starting a project determines the sequence of its completion. The construction delay accounts for the time delay between the start of construction for a project and the commissioning of that project. The construction delays are also longer for nuclear and pumped storage projects because of the size and complexity of these projects. The equations for CUC and PCR are given by Equations (13) and (14) respectively.

$$CUC(t)_j = CUC(0)_j + \int [PCSR_j - PCR_j]dt \tag{13}$$

$$PCR(t)_j = PCSR\left(t + ACD_j\right)_j \tag{14}$$

Once a power plant has been commissioned it is regarded as part of the installed operating capacity (OC) for the given technology. The PCR increases OC, which can be decrease in two ways; either through the plant degradation rate (PDR) or through plant decommissioning rate (PDCR). The PDR is calculated by multiplying the OC with the degradation factor (DF). The PDR accounts for decreases in operating capacity due to losses in plant efficiency over a power plants operating life. The DF is a parameter used to determine the yearly loss of plant capacity due to degradation of parts and components. The average plant life (APL) of a power plant for a specific technology determines the rate at which decommissioning takes place. The PDCR is calculated by shifting the PCR, minus PDR, by the APL. A fixed delay function is used to do this, with the delay equal to the APL. This allows the PDCR to be equal to the PCR, but with a time delay equal to the time over which the plant will operate. This assumes that every power plant has an operational life of exactly the APL. PDCR increases the decommissioned capacity (DC). The DC calculates the accumulated capacity that has been decommissioned over time. The SFDs for nuclear and pumped storage do not include the decommissioned capacity stock or the plant decommissioning flow. The reason behind this is the fact that nuclear and pumped storage power plants have long operating lives and no decommissioning of operating capacity will take place during the time period over which the model is run: 2000 – 2040. The equations for OC, DC, PDR, and PDCR are given by (15), (16), (17), and (18) respectively.

$$OC(t)_j = OC(0)_j + \int [PCR_j - PDR_j - PDCR_j]dt \tag{15}$$

$$DC(t)_j = DC(0)_j + \int[PDCR_t]dt \quad (16)$$

$$PDR(t)_j = OC(t)_j * DF_j \quad (17)$$

$$PDCR(t)_j = PCR(t - APL_j)_j - PDR(t - APL_j)_j \quad (18)$$

The OC, together with the capacity factor (CF) for the given technology and an energy conversion factor (ECF), determines the amount of electricity generated (EG) by the given technology. The equation for EG is given by (19).

$$EG(t)_j = OC(t)_j * CF(t)_j * ECF \quad (19)$$

The CF is specific to the technology and is time varying due to improvements in the CF over time for some technologies. The ECF converts the value of the OC from MW to GWh.

5.2.3. Electricity sector water demand

The water demand sub-model determines the total annual water requirement for each electricity generation technology, thus also determining the total annual water requirement (TAWR) for the electricity sector as a whole. The annual water requirement (AWR) for each technology is determined using the amount of EG by the installed operating capacity of that technology and the specific average water consumption (AWC) for the given technology. The equations for TAWR and AWR are given by (20) and (21) respectively.

$$TAWR(t) = \sum AWR(t)_j \quad (20)$$

$$AWR(t)_j = EG(t)_j * AWC_j \quad (21)$$

Gas power plants are the most water intensive of the five technologies, with wind and nuclear power plants being the least water intensive. The Western Cape Province’s only operating nuclear power plant – Koeberg – makes use of open loop cooling; using water directly from the ocean and then returning it to the ocean after it has gone through the cooling loop. This minimizes the amount of water that is required during the operation of the plant. The assumption is made that this process would be used for any other nuclear power plant built in the Province, as the specified locations for possible future nuclear power plants are all situated along the coast. The assumption is made that the water requirements of the Province’s electricity sector are met by water sources within the Province.

5.2.4. Electricity sector air emissions

The air emissions sub-model determines the level of annual air emissions (AAE) for each technology. The AAE are calculated and expressed in terms of CO_2 equivalent emissions. The CO_2 equivalent emissions for a specific technology are determined using the amount of EG by the installed operating capacity of the technology and the specific average air emissions (AVAE) for the technology. The air emissions sub-model does not only account for air emissions from EG within the Province, but also determines the air emissions for the total electricity consumption within the Province. The Province’s electricity supply does not meet its demand, requiring electricity to be imported from other provinces in the country through Eskom. Air emissions from imported electricity (AEIE) are calculated using the amount of imported electricity (IE) and the average emissions per kWh (AEE) for EG by Eskom. The AAE is the average air emissions per kWh for Eskom's installed electricity generation capacity in the country. The total annual air emissions (TAAE) for the Province's electricity sector are calculated using the annual air emissions (AAE) from EG within the Province and from AEIE originating from IE to the Province. The equations for TAAE, AAE, and AEIE are given by (22), (23), and (24) respectively.

$$TAAE(t) = \sum AAE(t)_j + AEIE(t) \tag{22}$$

$$AAE(t)_j = EG(t)_j * AVAE_j \tag{23}$$

$$AEIE(t) = IE(t) * AAE(t) \tag{24}$$

5.2.5. Electricity sectors employment

The employment sub-model determines the number of jobs created through the different phases of the capacity development process for a specific technology. Employment is created during the construction and operation phases of each technology's capacity development process. Construction jobs include those related to construction of the plant, installation of components, and manufacturing of components and parts. Operation phase jobs are those related to operating and maintaining the plant. Construction phase jobs are high volume and short-term jobs, with a large number of jobs created compared to operation phase jobs. These jobs only span over the construction period of the plant. Operation phase jobs are usually lower volume, but are long term and span for the duration of the plants life. Nuclear and pumped storage employment in the Province include very little manufacturing jobs because there is no significant local industry involved in manufacturing components and parts for these technologies. The same applies to manufacturing jobs in the gas power industry, but the presence of gas power plants creates the potential for jobs in the gas fuel supply industry.

The total electricity sector employment (TESE) is calculated by summing the total employment per technology (TEPT). This is shown in Equation (25).

$$TESE(t) = \sum TEPT(t)_j \tag{25}$$

The TEPT for nuclear and pumped storage are calculated by adding the construction phase employment (CPE) and the operation phase employment (OPE). The CPE is calculated by multiplying the construction manufacturing installation jobs (CMIJ) per MW by the CUC. The OPE is calculated by multiplying the operations and maintenance jobs (OMJ) per MW by the OC. The TEPT for gas power includes fuel supply employment (FSE). FSE is calculated by multiplying the EG for gas power with the fuel supply jobs (FSJ) per GWh and the fuel supply local jobs factor (FSLJF). The value for FSJ includes the assumption that a fully established fuel supply industry exists within the Province. This is, however, not the case. Thus, the FSLJF is a variable that can be used by the policymaker to investigate the effect of employment in the gas power industry for different scenarios related to the establishment of fuel supply infrastructure within the Province. These calculations are shown in Equations (26), (27), (28), and (29).

$$TEPT(t)_j = CPE(t)_j + OPE(t)_j + FSE(t)_j \tag{26}$$

$$CPE(t)_j = CUC(t)_j * CMIJ_j \tag{27}$$

$$OPE(t)_j = OC(t)_j * OMJ_j \tag{28}$$

$$FSE(t)_j = EG(t)_j * FSJ_j * FSLJF(t)_j \tag{29}$$

Renewable energy technologies offer the greatest potential for creating local manufacturing jobs. Solar PV and wind are the only technologies that could possibly receive a significant contribution to employment from manufacturing of parts and components, thus these are the only technologies specifically accounting for manufacturing employment. Figure 5.7 illustrates the different contributions to employment in the respective technology classes.

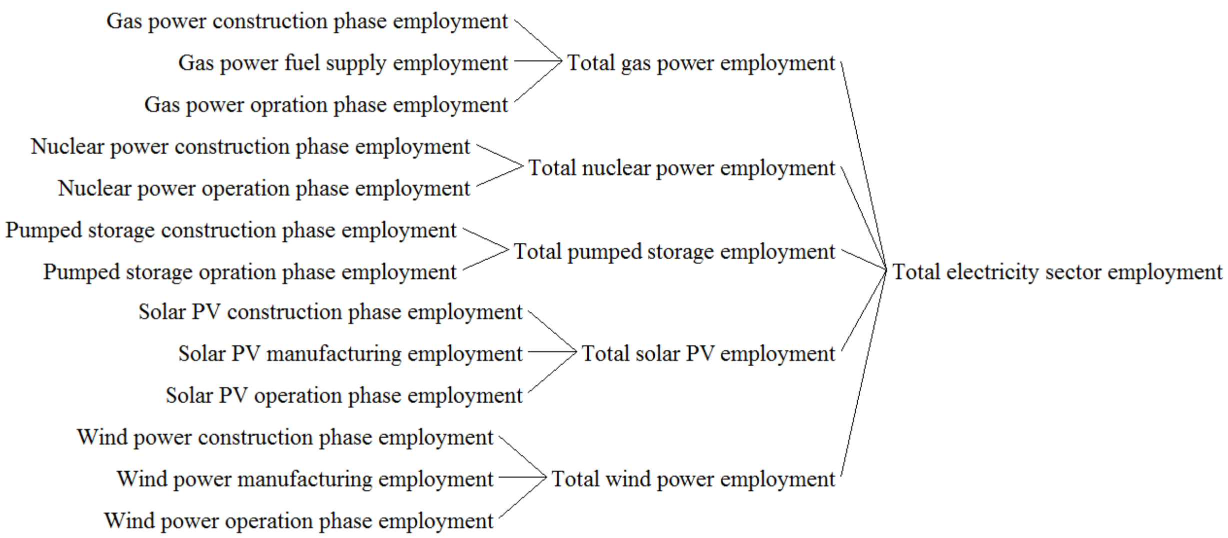

Figure 5.7: Causal tree for electricity sector employment

The TEPT for wind and solar PV are determined by adding the CPE, OPE, and the manufacturing employment (ME). CPE is calculated by multiplying the CUC by the construction and installation jobs (CIJ) per MW. The OPE is calculated using Equation (28). The ME is calculated by multiplying the CUC with the manufacturing jobs (MJ) per MW and the local manufacturing jobs factor (MLJF). The value for MJ includes the assumption that a fully established renewable energy technology manufacturing industry exists within the Province. This is, however, not the case. Thus, the MLJF is a variable that can be used by the policymaker to investigate the effect of employment for different scenarios related to the establishment of a manufacturing industry within the Province. The calculations for the TEPT, for wind and solar PV technologies, and MJ are given by Equations (30) and (31).

$$TEPT(t)_j = CPE(t)_j + OPE(t)_j + ME(t)_j \tag{30}$$

$$ME(t)_j = CUC(t)_j * MJ_j * MLJF(t)_j \tag{31}$$

The job factors – FSLJF and MLJF – can be defined as constants or as time varying parameters in order to investigate the effect of an evolving establishment of manufacturing or fuel supply industries in the Province.

These job factors can be varied by the user of the model, or policymakers, to investigate the impacts on employment for different scenarios.

5.2.6. Electricity technology share

The electricity technology share sub-model calculates the proportional contribution made by each electricity generation technology to the total electricity supply and to the total electricity generation capacity in the Province. Equation (32) and (33) calculate the total operating capacity (TOC) and the share of renewable energy operating capacity (SREOC) respectively.

$$TOC(t) = \sum OC(t)_j \tag{32}$$

$$SREOC(t) = \frac{OC(t)_{wind} + OC(t)_{solar\ PV}}{TOC(t)} \tag{33}$$

Equations (34) and (35) calculate the total electricity generation (TEG) and the share of renewable energy electricity generation (SREEG) respectively.

$$TEG(t) = \sum EG(t)_j \tag{34}$$

$$SREEG(t) = \frac{EG(t)_{wind} + EG(t)_{solar\ PV}}{TEG(t)} \tag{35}$$

The sub-model also calculates the gap between electricity demand and supply, the demand supply gap (DSG), in the Province. The amount of imported electricity (IE) is equal to the DSG. The DSG is calculated by subtracting the total net electricity generated (TNEG) from the total electricity demand (TED). The TNEG is determined by subtracting the electricity losses (EL) from the TEG. Electricity losses occur in the transmission and distribution of electricity as these processes are not 100% efficient. A transmission and distribution loss factor (TDLF) of 4% was used, which was obtained from Stats SA (2009). This TDLF value is the national average over the past ten years. The share of locally produced electricity (SLPE) is the fraction of the TED that is supplied from electricity capacity within the Province. The equations for these calculations are given below by (36), (37), (38), and (39).

$$DSG(t) = TED(t) - TNEG(t) \tag{36}$$

$$TNEG(t) = TEG(t) - EL(t) \tag{37}$$

$$EL(t) = TEG(t) * TDLF \tag{38}$$

$$SLPE(t) = \frac{TNEG(t)}{TED(t)} \tag{39}$$

5.2.7. Electricity sector investments

The electricity sector investments sub-model determines the allocation of investments to the different electricity generation technologies. This sub-model determines how the gap between electricity demand and supply should be filled with the proportional investments in different technologies. The first function of the sub-model is to determine how much capacity from each technology is needed to fill the DSG. In order to determine this, a policy decision must be made as to what proportion of the electricity demand gap should be filled by each technology, e.g., 40% Gas power, 30% wind power, 30% solar PV power. These values, the new electricity supply factor (NESF), can be varied by the user of the model, or policymakers, in order to investigate different scenarios. The demand for new electricity supply (DNES) is then calculated for each technology. The DNES, a capacity factor (CF), and an energy conversion factor (ECF) are then used to determine the new capacity needed from each technology. The required new capacity (RNC) for each technology is then calculated. These calculations are shown by Equations (40) and (41).

$$DNES(t)_j = NESF(t)_j * DSG(t) \tag{40}$$

$$RNC(t)_j = MAX\left[\frac{DNES(t)_j}{CF(t)_j * ECF}, 0\right] \tag{41}$$

A MAX function is used in Equation (41) to account for the case when the DSG is negative, that is, when supply exceeds demand. In such a case, the MAX function prevents the RNC from reaching a negative value. Determining the RNC, allows for the required investment in new capacity (RINC) for a given technology to be calculated. The cost per MW (CPMW) for each technology is used to calculate the RINC. The total required investment in new capacity (TRINC) is calculated by summing the RINC for each technology. The calculations for RINC and TRINC are given in Equations (42) and (43).

$$RINC(t)_j = RNC(t)_j * CPMW(t)_j \tag{42}$$

$$TRINC(t) = \sum RINC(t)_j \tag{43}$$

The TRINC is a total amount and not a yearly amount, and will significantly outweigh the annual amount of capital that is available to invest in new projects. The TRINC needs to be converted to a form that determines the proportion of available capital that must be invested in each technology. Thus, an investment fraction (IF) is calculated. The IF determines the required proportion of available capital that must be assigned to projects for each technology class. The TRINC cannot be covered in one year, therefore, a measure of how much capital can be made available each year is required. The value of Western Cape GDP (WCGDP) was used as this measure. The total investment in new capacity (TINC) is determined by multiplying the WCGDP with a GDP investment fraction (GDPIF). The GDPIF is defined as the percentage of GDP which is made available for TINC. The TINC and the IF are then used to calculate the investment in new capacity (INC) that is allocated to each technology class. The calculations for IF, TINC, and INC are given by Equations (44), (45), and (46)

$$IF(t)_j = \frac{RINC(t)_j}{TRINC(t)} \tag{44}$$

$$TINC(t) = MIN\left[WCGDP(t) * GDPIF, \frac{TRINC(t)}{TTI}\right] \tag{45}$$

$$INC(t)_j = TINC(t) * IF(t)_j \tag{46}$$

The scenario may develop where the TINC exceeds the TRINC. In this case it would be considered not ideal to invest more in new capacity than is needed. A MIN function is used to accommodate this scenario. The

MIN function prevents the TINC from exceeding the TRINC. The TRINC is a total amount and needs to be converted to a yearly value. The time to invest (TTI) parameter has a value of one year, and represents the time it takes to meet the TRINC if enough capital was available to do so. This assumption states that no significant delays are experienced when investment allocations are determined. The GDPIF is an important parameter because it can investigate the effect of different levels of investment in the electricity sector, and can be varied by the user of the model, or policymaker, in order to investigate these different scenarios.

5.2.8. Model settings

The model was developed, constructed, and simulated using Vensim DSS – developed by Ventana Systems. A simulation time frame of 40 years was chosen: spanning from 2001 to 2040. This timeframe was selected for two reasons: (1) a majority of the required data spans back to only 2000; and (2) many of the Province's goals and projections – including those in the Western Cape Infrastructure Framework (WCIF) – span until 2040. The model was simulated using the time interval of one year and a unit of years. A time step of 0.0625 was selected. A time step must be evenly divisible by the time interval that was chosen. Computer simulations, such as Vensim, integrate the stocks of a model. The time step represents the time delay between iterations of the models calculations. The Euler method was chosen for numerical integration purposes. Euler is the default simulation method for many system dynamics simulation software packages, including Vensim (Sterman, 2000), with other methods used in rare circumstances when the Euler method is not adequate. The level of data uncertainty, speed requirements, and lack of specificity requirements warranted choosing the Euler method over the Runge-Kutta 4 method.

5.2.9. Data collection

The data used for developing the electricity sector of the WeCaGEM were collected from various sources, see Table B.1 in Appendix B. An effort was made to collect data that are nationally available, or to use expert based documents in South Africa. Where this approach was not possible, the internationally best available data were used in the form of data from global organisations, such as the International Energy Agency and World Energy Council, or in the form of peer reviewed journal articles. In cases where data was unavailable for South Africa, assumptions were made using data for developing countries.

5.3. Model verification and validation

George Box once wrote that "*Essentially, all models are wrong, but some are useful.*" (Box & Draper, 1987). Thus, the main questions for most modellers are how useful the model is and how one can be assured of its usefulness. In order for a model to be useful, it must be considered as suitable and consistent. Any simulation model can only be developed as an approximation of the actual system, regardless of the time and effort that goes into building the model (Law, 2009). Hahn (2013), states that model validation checks whether the right system was built, while model verification checks whether the model was built right. Law (2009) describes validation as the process of determining whether, for the particular objectives of the study, the simulation model is an accurate representation of the system it is describing. Due to certain characteristics that have made the application of standard statistical tests inappropriate, the system dynamics methodology has been criticised for its lack of quantitative behaviour evaluation tools (Barlas, 1989). Validating system dynamics models requires a combination of qualitative and quantitative methods. These methods should focus on major time patterns, instead of on individual data points (Barlas, 1989).

According to Barlas (1989), system dynamics models should be subjected to two types of tests: structural validity tests and behaviour validity tests. Structural validity tests aim to determine whether the structure of the model is an acceptable representation of the actual system structure. Behaviour validity tests aim to determine whether the model is able to produce an output behaviour that is close enough to the behaviour of the actual system. Determining whether the appropriate structure has been implemented is the first step in establishing the validity of a system dynamics model (Qudrat-Ullah, 2012). Once the structural validity has been sufficiently proven, behaviour validity can be assessed in order to achieve overall validity of the model. Structural testing must take place before behaviour testing is attempted. This is due to the fact that a model with obvious structural errors is still capable of producing very accurate behaviour predictions (Barlas, 1989). If it is clear that the structure of the model is sound, then any weak pattern prediction ability can be attributed to parameters or exogenous variables that have been misinterpreted (Barlas, 1989).

Forrester and Senge (1980) suggest 17 separate tests for model validation. Of these 17 tests, five are tests for model structure, eight are tests for model behaviour, and four are tests for policy implications. They, however, identified a subset of these tests that are known as “core tests”, which are more heavily relied upon by modellers to perform model validation. All five model structure tests are considered core tests, with three of the behaviour tests and two of the policy implementation tests being considered core tests. This gives a total of ten core validation tests. Maani and Cavana (2007) adopted these ten tests and suggest them for confidence building in system dynamics models. These five model structure tests, together with some of the behaviour validity tests, also appear in Barlas (1996) and Sterman (2000). Qudrat-Ullah and Seong (2010) carries out an extensive system dynamics model validation test using this framework, suggested by Forrester and Senge (1980), on an energy policy model, applying model structure and model behaviour tests. The five core structure tests and three core behaviour tests were applied to the model. Due to the lack of historical data for green economy intervention in the Western Cape Province, the policy implication tests could not be implemented. Instead, expert opinions and inputs were relied upon to verify the policies that were implemented during the simulations.

5.3.1. Model structure validity tests

As mentioned above, Forrester and Senge (1980) suggest five tests for validating the structure of the model: (1) structure verification test; (2) parameter verification test; (3) extreme conditions test; (4) boundary adequacy test; and (5) dimensional consistency test. Sterman (2000) lists these as the first five tests, of a total of twelve, to be carried out on a system dynamics model. Barlas (1996) describes the boundary adequacy test as a “structure-oriented behaviour test”, with the remaining four listed as “direct structure tests”.

Structure verification test:

This test directly compares the structure of the model with the structure of the real system. A model will pass this test if it does not contradict knowledge about the structure of the real system (Forrester & Senge, 1980). This test is highly qualitative and cannot simply be captured by a set of numerical data, according to Barlas

(1996). An important factor to check is whether the conceptual model (CLDs) corresponds with the structure of the real system (Maani & Cavana, 2007). Then, one should check whether the dynamic model corresponds to the conceptual model, and whether the equations of the dynamic model correspond with the relationships of the real system (Barlas, 1996). Qudrat-Ullah (2010) suggests the utilisation of available knowledge about the real system, and sub-models or structures of existing models that have been developed. The electricity sectors of South Africa and of the Western Cape Province have been discussed in previous chapters. This insight was gained through relevant literature, as well as documents from the state utility, Eskom. The previous sub-chapters describe the process of building the conceptual model. The electricity sector of the SAGEM (Musango, et al., 2014a; Musango, et al., 2014b) was used as a guideline of building a system dynamics model for the electricity sector. Other electricity sector system dynamics models were also used as guidelines (Qudrat-Ullah & Davidsen, 2001; Qudrat-Ullah, 2013; Aslani, et al., 2014; Pereira & Saraiva, 2013). Another step used to verify the model structure was to have the model reviewed by people who are highly knowledgeable in model building. The author's supervisors were used during the modelling process to review assumptions and decisions regarding the conceptual and dynamic models. These steps ensured that the CLDs correspond to the real system and that the equations used in the dynamic model accurately represent the causal relationships of the real system.

<u>Parameter verification test:</u>

The verification of model parameters (constants) against characteristics of the real system can be achieved in the same way that the model structure can be verified (Forrester & Senge, 1980). The parameter values of the system need to be consistent with the relevant conceptual and numerical knowledge of the system (Sterman, 2000). Structure verification and parameter verification are interrelated, with structure verification being thought of as including parameter verification (Forrester & Senge, 1980). Any parameters that are used in the model must have counterparts in the real system, and must fall within a plausible range of values. The values that were assigned to the parameters in the model were sourced from existing knowledge and numerical data. The data collection procedures are explained in Chapter 5.2.9 and the data sources are provided in Appendix B.

<u>Extreme conditions test:</u>

This test is intended to uncover flaws in the model structure and reveal omitted variables by subjecting the model structure to extreme conditions (Forrester & Senge, 1980). The validity of model equations is tested by subjecting them to certain extreme conditions whose outcomes on the real system are known to the modeller. This test is carried out by first inspecting each equation in a qualitative manner and then running the model under certain extreme conditions. These extreme conditions are modelled as shocks to the system, in the form of pulse or step functions (Maani & Cavana, 2007). The electricity demand sub-model was tested using step functions. The step function was set to create a step of magnitude ten between the years 2021 and 2030. This step function was then applied to each of the drivers of electricity demand in order to investigate the effect on total electricity demand. What this does is multiply each driver of electricity demand with a factor of ten for the specified time period. The step function was then applied to the electricity demand in order to investigate its affect on the demand supply gap and the total required investment in new capacity. Increasing price decreases demand. Increasing the other drivers increases demand. These tests produced the results that were expected from the real system. The graphs produced by these tests can be seen in Appendix C1.

Another approach was to increase certain initial values by tenfold and to observe whether the expected outcomes were produced. A tenfold increase was applied to the initial electricity demand. This significantly increased the demand supply gap, as expected. A tenfold increase was also applied to the initial operating capacities of the electricity generation technologies, causing the expected increases in installed capacity, electricity generation, and a surplus in electricity generation. Increasing the construction delays by tenfold significantly delays the commissioning of new capacity, the same applying to increasing the planning delays. When the cost per MW for each technology is increased by tenfold, the addition of new capacity is significantly decreased. The investment in new capacity is regulated by the gap between supply and demand, thus preventing overinvestment in new capacity. Increasing the investment fraction of GDP going towards new capacity by tenfold, significantly increases the investment in new infrastructure for a short time as the supply demand gap is being filled faster. These tests produced the model outputs that were expected, thus passing the overall extreme condition test. The graphs produced by these tests can be seen in Appendix C1.

