Sustainability assessment of technology systems that address the energy-water nexus: The case of desalination in the Western Cape

by

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DECLARATION

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ABSTRACT

In recent decades, the critical interdependencies that exist between the energy and water sectors, referred to as the energy-water nexus, have been investigated. It has become apparent that a policy change or intervention in one of the sectors can have a significant impact on the other. The impact on the entire energy-water nexus, therefore, needs to be considered when implementing changes in either sector. The Western Cape Province needs to increase its available water supply to ensure that the future water demand can be met. The aim of this research was to investigate the appropriateness of seawater desalination used in conjunction with renewable energy as a possible water supply intervention. The objectives of this research were to: select an appropriate modelling approach; compile, verify and validate the model; simulate different scenarios with and without the technology; and provide policymakers with recommendations regarding the sustainability of implementing a desalination technology system.

It was determined that the Western Cape Province's energy-water nexus is a complex system, because of the number of subsystems that exist within the system. A literature survey of the previous efforts that had been made to model similar systems was conducted. System dynamics modelling was found to be the most appropriate modelling tool, given the objectives of the research and the complexity of the problem.

A systems thinking and modelling process was followed to develop a model of the Western Cape Province's energy-water nexus. The first phase was problem formulation, and the second phase was the development of the conceptual model using causal loop diagrams. The construction, verification and validation of the dynamic computer simulation model was done in the third phase.

Once confidence in the dynamic model was established, the fourth phase of the modelling process was completed. For this phase, a number of scenarios were developed and simulated to determine the effect of different desalination technology systems on the Western Cape Province. The impact of multi-effect distillation (MED) and reverse osmosis (RO) were compared. The effects of combining these technologies with different renewable energy sources, including thermal waste heat and solar energy, were also investigated. It was seen that the Western Cape Province's water supply would be unable to meet the future water demand if no intervention was made. The results indicated that RO with photovoltaics would be the most sustainable and that the system's life cycle cost up until 2040 is the lowest of all the simulated systems. In phase five, it was recommended to policymakers that, of all the systems that were considered, this system would be the best to implement. Additional water supply interventions, however, need to be investigated, as the recommended desalination system would not be enough to ensure sufficient future water supply.

This research provides a better understanding of the complexities involved in the installation of a new technology system, such as desalination, in the Western Cape Province's energy-water nexus. This research can be used as a platform to further explore the impacts of a desalination system or to investigate the sustainability of other technology systems that will affect the nexus.

OPSOMMING

Die kritiese skakels tussen die energie en water sektore, waarna verwys word as die energie-water nexus, word in die afgelope dekades ondersoek. Dit is duidelik dat die beleidveranderings en ingrypings wat in een sektor uitgevoer word 'n beduidende impak op die ander sektor kan hê. Die impak op die hele energie-water nexus moet dus oorweeg word, wanneer veranderinge in enige van die sektore uitgevoer word. Die Wes-Kaapse Provinsie moet sy beskikbare watervoorsiening verhoog om aan die toekomstige wateraanvraag te kan voorsien. Die doel van hierdie navorsing is om die toepaslikheid van seewater ontsouting, gepaard met hernubare energie, te ondersoek as 'n moontlike watervoorsieningsingryping. Die doelwitte van die navorsing was om: 'n toepaslike modelleringsbenadering te kies; die model saam te stel, te verfieer en te valideer; verskeie scenarios te simuleer; en beleidsmakers met aanbevelings rakende die volhoubaarheid van 'n ontsoutingstegnologiestelsel te voorsien.

Daar is bevind dat die Wes-Kaapse energie-water nexus 'n komplekse stelsel is as gevolg van die aantal substelsels waaruit die stelsel bestaan. 'n Literatuuroorsig van vorige pogings om soortgelyke stelsels te modelleer is uitgevoer. Daar is bevind dat stelseldinamika die mees toepaslike modelleringstegniek is, gegewe die doelwitte en kompleksiteit van die probleem.

'n Stelseldenke en modelleringsproses is gevolg om die model van die Wes-Kaapse energie-water nexus te ontwikkel. Die eerste fase was om die probleem te formuleer en die tweede fase was om die konsepsionele model te ontwikkel. Die dinamiese rekenaarsimulasie model is in die derde fase ontwikkel, geverifieer en gevalideer.

Nadat vertroue in die dinamiese model bevestig was, is die vierde fase van die modelleringsproses voltooi. Vir die fase is 'n aantal scenarios ontwikkel en gesimuleer om die gevolge van verskillende ontsoutingstegnologiestelsels vir die Wes-Kaapse Provinsie te bepaal. Die impak van multi-effek distillasie (MED) en omgekeerde osmose (RO) is vergelyk. Die gevolge van die kombinasie van die tegnologieë met hernubare krag, soos termiese afvalhitte en sonkrag, is ook ondersoek. Die simulasieuitslae het aangedui dat die Wes-Kaapse watervoorsiening nie voldoende is vir die voorspelde wateraanvraag nie. Die uitslae het ook aangedui dat RO met fotovoltaïese panele die mees volhoubare stelsel is en dat die stelsel se lewenssikluskoste tot en met 2040 die laagste van al die gesimuleerde stelsels is. In die vyfde fase is beleidsmakers aanbeveel dat hierdie stelsel, van al die stelsels wat oorweeg is, die beste is om te implementeer. Addisionele watervoorsieningsingrypings moet egter ondersoek word, aangesien die aanbevole ontsoutingsstelsel nie voldoende sal wees om aan toekomstige wateraanvraag te voorsien nie.

Die studie het gelei tot 'n beter begrip van die kompleksiteit rakende die installering van 'n nuwe tegnologiestelsel, soos ontsouting, in die Wes-Kaapse energie-water nexus. Die studie kan gebruik word as 'n platform om verder die gevolge van 'n ontsoutingsstelsel te ondersoek, of om die volhoubaarheid van ander tegnologiesisteme wat die nexus sal raak, te ondersoek.

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LIST OF ACRONYMS AND ABBREVIATIONS

BAU	Business As Usual
CCGT	Combined Cycle Gas Turbine
CLD	Causal Loop Diagram
CSP	Concentrated Solar Power
DPSIR	Driving force-Pressure-State-Impact-Response framework
DSS	Decision Support Software
EU	European Union
IRENA	International Renewable Energy Agency
IRP	Integrated Resource Plan
MED	Multi-Effect Distillation
MULINO	Multi-sectoral, integrated and operational decision support system for sustainable use of water resources at the catchment scale
MSF	Multi-Stage Flash
OCGT	Open Cycle Gas Turbine
PV	Photovoltaic
REI4P	Renewable Energy Independent Power Producer Procurement Programme
RO	Reverse Osmosis
SFD	Stock and Flow Diagram
SysML	Systems Modelling Language
UAW	Unaccounted for Water
UGEP	Utilisable Groundwater Exploitation Potential
USA	United States of America
WaCaGEM	Western Cape Green Economy Model
WC/WDM	Water Conservation/Water Demand Management
WCWSS	Western Cape Water Supply System
WWTW	Waste Water Treatment Works

CHAPTER 1: INTRODUCTION

This study focuses on investigating the sustainability of implementing a desalination system in the Western Cape Province. The purpose of this chapter is to provide the background to the research conducted, and emphasise the value and relevance of this research project. The first four sections in this chapter provide background information on the research topic, and an overview of the problem. In the first section, the energy-water nexus is described broadly and the links between the energy and water sectors are discussed. In the second section, the energy and water sectors of South Africa are briefly discussed, as well as the problems both sectors are facing. The nexus which exists between the sectors is also described. The energy-water nexus in the Western Cape Province context is given in the third section. In the fourth section, desalination as a technology system that addresses the energy-water nexus is discussed. In the last four sections, the research problem and objectives are given, as well as the research design and document outline. This is to guide the reader and provide a better understanding of the research.

1.1 Energy-water nexus

Globally, water and energy have been recognised separately as resources that are critical to the growth of modern economies. According to Hussey & Pittock (2012), in recent years the energy and water sectors have undergone rapid reform, which is driven by environmental sustainability, security of supply, and economic efficiency. The reformation of the water and energy sectors mostly occurred in isolation from one another, despite the links between the sectors. It is only in recent decades that the interdependency of water and energy has become apparent and efforts are being made to address this nexus (Marsh, 2008).