Boundary adequacy test:

This test investigates whether the model includes all relevant structures and whether the model aggregation is appropriate (Forrester & Senge, 1980). The boundary of the model must correspond with the purpose of the model in order for the model to be able to serve its purpose, and must contain the structural relationships to do so. The purpose of the WeCaGEM electricity sector model is to investigate the effect that different investment scenarios could have on electricity generation, air emissions, water consumption, and employment in the electricity sector. Chapters 5.1 and 5.2 describe the development process for the conceptual and dynamic models. They also described which variables are endogenous and exogenous, and the reasons for these decisions. An argument can always be made for making variables endogenous and adding the additional structure to do so. The question then, however, becomes whether the added structure ultimately contributes to the purpose of the model or not. As with the structure verification test, the knowledge of the author's supervisors contributed to building confidence in the adequacy of the boundary.

Dimensional consistency test:

Testing for dimensional consistency is often carried out in conjunction with the parameter verification test (Forrester & Senge, 1980). Combining these two tests tends to uncover parameters that are used as dimension fillers, or dummy variables, and have little or no significance as independent structural components. It is also critical that the dimensions of the parameters and variables are consistent with their counterparts in the real system. The WeCaGEM electricity sector model has no such dummy variables and all variables have real system counterparts. The test entails carrying out dimensional analyses on the parameters, variables, flows, and stocks of the system. The Vensim modelling software has a built-in function that checks for dimensional consistency and highlights equations where dimension problems occur. This function was utilised throughout the dynamic modelling process.

5.3.2. Model behaviour validity tests

Once the validity of the model structure is confirmed, one can investigate whether the model produces the expected behaviour over time. Behaviour validity tests indirectly investigate the validity of the model structure by measuring how accurately the model structure can reproduce the behaviour patterns produced by the real system. These tests have the advantage of being quantifiable, unlike direct structure tests, which are mostly qualitative in nature (Barlas, 1996). The behavioural validation of the model is enhanced by comparing the simulated data with historical data (Qudrat-Ullah, 2012), but this is not the only factor that should draw attention. Apart from the five structure validity tests, Forrester and Senge (1980) suggest three tests to investigate the validity of the models behaviour: (1) behaviour reproduction test; (2) behaviour anomaly test; and (3) behaviour sensitivity test. These three tests are also described in Barlas (1996) and can be found in Sterman (2000) and Cavana and Maani (2007).

Behaviour reproduction test:

The emphasis on behaviour reproduction tests should be on pattern behaviour, and not on the ability of the model to produce point predictions (Barlas, 1996). The effectiveness of this test was made difficult by the lack of available data. Another limitation is the lack of any renewable energy capacity within the Province before 2012. Thus, it is not possible to compare the effect of investment in these technologies for the model and the real system. Eskom does not release the electricity generated by its individual power plants, nor does it release data of electricity generated by each province. Eskom does, however, release data for the electricity supplied to each province. The assumption is made that there is no gap between supply and demand and that supply equals demand. The electricity demand produced by the model corresponds very well to the historical data for electricity demand. Another indicator that was used is the prediction for growth in electricity demand for the Province. The WCIF (Palmer & Graham, 2013) predicted an annual increase in electricity demand of 1.4% for the Province between 2012 and 2040. The model's output for electricity demand also corresponded very well with this prediction. A comparison was also made between the model's output for total installed operating capacity and the historical data for that of the Province. The output graphs for these three behaviour reproduction tests are given in Appendix C2. The fact that only a limited number of the system variables could be tested in this way points to a possible weakness of the model. The fact that the structure of the main driver of electricity expansion – electricity demand – could be tested and validated, gives a positive outcome of this test.

Behaviour anomaly test:

Forrester and Senge (1980) explain that the behaviour anomaly test can be used to justify certain model structure assumptions by demonstrating how implausible behaviour arises if the assumption is altered. Three model assumptions are going to be explained and defended using this test. The first model assumption is the use of a fixed delay for the plant commissioning rate and the plant decommissioning rate. Previous models (Musango, et al., 2014a; Musango, et al., 2014b) have made use of first order delays for these rates. An example using the gas power operating capacity and decommissioning rate will be used. If a power plant with a certain operating capacity is commissioned, the operating capacity for this plant should stay constant – no plant decommissioning – for the duration of the plants operational life, given that no plant degradation takes place. The first order delay does not allow for this, as its formulation will cause the plant decommissioning to reach its highest level in the year that the plant was commissioned, decreasing as time goes on. This is not realistic behaviour and warrants the need for a fixed delay to represent construction and decommissioning delays. The graphs in Appendix C3 provide a visual demonstration of this explanation.

The second assumption to be explained is the one that includes the air emissions of imported electricity. One can argue that the Province is not responsible for air emissions resulting from power plants not situated in the Province. In order to raise the flaw with this argument, one has to look at the case where total generating capacity within the Province is equal to zero. In this case, the air emissions originating from the Province's electricity sector would be zero, hinting that the Province makes no contribution to air emissions whatsoever. This is, however, not the case as the Province's use of electricity generated outside its borders, and its effects on air emissions, should still be taken into account.

The third assumption involves the total annual investment in new capacity (TINC). This variable requires the use of a MIN function in order to limit it to the total required investment in new capacity (TRINC). The use of MIN, MAX, and IF THE ELSE functions should be limited and properly motivated. This MIN function is required to ensure that over investment in new capacity does not occur, as explained in Chapter 5.2.7. An example is used where this MIN function is omitted and the investment in new capacity is equated to the portion of GDP that is made available for investment in new capacity. When one takes the case where ten times the GDP is made available for investment in new capacity, the total operating capacity within the Province will greatly exceed the required capacity and supply will significantly exceed supply. This is abnormal behaviour and warrants the use of the MIN function connected to the required investment in new capacity. A figure displaying the effect of this example is provided in Appendix C3.

<u>Behaviour sensitivity test:</u>

This test investigates how sensitive the model behaviour is to changes in parameter values. Plausible changes in parameter values can, on occasion, result in a model failing behaviour tests that were previously passed (Forrester & Senge, 1980). The absence of such parameters enhances the confidence in the model. The presence of such sensitive parameters does, however, not invalidate the model (Forrester & Senge, 1980), but does highlight possible weak points in the model that need to be taken note of. If the real system is similarly sensitive to these parameters, then these parameters may be valuable for policy analysis carried out by the model. For the electricity sector model, the elasticities of the drivers on demand – price, GDP, GDP per capita, and population – are the parameters drawing the most interest when it comes to sensitivity. The elasticity values play a significant role in determining the electricity demand, which then determines how much electricity capacity is needed. The elasticity values of the drivers of electricity demand are also sensitive in the real system, determining how demand develops over time for a certain electricity sector. A sensitivity analysis was carried out separately on each driver of electricity in order to investigate the effects of changes in these parameters. The price elasticities for the five sectors were tested for their sensitivity between the values of -1 and 0. The population elasticity on electricity demand was tested for sensitivity of values between 0 and 2, with the remaining two drivers – GDP and GDP per capita – being tested for sensitivity of values between 0 and 1. Electricity demand was the most sensitive to variations in the price elasticity, mostly due to the fact that all drivers of electricity are affected by the price. The sensitivity of electricity demand to variations in the elasticity of GDP and population was also significant. This behaviour is to be expected from the real system, as changes in elastcities will have a significant effect on the electricity demand. The graphs for the sensitivity analyses are shown in Appendix C4.

5.4. Scenario planning and modelling

The purpose of developing the WeCaGEM electricity sector model was to investigate how different investment policies would affect the sustainability of the Province's electricity sector. This meant investigating the impact investments had on the electricity generating capacity and the broader impacts on the social and environmental sectors. Thus, exploring how such investments could be allocated within the Province was of particular interest. The Western Cape Province is currently a net importer of electricity. Its electricity sector is currently dominated by nuclear and gas power generation technologies, with the imported electricity being generated by Eskom's predominantly coal-based fleet. The Western Cape Infrastructure Framework (WCIF) (Palmer & Graham, 2013) is intended to align the planning, delivery, and management of infrastructure to the strategic agenda and vision for the Province. It states that the current deficits in the electricity sector lie in the capacity to generate and source electricity for the growing demand of the consumers. A focus is also placed on lowering the carbon footprint by implementing renewable energy technologies and facilitating locally generated electricity. Three key electricity sector transitions were identified: (1) using gas as a transition away from coal-based electricity towards renewable energy technologies; (2) facilitating the expansion of renewable energy capacity in the Province; and (3) and developing the associated manufacturing opportunities, which supporting the expansion of renewable energy expansion, in the Province.

The scenarios were developed in order to align with these three key electricity sector transitions. Three scenarios were developed in order to investigate different investment policies: (1) business-as-usual (BAU), (2) renewable energy (RE), and (3) renewable energy with gas transition (RE+GT). For the RE and RE+GT scenarios, strategic investments are only made from 2015 onwards. All three scenarios follow the same initial development from 2001 to 2014, which reflects the historic development of the sector during this time. This initial period involved no expansion of nuclear power or pumped storage capacity. This period included the development of the Ankerlig and Gourikwa gas power stations that were developed between 2006 and 2009, totalling installed capacity of 2084 MW. The wind and solar projects that were approved before the end of 2015, during the first four REIPPP programme bid windows, were also included in this initial period.

The two strategic investment scenarios – RE and RE+GT – were investigated for two investment cases. The first investment case – low investment case (LIC) – allocates 0.4% of Western Cape GDP towards investments in new capacity. Thus, the GDP investment fraction (GDPIF) is equal to 0.004 for these two scenarios. The second investment case – high investment case (HIC) – allocates 0.7% of GDP towards investments in new capacity, translating into a GDPIF of 0.007 for the two scenarios. These values of 0.4% and 0.7% were used in the SAGEM analysis' green economy investment scenario (Musango, et al., 2014a). The 0.4% value originated from a SAGEM green investment scenario where 2% of GDP was invested in green economy projects across five sectors. One of these sectors was the electricity sector, thus allocating 0.4% of GDP to investments in the electricity sector. The 0.7% value originated from a second SAGEM green economy investment scenario where investments were strategically focused towards the electricity sector. The SAGEM's analysis took place at a national level, and it was decided to investigate what these investment allocations would lead to at a provincial level. For the two strategic investment scenarios, the policy decision is not made on what fraction of investments should go towards each technology, but rather on what fraction of the demand supply gap (DSG) should be filled by which technology. Table 5.2 gives a summary of the net electricity supply factor for each scenario over the simulation period. The BAU scenario does not change for the two investment cases, thus giving a total of five scenarios.

The Business-As-Usual (BAU) scenario was developed to investigate the case where the current investment policies would be continued up until 2040. In Chapters 5.2, describing the dynamic model, it was stated that additional capacity is added through strategic investments in new capacity or through integrated resource plan commitments, which have been forecasted by the Department of Energy (DoE). The BAU scenario assumes no strategic investments are made in new capacity and all capacity expansion is determined by the DoE's commitment forecasts.

The Renewable Energy (RE) scenario investigated the effects of a policy that aims to fill the demand supply gap using only wind and solar power, thus focusing all strategic investments on wind and solar technologies. For this scenario, all investments in new capacity are shared between wind and solar power technologies from 2015 to 2040. There is greater potential for wind power in the Province than there is for solar power, and wind power capital costs are slightly lower. Taking this into account, wind is preferred over solar and the new electricity supply fractions (NESF) are split 70:30 between wind and solar, with 70% of the demand supply gap allocated to wind power projects, and 30% going to solar power projects.

The Renewable Energy with Gas Transition (RE+GT) scenario investigated the case where natural gas power plants are used as a transition technology. Initially, gas power is targeted to fill a portion of the demand supply gap, thereafter only wind and solar technologies are targeted to fill the demand supply gap. The new electricity supply factor split from 2015 to 2019 is 70:20:10 for gas, wind, and solar respectively. From 2020 to 2040, the split is 70:30 for wind and solar respectively. This policy is intended to close the gap between demand and supply rapidly by adding natural gas power capacity, before diversifying the energy mix and introducing significant renewable energy capacity.

Table 5.2: New electricity supply factor (NESF) split for the BAU, RE, and RE+GT

Scenarios		GDPIF (%)	NESF split (gas : wind : solar)		
			2001-2014	2015-2019	2020-2040
BAU		0	-	-	-
LIC	RE	0.4	-	0:70:30	0:70:30
	RE+GT	0.4	-	70:20:10	0:70:30
HIC	RE	0.7	-	0:70:30	0:70:30
	RE+GT	0.7	-	70:20:10	0:70:30

In order to investigate the effects that these scenarios would have on the employment sector, three sub-scenarios were investigated for each of the five main scenarios: (1) low localisation, (2) medium localisation, and (3) high localisation. These three sub-scenarios relate to the three local jobs factors used in the employment sub-model: (1) fuel supply local jobs factor (FSLJF); (2) manufacturing local jobs factor (MLJF) for wind technologies; and (3) manufacturing local jobs factor for solar technologies. All three local jobs factors were assigned values of 0.2, 0.6, and 1.0 for the low localisation, medium localisation, and high localisation sub-scenarios respectively. Thus, investigating what the effects on employment would be for scenarios where 20%, 60%, and 100% of the manufacturing and fuel supply jobs were created locally. Low localisation would imply that the majority of the parts and components for renewable energy technologies are imported from other countries, while high localisation would imply that the majority of these parts and components are manufactured locally.

5.5. Conclusion: Modelling the electricity sector of the Western Cape Province

The WeCaGEM was developed on the same conceptual framework as SAGEM, but was implemented to investigate green economy investment interventions on a provincial level. WeCaGEM consists of a number of sector models. This study focused on the development and implementation of the electricity sector model and its implementation in analysing green economy investment interventions. The development of the conceptual model was first discussed, followed by a discussion of the development of the dynamic model. The dynamic model of the electricity sector consisted of seven sub-models: (1) electricity demand, (2) electricity supply, (3) electricity technology share, (4) electricity sector employment, (5) electricity sector water requirements, (6) electricity sector air emissions, and (7) electricity sector investments. Data collection and model settings were two issues that were also discussed for the dynamic model. Model structure and model behaviour validity tests were carried out in order to validate and verify the model, and to determine possible sensitive parts of the model. The five scenarios that were developed – BAU, LIC RE, LIC RE+GT, HIC RE, and HIC RE+GT – were discussed and their formulation explained.

Chapter 6

Simulation results and analysis

The Western Cape Province is currently reliant not only on its nuclear and gas power capacity for electricity supply, but also on Eskom's coal dominated electricity capacity for imported electricity. As the Province aims to improve its electricity situation, it needs to determine the best policies to follow with regard to investing in new electricity generating technologies and expanding its generating capacity. Five scenarios – BAU, LIC RE, LIC RE+GT, HIC RE, and HIC RE+GT – were simulated in order to investigate the effects of different investment policies on the electricity sector, as well as their environmental and socio-economic impacts. The main focus of the results was to investigate to what extent two of the key transitions of the Western Cape Infrastructure Framework (WCIF) were achieved during the three scenarios. These two key transitions are the expansion of the Province's electricity generating capacity and renewable energy capacity. This translates to developing electricity generating capacity, of which a significant portion must consist of renewable energy technologies, in the Province. Apart from this main focus, the five scenarios were also investigated for their consequent effects on the air emissions and the water requirements of the electricity sector, as well as their impact on employment creation in the sector. This allows for the simulations to investigate the overall sustainability of the investment policy scenarios that were considered.

These results should be viewed as possible projections of future developments of the Western Cape Province's electricity sector given the implementation of certain investment policies. The main simulation results will be discussed and compared in this chapter, including the most important variables and indicators. This will be done in the form of graphs and tables that show the results for each simulated scenario. Those variables and indicators not presented in this chapter are presented in Appendix D.

6.1. The electricity supply

An important output of the electricity sector model is the total electricity demand (TED). The total electricity demand is the major determinant of how much electricity generating capacity is needed and how much new capacity should be added to the installed operational capacity. The projected total electricity demand was the same for the five scenarios, as the variables that are varied in the different scenarios do not impact on electricity demand. Thus, only the values of total electricity demand for the BAU scenario are given in Figure 6.1. The total electricity demand is expected to experience an increase of 70% between 2001 and 2040, increasing from 19 420 GWh/year in 2001 to 32 990 GWh/year in 2040. The period between 2015 and 2040, where the policy implementations are active, is expected to see an increase of 38%. This growth will be driven by growth in the Western Cape GDP and the Western Cape population.

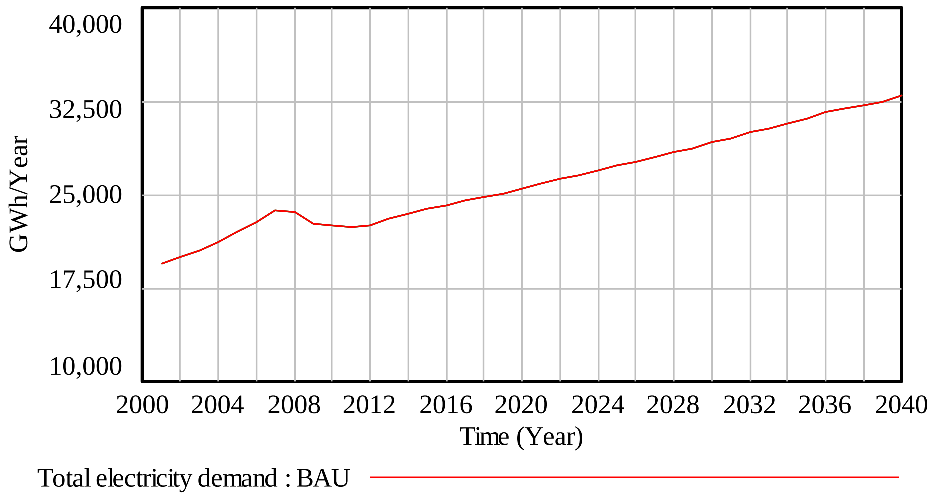

Figure 6.1: Simulation results for total electricity demand (TED)

The Province's electricity demand has to be met by the electricity generated from the Province's installed electricity generating capacity, or electricity has to be imported. As the total electricity demand increases, there is an increasing demand for additional operating capacity in the Province. Thus, total electricity demand acts as a driver of the total operating capacity (TOC) by creating the need for investments in new capacity. Table 6.1 presents the results for total investment in new capacity (TINC), which is an annual investment in new electricity generating capacity. In Table 6.1, the low investment case (LIC) represents the total investment in new capacity for LIC RE and LIC RE+GT, and the high investment case (HIC) represents the total investment in new capacity for HIC RE and HIC RE+GT. The strategic investment policies start in 2015, thus the value of total investment in new capacity is equal to zero between 2001 and 2014. The total investment in new capacity for both cases sees an increase of 58% from 2015 to 2040, which is equal to the projected growth in Western Cape GDP over this period.

Table 6.1: Simulation results for TINC

Scenario	2001	2010	2015	2020	2025	2030	2035	2040
Total investment in new capacity (TINC) (Billion Rand)								
BAU	0	0	0	0	0	0	0	0
LIC	0	0	1.29	1.42	1.57	1.72	1.87	2.05
HIC	0	0	2.26	2.48	2.74	3.01	3.28	3.58

The projected results of the total operating capacity are given in Table 6.2, which also present the projected results for the total net electricity generated (TNEG). The Province had total operating capacity of 2594 MW in 2001, which consisted of two nuclear power reactors, two pumped storage schemes, and three small gas power stations that are mainly used for peak supply and backup generation. The total operating capacity in 2001 supplied only 69% of the Province's electricity demand (see Figure 6.3). The 87% increase in total operating capacity between 2001 and 2015 represents an addition of 2258 MW to the capacity in the Province. This additional capacity was mainly due to the development of the Gourikwa and Ankerlig gas power stations during this time, with the development of a small number of solar and wind power stations also contributing to the total operating capacity.

Table 6.2: Simulation results for TOC and TNEG

Scenario		2001	2010	2015	2020	2025	2030	2035	2040
Total operating capacity (TOC) (MW)									
BAU		2594	4571	4852	5298	5564	5811	5782	5540
LIC	RE	2594	4571	4852	5579	6241	6926	7385	7405
	RE+GT	2594	4571	4852	5773	6588	7277	7738	7914
HIC	RE	2594	4571	4852	5790	6748	7762	8586	8805
	RE+GT	2594	4571	4852	6128	7354	8375	9203	9693
Total net electricity generated (TNEG) (GWh/year)									
BAU		13400	16900	17630	18960	19730	20450	20340	19640
LIC	RE	13400	16900	17630	19700	21510	23370	24530	24500
	RE+GT	13400	16900	17630	19920	21960	23840	25010	25410
HIC	RE	13400	16900	17630	20260	22850	25560	27670	28140
	RE+GT	13400	16900	17630	20630	23630	26380	28510	29730

The BAU scenario sees an increase in total operating capacity of only 14% from 2015 to 2040, with a peak of 5811 MW reached in 2030. The decrease in total operating capacity from 2030 to 2040 is mostly due to the decommissioning of wind and solar power stations that were commissioned between 2010 and 2020. All four strategic investment scenarios achieve higher total operating capacity values than the BAU scenario, with increases in total operating capacity of 53%, 63%, 81%, 100% between 2015 and 2040 for LIC RE, LIC RE+GT, HIC RE, and HIC RE+GT respectively. Both HIC scenarios achieve higher total operating capacity values than the LIC scenarios, with the HIC RE+GT scenario doubling the total operating capacity between 2015 and 2040. Both RE+GT scenarios achieve bigger increases in total operating capacity than their RE scenario counterparts. Gas technologies have lower capital costs per MW, thus more capacity can be added for the same investment compared to wind and solar technologies. Another reason for RE+GT adding more capacity over the long term is the fact that gas technologies have longer operational lives, while the wind and solar plants that were commissioned between 2010 and 2020 will be decommissioned between 2030 and 2040. The BAU scenario sees no significant intent to add new capacity to the already existing capacity in the Province.

The operating capacity in the Province determines the amount of electricity that is generated in the Province. From Table 6.2 one can see the 87% increase in total operating capacity between 2001 and 2015 translated into a 32% increase in total net electricity generated during the same period. This is due to the high capacity factor of the installed nuclear power reactors and the addition of lower capacity factor gas technologies that were installed during this period. For the BAU scenario, the 14% increase in total operating capacity between 2015 and 2040 translated into an increase in total net electricity generated of only 11%. Comparing this to the 38% increase in electricity demand over this period points to the inadequacy of the BAU scenario in dealing with the electricity supply deficit. From Figure 6.2 one can see the increase in the supply gap for the BAU scenario.

The LIC RE and LIC RE+GT achieve increases in total net electricity generated of 39% and 44% respectively between 2015 and 2040, which is sufficient to cover the growth in total electricity demand over this period, but will not close the supply deficit that already exists in 2015. From Figure 6.2 one can see the supply gap being slightly decreased by the two LIC scenarios, but eventually increasing again after 2032 to above the 2015 levels. The HIC RE and HIC RE+GT scenarios achieve increases in total net electricity generated of 60% and 69% respectively between 2015 and 2040. These increases are still not sufficient to significantly lower the supply gap by 2040 (see Figure 6.2).

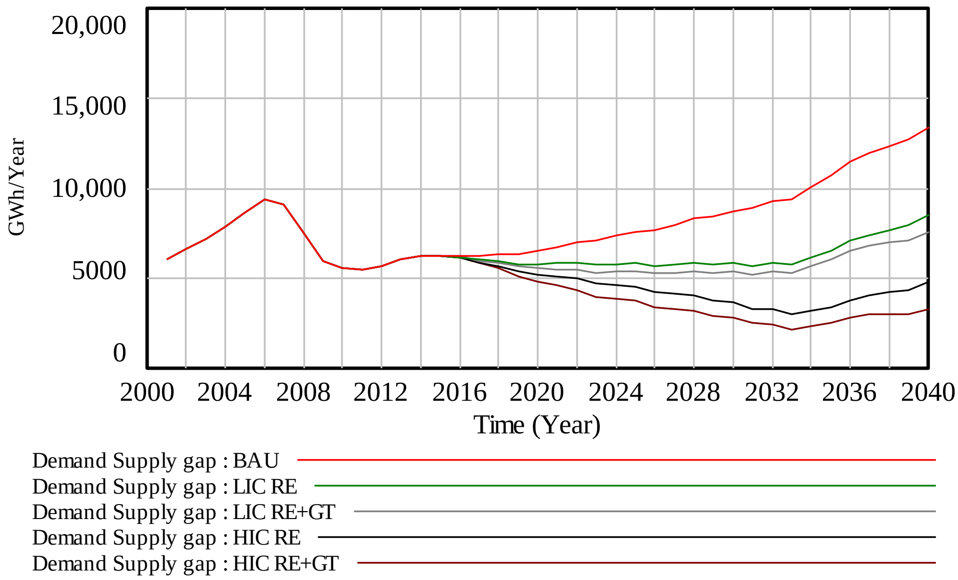

Figure 6.2: Simulation results for demand supply gap (DSG)

The five scenarios display similar patterns for demand supply gap after 2015, with a sudden increase in the demand supply gap occurring after 2032. The total electricity demand does not show significant increases during this period, thus the occurrence must be affected by the total net electricity generated. The reason for this increase in demand supply gap is the fact that the wind and solar plants that were commissioned in 2012, and after, will start being decommissioned. These projects have an operational life of twenty years, and their decommissioning reduces the net capacity added annually to the total operating capacity after 2032. This is also evident from Table 6.2, where one can see that the growth in total operating capacity and total net electricity generated slows down between 2030 and 2040, with less net capacity being added annually, compared to the preceding period between 2015 and 2030.