As illustrated by Figure 1.1, there are numerous and varied links and interdependencies between the water and energy sectors and such links and interdependencies exist across a number of industries. However, for the purpose of this study only the electricity sector's water use for electricity generation (i.e. water used for thermoelectric cooling), and the water sector's electricity use for water supply (i.e. electricity used for the abstraction, conveyance, treatment and distribution of water, and waste water collection and treatment) are discussed. This is because the other links and interdependencies, such as water used for extraction and mining, and fuel processing, are not relevant to this study. For this reason, the only part of the energy sector that was considered is the electricity sector. The use of water for electricity generation alters water levels and water quality, which may result in negative impacts on the hydrological cycle, aquatic environments and human health (Wang, 2013). Reduced water supply would also inhibit economic growth. The world's energy sectors are the largest emitters of greenhouse gases and are therefore responsible for a significant portion of the impacts of climate change (Raupach, Marland, Ciais, Le Quéré, Canadell, Klepper & Field, 2007). According to Wang (2013), the water sector is not only negatively impacted by climate change, but also exacerbates climate change through the sector's energy use. The links and interdependencies that exist between the energy and water sectors, therefore, result in a complex system that is intertwined with societal and ecological systems.

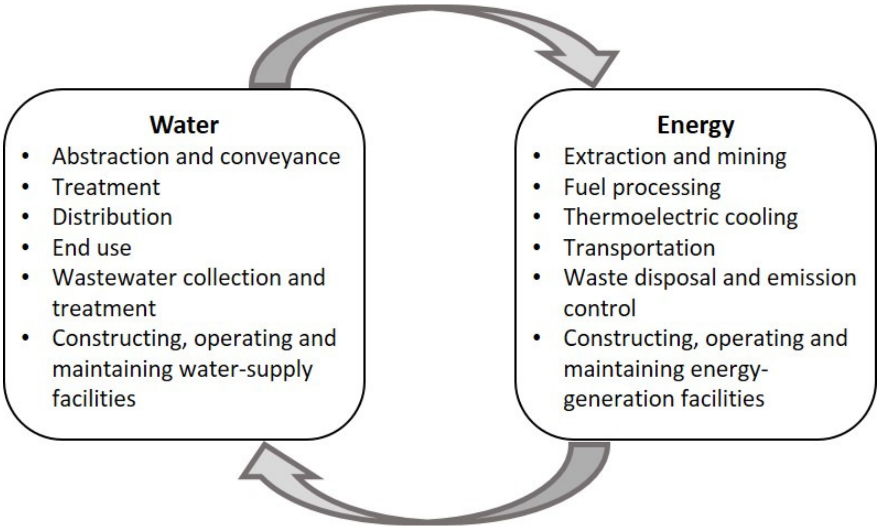

Figure 1.1: Schematic illustration of the energy-water nexus (Wang, 2013)

The energy sector is highly dependent on water for electricity generation (Marsh, 2008). Large volumes of cooling water are required for thermoelectric power plants, small amounts of which are lost due to evaporation (Bazilian, Rogner, Howells, Hermann, Arent, Gielen, Steduto, Mueller, Komor, Tol & Yumkella, 2011). It was estimated that, in 2005, 41% of freshwater withdrawals in the United States of America (USA) were for the cooling of thermoelectric power plants (Macknick, Newmark, Heath & Hallett, 2012). According to Macknick et al. (2012), the water consumption of thermoelectric power plants is highly dependent on the cooling system employed and the two main types of cooling technologies used are once-through technologies and tower technologies.

The difference between water withdrawal and water consumption must be noted. Withdrawal is the amount of water diverted from a water source for use, but is not necessarily consumed, and consumption is the amount of water that is evaporated or otherwise removed from the immediate water environment (Macknick et al., 2012). Cooling towers are used to recycle water and have a higher consumptive use because more water is lost to evaporation, but withdraw less water (Macknick et al., 2012). Whereas, in a once-through cooling system the water from a nearby water source is used only once and then returned to the source. These systems, therefore, withdraw up to 100 times more water than tower systems, but the evaporation at the site is lower (Macknick et al., 2012). The added heat to the water source, however, results in increased evaporation downstream, which adds to the overall evaporation caused by the cooling technology (Torcellini, Long, Judkoff & others, 2003). Therefore, both technology types consume considerable amounts of water.

Hydroelectric power plants withdraw significant amounts of water for electricity generation, but the water consumption during the electricity generation process is negligible because the water which flows through the turbines is returned to the water source and is immediately available for other use (Macknick et al., 2012). However, the increased surface area of the reservoirs required for these hydroelectric power plants does result in increased water evaporation (Torcellini et al., 2003). Macknick et al. (2012) allocates all reservoir evaporation to power production, and therefore includes reservoir evaporation in the total water consumption of hydroelectric power plants. Other power generation technologies also consume significant amounts of water primarily for cooling purposes, including nuclear and concentrated solar power (CSP) technologies (Macknick et al., 2012). Only photovoltaic (PV) solar energy and wind energy consume negligible amounts of water (Macknick et al., 2012). Table 1.1 compares the water consumption of various power generation technologies.

Table 1.1: Water consumption of various power generation technologies (Macknick et al., 2012)

Fuel source	Water cooling method	Water consumption (kL/kWh)
Coal	Tower	1820 – 4160
	Once-through	380 – 1200
Nuclear	Tower	2200 – 3200
	Once through	76 – 380
Hydropower	Once-through	5400 – 68000
CSP – trough	Tower	2750 – 4200
PV	N/A	0 – 20
Wind	N/A	0 – 6

The water sector does not appear to be a significant energy user as it is estimated that the treatment and pumping of water for residential, commercial and industrial use is only between 2% and 3% of the world's energy consumption[1] (Segrave & Pronk, 2007). However, the operation of the water sector is dependent on the energy sector, without which water distribution would cease. The water sector should therefore be considered a priority energy user that requires consideration. Furthermore, the effect of the water sector's energy use is important to consider because this energy use contributes to climate change (Wang, 2013). The energy consumption within the water sector is highly dependent on the water treatment method used. Abstraction, conveyance and distribution of water also adds to the water sector's energy consumption (Bazilian et al., 2011). Desalination, which is the technology being investigated, is energy intensive when compared to alternative water treatment technologies, and seawater desalination specifically is the most energy intensive when compared to other water treatment technologies. Table 1.2 illustrates this.

Table 1.2: Energy consumption of various water treatment options (Marsh, 2008)

Water treatment option	Energy consumption (kWh/kL)
Conventional water treatment	0.1 – 0.6
Conventional wastewater treatment	0.4 – 0.5
Brackish water desalination	0.7 – 1.2
Advanced wastewater treatment	0.8 – 1.5
Seawater desalination	3.0 – 5.0

These linkages and interdependence between the water and energy sectors mean that a shortage of one resource could potentially trigger shortages of the other. If, for instance, a drought occurs it could result in a shortage of water available for power generation. Another example that illustrates

[1] The transport sector consumes about 27% and industry consumes about 28% of the world's energy (World Energy Council, 2016)

these interdependencies is that in the event that electricity prices should increase, the cost of producing potable water increases. Furthermore, if an energy crisis occurs and the electricity supply is insufficient to meet the electricity demand, water treatment would also be affected (Marsh, 2008; Gober, 2010; Bazilian et al., 2011). Gober (2010) uses the Hoover Dam in the USA as an example of how a water shortage can affect both the water and energy sectors. In 2010 the lowered water levels behind the Hoover Dam meant that Las Vegas was at risk of losing a large portion of its drinking water and at the same time Los Angeles would lose a major power source because the hydroelectric turbines at the Hoover Dam would have to shut down as a result of the water shortage.

It is important to understand the linkages and interdependencies between the energy and water sectors when developing and implementing policies affecting the water and energy sectors. Incomplete, inaccurate or misrepresented information about these interdependencies can mean that policies designed to improve one sector could potentially have an adverse effect or unintended consequence on the other (Hussey & Pittock, 2012). Negative trade-offs in the energy-water nexus may be unavoidable, but a thorough study of the interdependencies between the energy and water sectors will enable the making of informed decisions, which integrate the sectors (Hussey & Pittock, 2012; Gulati, Jacobs, Jooste, Naidoo & Fakir, 2013).

1.2 The South African context

1.2.1 The water sector

South Africa is a water scarce country, with an average annual rainfall of 464 mm, which is significantly lower than the global average of 860 mm (Brand South Africa, 2017). The country is facing numerous water challenges, including security of supply, resource pollution and environmental degradation (Department of Water Affairs, 2013)[2]. According to the Department of Water Affairs (2013), the growing economy and social development are engendering a growing water demand. Water security is crucial to economic growth and national planning initiatives, including agricultural development, mining and industry (Department of Water Affairs, 2013). The country is approaching full utilisation of available surface water yields, with limited suitable sites available for new dams, and a mix of water resources will be needed to reconcile future demand and supply (Department of Water Affairs, 2013).