The share of electricity demand that is supplied by local power stations is given in Figure 6.3. The scenario trends for the supply of locally produced electricity are closely linked to those of the demand supply gap, with an increasing demand supply gap generally translating to a decreasing share of locally produced electricity, and vice versa. The share of locally produced electricity is 69% in 2001, dropping and then rising again before it reaches 74% in 2015. The growing demand supply gap between 2015 and 2040 during the BAU scenario translates to the share of locally produced electricity decreasing from 74% in 2015 to 60% in 2040. The HIC RE+GT scenario performs the best, reaching a peak share of locally produced electricity of 93% in 2033, but decreases to 90% by 2040. The two LIC scenarios only manage to match the supply of locally produced electricity achieved in 2015, with the trend suggesting that these values will decrease further after 2040.

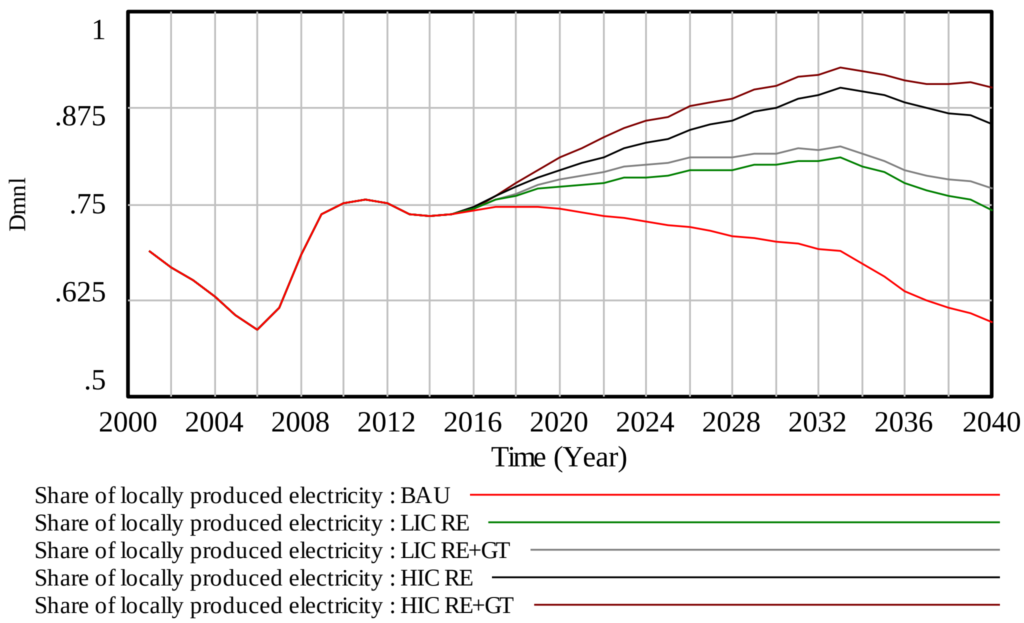

Figure 6.3: Simulation results for the share of locally produced electricity (SLPE)

The BAU scenario shows the least capability of reaching the Western Cape Infrastructure Framework's main goal of transitioning the Province's electricity sector to one that can fully supply the Province's growing electricity demand. As expected, the HIC scenarios are the most effective in decreasing the Province's demand supply gap. For each investment case, the RE+GT scenario outperforms its RE counterpart in terms of adding to the total operating capacity and total net electricity generated and decreasing the demand supply gap. The thing to notice is the decreasing trend of the share of locally produced electricity for all scenarios, with the trend suggesting that these figures will continue to decrease after 2040. Even the HIC RE+GT scenario, which reaches a peak share of locally produced electricity of 90% in 2033, is expected to decrease after 2040. The HIC scenarios manage to increase the share of locally produced electricity significantly between 2015 and 2040, but the short operational lives of the wind and solar technologies should be taken into account when investment decisions are made.

6.2. The expansion of renewable energy capacity

The Western Cape Infrastructure Framework not only targets the expansion of the Province's total operating capacity, but also aims to diversify the electricity generating capacity by using renewable energy technologies. The four strategic investment scenarios specifically aim to increase the share of renewable energy in the Province by investing in wind and solar power plants. It is important to take into account the share of locally produced electricity when comparing the share of renewable energy operating capacity (SREOC) or the share of renewable energy electricity generation (SREEG) for the different scenarios. A policy that significantly increases the share of renewable energy operating capacity or share of renewable energy electricity generation is not effective if it decreases the share of locally produced electricity. A policy will only meet the goals of the Western Cape Infrastructure Framework if it increases the share of renewable energy and also increases the share of locally produced electricity. The share of renewable energy operating capacity represents the proportion of the total operating capacity that consist of renewable energy capacity, with the share of renewable energy electricity generation representing the proportion of locally supplied electricity that originates from renewable energy technologies. From Table 6.3, one can see that the share of renewable energy operating capacity was less than 1% before 2012, with no significant installed renewable energy capacity in the Province.

Table 6.3: Simulation results for the SREOC

Scenario		2001	2010	2015	2020	2025	2030	2035	2040
Share of renewable energy operating capacity (SREOC) (%)									
BAU		>1	>1	5.5	14.2	19.1	23.3	23.7	21.1
LIC	**RE**	>1	>1	5.5	18.6	27.9	35.7	40.2	41.0
	RE+GT	>1	>1	5.5	15.2	23.2	31.1	35.9	38.0
HIC	**RE**	>1	>1	5.5	21.5	33.3	42.6	48.6	50.4
	RE+GT	>1	>1	5.5	15.9	25.5	35.3	41.7	45.3

The four strategic investment scenarios, once again, outperform the BAU scenario. The BAU scenario does achieve diversification of the electricity sector to a certain extent, but it does so while failing to achieve significant increases in electricity supply (see Figure 6.3). It also fails in increasing the share of renewable energy operating capacity and share of renewable energy electricity generation after 2032, with both indicators decreasing between 2032 and 2040. The two RE+GT policies only show a small increase over the BAU case by 2020 due to the initial investment focus on gas technologies, but manage to significantly outperform the BAU scenario after 2020. The two RE policies, with their focus exclusively on renewable energy technologies, manage a higher share of renewable energy operating capacity than their RE+GT scenario counterparts. The HIC RE policy performs the best, managing to transform the electricity sector to a point where half of the total operating capacity consists of renewable energy technologies by 2040, translating to a share of renewable energy electricity generation of 42%. The reason for the share of renewable energy operating capacity values being smaller than the share of renewable energy electricity generation values is due to the renewable and gas technologies having a smaller capacity factor than the two nuclear power reactors. Thus, with nuclear power as base supply, an increase in share of renewable energy operating capacity will not translate into an equal increase in share of renewable energy electricity supply.

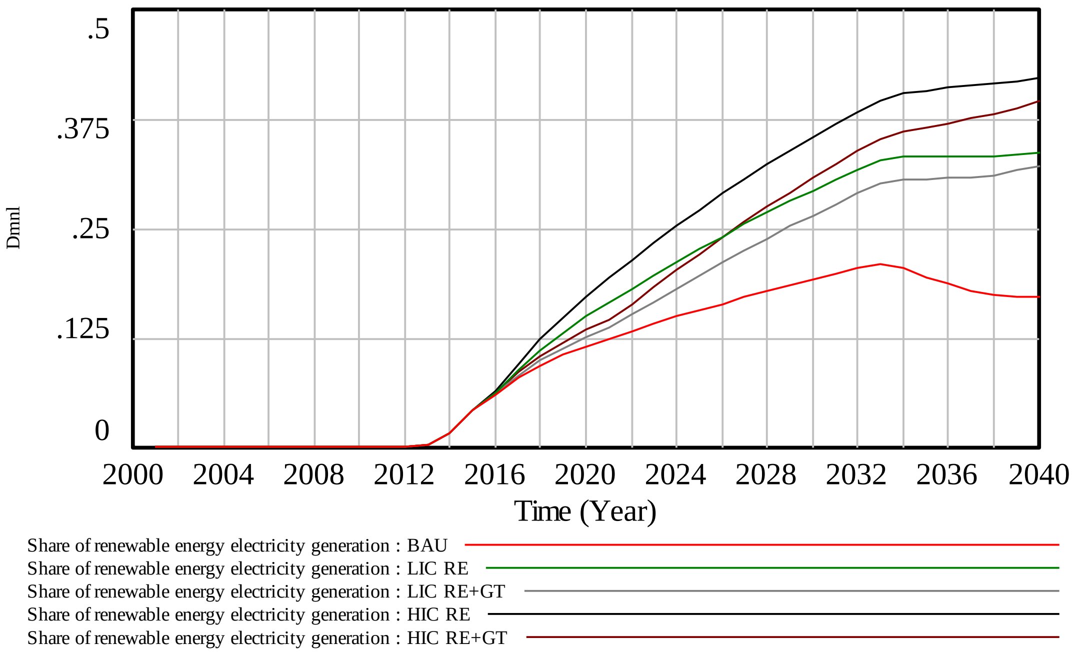

Figure 6.4: Simulation results for the share of renewable energy electricity generation (SREEG)

The trend of decreasing growth after 2032 continues in the results for the share of share of renewable energy operating capacity and share of renewable energy electricity generation. Once again, this is due to the decommissioning of wind and solar capacity after 2032. The trade-off between the RE and RE+GT policies are evident from the simulation results so far. The two RE+GT policies manage greater increase in the electricity supply compared to their RE policy counterparts, but the RE policies offer a greater benefit in terms of diversifying the electricity generating capacity. The question is which policy contributes more to the overall sustainability of the electricity sector. A number of other indicators – including environmental and socio-economic indicators – have to be taken into account when investigating the overall sustainability of the electricity sector.

6.3. The environmental impacts

When considering the overall sustainability of any electricity sector, it is essential to take into account its impact on the environmental sector. The domination of fossil fuel technologies in most electricity sectors gives rise to the large environmental footprint that these sectors often have. The South African electricity sector, dominated by coal-fired power stations, is one of the most carbon and water intensive globally. Only a small portion of the country's fossil fuel fleet is present in the Western Cape Province, but a share of the Province's electricity demand is supplied with electricity generated from these carbon intensive energy sources. Because of its large environmental footprint, the electricity sector has huge potential in overall environmental mitigation. The implementation of renewable energy technologies is an effective way of reducing the environmental footprint of an electricity sector. Wind and solar PV technologies, especially, have almost negligible water requirements and carbon emissions during their operational phase.

The simulation results for the total annual air emissions (TAAE) produced during the five scenarios are given in Table 6.4. In 2001, the power stations within the Province had a low carbon footprint, with the existing combination of nuclear reactors, pumped storage schemes, and back-up gas power turbines being responsible for only a small share of total annual air emissions. The majority of the 6.6 Billion kg of CO_2 emissions originating from imported electricity. Between 2000 and 2010, there was a large increase in the total operating capacity within the Province (see Table 6.2), with the majority of the new capacity coming from gas power technologies. During this period there was no significant net change in the demand supply gap (see Figure 6.2), thus no net increase in imported electricity. One can conclude that the 26% increase in total annual air emissions between 2001 and 2010 was due to the additional gas power capacity.

Table 6.4: Simulation results for TAAE

Scenario		2001	2010	2015	2020	2025	2030	2035	2040
Total annual air emissions (TAAE) (Billion kg CO_2/year)									
BAU		6.6	8.3	9.0	9.3	10.4	11.6	13.5	16.3
LIC	**RE**	6.6	8.3	9.0	8.5	8.6	8.6	9.3	11.3
	RE+GT	6.6	8.3	9.0	8.6	8.7	8.7	9.3	10.9
HIC	**RE**	6.6	8.3	9.0	8.0	7.2	6.4	6.1	7.6
	RE+GT	6.6	8.3	9.0	8.2	7.4	6.5	6.2	6.9

From 2015 to 2040, the results for total annual air emissions follow a similar trend to that of the demand supply gap (see Figure 6.2). This is due to the very low carbon emissions from the wind and solar capacity that is added during this period, leading to the changes in total annual air emissions being largely determined by the annual rate of electricity imports. The BAU scenario sees a continuous rise in total annual air emissions from 2001 to 2040, with an 81% increase between 2015 and 2040. The two LIC policies show a decrease in total annual air emissions between 2015 and 2033, with the total annual air emissions increasing after 2033 due to increased electricity imports. The same pattern is evident for the two HIC policies. The two HIC policies are the only policies that manage to reduce the total annual air emissions in 2040 below their 2015 levels. The HIC RE and HIC RE+GT policies reduce total annual air emissions levels by 16% and 23% respectively between 2015 and 2040. The LIC RE and LIC RE+GT policies increase total annual air emissions levels by 26% and 21% respectively between 2015 and 2040.

An important observation from Table 6.4 is the two RE+GT policies obtaining lower total annual air emissions values by 2040 than their RE policy counterparts. This happens despite the higher CO_2 emissions from the additional gas capacity added by the RE+GT policies. The additional total net electricity generated from the RE+GT policies (see Table 6.2) offer a larger decreases in long-term total annual air emissions than the RE policies, mainly due to the fact that they decrease the need for carbon intensive electricity imports.

The water sector is another area of interest when assessing the impacts of the electricity sector. Nuclear and coal power stations that make use of steam turbine technologies are often very water intensive. This is a feature of many of the coal-fired power stations in South Africa. The two nuclear reactors in the Province make use of sea water in an open-loop cooling system, thus significantly reducing the fresh water requirements of the reactors, as compared to reactors with other cooling systems. Table 6.5 presents the simulation results of the total annual water requirements (TAWR) for the Province’s electricity sector. In 2001, 65% of the total annual water requirement came from the installed pumped storage power capacity, with 34% coming from the two installed nuclear reactors. The 11% increase in total annual water requirement between 2001 and 2010 is mostly due to the additional gas power capacity that was developed.

Table 6.5: Simulation results for TAWR

Scenario		2001	2010	2015	2020	2025	2030	2035	2040
Total annual water requirement (TAWR) (Billion litres/year)									
BAU		56.5	62.2	62.1	61.7	61.3	61.0	60.6	60.2
LIC	RE	56.5	62.2	62.1	61.7	61.3	61.0	60.6	60.2
	RE+GT	56.5	62.2	62.1	62.8	63.1	62.7	62.3	61.9
HIC	RE	56.5	62.2	62.1	61.7	61.3	61.0	60.6	60.2
	RE+GT	56.5	62.2	62.1	63.6	64.4	64.0	63.6	63.1

Overall, the five scenarios had very little impact on the total annual water requirement of the electricity sector. Solar and wind technologies have water requirements that are negligible compared to the nuclear, pumped storage and gas power technologies. Thus, the projections for the total annual water requirement of the two RE policies are identical to those of the BAU scenario. The gas power capacity added by the LIC RE+GT and HIC RE+GT policies only cause 3% and 5% increases respectively in total annual water requirement compared to the other three scenarios.

6.4. The socio-economic impacts

The development of electricity sector employment was simulated in order to investigate the socio-economic impacts of the five policies. These five policies were simulated for three localisation scenarios – low, medium, and high localisation – in order to assess the effect that the localisation of manufacturing activities has on the employment sector. Table 6.6 presents the results for total electricity sector employment (TESE) for the 15 scenarios that were simulated.

Table 6.6: Simulation results for total electricity sector employment (TESE) for low, medium, and high localisation cases

Scenario		2001	2010	2015	2020	2025	2030	2035	2040
Low localisation (persons employed)									
BAU		1341	1893	2504	2409	2566	2718	2720	2592
LIC	**RE**	1341	1893	2630	3040	3514	4013	4404	4513
	RE+GT	1341	1893	2692	3414	3490	3989	4385	4589
HIC	**RE**	1341	1893	2724	3513	4224	4983	5668	5952
	RE+GT	1341	1893	2828	4168	4181	4941	5633	6084
Medium localisation (persons employed)									
BAU		1341	1893	3340	3000	3149	3295	3292	3161
LIC	**RE**	1341	1893	3551	3942	4458	5007	5456	5608
	RE+GT	1341	1893	3569	4228	4528	5077	5529	5774
HIC	**RE**	1341	1893	3709	4648	5441	6290	7080	7442
	RE+GT	1341	1893	3734	5149	5562	6412	7206	7733
High localisation (persons employed)									
BAU		1341	1893	4177	3591	3731	3872	3863	3728
LIC	**RE**	1341	1893	4472	4844	5403	6001	6508	6702
	RE+GT	1341	1893	4446	5042	5567	6164	6673	6959
HIC	**RE**	1341	1893	4694	5783	6657	7597	8492	8933
	RE+GT	1341	1893	4640	6129	6942	7882	8779	9382

The BAU policy fails to increase employment after 2015, regardless of the level of localisation. The strategic investment policies significantly outperform the BAU policy across all three localisation scenarios. The RE+GT policies add more jobs to the sector than their RE policy counterparts, with the difference between these two policies increasing as the localisation factor increases. This suggests that gas power plants create more employment in supporting fuel supply sector, than renewable energy plants do in the supporting manufacturing sector.

The results emphasise the effect that localisation can have on employment in the electricity sector. For the four strategic investment scenarios, the medium localisation policy created, on average, 25% more jobs than the low localisation policy. The high localisation policy created, on average, 52% more jobs than the low localisation policy. These increases are for total electricity sector employment, and not only for manufacturing employment. This can fuel the argument that renewable energy and gas power development can have a larger contribution to the employment sector if the manufacturing of components, for renewable technologies, and the development of fuel supply infrastructure, for gas technologies, are localised. The low localisation scenario is closely related to where the Province is at the moment in terms of manufacturing capability. The medium localisation scenario is a more realistic view of where the sector can move towards, as the 100% localisation used in the high localisation scenario is highly unlikely to materialise. The high localisation scenario was merely used to investigate the effect of higher localisation factors on the employment sector.

6.5. Conclusion: Simulation results and analysis

The simulation results for the five scenarios – BAU, LIC RE, LIC RE+GT, HIC RE, and HIC RE+GT – were presented and discussed in this chapter. Results were presented in the contexts of electricity supply, renewable energy capacity expansion, environmental impacts, and socio-economic impacts. The results highlight the advantages of green economy investment interventions and the inadequacy of a BAU scenario to tackle the issues that are prevalent in the Province's electricity sector. The importance of localisation of manufacturing and fuel supply jobs was also presented by the simulation results. The HIC outperformed the LIC in most instances, which is to be expected because of the larger sum of investments implemented in the HIC. The advantages of using gas as a transition fuel was also presented by the simulation results, which suggest that investments in gas power technology could increase electricity supply without having severe effects on the environmental or social sectors.

Chapter 7

Main findings and recommendations

The Western Cape Government has stated its intent to facilitate a green economy transition in the Province. Transforming the Province's electricity sector will be critical in achieving such a transition. The current electricity sector is heavily reliant on nuclear and gas power technologies, as well as imported electricity predominantly from coal-fired power stations situated in other provinces. Developing renewable energy capacity, such as wind and solar power plants, has the potential to transform the Province's electricity sector into one that is more sustainable from an economic, environmental, and social perspective.

The five policy scenarios were simulated and their results compared. The BAU scenario serves as the baseline scenario, giving an indication of what the development of the electricity sector will look like if it continues on its current path. The goal of the LIC and HIC policies was not to directly compare the two scenario results with one another. The expectation is that the two HIC policies will outperform the two LIC policies and the BAU policy because of the larger share of GDP that is invested during the two HIC scenarios. The focus should be placed on the impacts that these larger investments have on the electricity sector and how much of an improvement is offered by a larger investment. The HIC and LIC policies should be compared to the BAU policy scenario, in order to investigate what different levels of investment will have on the electricity sector compared to the baseline scenario.

It is important to view the results from the simulation correctly and to understand what to focus on. System dynamics models are not intended to produce results that are numerically indisputable and display perfect numerical accuracy. The absolute values of the results can be challenged and disputed, but the area of interest is the development of trends and changes over time. The focus should be placed on changes in variables that occur and why these changes occur. Thus, the point values are discussed, but the focus of discussion is predominantly on the changes of these variables over time.

The Western Cape Government has not set out specific goals for the electricity sector, but has identified certain priorities in terms of electricity sector infrastructure development. The Green Economy Report (Western Cape Government, 2014a) and the Western Cape Infrastructure Framework (Palmer & Graham, 2013) state the importance of developing natural gas infrastructure and renewable energy capacity, together with their fuel processing and component manufacturing capabilities.

The results for the BAU scenario clearly show the inadequate development of the electricity sector without the additional green economy investments. The Share of renewable energy technologies increases during the BAU scenario, but this while the supply gap and electricity sector air emissions also increase. The four strategic investment policies show significant improvements in all indicators.

7.1. The techno-economic context

The model projects an increase in electricity demand of 38% between 2015 and 2040. An increasing population and economic growth in the Province will drive this increase. Any investments in new electricity generating capacity would have to be sufficient to not only fill the current shortfall in electricity supply, but also to confront the expected growth in demand. The LIC and HIC allocate 0.4% and 0.7% of the Western Cape GDP respectively to strategic investments in new electricity capacity. This amounts to annual investments of 1.29 and 2.26 Billion Rand in 2015 for the LIC and HIC respectively, growing to annual investments of 2.05 and 3.58 Billion Rand in 2040 for LIC and HIC respectively. Over the period between 2015 and 2040, these annual investments amount to total nominal investments of 42.35 and 74.10 Billion Rand for the LIC and HIC scenarios respectively. These figures fall within the expected 850 Billion Rand required for infrastructure investments in the Province between 2012 and 2040 (Palmer & Graham, 2013).

The simulation results suggest that annual investments of 0.4% and 0.7% of GDP in new electricity capacity could increase the share of renewable energy technologies significantly by 2040. The question is whether these investments can solve the electricity supply shortfall. With a 0.4% investment policy, the results suggest that such a policy could steady the supply gap and increase the share of locally produced electricity before 2032, but that it would be insufficient to do so after 2032. A 0.7% policy could decrease the supply gap and increase the share of local supply, but also only until 2032, when the supply gap starts increasing again and the share of local supply starts decreasing.

An important observation from the simulation results is the effect that the shorter operating life of wind and solar power plants has on the development of operating capacity in the Province. The development of renewable energy capacity under the strategic investment scenarios manages to significantly increase the electricity capacity and electricity supply over the simulation period. The net increase in capacity, however, slows down once the decommissioning of renewable energy capacity starts. This then leads to increasing supply deficits for all five scenarios. The long operating lives of more conventional electricity technologies – nuclear, coal, gas, and hydro – may give them a perceived advantage over renewable energy technologies. This does not mean that renewable energy technologies are inferior to more conventional technologies, but it does highlight the importance of proper long-term planning when investing in renewable energy technologies.

Another important observation from the simulation results is that an increase in operational capacity does not always translate into an identical increase in electricity generation. This is especially the case with renewable energy technologies, because of their lower capacity factors compared to more conventional technologies. The capacity factor of a certain technology at a certain location is a critical determinant of whether a power plant will be financially and technologically viable. The lower capacity factors of renewable energy technologies means that these technologies do not contribute as much generated electricity per installed MW as their fossil fuel counterparts. This again points to the importance of taking into account all relevant factors and planning properly when investing in renewable energy technologies.

The two RE+GT policies manage to decrease the supply gap more than their respective RE policies. Gas power technologies have lower capital costs, thus more capacity can be added, compared to renewable energy technologies, for the same investment. The long operating life of power plants is another advantage that gas power has over renewable energy technologies. The two RE policies, however, achieve higher shares of renewable energy capacity and renewable energy electricity generation. The question is what the advantage is of having a higher share of renewable energy electricity generation, because having a higher share of renewable energy is not an advantage in itself. In order to investigate what the advantages are of having a higher share of renewable energy, one has to look at the environmental and socio-economic factors.

7.2. The environmental context

The BAU scenario leads to increasing air emissions, with annual air emissions 81% higher in 2040 than they were in 2015. This is due to the high carbon intensity of the electricity imported from the other provinces through Eskom. The two LIC investment policies manage to stabilise air emissions between 2015 and 2033, but the need for increasing imported electricity after 2032 leads to an increase in annual air emissions. The two HIC investment policies show a similar pattern, decreasing the annual air emissions from 2015 to 2032, before increasing again slightly after 2032. The two HIC policies were the only policies to lower annual emissions below their 2015 levels by 2040.

The renewable energy capacity added during the simulation period makes a very small contribution to the annual air emissions, because of their almost negligible air emissions during their operational life. The gas technologies added by the two RE+GT policies contribute to decreasing the air emissions of the electricity sector. Gas power plants burn fossil fuels, but release about half as much carbon as coal and oil fired power plants. This contributes to the two RE+GT policies managing to achieve lower annual air emissions compared to their respective RE policy counterparts. The RE+GT policies manage to add more electricity supply, thus requiring less imported electricity, which ultimately lower the annual air emissions. This suggests that gas power technologies can be used to decrease the annual air emissions of the Province, simply because they are less carbon intensive than the coal-fired power stations generating the imported electricity.