The national water consumption for 2012 was estimated to be 9 748 million m^3/year (Department of Water Affairs, 2013). Water consumption in the domestic sector increased from 22% to 27% of total water use from 2002 to 2012 and total water demand is expected to increase by 1.2% each year between 2012 and 2022 (Department of Water Affairs, 2013). This would result in a total water consumption of approximately 10 980 million m^3/year by 2022. Under-investment has resulted in backlogs in the rehabilitation and maintenance of water resource infrastructure, which are causing a reduction in the available water supply, as well as resulting in major water losses, mainly due to

[2] In recent years, the Department of Water and Sanitation has undergone two name changes. In 2009, it was changed from the Department of Water Affairs and Forestry to the Department of Water Affairs and in 2014 it was changed to the current name, the Department of Water and Sanitation. In the text, the departmental structure will be referred to by the name that was in use when the document being referred to was published.

leakages (Department of Water Affairs, 2013). South Africa's high levels of water wastage and inefficient use is another problem that must be addressed. Lack of maintenance and poor water management results in an average of 37% of the total water supply being classified as non-revenue water[3], with an estimated loss of up to 60% in some areas (Department of Water Affairs, 2013). The average amount of water classified as non-revenue water is therefore equal to 3 607 million m^3/year. This is enough water to supply approximately 39.5 million households for a year, if the typical household consumption of 250 L/day is used (Statistics South Africa, 2010).

Water scarcity is further exacerbated by climate change, which is affecting rainfall and temperature and thereby decreasing water supply (Gulati et al., 2013). Starting in 2015, large parts of South Africa were experiencing drought conditions, with eight out of nine province's being declared disaster areas by June 2016 (Department of Cooperative Governance & Traditional Affairs, 2016). The drought had a measurable impact on cereal production in South Africa. A significant reduction in annual maize production resulted in the maize prices reaching record highs in 2016 (Food & Agriculture Organisation of the United Nations, 2017). In 2017, most of the country's drought conditions have been relieved, but the Western Cape Province is still a disaster area due to poor rainfall during 2016 (Western Cape Government, 2017a).

1.2.2 The electricity sector

It has already been stated that only the electricity sector, and not the entire energy sector, were considered for this research. It is for this reason that only the electricity sector will be discussed. In 2008, South Africa suffered an electricity crisis, which led to the implementation of load shedding[4] across the country (Inglesi, 2010). Load shedding was again implemented in 2015. Eskom, the state-owned electricity supplier in South Africa, lacked the capacity to generate and reticulate enough electricity to meet the South African demand in both the instances mentioned above (Eskom, 2017a). It has been argued that lack of research and planning had led to Eskom's inability to meet the electricity demand (Inglesi, 2010). The situation improved in 2016 when load shedding was no longer necessary. Eskom claims this is because improved generation performance has increased generation capacity (Eskom, 2016b). Others argue the lack of load shedding is due to a lowered electricity demand caused by a decline in the mining and industrial sectors (Naidoo, 2016). Electricity costs have also risen in recent years with the national energy regulator approving year-on-year energy tariff increases of 25% between 2010 and 2013 and a further average increase of 8% up to 2018, which impacts all economic sectors, including the water sector (Baker, Newell & Phillips, 2014).

Whilst Eskom is aiming to increase its electricity supply capacity by building more coal-fired power stations, other initiatives are focusing on increasing electricity generation capacity through renewable energy (Walwyn & Brent, 2015). One example of an alternative initiative that is being implemented is the Renewable Energy Independent Power Producers Procurement Programme

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[3] Non-revenue water incorporates the following items: unbilled authorised consumption; commercial losses; and physical leaks (Mckensie, Siqalaba & Wegelin, 2012).

[4] Load shedding is the management of electricity demand through planned shutdowns of electrical power in areas across the country to protect the electricity power system from a complete blackout (Eskom, 2017a).

(REI4P), which aims to install 17.88 GW of electricity generation capacity from renewables between 2012 and 2030 (Walwyn & Brent, 2015). Despite the planned expansion of the country's renewable energy generation capacity, it is expected that coal-fired power stations, which have an average water consumption of 1.32 L/kWh, will remain the dominant electricity generation facilities for the next 15 to 20 years (Department of Energy, 2016; Eskom, 2017b). Eskom accounts for approximately 1.5% of the country's total water consumption and the energy sector is given the fourth highest water allocation priority (Department of Water Affairs, 2013; Eskom, 2017b). Conversely, the water sector is dependent on a constant and reliable electricity supply to treat and transfer water (Department of Water Affairs, 2013).

1.3 The Western Cape Province context

Climate projections for the Western Cape Province predict higher mean annual temperatures and general drying as a result of lower average annual rainfall and increased evaporation due to higher temperatures (Western Cape Government, 2014). Furthermore, these projections show that the frequency and magnitude of extreme events, such as droughts and flooding, will increase in the Western Cape Province (Western Cape Government, 2014). The Western Cape Province's agriculture sector, which is the third largest contributor to the province's GDP, is particularly vulnerable to climate change because of the effects of climate change on water availability (Western Cape Government, 2014).

The Western Cape Province is mainly dependent on surface water for water supply (Department of Water Affairs, 2013). It is because of this dependence on surface water that climate change will have a severe impact on the Western Cape Province's surface water supply. As temperatures increase and rainfall decreases, runoff[5] into dams and rivers will also decrease, resulting in lower dam levels (Department of Water Affairs, 2013). The Western Cape Province's total dam capacity is 1 867 million m^3 (Department of Water & Sanitation, 2017).

A large portion of the Western Cape Province's water resources are managed by the Western Cape Water Supply System (WCWSS), which mainly supplies to the City of Cape Town and its surroundings. The Department of Water & Sanitation (2016) reports that the WCWSS has a yield of 570 million m^3/a. It was determined that the total water consumption from the WCWSS in 2014/2015 was 547 million m^3/a (Department of Water & Sanitation, 2016). The Department of Water & Sanitation (2016) predicts that the water demand from the WCWSS will exceed the system's yield by 2018, if no intervention is made and the effect of climate change is not taken into account. In an effort to manage water demand, the Department of Water Affairs restricted the water use of the agricultural sector and implemented the Water Conservation/Water Demand Management (WC/WDM) programme as part of the WCWSS Reconciliation Strategy. WC/WDM aims to reduce non-revenue water by installing new water meters, water efficient fittings and implementing leakage detection and repair, as well as reduce wastage by consumers through user education (Department of Water & Sanitation, 2016). Additional strict water restrictions for various

[5] Runoff is the water from rain that did not absorb into the soil or evaporate, and flows into places that collect water, such as dams and rivers.

sectors have been implemented by the Western Cape Government because of the drought that continues to affect the Western Cape Province and is resulting in a rapid decrease dam levels (Western Cape Government, 2017a).

As of 2016, all WCWSS supply-side interventions are still in the feasibility study phase (Department of Water & Sanitation, 2016). This includes the possibility of investing in aquifers to increase groundwater supply and the implementation of seawater desalination (Department of Water & Sanitation, 2016). Due to the increasing scarcity of surface water and growing population of Cape Town, desalination has been investigated as an alternative water resource since as early as 2005 (City of Cape Town, 2005). It is, however, a concern that an energy intensive process such as seawater desalination will place strain on South Africa’s, and more specifically the Western Cape Province’s energy sector.

Most of the Western Cape Province’s electricity is purchased from Eskom. The Eskom owned Koeberg Nuclear Power Station is the largest electricity generator in the Western Cape Province and a significant portion of the Western Cape Province’s electricity is generated there (Western Cape Government, 2007; Department of Water & Sanitation, 2016). This is supplemented by electricity generated by a number of small gas power plants and pumped storage schemes. A substantial amount of electricity, however, needs to be imported from other provinces, most of which is from coal-fired power stations. The Western Cape Province is, therefore, highly dependent on Eskom and other provinces for secure power supply (Western Cape Government, 2007).

In 2013, the Western Cape Government implemented the Green is Smart Green Economy Framework. The aim of this framework is to implement policies which promote inclusive and sustainable economic growth (Western Cape Government, 2015). In 2014, it was reported that the expected average economic growth rate for the Western Cape Province between 2014 and 2019 was 3% (Western Cape Government Provincial Treasury, 2014). According to the same report, the Western Cape Province’s economy is showing signs of the “middle income trap”, including low investments and slow growth in the secondary sectors (Western Cape Government Provincial Treasury, 2014). The middle income trap refers to a middle-income economy that is struggling to achieve high-income status and has a GDP growth rate that is slowing down (The World Bank, 2017). Energy supply insecurity is one of the constraints on local economic development in the Western Cape Province and must therefore be addressed in order to increase the GDP growth rate (Western Cape Government, 2015). Among other things, the Western Cape Government wants to use the Green is Smart Green Economy Framework to respond to energy security needs by installing sustainable technologies that stimulate the creation of local jobs (Western Cape Government, 2015). The framework also addresses the need for better water management to support growth and development in economic sectors, especially in the agriculture sector (Western Cape Government, 2015).

Additional water supply is required in the Western Cape Province to ensure future water demand can be met and to support economic growth. Seawater desalination is one possible option and will be the focus of this study.