There lies potential in decreasing the Province's electricity sector air emissions simply by decreasing the need for imported electricity. Gas power technologies are less carbon intensive than coal and oil power technologies, but they still contribute significantly more to air emissions than renewable energy technologies. The combination of gas and renewable should pose the best solution to lowering the Province's annual air emissions in a sustainable manner.

There is very little separating the different scenarios in terms of their annual water requirements. The majority of the Province's electricity sector water requirements originate from the two pumped storage power schemes. The additional renewable energy and gas power stations added by the four investment policies are not water intensive and have very little effect on the total annual water requirements of the sector. This is very advantageous, as the Province is expected to experience water constraints over the coming decades. The pumped storage schemes act as water reservoirs, helping the Province to store water for when it is needed. The Province's current electricity generating fleet is not very water intensive, compared to the coal-fired power stations used in the other Provinces. This is an important factor and technologies with low water intensity should continue to be used in the Province. Wind, solar, and open cycle gas turbine (OCGT) technologies require little water in their operational phase and can ensure that the Province's electricity sector continues to have little effect on its water requirements.

7.3. The socio-economic context

The BAU scenario fails to significantly increase employment in the electricity sector after 2015, and decreases the number of jobs between 2015 and 2040 for the medium and high localisation scenarios. The HIC policies manage to add more jobs than their respective LIC policy counterparts. More jobs are also added by the RE+GT policies compared to their respective RE policy counterparts, although these differences were rather small. The main observation from these results is not the difference in employment figures between the respective RE and RE+GT scenarios, but rather the difference in employment figures between the low, medium, and high localisation scenarios. Power plants do not offer huge employment potential in their operational phase. The large employment opportunities lie in the manufacturing and gas supply sectors that support the power plants. The results show the large effect that localisation can have on electricity sector employment.

The Province's electricity sector is not a large employer within the Province, but it can still make a contribution to creating employment opportunities within the Province. The results from the four strategic investment scenarios suggest that investing in renewable and gas power technologies has the potential to stimulate employment creation in the electricity sector, even for a low localisation scenario. The development of manufacturing and fuel supply industries to support the electricity sector can, however, significantly boost the number of jobs in the sector, and is a game changer in this regard.

7.4. Model limitations and recommendations for future research

One of the challenges of SAGEM is that it addresses the green economy issues at a national level and not at a disaggregated provincial or city level. The WeCaGEM and its electricity sub-model do address these issues at a provincial level, but only with the Western Cape Province as an isolated province. For the sake of investigating the Province's electricity sector as an independent entity, the assumption was made that the Province's electricity sector will be regarded as being independent and isolated from the national electricity sector. This is, however, not the case in reality and the Western Cape Province is interlinked and interdependent on the other eight provinces in South Africa. The development of sub-models for the other eight provinces would greatly benefit the understanding of how the provinces interact and interlink with one another, especially with regard to the national electricity sector.

The model investigates the allocation of investments in electricity generation infrastructure within the Province, but it does not address the source of these funds. The model simply addresses the impacts that these funds can have on the sector if they are invested in a certain manner. Such investments would come from a number of sources including national government, local government, private investors, and institutional investors. On a national level, in the past, such funds have come from national government, either directly or through government guaranteed loans. With the introduction of the REIPPP programme, the funding of renewable energy projects has increasingly come from private and institutional investors. The

Provincial Government is unlikely to fund any significant part of these investments, but it plays a critical role in developing policies and regulations to ensure that these funds are invested in a way that promotes its infrastructure goals. The electricity sector model can only benefit from additional structure to more comprehensively investigate the full cycle of funding, from the source to final destination.

Due to the long-term horizon of the electricity sector model, the issue of base-load power generation is not considered. The daily cycles of electricity supply and demand determine the need for base-load power. Thus, the one year time unit used in the model limits its ability to address the issue of base-load power. Base-load power needs to be taken into consideration, as wind and solar technologies are not well suited to provide base-load power, but rather to supplement the existing base-load power generating capacity. The ability of a long-term model to address this is very limited. Thus, it is an issue that should be considered and taken into account by the users of the model.

The electricity sector model investigates the sector's employment potential under certain conditions. This includes employment originating from the manufacturing sector supporting the electricity sector. Employment from manufacturing is determined using employment factors for wind and solar technologies. The model could greatly benefit from additional structure investigating this manufacturing sector supporting the development of renewable energy capacity. This could be used to more comprehensively investigate the employment originating from these manufacturing activities. Such a sub-model investigating the supporting manufacturing sector can also give greater insight into how the electricity sector affects the broader economy.

The model uses Western Cape GDP as an exogenous variable and provides no feedback to the Western Cape GDP. The effect that electricity sector employment has on the GDP is negligible, and the effect that electricity supply has on the economy is difficult to determine and was not included in the model. An oversupply of electricity has no effect on the economy, but an undersupply will negatively impact on the economy. The assumption is made that electricity is imported when there is an undersupply, and that total supply always meets demand. It would be beneficial to incorporate additional structure to address the issue of how the electricity sector affects the economy. This could be done by incorporating the supporting industries, such as manufacturing, and their outputs in order to determine their contribution to the Western Cape GDP.

7.5. Recommendations for policymakers

Models of complex system behaviour, particularly system dynamics models, are increasingly being used to support governments and institutions with making decisions on green economy investments. Such models offer the ability to help build consensus on how systems work and which management options are the most effective. The electricity sector of the Western Cape Province forms a critical part of the province's economy and will be a critical component of any transition towards a green economy. It is a complex system that should be managed properly in order for it to contribute to a green economy transitions. Provincial policymakers play an important role in managing such transitions of the electricity sector and of the broader economy. Decisions and policies regarding the electricity sector cannot be effectively formulated unless the full extent of the impacts of such decisions and policies on the broader economic, environmental, and social sectors are taken into account. Thus, this electricity sector model aims to provide some insight to policymakers on the possible scenarios that can develop given the implementation of certain policies.

The long-term nature and impacts of investments in the electricity sector need to be thoroughly understood. The model results show the effect that increasing electricity demand and the short operational life of wind and solar power technologies have on the electricity sector. Future electricity demand is a very important factor that needs to be taken into account when decisions are made on where and how investments are made in the sector. Renewable energy technologies can significantly diversify the energy mix, offering a greener option of expanding electricity generating capacity. The lack of proper planning, when investing in these technologies, could, however, lead to supply problems in twenty years when these power plants need to be decommissioned. These plants do not enjoy the long operating lives that more conventional power technologies – nuclear, coal, and hydro – are known for. When wind and solar plants are commissioned, plans should already be in place to replace the capacity once the plants need to be decommissioned.

Another aspect of renewable energy technologies that needs to be considered is the low capacity factor that many of these technologies – wind and solar in particular – are subject to. These technologies are not well suited to base-load power supply, and are often more effective in supplementing power supply from base-load sources. The role that these technologies are intended to play in the Province's electricity sector should be determined and consequent planning should follow. This is an issue that can be aided by the use of natural gas power technologies. The open cycle gas turbines (OCGT), currently used in the Province, offer low start-up delays and can be synchronised to the grid far quicker than nuclear reactors or coal-fired steam turbines can. This could allow them to function in a manner that would supplement the electricity supply from renewable energy sources. Short-term forecast can predict the output from solar and wind sources, allowing the operators to plan when the gas turbines should be used to supply electricity. The results suggest that the use of gas power technologies, in addition to renewable energy technologies, could possibly offer greater environmental benefits simply focusing on renewable energy capacity expansion.

The results strongly suggest the employment benefit in localising manufacturing and fuel supply jobs. This would entail developing a manufacturing industry, supporting the renewable energy capacity expansion, and gas fuel processing and supply infrastructure, supporting the natural gas power plants. The majority of the renewable energy technologies used in the country are imported from other countries. This means that only the minimum number of jobs is currently created by the electricity sector. Significant employment potential lies in localising these jobs by establishing these industries locally. The renewable energy industry is set to grow over the coming decades, not only in the Western Cape and South Africa, but globally. A large proportion of this growth is expected to come from the African continent. This creates further incentive to establish these industries locally, which would allow the Province to benefit from the growth of these technologies by exporting the outputs from these industries.

7.6. Conclusion: Main findings and discussion

The main findings were discussed from three contexts: (1) techno-economic, (2) environmental, and (3) socio-economic. From a techno-economic perspective, the results highlighted the projected future growth in electricity demand, the monetary value of financial investments that would be required for the different scenarios, and the effect that these investments would have on the electricity sector. These green economy investments are expected to significantly increase the electricity supply and the share of renewable energy in the Province. Apart from these positive impacts, the results also highlighted the importance of taking into account the short operating life of wind and solar PV technologies, as well as their capacity factors. From and environmental perspective, the results focused on air emissions and water requirements for the electricity sector. The water requirements did not vary significantly for the five scenarios, in comparison with each other, but the air emissions showed more significant variations for the five scenarios. The model limitations were then discussed together with the recommendations for future research. Four main recommendations were then discussed for policymakers.

Chapter 8

Conclusion

Global energy demand, including electricity demand, is expected to increase over the next 25 years. The majority of this increase is expected to come from emerging economies, such as South Africa. The electricity sector is a vital part of any country's economy, and has an impact on the economic, environmental, and social sectors of a country. The electricity sector in South Africa is facing a number of issues that include lack of generating capacity and a heavy reliance on fossil fuel technologies. These issues have negative impacts on the economic, environmental, and social wellbeing of the country. The Western Cape Province, as a Province in South Africa, is not unaffected by these impacts and faces the same issues from its own electricity sector. This study aimed to investigate how different investment policies and scenarios would facilitate the transformation of the Western Cape Province's electricity sector to one that is more in line with the green economy.

The concept of the green economy is considered as a valuable tool to simultaneously address economic, social, and environmental issues. The Western Cape Province has committed itself to lowering its carbon footprint and becoming a green economy hub on the African continent. This would require, among other sectors, a transition of the electricity sector towards one that is more in line with the green economy. Such ambitious plans require a good understanding of green economy transitions and also technology transitions. These transitions require large investments and proper management in order to take place successfully. The economic and governance issues in South Africa create certain challenges for the drivers and facilitators behind these transitions. Computer-based modelling tools can contribute significantly to assisting policymakers in making informed decisions on these transitions. Such modelling tools would be required to carry out investment and policy analyses. A number of modelling methodologies were reviewed in the study, with the system dynamics methodology being considered the best suited to modelling green economy transitions.

The system dynamics methodology was utilised to develop a conceptual and dynamic model of the electricity sector in the Western Cape Province. Five scenarios – BAU, LIC RE, LIC RE+GT, HIC RE, and HIC RE+GT – were developed and simulated using the dynamic model. These scenarios considered different policies relating to how much money is invested and towards which technologies these investments go. The model was subjected to validation tests, which were addressed in the study, and certain limitations of the model were identified and addressed. The results and main findings of the simulation results were presented with regard to three main contexts: (1) techno-economic, (2) environmental, and (3) socio-economic. The results were used to formulate recommendations for policymakers on the issue of transitioning the electricity sector in the Province. Such a study has not yet been conducted on a provincial level in South Africa. Thus, offering a foundation from which future research can be conducted.