1.4 Desalination

Many drought-prone countries have strained freshwater resources, and unsustainable levels of freshwater exploitation, and are therefore considering desalination as a means to provide freshwater in the future (Ostergaard, Lund & Mathiesen, 2014). This will, however, have an impact on the energy sector of a country due to the significant energy demands associated with desalination. According to the International Renewable Energy Agency or IRENA (2015) water shortages in the Middle East and Northern Africa, which is one of the most water scarce regions in the world, will be met mostly through desalination by 2050.

However, from an economic and environmental perspective, desalination will not be sustainable using fossil fuels and therefore the energy demands of desalination plants may need to be met using renewable energy (IRENA, 2015). Fossil fuels are a finite resource and their use for desalination will exacerbate environmental pollution problems and climate change because the combustion of fossil fuels emit large amounts of greenhouse gases (Ayoub & Malaeb, 2012). Solar desalination systems, as a possible solution, are the most suitable for use in arid and semi-arid areas where there is a combination of ample sunshine and freshwater scarcity (Ayoub & Malaeb, 2012). Saudi Arabia already announced its Initiative for Solar Water Desalination in 2010 (IRENA, 2015). Alternatively, wind energy can be used to generate the electricity required for desalination (Ayoub & Malaeb, 2012).

IRENA (2015), however, states that not only must the associated energy demand of the expansion of desalination be considered, but the social, economic and environmental impact must also be considered.

1.5 Problem statement

The Western Cape Province of South Africa is in need of a solution to the water scarcity in the province. Solutions, such as desalination as a source of freshwater, that have successfully addressed similar challenges in other areas of the world, should be investigated within the context of the Western Cape Province. The water and energy sectors, as well as the effect of desalination technology systems on these sectors, have been researched separately in the past. Comparatively, very little research has been done regarding the energy-water nexus, especially in the Western Cape Province.

This research aims to investigate the appropriateness of desalination used in conjunction with renewable energy, such as solar power, as a possible solution to the freshwater scarcity in the Western Cape Province. The sustainability of this technology and its effect on the energy-water nexus and the economy of the Western Cape Province is unknown. This, therefore, needs to be evaluated.

1.6 Research objectives

The aim of the research effort is to compare the sustainability of different desalination technology systems in the context of the Western Cape Province's economy, and specifically to understand the implications of such a desalination technology system for the energy-water nexus of the Western

Cape Province, as well as to determine the investment required to install and operate such a system. This aim of the research effort will be supported by:

i. Selecting an appropriate modelling approach for the research problem;
ii. Compiling, verifying and validating an appropriate model;
iii. Simulating scenarios for the Western Cape Province, with and without the technology; and
iv. Reaching conclusions on the sustainability of desalination technology and making recommendations to policymakers.

1.7 Research design

The purpose of this research was to investigate the sustainability of a desalination technology system in the Western Cape Province. The investigation took into account the dynamics and prospects of the desalination system in the context of the Western Cape Province energy-water nexus. The aim of the research design was, thus, to develop a research strategy that supports coherency and congruency between the real-world problem and the sustainability assessment.

According to Decker & Fleischer (2010), the sustainability assessment of a technology system is generally classified as problem-orientated and therefore requires a multi-disciplinary approach. Sustainability assessments must provide decision-makers with short- and long-term perspectives on the integrated social, environmental, and economic systems, and provide an understanding of the problem outside science (Musango, 2012). This requires a complex and multidimensional evaluation (Musango, 2012). The timeframe associated with the impact of technology systems is a number of years, and policymakers require information regarding the potential consequences of introducing a new technology before the technology is implemented. It is, therefore, unrealistic to study these impacts in real-time. The complexity of the system that is being studied results in attempting to replicate this type of system in a laboratory environment as also being unrealistic. Furthermore, the impacts of complex systems cannot easily be measured quantitatively due to the ambiguity and uncertainty associated with complex systems (Glouberman & Zimmerman, 2002).

Wenzel, Senf & Koch (2016) suggested that a qualitative research method could provide researchers with a better understanding of complex phenomena. According to Ali (2014), a multi-field approach that requires both qualitative and quantitative methods is a way of gaining wide perspectives on complex problems. The research study subsequently took a mixed-method design approach, with emphasis on qualitative results.

In order to address the objectives discussed in Section 1.6, both inductive and deductive research strategies were used. The research was deductive because it was informed by literature, and it was inductive because the case of implementing a desalination technology system in the Western Cape Province was investigated. The research strategy used for this study is presented in Figure 1.2.

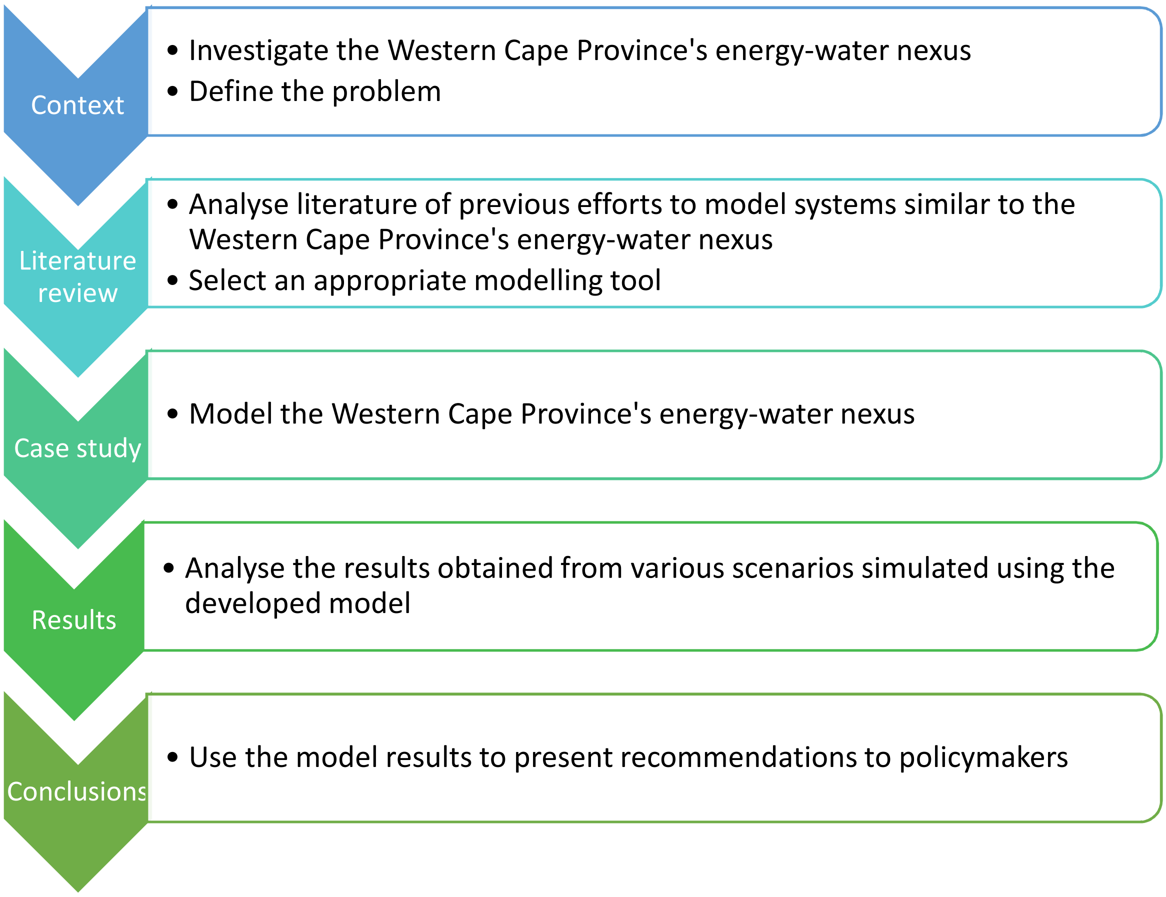

Figure 1.2: Research strategy

1.8 Document outline

This document is intended to present how the primary and secondary objective of this research were completed. An introduction to the research was given in Chapter 1, which provides concise information regarding the background of the study, states the objectives of the study and describes the research design used to complete the study. The background information highlights the importance of considering the entire energy-water nexus when implementing policies in either the energy or the water sector. A brief description of the current situation in South Africa and, more specifically, the Western Cape Province regarding the energy-water nexus is given. Desalination as a technology system that addresses the nexus is also discussed.

In Chapter 2 the context of the problem, the Western Cape Province’s energy-water nexus, is described in further detail to ensure the problem is fully understood and articulated. Some of the main concepts required to understand the problem are discussed, including sustainability and technology assessments, complex systems and systems thinking. Evaluation criteria for selecting an appropriate modelling tool are also divulged in this chapter. Chapter 3 is a review of the modelling tools that have previously been used for applications similar to this study. This review is used to evaluate the different modelling tools using the evaluation criteria discussed in Chapter 2 and, thus, select the modelling tool that is most appropriate for the research problem.

Chapter 4 further describes the selected modelling tool and the required modelling methodology. A description of the steps followed to construct the model of the Western Cape Province's energy-water nexus is provided. The development of the conceptual model is discussed followed by the development of the dynamic model. The results from this model are presented and discussed in Chapter 5. In Chapter 6, conclusions drawn from the results are used to provide recommendations to policymakers regarding the sustainability of desalination in the Western Cape Province. The limitations of the model and recommendations for future research are also discussed.

CHAPTER 2: UNDERSTANDING THE REAL-WORLD PROBLEM

A problem must be fully understood before a possible range of solutions can be developed. Thus, this chapter aims to contextualise the Western Cape Province's energy-water nexus, by investigating the current state of the water and the electricity sectors, respectively. The links, interactions and interdependencies that exist between the two sectors are also investigated and comprehensively defined. The concept of a sustainability- and technology assessment is discussed to provide a deeper understanding of the aim of this research, namely: to investigate the sustainability of a desalination system in the Western Cape Province. In the concluding sections of the chapter, the problem type and required approach is defined and the model functionality that is required from the modelling tool, which will be used in order to address the problem given the context, are divulged.

2.1 The Western Cape Province's Energy-Water Nexus

The aim of this research is to determine the sustainability of a desalination technology system in the context of the Western Cape Province's economy and its impact on the energy-water nexus. For this research, it is important to understand the links and interdependencies that exist between the water and electricity sectors in order to understand the overall nexus. In this section, a brief overview of the Western Cape Province and its water and electricity resources are given and then the links that exist between the sectors are defined.

2.1.1 An overview of the Western Cape Province's economy

The Western Cape Province, one of the nine provinces of South Africa, is located at the most southern point of the country and stretches along parts of the southern and western coast. More than 6.29 million people, which is equal to approximately 11.3% of the national population, live in the Western Cape Province (Western Cape Government, 2017b). Almost two-thirds of the Western Cape Province's population reside in the metropolitan area of South Africa's oldest city, Cape Town, which is also the Western Cape Province's capital city (City of Cape Town, 2012). The Western Cape Province is the province with the second largest inflow of migrants in the country, with an expected inflow of approximately 485 660 between 2016 and 2021 (Statistics South Africa, 2017a). This represents a 7.7% increase in population in a period of five years due to migration alone.

At 14%, the Western Cape Province contributes a significant amount to the South African GDP (Western Cape Government, 2015). In 2015, the agriculture sector contributed a total of R 16 513 million to the provincial GDP, which represents 3.9% of the provincial GDP (Western Cape Government Provincial Treasury, 2017). This makes the agriculture sector the third highest contributor, surpassed only by the manufacturing and construction sectors, which contributed 13.8% and 4.0%, respectively (Western Cape Government Provincial Treasury, 2017). Furthermore, the agriculture sector accounted for 448 233 jobs in the province, which is approximately 8% of the provincial total (Western Cape Government Provincial Treasury, 2017).

The current drought, however, is expected to have a measurable impact on the Western Cape Province's economy, with 94% of companies in the province reporting water shortage as a direct risk to their operation (Western Cape Government Provincial Treasury, 2017). The forecasted GDP growth rate for 2017 is 0.5%, which is significantly lower than the predicted long-term average of 1.8% (Western Cape Government Provincial Treasury, 2017). The agriculture sector is particularly at risk and it has been estimated that the sector's GDP experienced a negative growth of 7.4% in 2016 (Western Cape Government Provincial Treasury, 2017). Forecasts show that this should improve to a positive growth of 5.3% in 2017, but this will largely be due to technical factors rather than the abatement of drought conditions (Western Cape Government Provincial Treasury, 2017).

As discussed in Chapter 1, the Western Cape Government implemented the Green is Smart Green Economy Framework with the aim of implementing policies which promote inclusive and sustainable economic growth (Western Cape Government, 2015). The Western Cape Government has identified two economic sectors that offer opportunities to stimulate investment and inclusivity. The first sector is the energy sector. Energy security is required to promote economic growth and the Green is Smart Green Economy framework aims to respond to energy security needs by installing sustainable technologies that stimulate the creation of local jobs (Western Cape Government, 2015). The second sector is the agriculture sector, which has the potential to grow through the adoption of sustainable practises, such as improvements in energy efficiency and the treatment and re-use of water (Western Cape Government, 2015). The framework also addresses the need for better water management to support growth and development in economic sectors, especially in the agriculture sector (Western Cape Government, 2015). Another aim of the framework is to combat climate change and its impacts by reducing the Western Cape Province's carbon footprint through the implementation of more sustainable technologies and practises (Western Cape Government, 2015).

The Western Cape Province's economy is dependent on water to ensure continued growth. From the above discussion, it can be concluded that water security should be a high priority as water shortages, such as the shortages caused by the current drought, not only decrease the economic growth rate, but result in negative growth in sectors that are heavily dependent on water, including the agriculture sector. A decline in these sectors places a number of jobs and the livelihood of members of the population at risk, as well as having a detrimental effect on the Western Cape Province's economy.

2.1.2 The Western Cape Province's water sector

Important facts regarding the Western Cape Province's water sector are discussed in this subsection. The purpose of this subsection is to provide a better understanding of the Western Cape Province's water sector by investigating the main sources of water supply and the drivers of water demand.

Overview

The Western Cape Province has the dry summers and wet winters typical of a Mediterranean climate. The annual average rainfall varies greatly throughout the province. Over parts of the Karoo and the north-west region rainfall is as little as 150 mm per annum, whereas a rainfall of well over 1000 mm per annum can be expected in some of the mountainous regions (Western Cape Department of Agriculture, 2017). As seen in Figure 2.1, the Western Cape Province's water resources are divided into two water management areas, namely the Breede-Gouritz and the Berg-Olifants water management areas (Department of Water Affairs, 2013).

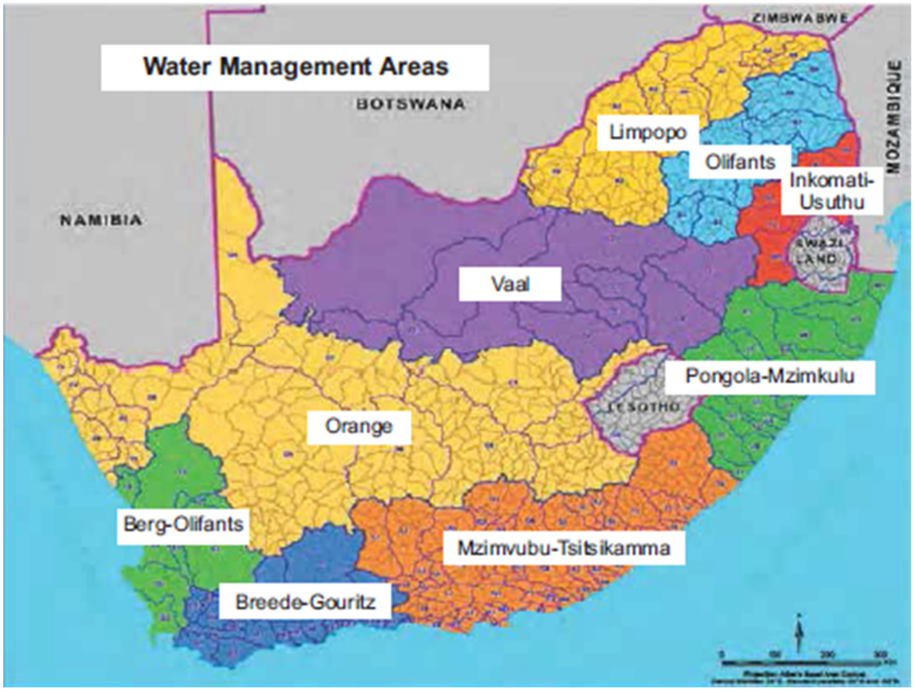

Figure 2.1: South Africa's water management areas (Department of Water Affairs, 2013)

The Western Cape Province is the province with the highest population growth in South Africa due to a high migration rate into the province from other parts of the country. This high migration rate will cause a significant increase in water demand. If the migration inflow is 485 560 between 2016 and 2021, as is predicted by Statistics South Africa (2017a), and it is assumed the average per capita water demand is 320 L/person/day[6], then the water demand will increase by 56.7 million m^3/year by 2021 due to migration alone. The growing economy, which is dependent on water to ensure continued growth, is causing an additional increase in water demand (Western Cape Government, 2015).

While the Western Cape Province's water demand is steadily increasing, the freshwater yield may be reduced due to climate change (Department of Water Affairs, 2013). According to Gulati et al. (2013), climate temperatures in South Africa are expected to rise and consequently higher rates of freshwater evaporation and decreased runoff will result in lower dam levels. The Department of Water Affairs (2011) reports that historical and projected changes in weather patterns suggest that there will be a general decrease in precipitation across the Western Cape Province and that the rainfall season will become shorter. This means that the Western Cape Province will become an increasingly water constrained area. The combination of increasing demand and decreasing supply would most likely lead to water shortages in this area.