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Appendices

A. The electricity sector model structure

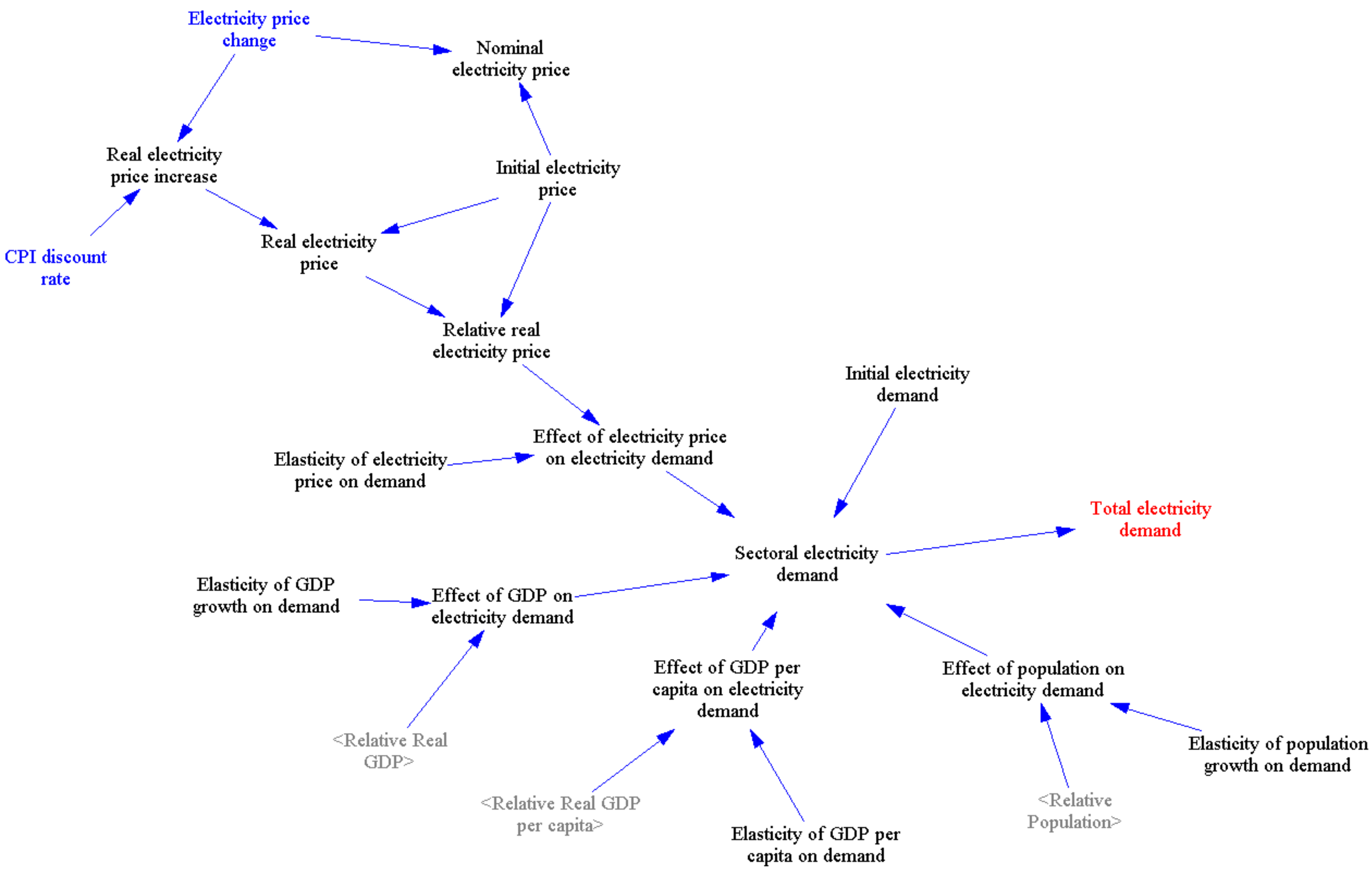

Figure A.1: Electricity demand sub-model

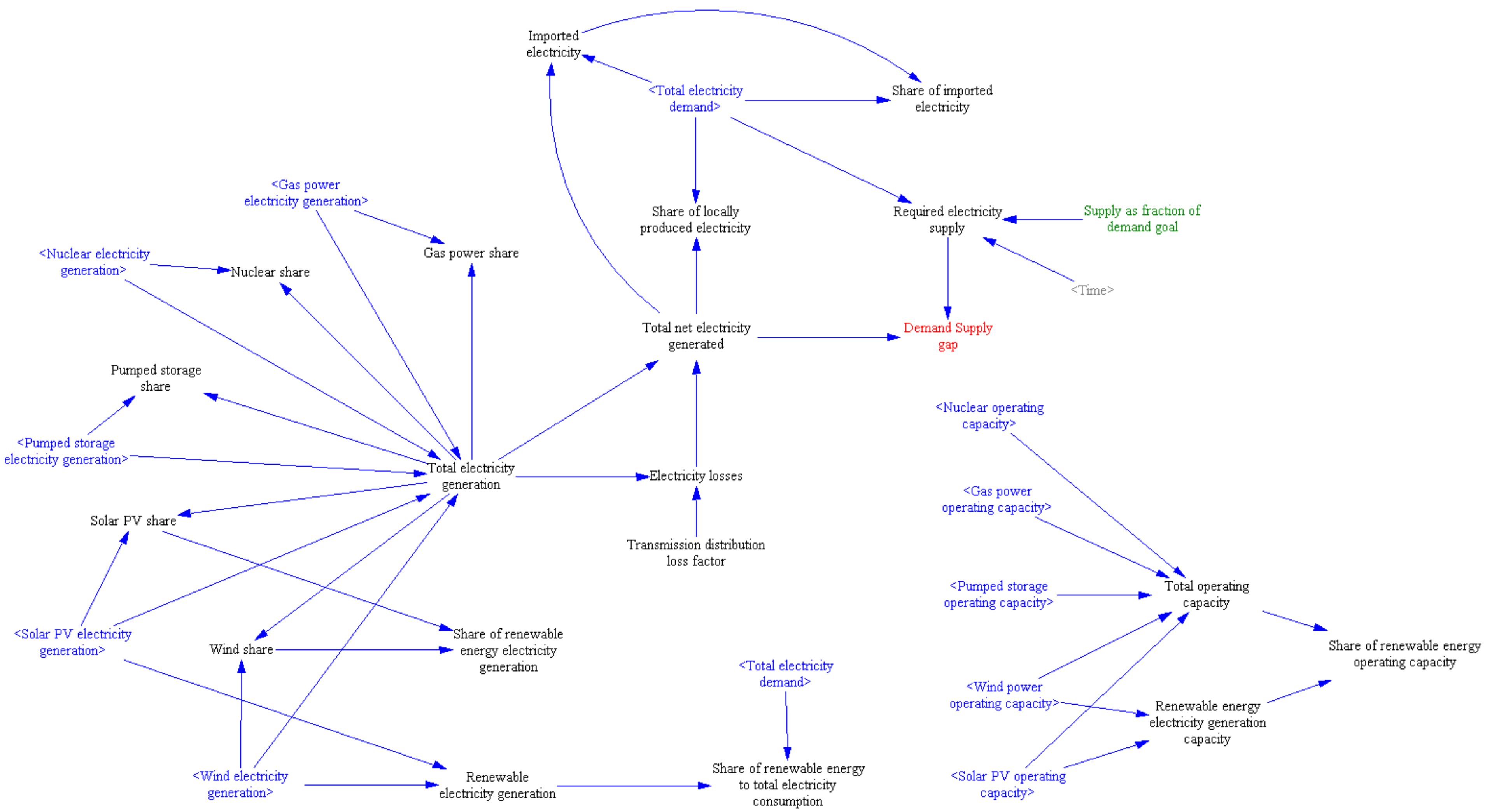

Figure A.2: Electricity technology share sub-model

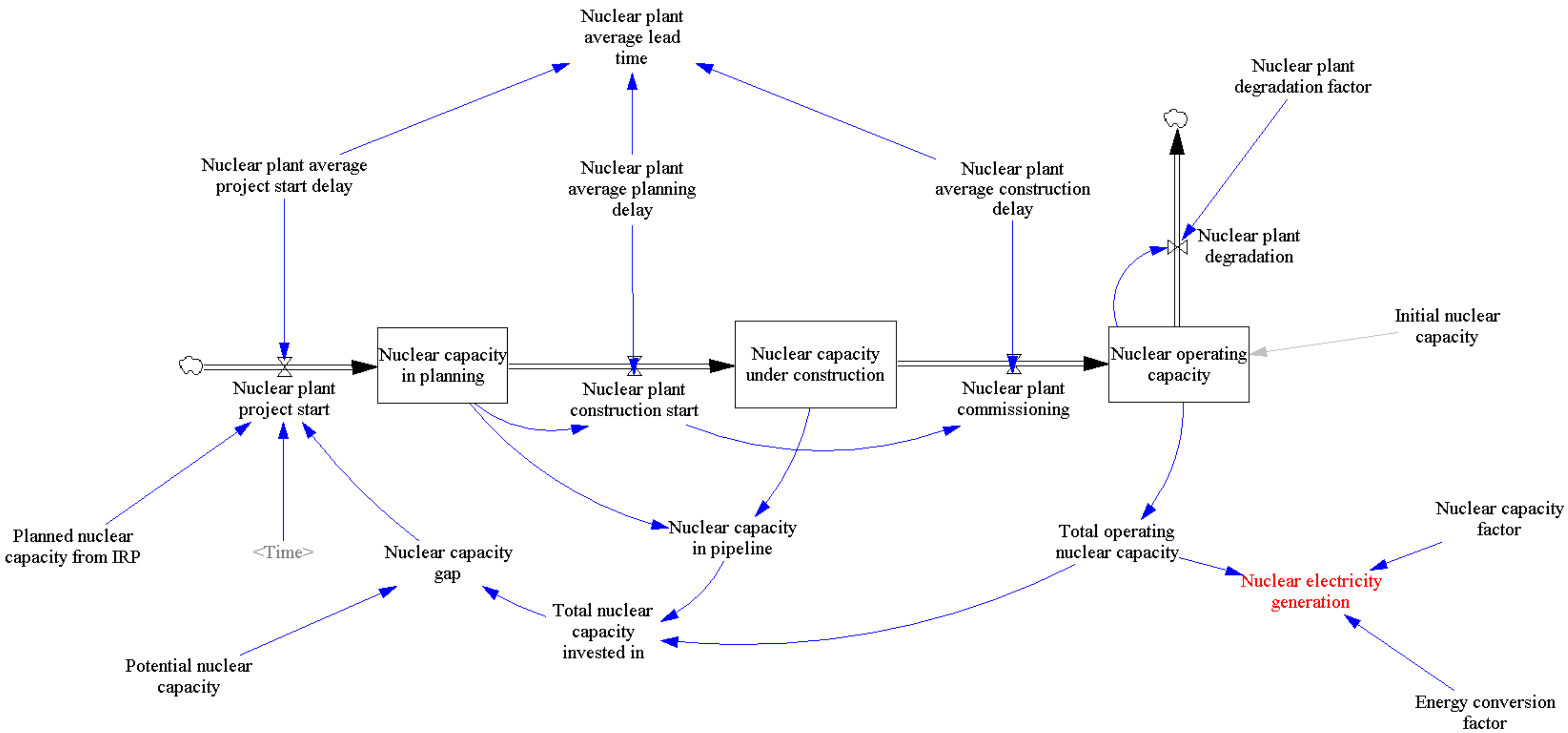

Figure A.3: Nuclear power supply sub-model

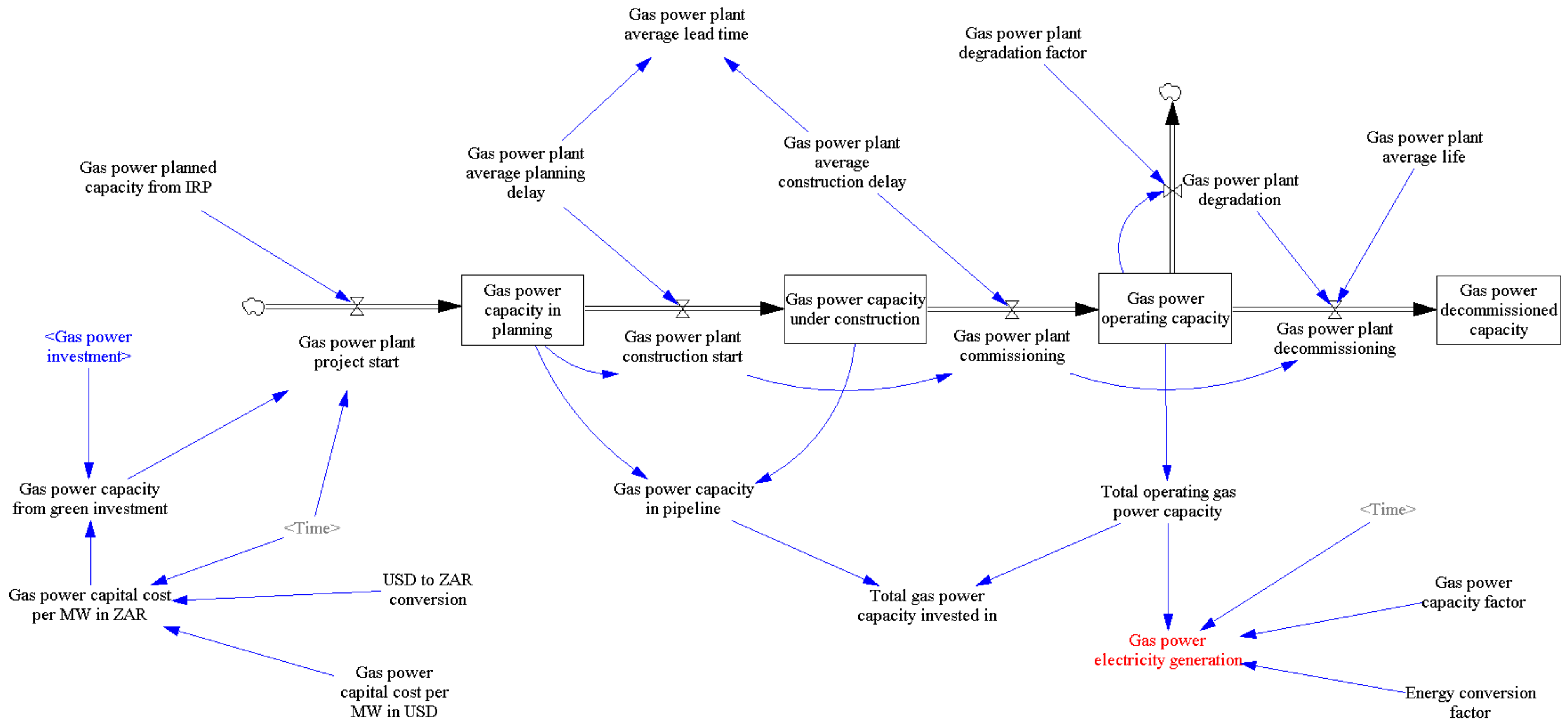

Figure A.4: Gas power supply sub-model

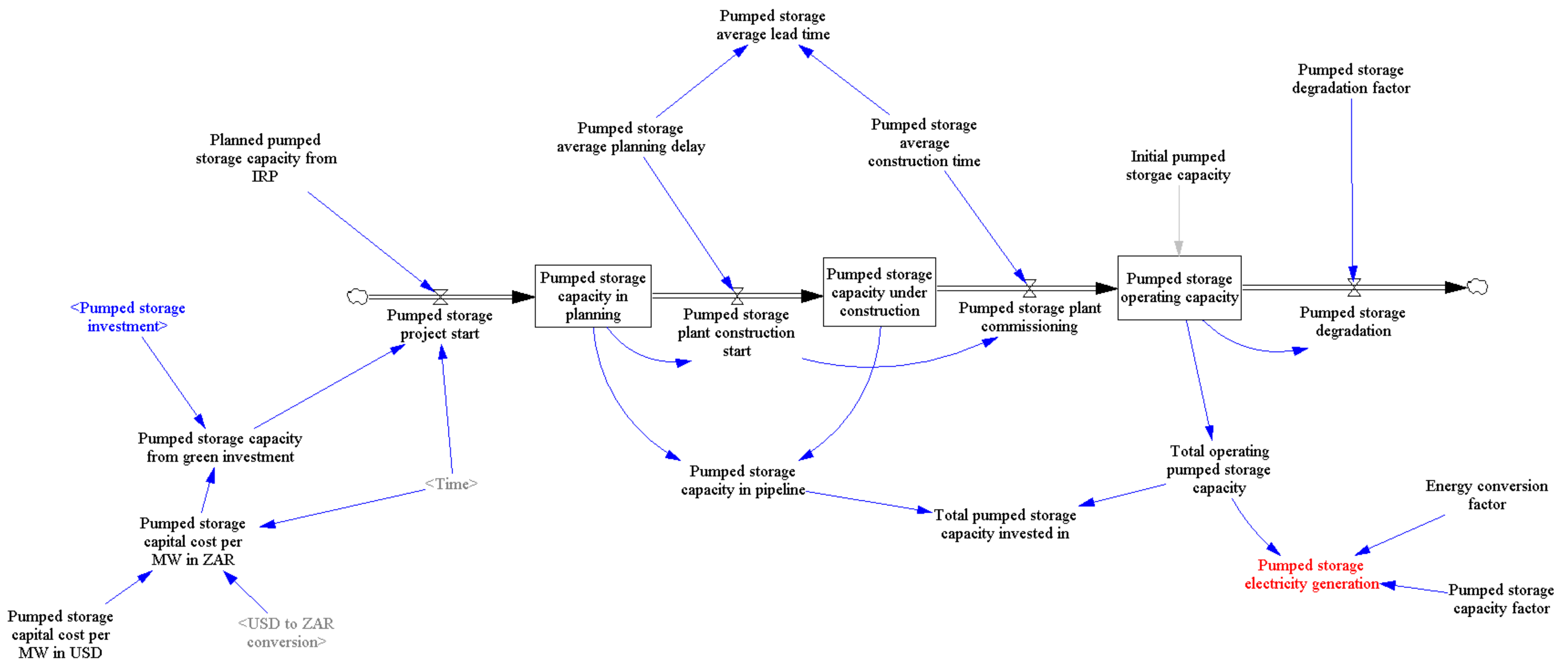

Figure A.5: Pumped storage power supply sub-model

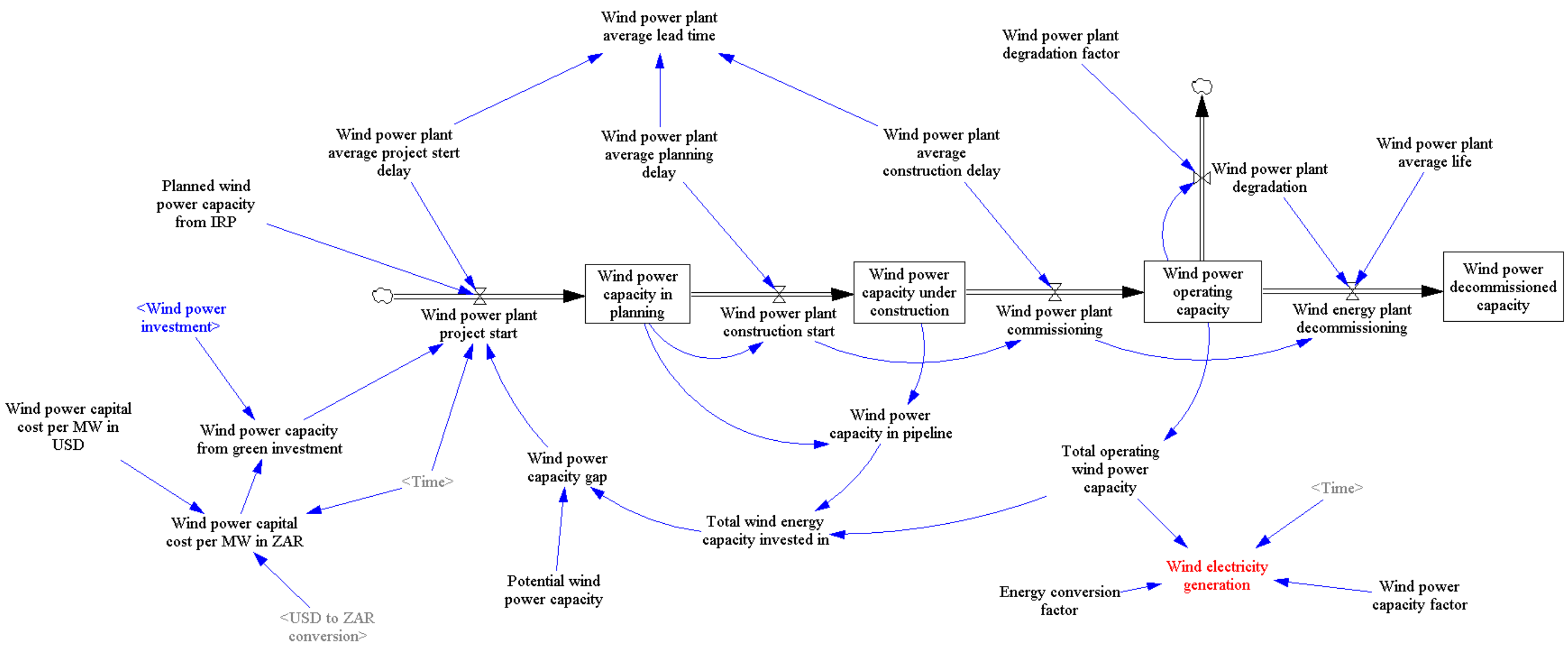

Figure A.6: Wind power supply sub-model

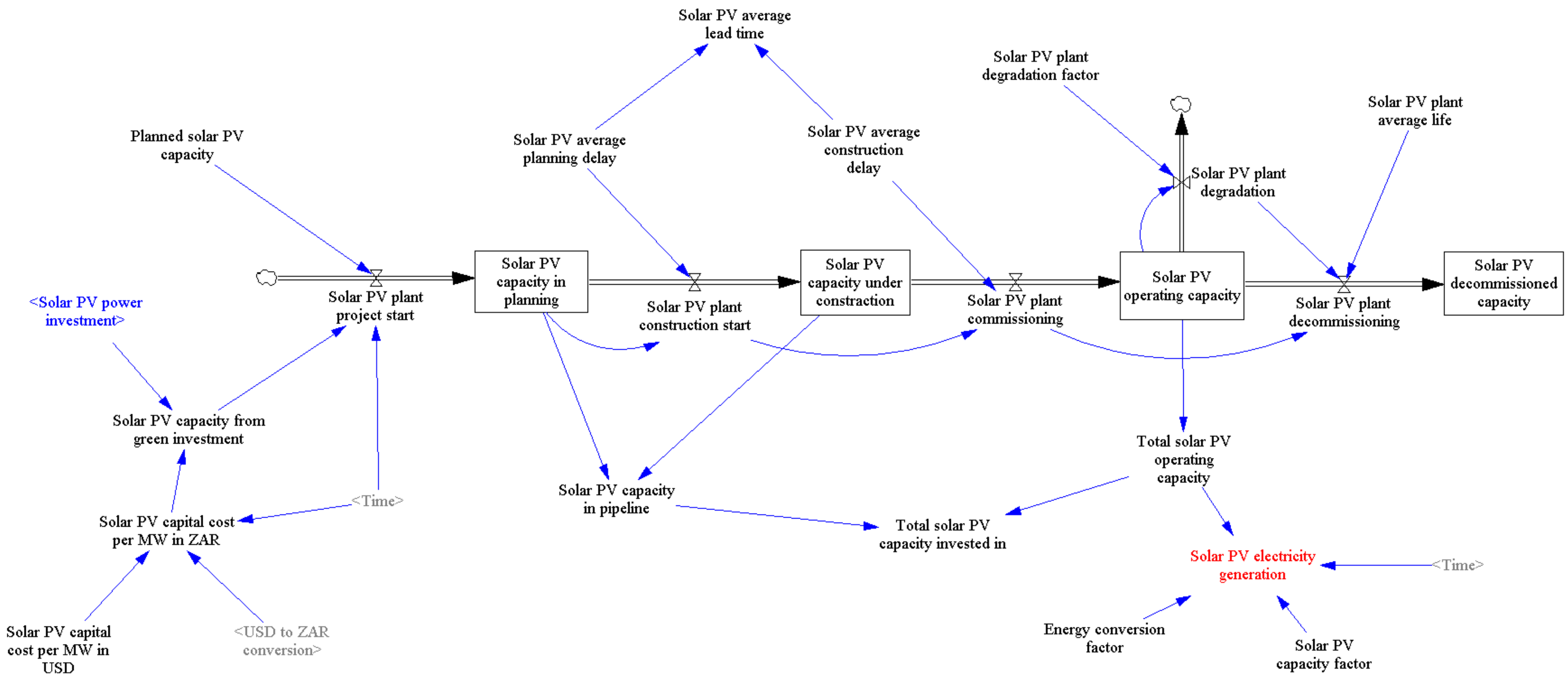

Figure A.7: Solar PV power supply sub-model

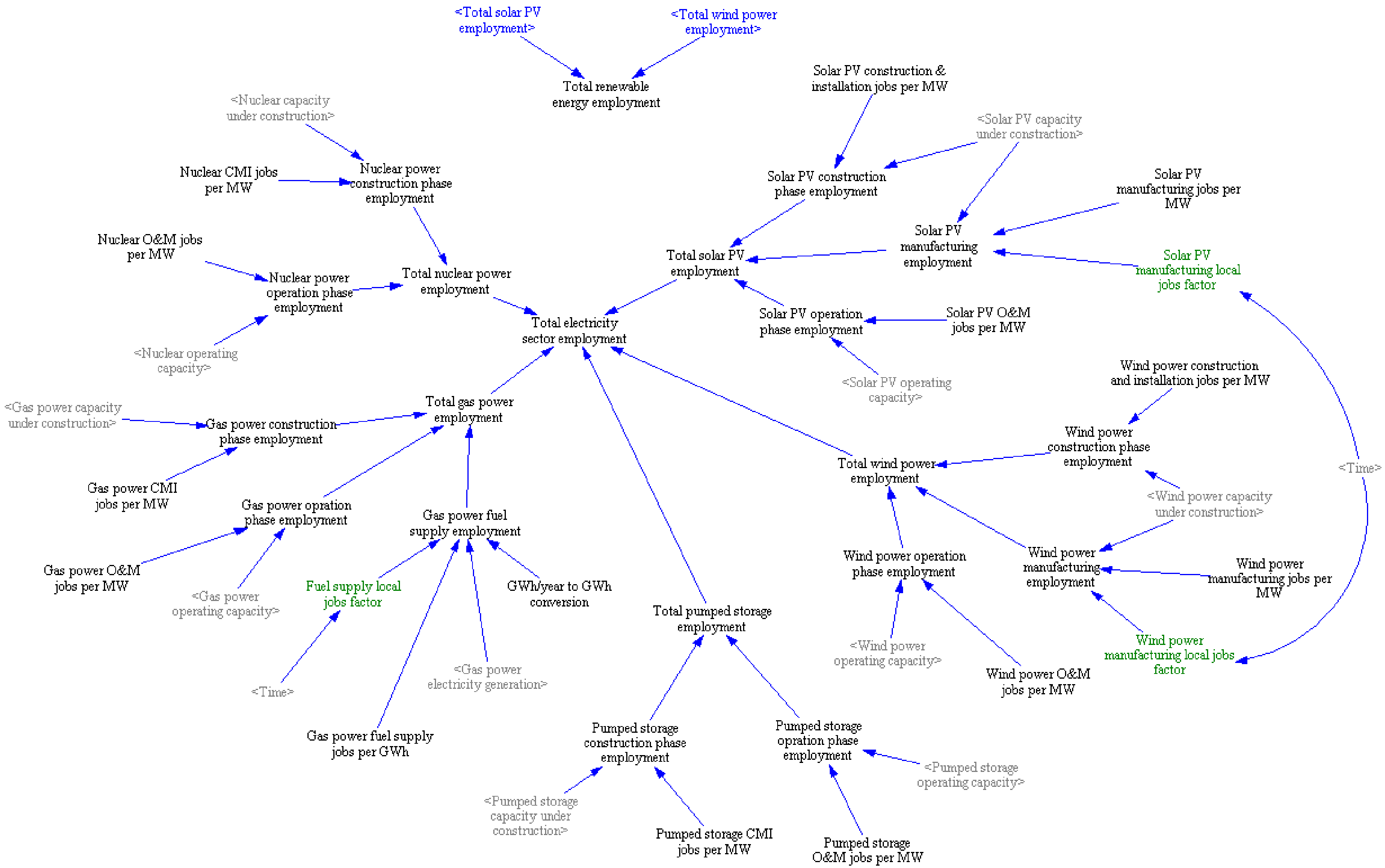

Figure A.8: Electricity sector employment sub-model

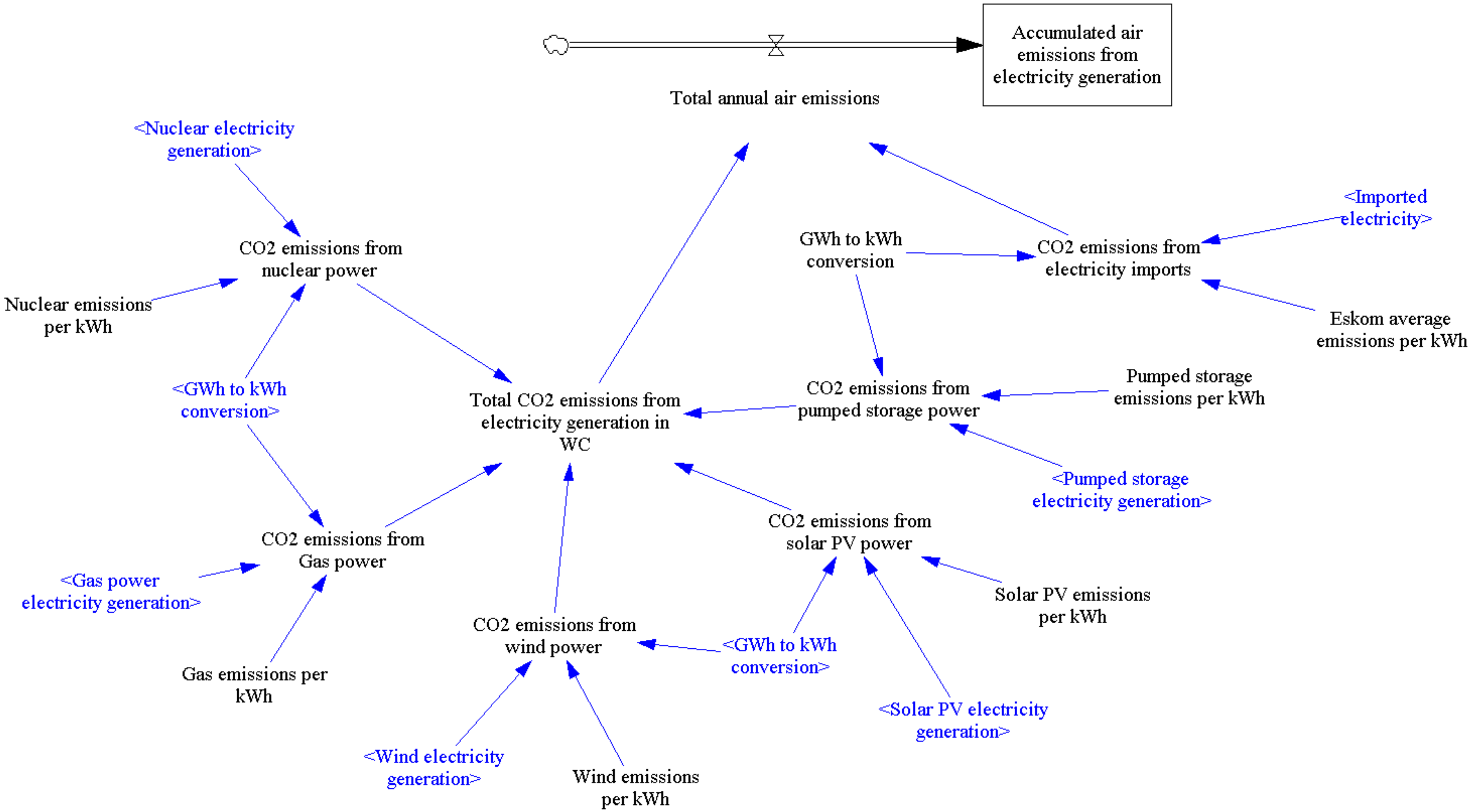

Figure A.9: Electricity sector air emissions sub-model

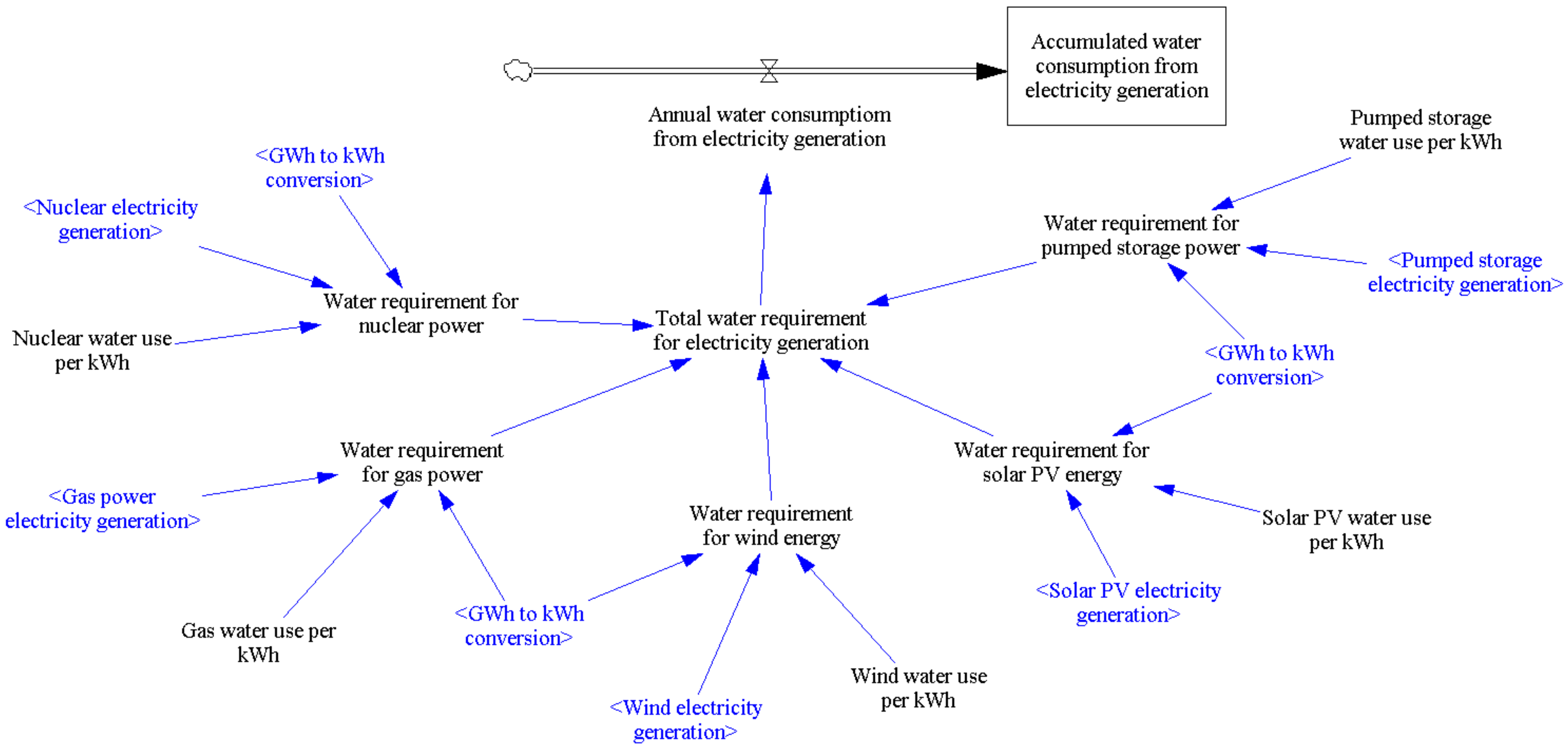

Figure A.10: Electricity sector water requirements sub-model

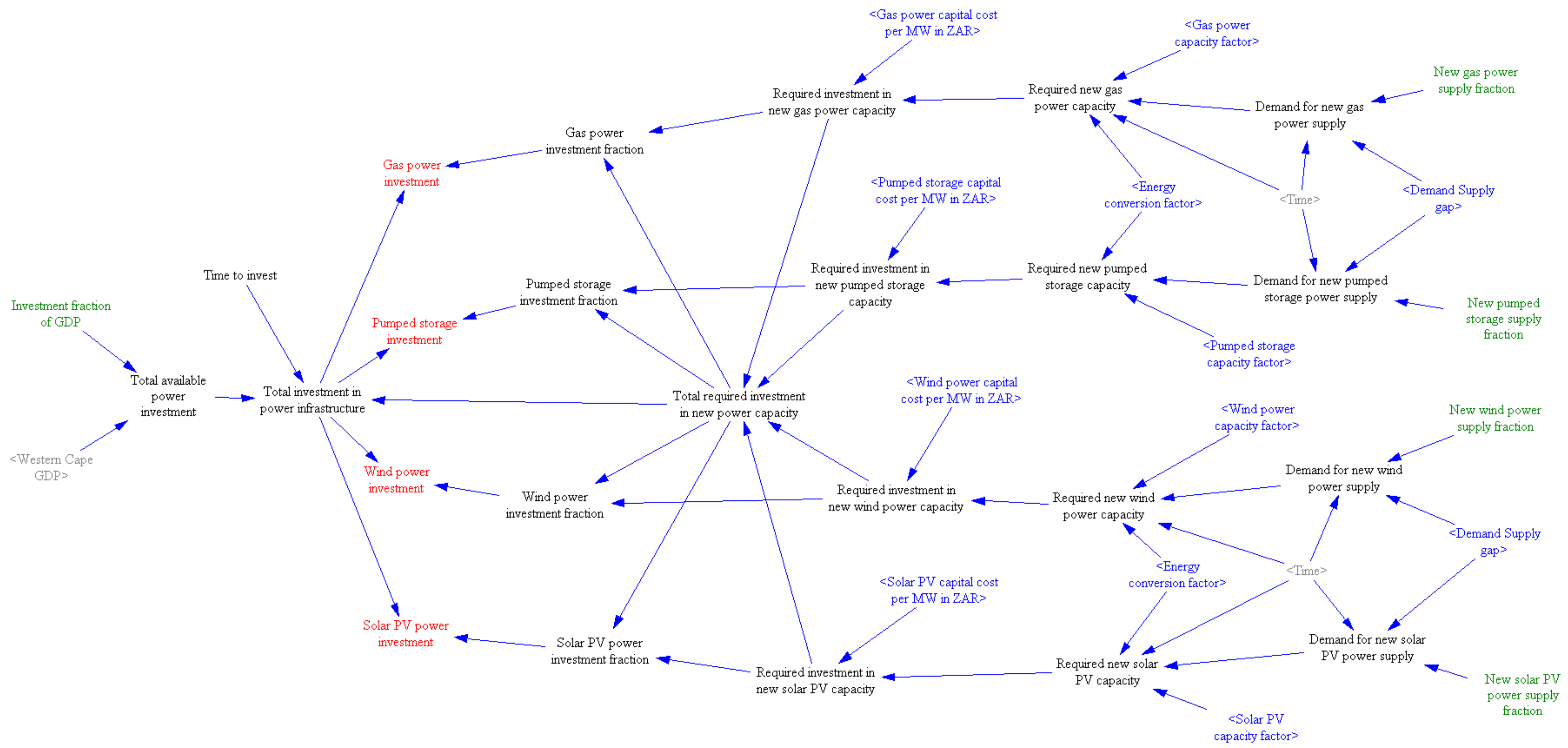

Figure A.11: Electricity sector investments sub-model

B. Parameter values and sources

Table B.1: Data sources used for the model parameters

Sub-model	Data sources
Electricity demand	NERSA; Stats SA; (Ziramba, 2008); (Inglesi-Lotz & Blignaut, 2011); (Deloitte, 2012); (Inglesi, 2010); (Kowalik & Coetzee, 2005)