[6] The Western Cape Province's total population was 4 524 334 in 2001 and the domestic water demand was 529 000 million L/year in 2000 (Department of Water Affairs & Forestry, 2004; City of Cape Town, 2012). Assuming the domestic water demand remains similar, the per capita water demand can be calculated and is equal to 320 L/person/day.

Water Supply

It was found that data regarding the supply and demand of water in the Western Cape Province is scarce. Two documents that provide information regarding the Western Cape Province's water sector are the *State of the Environment Outlook Report: Inland Water Chapter* by Collins & Herdien (2013) that was written for the Department of Water and Sanitation, and GreenCape's *Market Intelligence Report* (2015) on the water sector. The data provided by these reports were collected in 2012 and 2014, respectively. Although the data from the two reports was not collected at the same point in time, the results from the reports were compared to provide an overview of the Western Cape Province's water supply sources. Figure 2.2 shows the Western Cape Province's water supply sources according to these two reports.

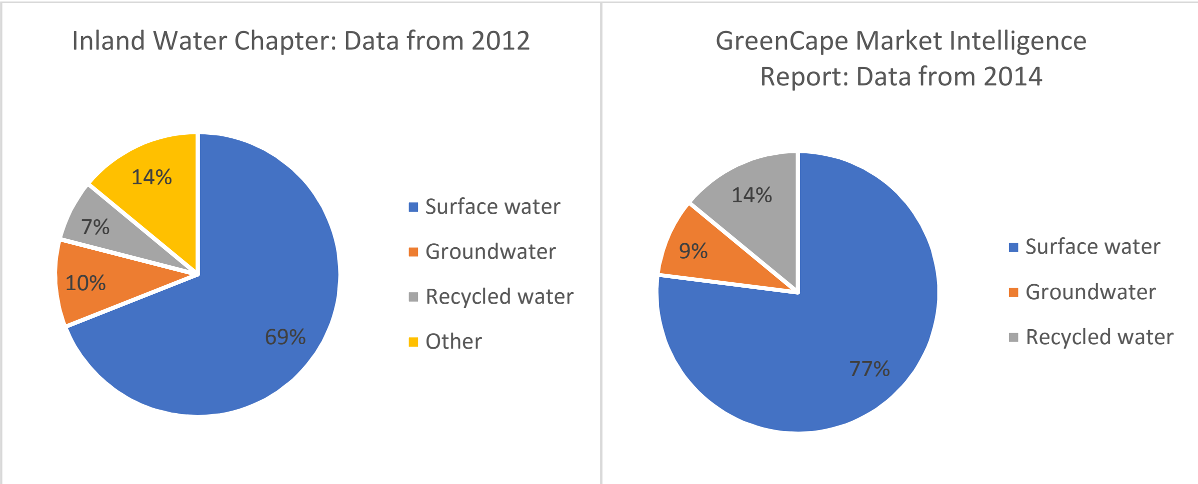

Figure 2.2: The Western Cape Province's water supply sources (Collins & Herdien, 2013; GreenCape, 2015)

It can be seen that uncertainty exists with regard to the exact contributions of the Western Cape Province's different supply sources. However, it is clear that surface water is the Western Cape Province's primary water source with the indices stating that this water source accounts for between 69% and 77% of the Western Cape Province's water. The other two base supplies of the Western Cape Province are groundwater and recycled water. The "other" sources of supply referred to in Figure 2.2 consists of supply water gained from potential afforestation and alien plant removal, water transfers between water management areas, desalinated water and rain water harvesting (Collins & Herdien, 2013).

The surface water resources, for a large proportion of the Western Cape Province, are managed by the Western Cape Water Supply System (WCWSS). The WCWSS consists of a number of dams and conveyance pipelines, which are used to supply freshwater for residential, commercial, industrial and agricultural use (Department of Water & Sanitation, 2016). The Waste Water Treatment Works (WWTW) also form part of the WCWSS. Table 2.1 shows the main surface water sources; the raw[7] water supply dams and their storage capacities. These dams have a total capacity of 839 million m^3 and account for 45% of the WCP's surface water (Department of Water & Sanitation, 2017). The

[7] Raw water refers to untreated water found in the environment, such as dam water, river water and rain water.

total capacity of all the Western Cape Province's dams is 1 867 million m^3 (Department of Water & Sanitation, 2017).

Table 2.1: The storage capacities of the Western Cape Province's major dams (Department of Water & Sanitation, 2016)

Dam	Capacity (million m^3)
Theewaterskloof Dam	432
Voëlvlei Dam	158
Wemmershoek Dam	58
Upper Steenbras Dam	30
Lower Steenbras Dam	34
Berg River Dam	127

The WWTW are used to treat waste water and produce recycled water. This contributes to between 7% and 14% of the Western Cape Province's water supply, as can be seen in Figure 2.2. In 2016, the City of Cape Town only recycled about 5% of used water (City of Cape Town, 2017). Given the current water recycling practices, recycled water is not suitable for drinking and is only used for industrial use and irrigation (City of Cape Town, 2017). To encourage industries to rather use recycled water, recycled water is provided at a lower cost than potable water. The Western Cape Province's current WWTW capacity is 1031 ML/day, and operates at 87% of its capacity, thus allowing for a possible 13% increase in utilisation (GreenCape, 2017).

Approximately 10% of the Western Cape Province's water supply is sourced from groundwater (Collins & Herdien, 2013; GreenCape, 2015). According to the Department of Water Affairs (2013), the Utilisable Groundwater Exploitable Potential (UGEP) of the Western Cape Province is as much as 1049.3 million m^3/annum. However, although it is challenging to accurately determine the properties of the aquifers, estimations show that only a fraction of the UGEP in the Western Cape Province is being exploited (Department of Water Affairs, 2010).

Desalination, which forms part of the "other" sources of water supply referred to in Figure 2.2, is not a major source of water supply in the Western Cape Province. The Western Cape Province's existing desalination plants are operated only when needed because of the high energy demand of these plants (Blersch, 2014). The Western Cape Province's large-scale desalination plants and their capacities are given in Table 2.2.

Table 2.2: Western Cape Province large-scale desalination plants (Blersch, 2014; Veolia, 2017)

Town	Capacity (ML/day)	Year commissioned
Mossel Bay	15	2011
Lamberts Bay	1.7	2014
Sedgefield	2	2009
Saldanha Bay	2.4	2012
Plettenberg Bay	2	2010
Bushman's Mouth	1.8	1982

The Western Cape Province's large-scale desalination plants can thus add a total of 24.9 ML/day of water to the province's water supply system.

Water Demand

The GreenCape (2017) document categorises the Western Cape Province's water demand into five sectors, namely irrigation, livestock, domestic water supply services, commercial and urban-industrial. This can be seen in Figure 2.3. Collins & Herdien (2013) categorises the demand slightly differently. However, it is clear from Figure 2.3 that both reports agree that irrigated agriculture has the largest water demand followed by urban water demand, which is categorised into domestic, commercial and industrial water demand by GreenCape (2015).

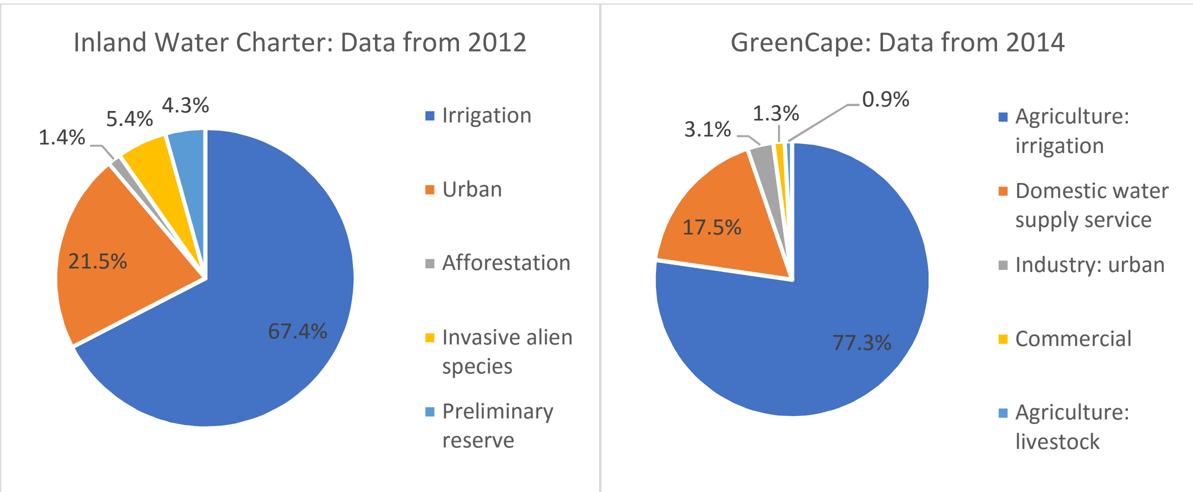

Figure 2.3: Western Cape Province water demand (Collins & Herdien, 2013; GreenCape, 2015)

Each of the sectors have a specific driver which causes the water demand of that sector to increase. The domestic demand increases primarily due to population growth, but can possibly be reduced by factors such as education about water scarcity and water saving practices, as well as water demand management (Department of Water Affairs, 2013). According to Wang, Xu, Yang & Wang (2014), all non-domestic demand, including irrigation, afforestation, mining and bulk industries, increases as there is growth in the economy, and therefore GDP growth, which represents economic growth, is an appropriate driver to use for non-domestic demand.