Electricity technology share	N/A
Nuclear power supply	Eskom; Integrated Energy Plan 2012; Integrated Resource Plan 2010; Stats SA; World Energy Council
Gas power supply	Eskom; Integrated Energy Plan 2012; Integrated Resource Plan 2010; International Energy Agency; (Brooks, 2000); World Energy Council
Pumped storage power supply	Eskom; Integrated Energy Plan 2012; Integrated Resource Plan 2010; International Energy Agency; World Energy Council
Wind power supply	Eskom; Integrated Energy Plan 2012; Integrated Resource Plan 2010; International Energy Agency; (Staffel & Green, 2014); (Sager, 2014); World Energy Council
Solar power supply	Eskom; Integrated Energy Plan 2012; Integrated Resource Plan 2010; International Energy Agency; (Sager, 2014); (Jordan & Kurtz, 2012); World Energy Council
Electricity sector employment	International Energy Agency; Eskom; (Maia, et al., 2011); (Rutovitz & Atherton, 2009); (Rutovitz, 2010);
Electricity sector air emissions	Eskom; International Energy Agency; National Renewable Energy Laboratory; (Evans, et al., 2009)
Electricity sector water requirements	Department of Energy; International Energy Agency; (Meldrum, et al., 2013); (Evans, et al., 2009)
Electricity sector investments	N/A

C. Model verification and validation figures

C.1. Extreme condition test:

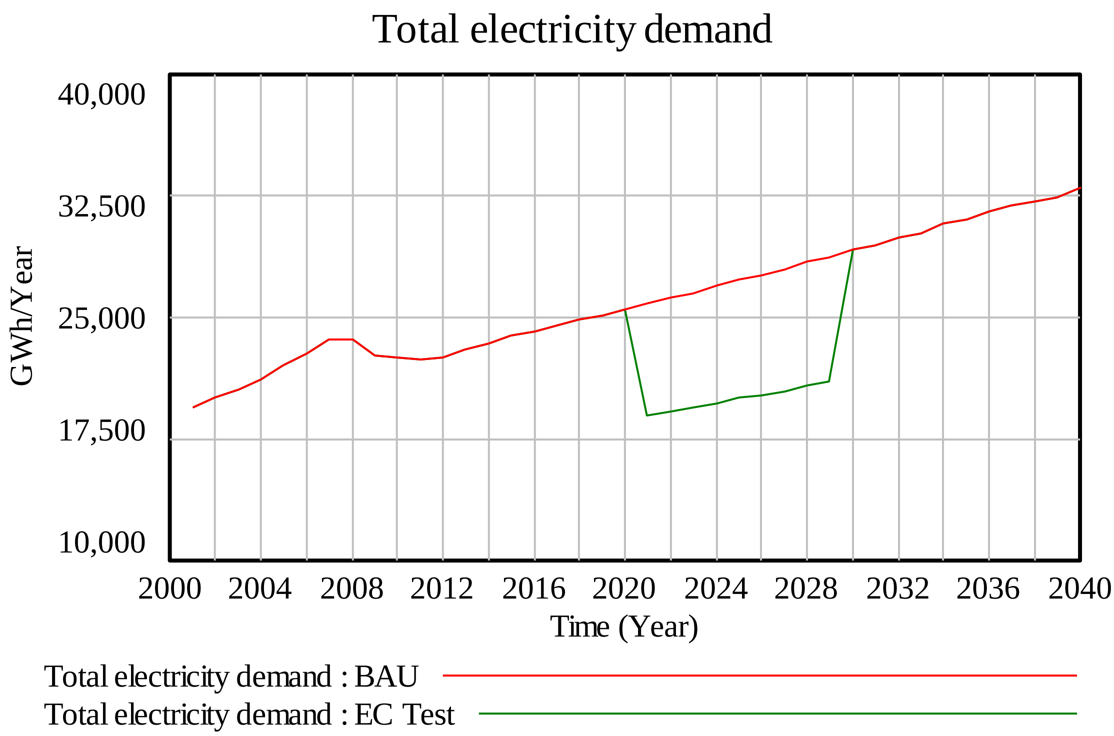

Figure C.1: Effect on TED of a tenfold step in electricity price

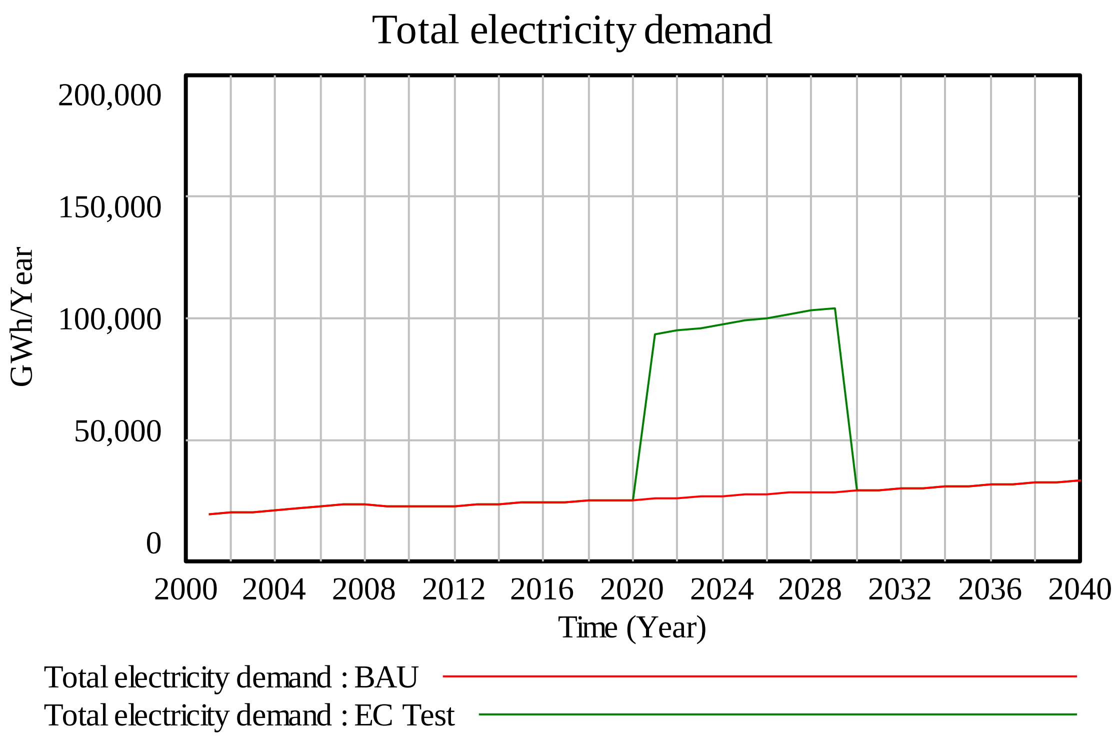

Figure C.2: Effect on TED of a tenfold step in GDP

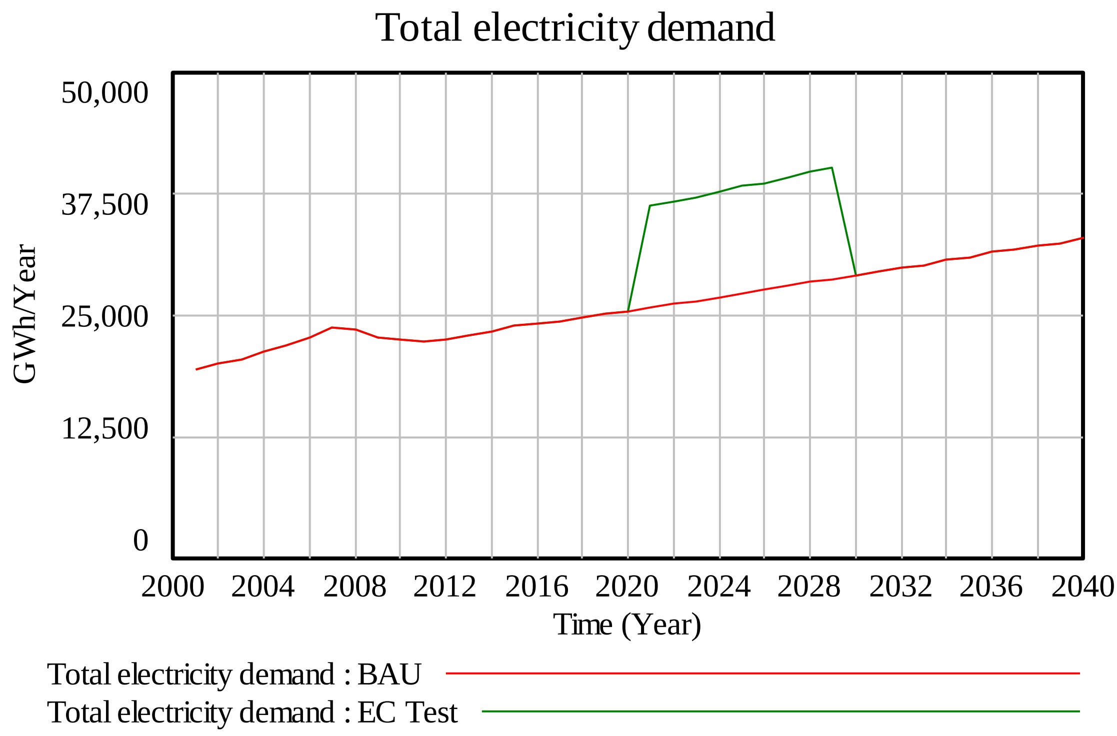

Figure C.3: Effect on TED of a tenfold step in GDP per capita

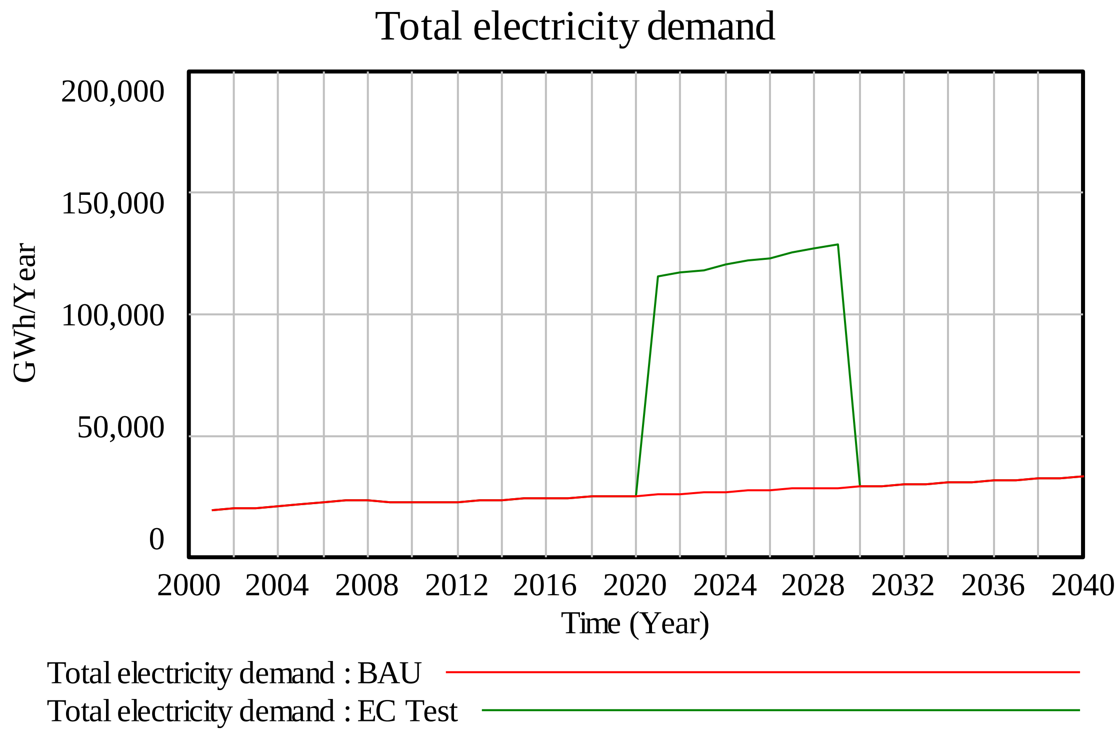

Figure C.4: Effect on TED of a tenfold step in population

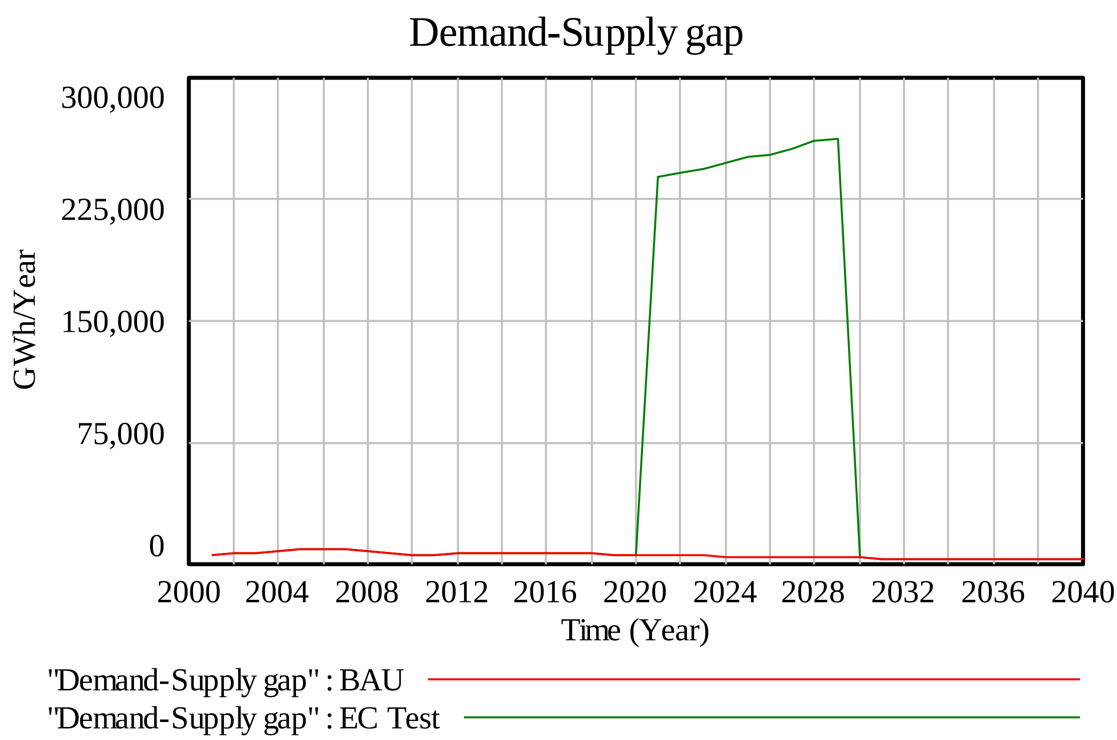

Figure C.5: Effect on DSG of a tenfold step in electricity demand

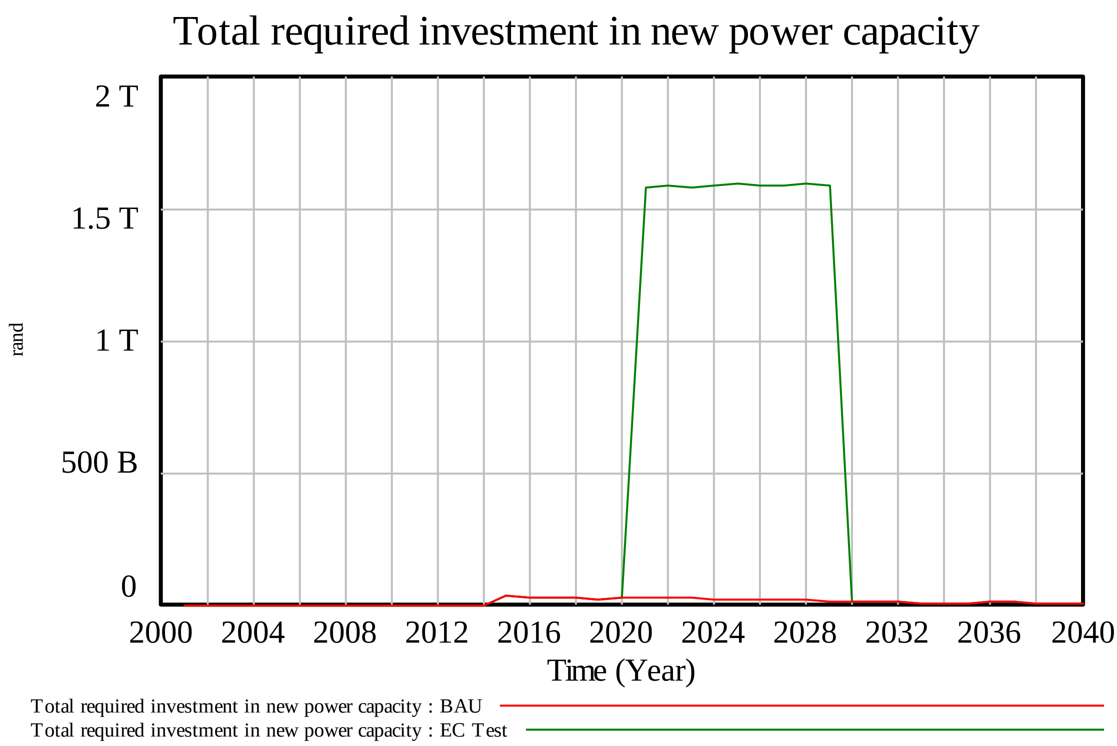

Figure C.6: Effect on TRINC of a tenfold step in electricity demand

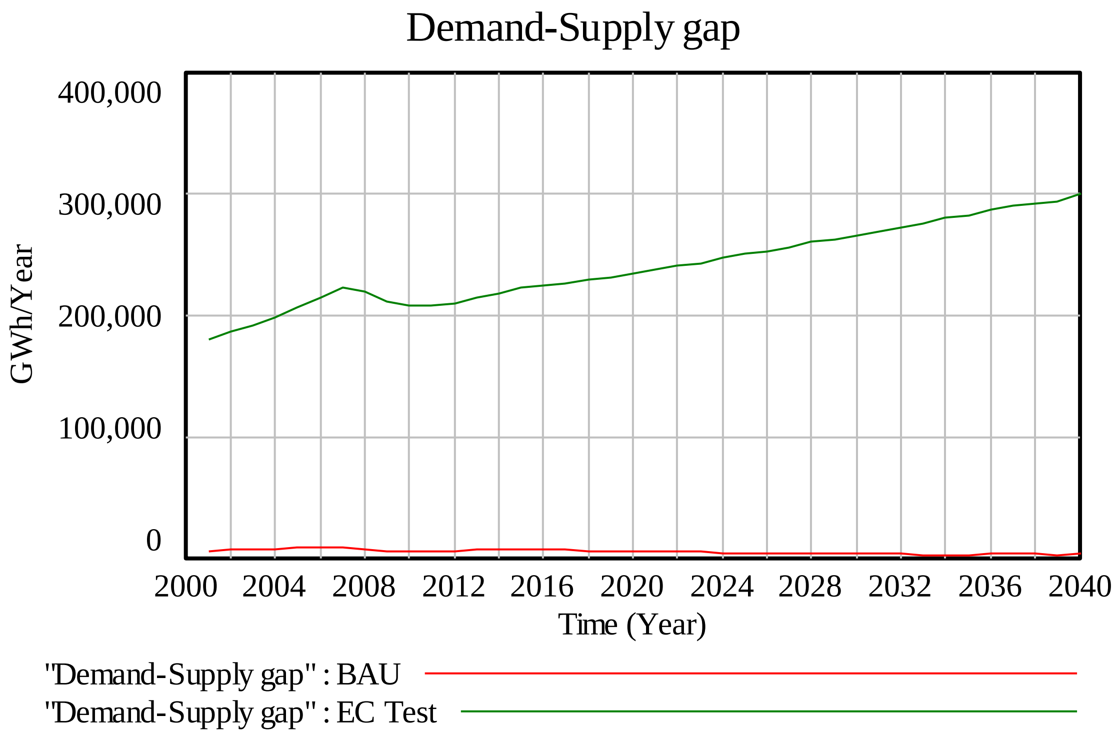

Figure C.7: Effect on DSG of a tenfold step in initial demand

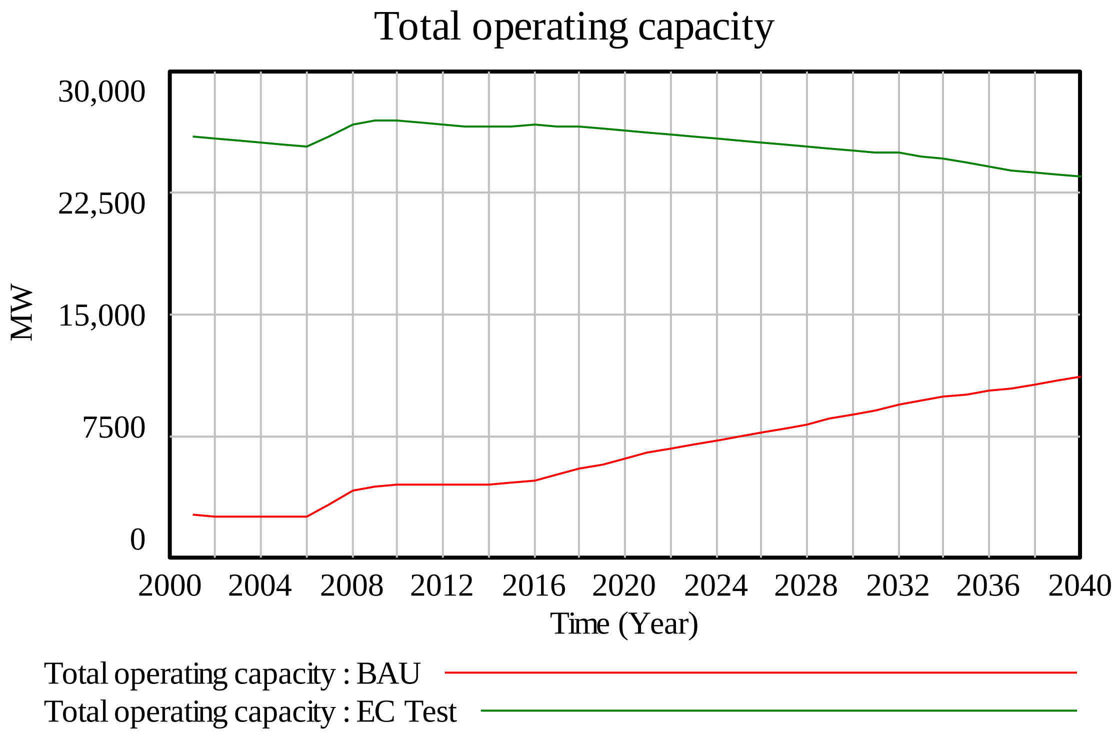

Figure C.8: Effect on TOC of a tenfold step in all initial operating capacities

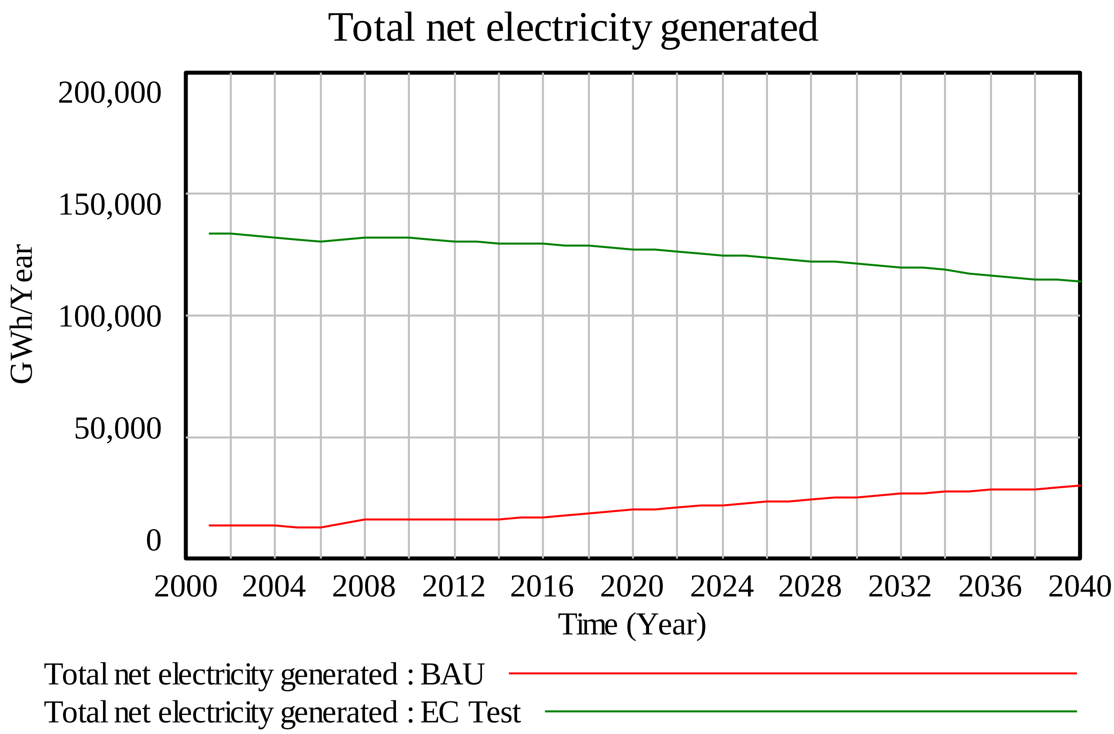

Figure C.9: Effect on TNEG of a tenfold step in all initial operating capacities

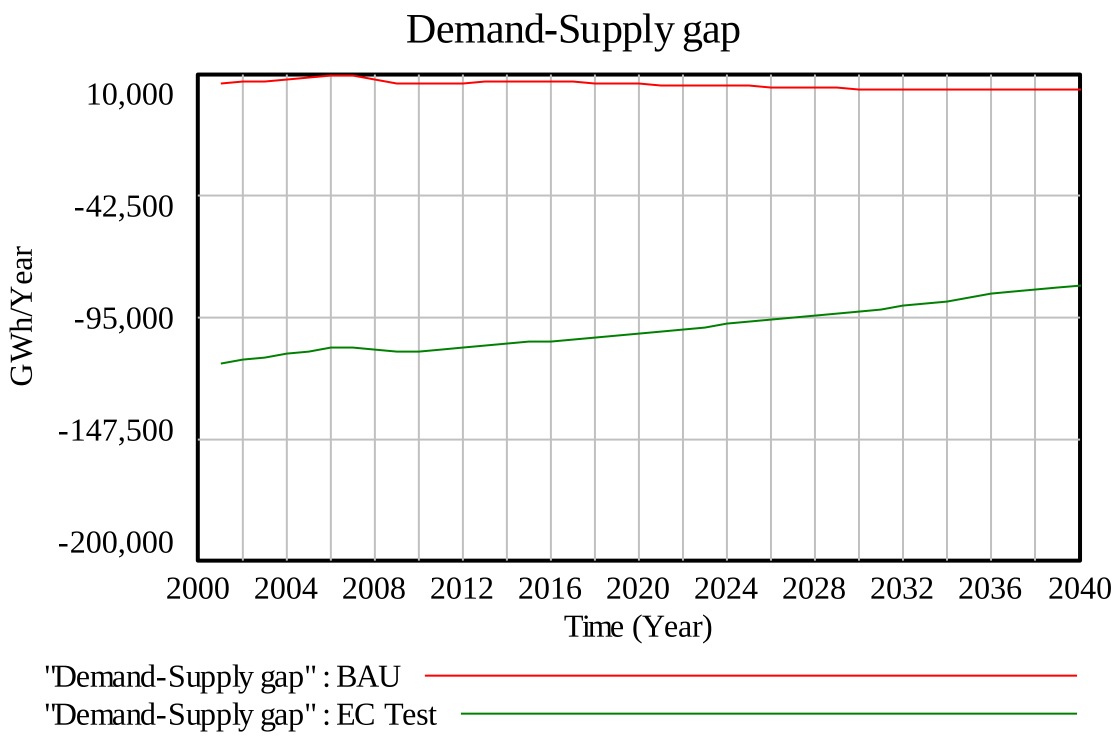

Figure C.10: Effect on DSG of a tenfold step in all initial operating capacities

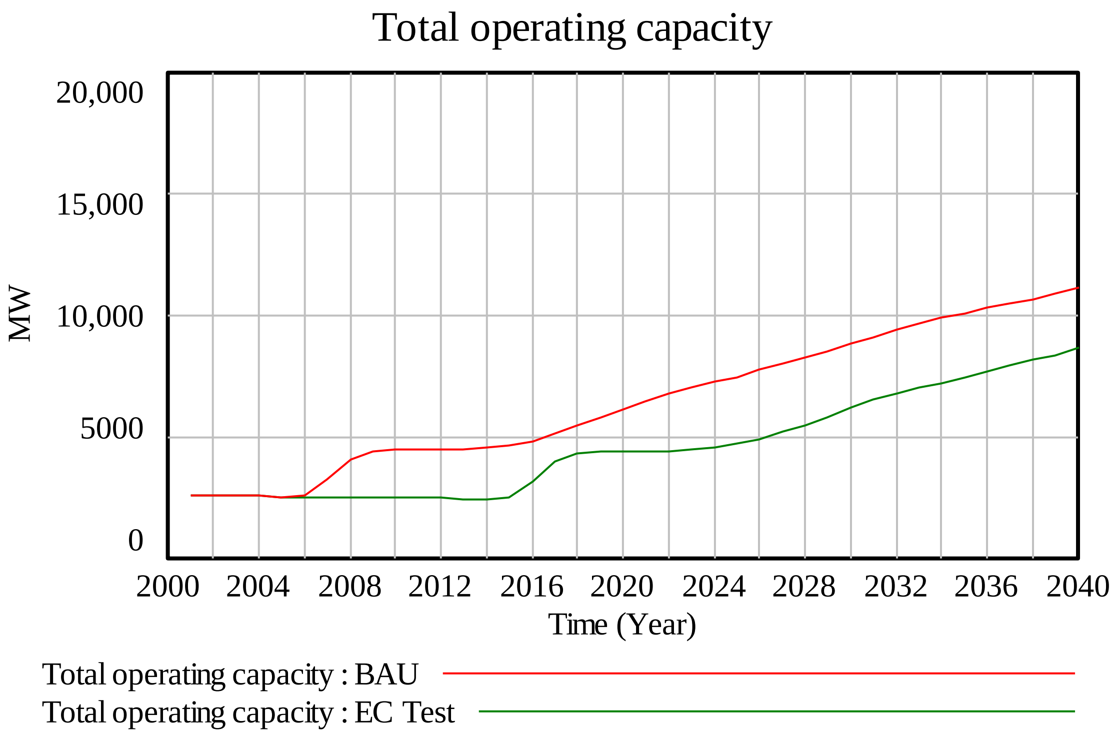

Figure C.11: Effect on TOC of a tenfold step in all construction delays

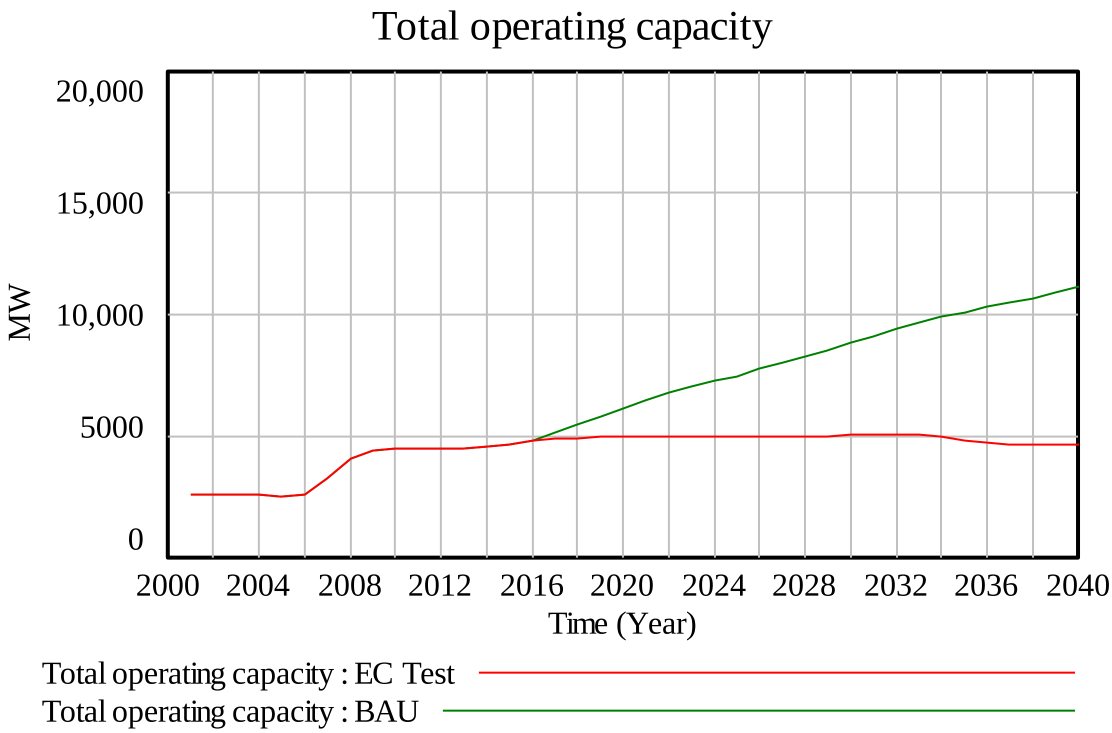

Figure C.12: Effect on TOC of a tenfold step in cost per MW

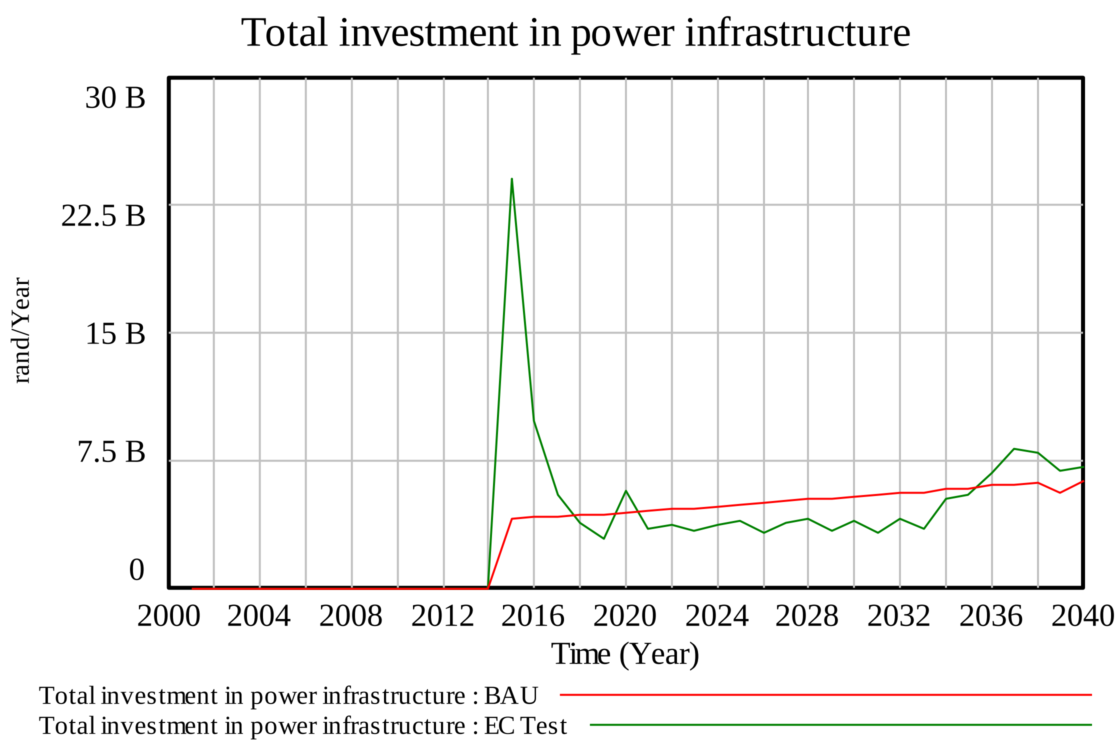

Figure C.13: Effect on total investment in power infrastructure of a tenfold step in GDP investment fraction