Uncertainty exists regarding the complex system that is the water sector of the Western Cape Province and data regarding the exact state of the sector is scarce. According to the Department of Water Affairs (2013) and Statistics South Africa (2010), municipalities do not necessarily keep a record of the water that is supplied through them and many reported water sector values are merely estimates.

2.1.3 The Western Cape Province's electricity sector

An overview of the Western Cape Province's electricity sector is given in this subsection. The information is given to provide a better understanding of the operations of the electricity sector, such as the electricity generation methods used and the drivers of electricity supply.

Overview

It is important to consider the fact that South Africa's primary electricity supply is a mandate of the National Government (Western Cape Government, 2007). The Western Cape Province's electricity supply and demand system is not a closed system as not all the electricity generated in the Western Cape Province is used within the province and not all the electricity consumed by the province is generated within its borders (Western Cape Government, 2007). However, for the purpose of this research it was assumed that all the electricity generated within the Western Cape Province is used in the province and therefore no electricity is exported from the province. If additional electricity is required to meet the demand, it is imported from other provinces.

South Africa's growing economy is resulting in energy becoming an increasingly key focus area for national and local governments because the energy sector directly and indirectly contributes approximately 15% to the country's GDP (Moodley & van Weele, 2013). In order to achieve continued economic growth and sustainable development, a transformation of the energy sector is required (Moodley & van Weele, 2013). Substantial investments in the energy sector are needed to ensure security of supply and adequate infrastructure availability to support and facilitate economic development (Western Cape Government, 2015).

Electricity supply

Koeberg Nuclear Power Station is the major generator of the Western Cape Province's electricity supply. This is supplemented by electricity generated by two pumped storage power plants and a number of gas power plants. Recently, renewable energy supply has begun to make a more significant contribution to the electricity grid. The renewable energy supply capacity consists predominantly of wind and solar PV technologies, and these will likely continue to make up the majority of new renewable energy capacity in the next few decades (Moodley & van Weele, 2013). There are no coal-fired power stations within the Western Cape Province, but the majority of electricity supplied to the Western Cape Province from other parts of the country is generated using coal (Western Cape Government, 2007). The National Government's Integrated Resource Plan (IRP) aims to add 17.8 GW of renewable energy capacity by 2030, a large portion of which would be in the Western Cape Province (Department of Energy, 2013). The IRP also suggests that large investments in nuclear and coal energy technologies should be made (Department of Energy, 2013). The Western Cape Government's future energy plans, however, do not fully align with the IRP (Western Cape

Government, 2013a). The Western Cape Government acknowledges the need for investment in renewable energies, but the Western Cape Province's future energy plans suggest investment in natural gas as opposed to nuclear and coal. Investments in natural gas technologies would increase power generating capacity, while still reducing the Western Cape Province's carbon footprint (Western Cape Government, 2013a).

Koeberg consists of two nuclear power reactors with a combined installed capacity of 1800 MW and generates approximately 6% of the national electricity supply. Eskom owns and operates Koeberg (Eskom, 2016a). In 2017, Koeberg is the only nuclear power plant in South Africa. The IRP suggests that large investments in nuclear technologies should be made but, although, the electricity costs of Koeberg are comparable to those of coal-based electricity, the cost of electricity produced by new nuclear power stations would be considerably higher (Department of Energy, 2016).

The gas power stations are not intended to supply base-load power to the grid, and are therefore only operated during times of peak electricity demand. All of South Africa's gas power stations are situated in the Western Cape Province and all operate using Open Cycle Gas Turbine (OCGT) technology. The Roggebaai and Athlone Gas Power Stations, with installed capacities of 40 MW and 36 MW respectively, operate using jet fuel, which is considered a cost intensive fuel compared to other fuels and resources used to generate electricity, and are therefore only used to regulate the load on the electricity grid (Moodley & van Weele, 2013). Acacia power station is primarily used as a back-up power supply to Koeberg and has a total installed capacity of 171 MW (Moodley & van Weele, 2013). Gourikwa power station in Mossel Bay, with an installed capacity of 746 MW, runs on diesel fuel from the nearby PetroSA fuel refinery (Moodley & van Weele, 2013). Ankerlig power station, situated in Atlantis, has a capacity of 1338 MW and runs on diesel fuel sourced from refineries in Milnerton (Moodley & van Weele, 2013). Gourikwa and Ankerlig were constructed in 2007 after the government realised that a power crisis was imminent and were intended to only supply power during peak demand times (Eskom, 2014). South Africa's recent electricity supply crisis[8], however, necessitated that both power stations be used in more of a base-load role up until the start of 2016 (Eskom, 2016b). Both Gourikwa and Ankerlig power stations have the potential to be converted to Combined Cycle Gas Turbine (CCGT) plants (Eskom, 2008a,b). CCGT plants have the same components as OCGT plants, but with the addition of a heat recovery device that uses exhaust heat to generate more electricity, which makes CCGT more energy efficient than OCGT (Chennu, 2016). Furthermore, Gourikwa and Ankerlig power stations can be converted to operate using natural gas instead of diesel fuel (Eskom, 2008a,b).

The Palmiet and Steenbras Pumped Storage Schemes are the only two hydropower projects in the Western Cape Province. Palmiet has an installed capacity of 400 MW and Steenbras has an installed

[8] Since 2007, Eskom has lacked the electricity generation capacity to ensure sufficient electricity supply during peak electricity demand periods, which necessitated the introduction of load shedding in the first quarter of 2008 and again in 2015 (Inglesi, 2010; Eskom, 2016b). The situation improved in 2016 when load shedding was no longer necessary. Eskom claims this is because improved generation performance has increased generation capacity (Eskom, 2016b). Others argue the lack of load shedding is due to a lowered electricity demand caused by a decline in the mining and industrial sectors (Naidoo, 2016).

capacity of 180 MW (Eskom, 2015a, 2017c). Pumped storage schemes do not supply the grid with net power, but rather act as energy storage facilities to provide power at peak electricity demand periods. Water is pumped from a lower reservoir to an upper reservoir using off-peak electricity. This water is then released and run through turbines to generate electricity at peak demand times (Moodley & van Weele, 2013).

The Western Cape Province has high potential for wind energy (Department of Environmental Affairs & Development Planning, 2010). The Department of Environmental Affairs & Development Planning (2010) estimates that 2800 MW capacity from wind power installations can be generated in the Western Cape Province and added to the national grid without any immediate challenges, such as major upgrades to the transmission grid. There are currently a number of large turbine based wind energy facilities within the Western Cape Province; an independent power producer launched the Darling Wind Farm, which has a capacity of 5.2 MW, in 2007 (Moodley & van Weele, 2013), and Eskom's 100 MW capacity Sere Wind Farm Project, which is part of the National Government's IRP, has been fully operation since 2015 (Eskom, 2015b). In recent years, the total installed wind power capacity has significantly increased due to the Renewable Energy Independent Power Producers Procurement Programme (REI4P). The projects that have been commissioned as part of the REI4P and that are fully operational include the 26.6 MW capacity Dassiesklip Wind Energy Facility outside Caledon, the 135.2 MW capacity Gouda Wind Facility, the 65.4 MW capacity Hopefield Wind Farm and the 90.8 MW capacity West Coast 1 facility near Vredenburg. A further three wind energy projects, with a combined capacity of 280 MW, will be commissioned under the REI4P (Energy Project Database, 2017).

A number REI4P solar PV projects have been completed in the Western Cape Province resulting in a current total installed solar PV capacity of approximately 135.15 MW (Energy Project Database, 2017). This is expected to continue to increase significantly in the next few years. The Western Cape Province, like most of South Africa, has a high solar energy resource resulting in a significant potential for solar energy expansion. Concentrated solar power (CSP) plants can be constructed in the northern parts of the country, but the annual solar radiation in the Western Cape Province is too low for CSP and more suited to PV applications, with the exception of very small areas in the province where CSP could be viable (Moodley & van Weele, 2013).

A summary of the various electricity supply sources in the Western Cape Province can be seen in Table 2.3.