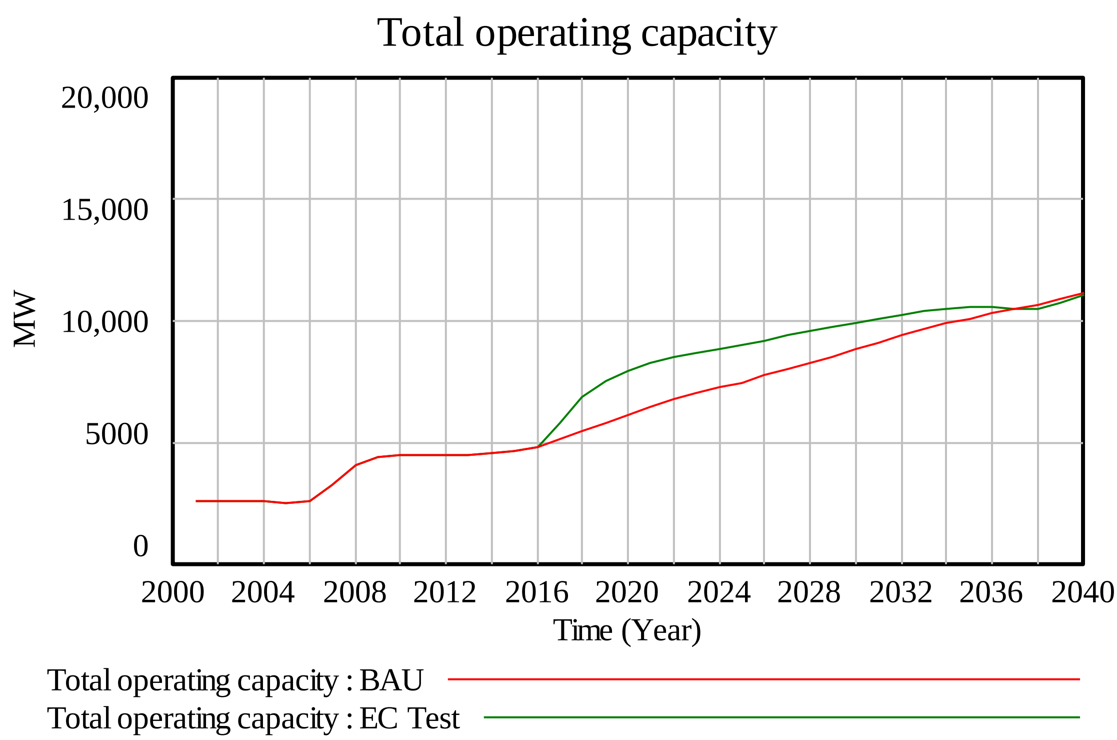

Figure C.14: Effect on TOC of a tenfold step in GDP investment fraction

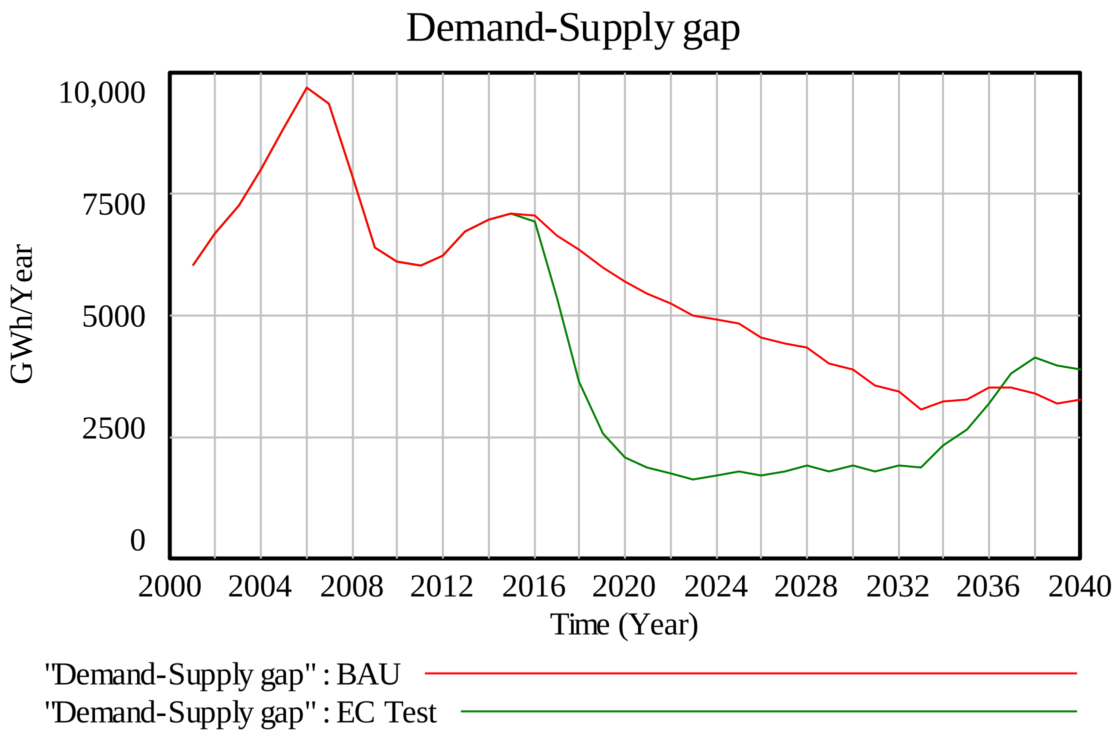

Figure C.15: Effect on DSG of a tenfold step in GDP investment fraction

C.2. Model behaviour reproduction test

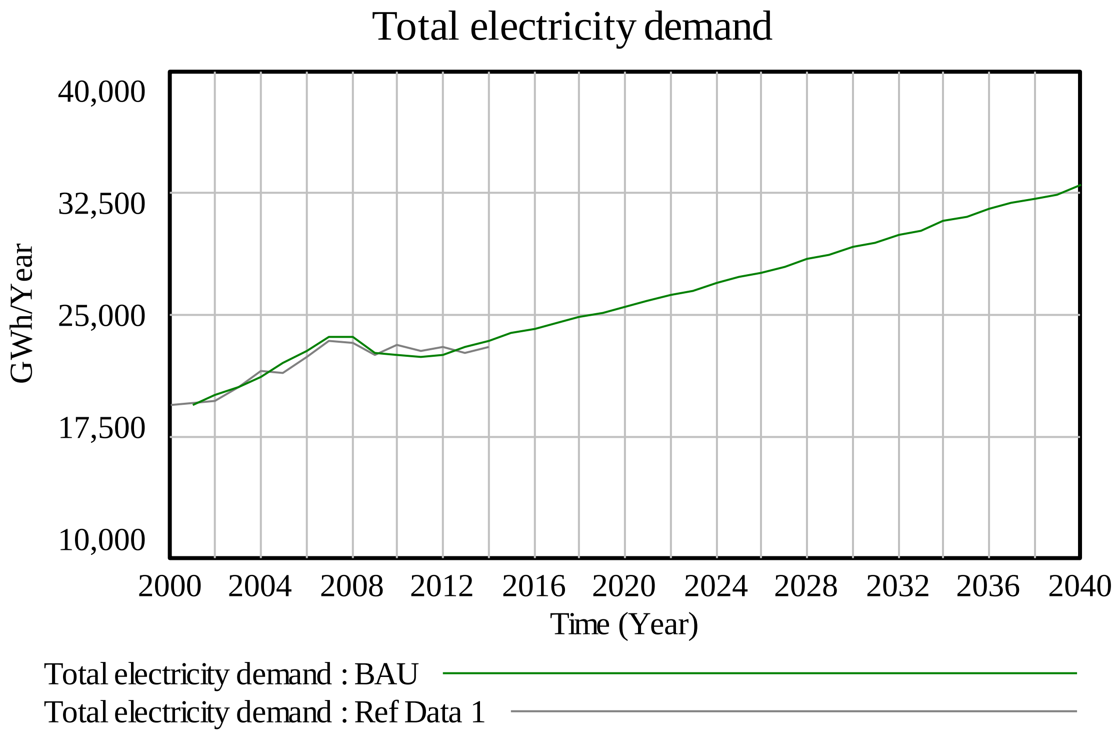

Figure C.16: Reference data for electricity demand

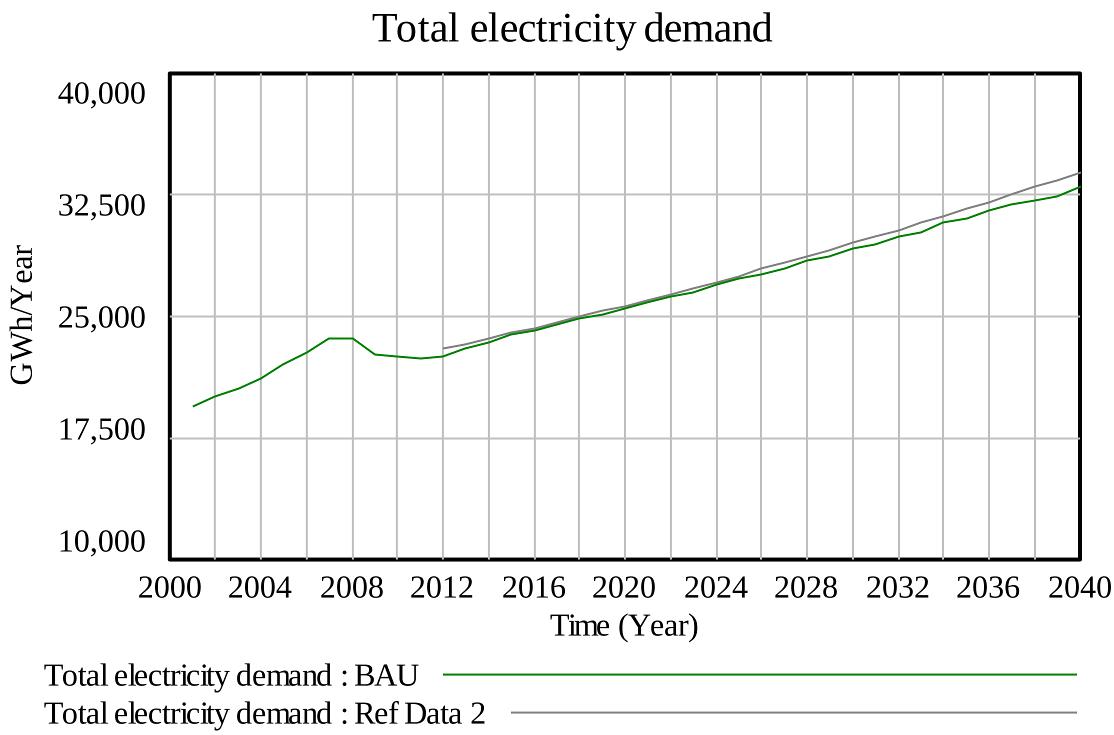

Figure C.17: WCIF electricity demand prediction

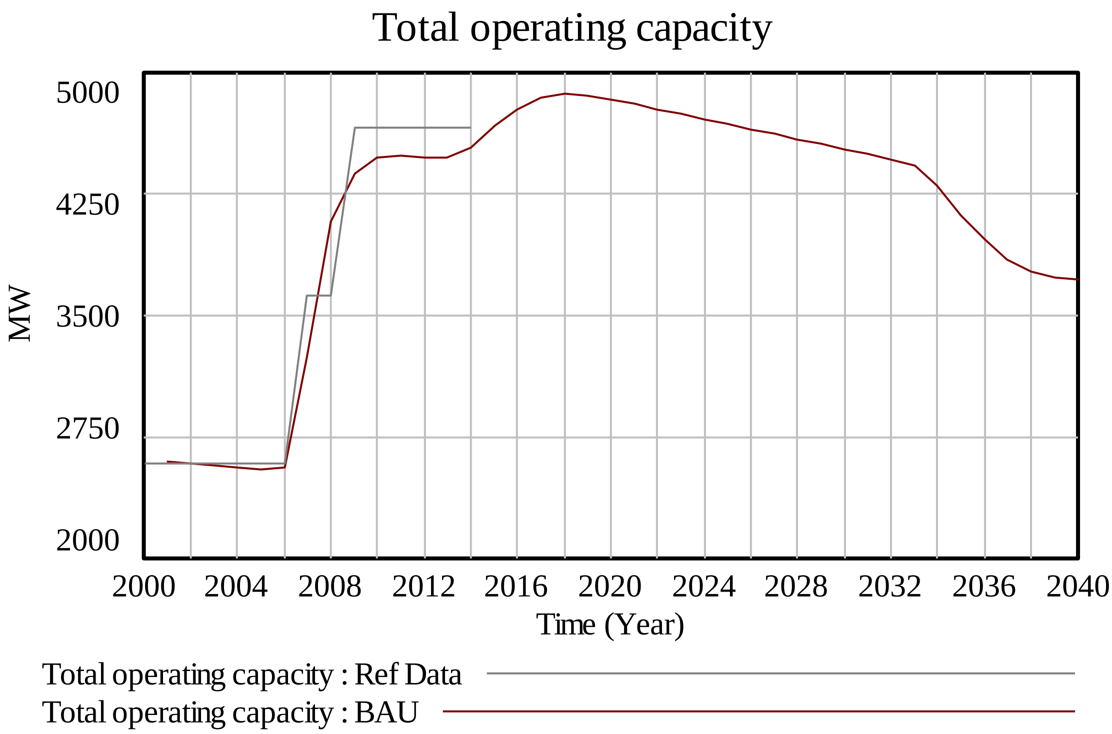

Figure C.18: Reference data for total operating capacity

C.3. Behaviour anomaly test

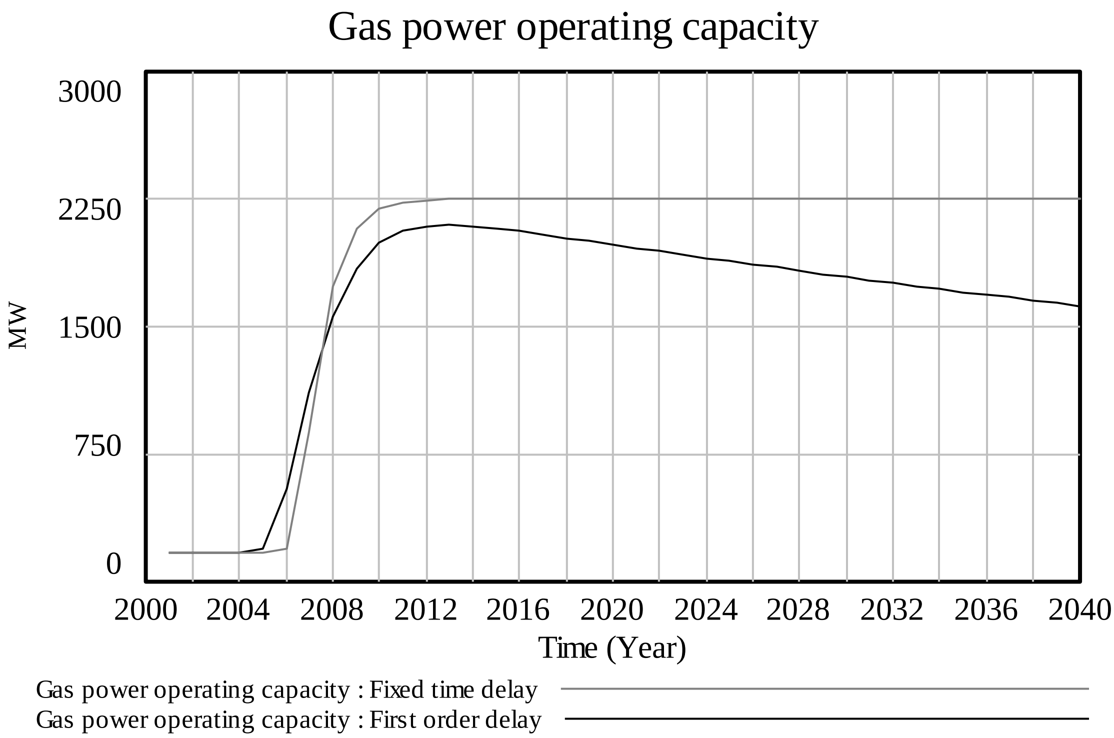

Figure C.19: Average plant life increased to 100 years

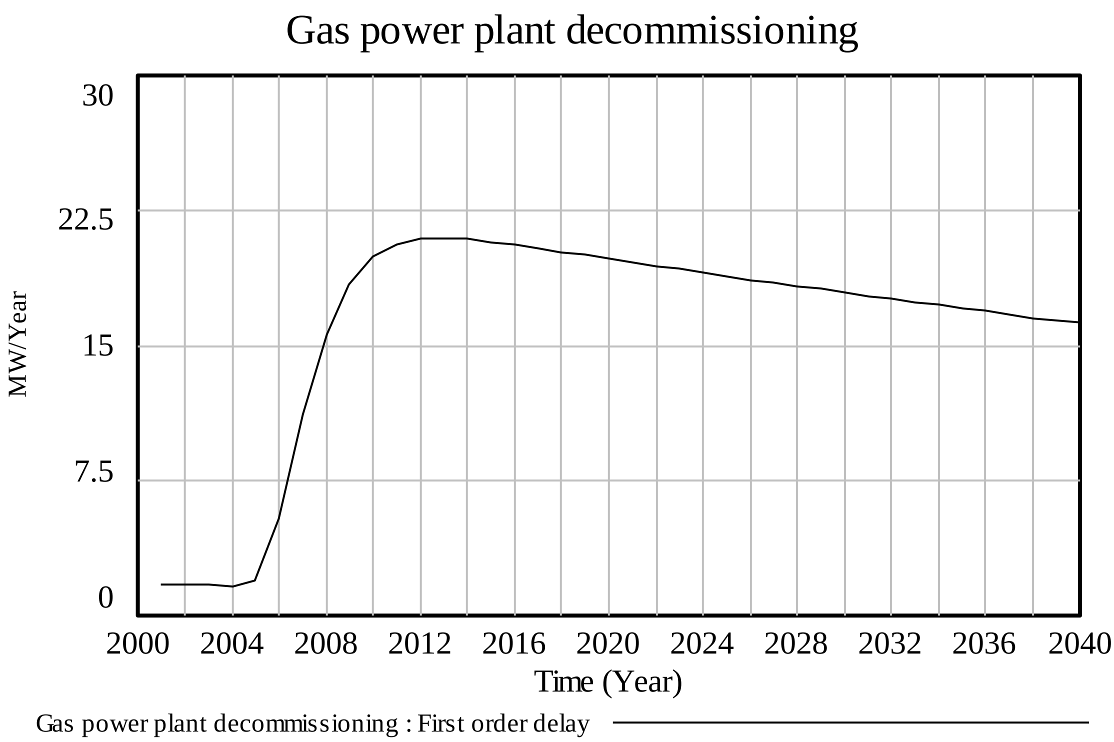

Figure C.20: Average plant life increased to 100 years

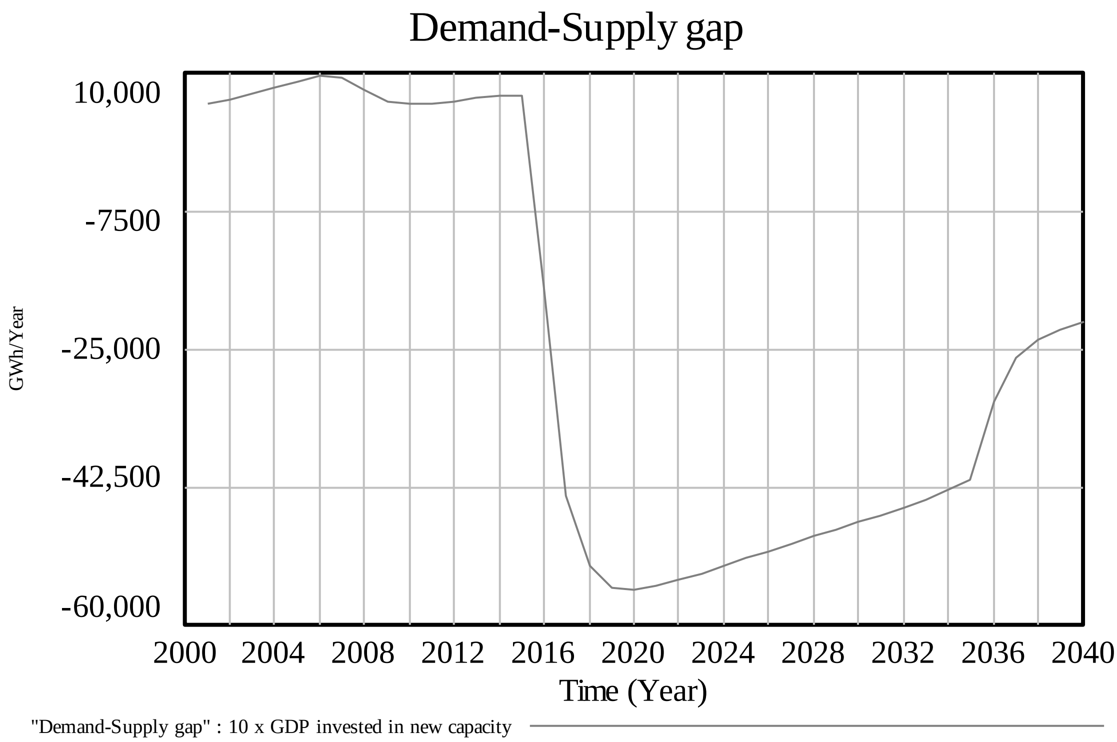

Figure C.21: Effect on DSG of a tenfold step simulated for GDP invested in new capacity

C.4. Behaviour sensitivity test

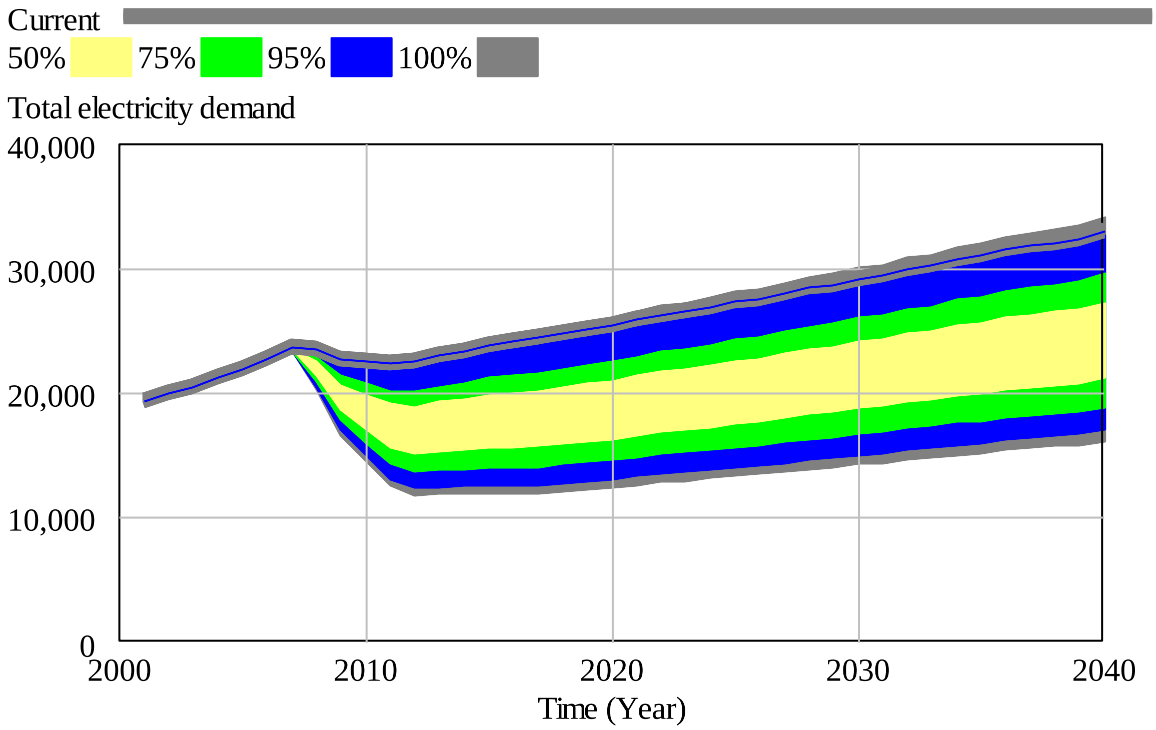

Figure C.22: Varying price elasticity between -1 and 0

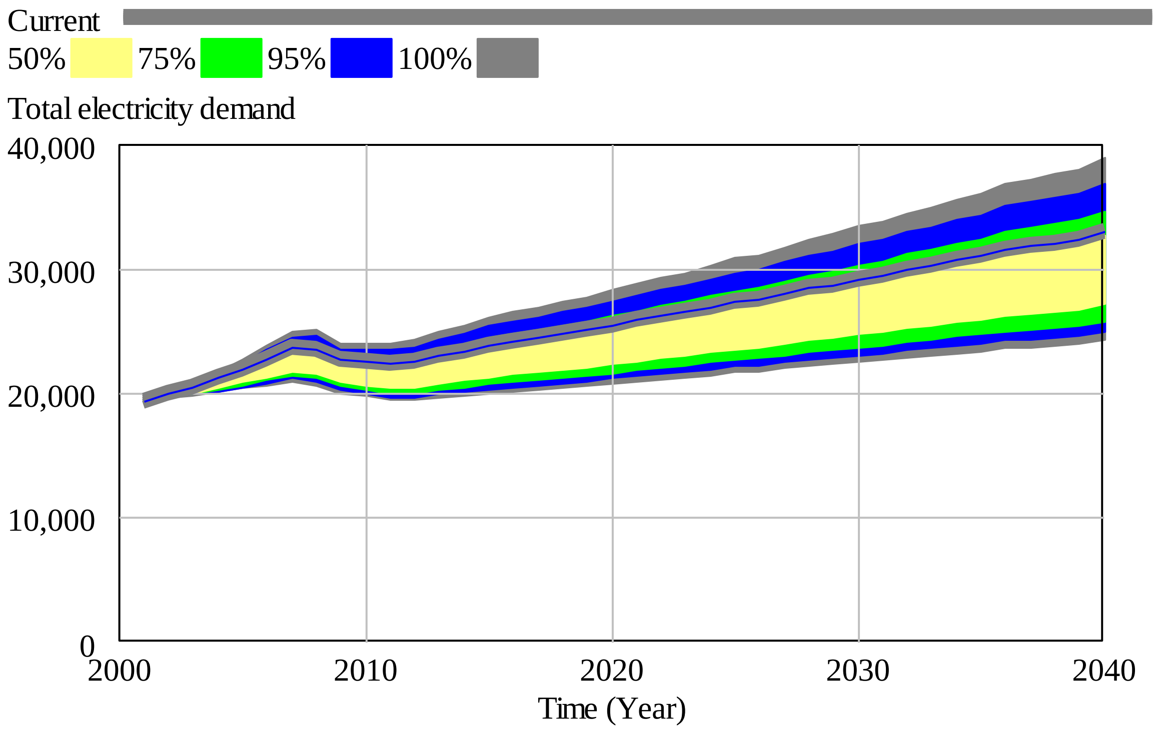

Figure C.23: Varying GDP elasticity between 0 and 1

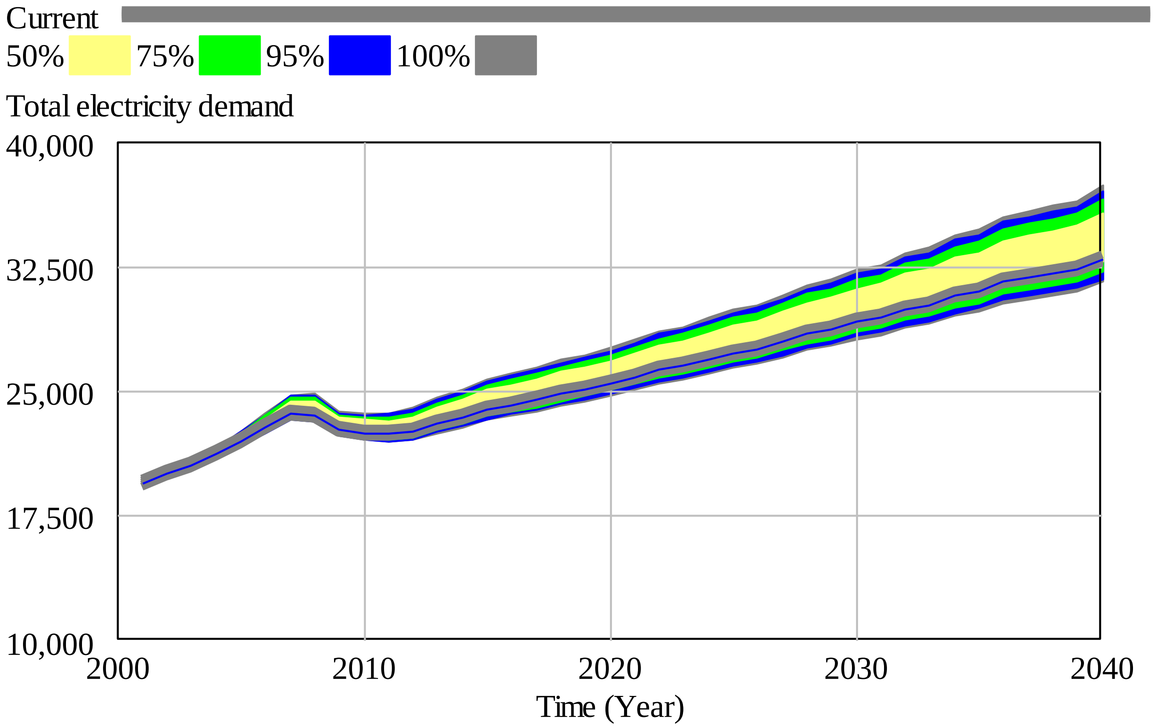

Figure C.24: Varying GDP per capita elasticity between 0 and 1

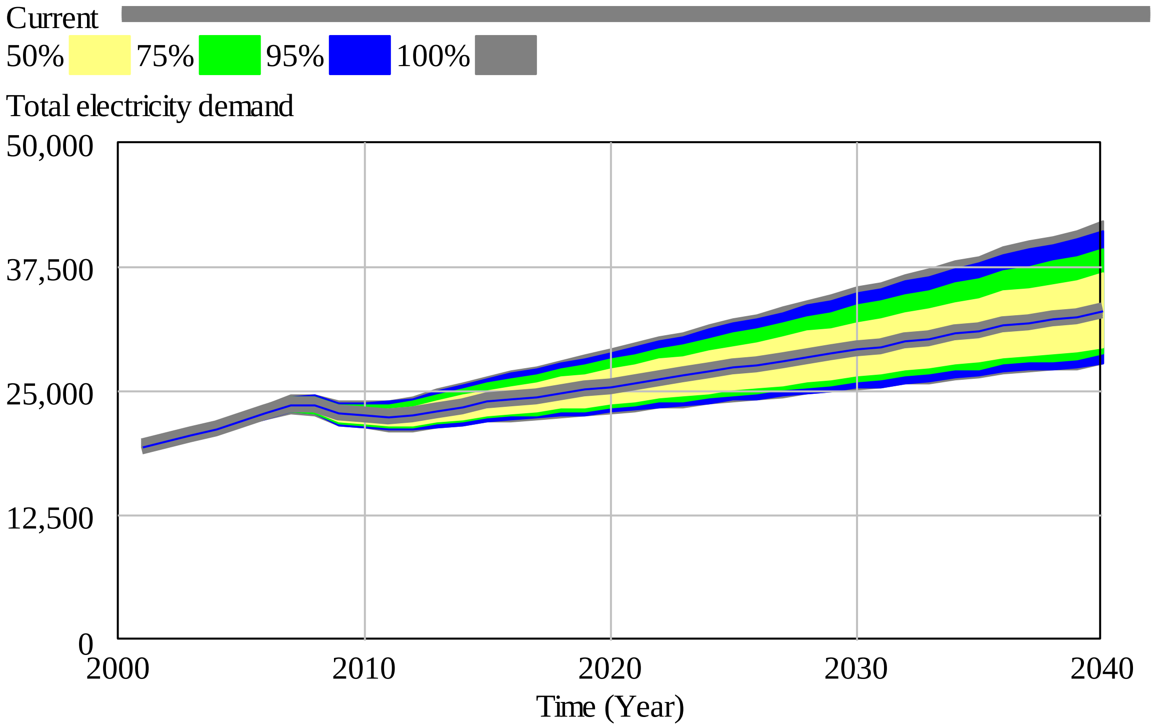

Figure C.25: Varying population elasticity between 0 and 2

D. Extended simulation results

Table D.1: Simulation results for selected model variables

Scenario		2001	2010	2015	2020	2025	2030	2035	2040
Western Cape population (Million people)									
All scenarios		4.52	5.34	5.82	6.27	6.67	7.06	7.43	7.80
Western Cape GDP (Rand/Year)									
All scenarios		188.4	273.0	323.0	354.7	391.8	430.1	468.4	511.9
Nuclear operating capacity (MW)									
All scenarios		1840	1824	1814	1805	1796	1787	1778	1770
Pumped storage operating capacity (MW)									
All Scenarios		580	575	572	569	566	563	561	558
Gas power operating capacity (MW)									
BAU		171	2170	2202	2169	2137	2105	2074	2043
LIC	RE	171	2170	2202	2169	2137	2105	2074	2043
	RE+GT	171	2170	2202	2520	2695	2657	2618	2579
HIC	RE	171	2170	2202	2169	2137	2105	2074	2043
	RE+GT	171	2170	2202	2782	3113	3070	3024	2979
Wind power operating capacity (MW)									
BAU		3	3	211	562	788	996	984	841
LIC	RE	3	3	211	719	1162	1606	1853	1839
	RE+GT	3	3	211	627	1040	1493	1747	1830
HIC	RE	3	3	211	838	1443	2064	2504	2587
	RE+GT	3	3	211	676	1228	1865	2319	2572
Solar power operating capacity (MW)									
BAU		0	0	54	192	277	359	386	328
LIC	RE	0	0	54	315	579	864	1119	1197
	RE+GT	0	0	54	252	490	777	1035	1177
HIC	RE	0	0	54	409	806	1242	1669	1848
	RE+GT	0	0	54	296	650	1090	1521	1814
Nuclear electricity generation share (%)									
BAU		90	71	68	63	60	58	58	59
LIC	RE	90	71	68	60	55	50	48	48
	RE+GT	90	71	68	60	54	49	47	46
HIC	RE	90	71	68	59	52	46	42	41
	RE+GT	90	71	68	58	50	45	41	39
Pumped storage electricity generation share (%)									
BAU		7	6	5	5	5	5	5	5
LIC	RE	7	6	5	5	4	4	4	4
	RE+GT	7	6	5	5	4	4	4	4
HIC	RE	7	6	5	5	4	4	3	3
	RE+GT	7	6	5	5	4	4	3	3
Gas electricity generation share (%)									
BAU		2	2	2	21	20	19	18	19
LIC	RE	2	2	2	20	18	16	15	15
	RE+GT	2	2	2	23	22	20	19	18
HIC	RE	2	2	2	19	17	15	14	13
	RE+GT	2	2	2	24	24	21	19	18
Wind electricity generation share (%)									
BAU		>1	>1	4	10	13	16	16	14
LIC	RE	>1	>1	4	12	18	23	25	25
	RE+GT	>1	>1	4	10	16	21	23	24
HIC	RE	>1	>1	4	14	21	27	30	30
	RE+GT	>1	>1	4	11	17	23	27	29

Scenario		2001	2010	2015	2020	2025	2030	2035	2040
Solar PV electricity generation share (%)									
BAU		0	0	>1	2	3	3	3	3
LIC	**RE**	0	0	>1	3	5	7	8	9
	RE+GT	0	0	>1	2	4	6	7	8
HIC	**RE**	0	0	>1	4	6	9	11	12
	RE+GT	0	0	>1	3	5	7	10	11
Investment in new wind power capacity (Million Rand)									
BAU		0	0	0	0	0	0	0	0
LIC	**RE**	0	0	554	640	739	850	972	1063
	RE+GT	0	0	233	640	739	850	972	1063
HIC	**RE**	0	0	970	1120	1293	1488	1701	1859
	RE+GT	0	0	408	1120	1293	1488	1701	1859
Investment in new solar power capacity (Million Rand)									
BAU		0	0	0	0	0	0	0	0
LIC	**RE**	0	0	738	779	828	870	901	985
	RE+GT	0	0	362	779	828	870	901	985
HIC	**RE**	0	0	1291	1363	1449	1523	1577	1724
	RE+GT	0	0	633	1363	1449	1523	1577	1724