Table 2.3: Western Cape Province electricity supply

Source	Capacity (MW)	Supply type
Nuclear	1800	Base-load
Gas power	2331	Peak power
Pumped storage	580	Storage
Wind energy	423.2	Intermittent power
Solar PV	135.15	Intermittent power

Electricity demand

The Western Cape Province's electricity demand accounts for 23.9% of the Western Cape Province's energy use. Other commonly used fuel types are coal, petrol and diesel (Moodley & van Weele, 2013). For the purpose of this research the focus will only be on electricity as a source of energy. The Western Cape Government (2013b) categorises the Western Cape Province's electricity consumption into six sectors, namely residential, commercial, industrial, transport, local government and agricultural. The Western Cape Province's electricity consumption by sector can be seen in Figure 2.4.

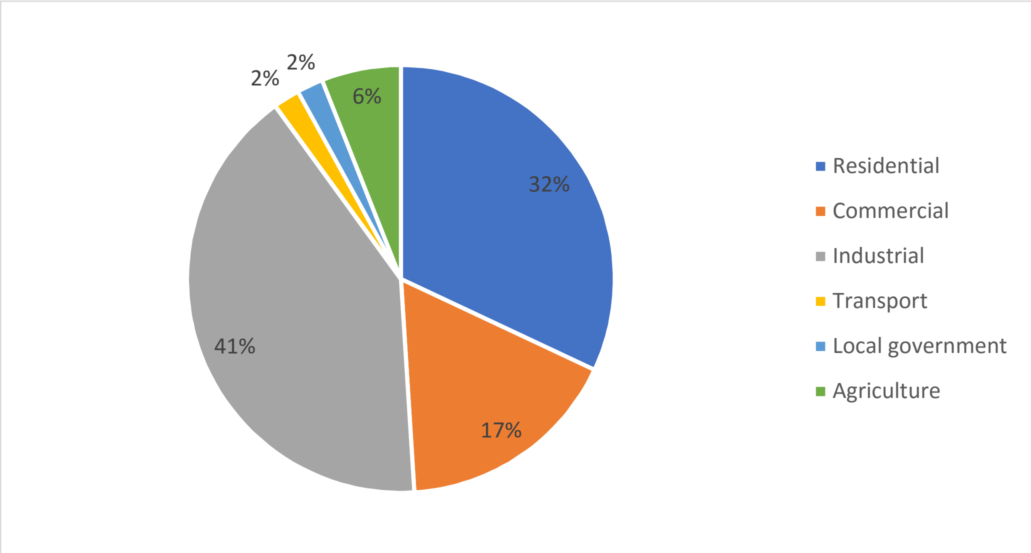

Figure 2.4: Western Cape Province electricity consumption (Western Cape Government, 2013b)

It is clear, from Figure 2.4, that the residential and industrial sectors consume the most electricity. According to Inglesi (2010), the main drivers of electricity demand in South Africa are the population, GDP and electricity price. Residential electricity demand is driven by population, electricity price and personal income (Ziramba, 2008). Data regarding the Western Cape Province's exact electricity demand is scares. Eskom does not release data regarding the electricity generated by each province, but data regarding the electricity supplied to each province is available. Assuming the electricity supplied to each province is equal to the consumption of each province, the Western Cape Province's total electricity consumption was 22 861 GWh in 2015 (Statistics South Africa, 2017b). The electricity demand, which represents the amount of electricity the province desires to use, may, however, be significantly higher than the electricity consumption.

2.1.4 Links between the electricity and water sectors of the Western Cape Province

This section defines the interdependencies and links that exist between the electricity and water sectors that constitute the energy-water nexus in the context of the Western Cape Province. Existing and potential future links are explored.

Electricity use by the water sector

The electricity demand of the water sector is highly dependent on the water supply method used. The methods currently used in the Western Cape Province are not very energy intensive, but given the growing water shortage, alternative, possibly more energy intensive methods such desalination will have to be explored as options for increasing water supply. Employing such energy intensive practices will greatly increase the amount of electricity the Western Cape Province's water sector uses. After thorough research, it was concluded that data with regards to the exact amount of electricity used by the Western Cape Province's water sector has not been recorded. According to Western Cape Government (2013b), 2% of the Western Cape Province's total electricity consumption is used by the local government, and in turn 23% of this is used for water and waste water treatment. This means that only 0.46% of the Western Cape Province's total electricity consumption is currently used for water treatment. This percentage, however, is determined using estimates supplied by municipalities and is therefore inaccurate. For this reason, the energy intensity of each water supply method that was used in the development of the energy-water model was determined using typical values from literature.

Water use by the electricity sector

The electricity sector mainly uses water for cooling. The amount of water consumed is highly dependent on the electricity generation technology type and the cooling method used. According to Statistics South Africa (2010), the water used for electricity generation in the Western Cape Province is zero.

Nuclear power stations require large amounts of water for cooling, but, according to Eskom, the Koeberg Nuclear Power Station is a strategic water consumer that uses no freshwater. Instead, seawater is used to cool the condensers and then returned to the ocean after use (Eskom, 2016a).

The gas power stations are OCGTs, which use zero water for electricity generation. Freshwater is only used for cleaning the turbines. The Gourikwa power station consumes 30kL of potable water per month, which is approximately 0.04 kL/MW of installed capacity (The Environmental Partnership, 2005). The water consumption of the other gas power stations is similar because the same technology is used. This water consumption is almost negligible, but was included in the model to improve accuracy.

The water consumed by hydropower plants is the water lost due to reservoir evaporation. In the Western Cape Province, the pumped storage schemes make use of the Palmiet and Steenbras dams. These dams are used for water supply and evaporation would occur regardless of whether the dams are used for pumped storage or not. The pumped storage schemes do not cause additional evaporation and therefore it is assumed that the water consumption of these schemes is zero. Wind energy and PV solar energy consume negligible amounts of water.

The water consumed for electricity generation in the Western Cape Province is almost negligible because the technologies currently being used consume little or no freshwater. The Western Cape Province does, however, import a large portion of the electricity the province consumes. Most of this electricity is generated using coal-fired power stations, which require large amounts of freshwater. Eskom's specific water use for electricity generation ranges from 1.26 L/kWh to 1.32 L/kWh for 2001 to 2006 (Eskom, 2017b). This is mainly used for coal-fired power stations. Although the impact of the Western Cape Province's electricity sector on the province's water sector is almost negligible, it has an impact on South Africa's water sector and must therefore be taken into account.

Future opportunities and potential problems

The Western Cape Government has a number of water supply projects that are in the feasibility study phase. The projects include increasing the amount of waste water that is treated for reuse, the desalination of seawater and the development of a number of aquifers to increase groundwater supply. These feasibility studies were identified and deemed necessary in the 2007 Reconciliation Strategy Study, but had not been concluded by 2016 (Department of Water & Sanitation, 2016). However, it is safe to assume that additional waste water treatment and seawater desalination could significantly increase the electricity consumed for water supply because both supply methods are energy intensive.

GreenCape (2017) identified some of the main links between the water and electricity sectors of the Western Cape Province, as well as some of the possible opportunities in the nexus. The energy efficiency of waste water treatment could be improved and there is growing development in large-scale solar powered desalination. This would reduce the impact these two water supply methods would have on the electricity sector. Some of the other opportunities identified by GreenCape (2017), are the potential of bioenergy in waste water and the generation of energy within water conveyance systems. The exploitation of these opportunities would mean that the water sector could positively impact the electricity sector by increasing the Western Cape Province's electricity generation capacity.

The Western Cape Government has increased the Western Cape Province's electricity supply through renewable energy such as wind power and solar PV, and plans to increase the Western Cape Province's renewable energy capacity in the future (Western Cape Government, 2007). Increasing the Western Cape Province's electricity generation capacity with renewable energy systems will improve the province's energy security by reducing the province's dependence on imported electricity without significantly impacting the water sector. Eskom has investigated the possibility of converting the Gourikwa and Ankerlig gas power stations from OCGT to CCGT (Eskom, 2008a,b). The conversions would make the power stations more efficient, but CCGTs require large amounts of water for power generation. Consequently, the conversions will significantly increase the water consumption of the gas power stations.

2.2 Sustainability and technology assessment

A sustainability assessment provides decision-makers with short- and long-term perspectives on the integrated social, environmental and economic systems. The aim of this is not necessarily to find an optimal solution, but to provide guidance regarding the policies that intend to achieve sustainable development goals (Musango, 2012).

In order to determine the sustainability of a technology system a technology assessment must be performed. There have been many different definitions of technology assessment over the years, but it is only recently that it has been recognized that technology systems are a part of broader socio-ecological systems (Musango, 2012). The conceptual framework used for technology assessment must therefore be defined by the three dimensions of sustainability, namely the social, ecological and economic dimensions (Assefa & Frostell, 2006). Technology assessment was redefined as "*the evaluation of an object, function, or sequence of functions – created by human society to assist in achieving a goal – with respect to sustainability in comparison of other solutions providing the same function(s)*" (Assefa & Frostell, 2006).

2.3 Conclusion: A systems thinking approach

In the previous sections, a deeper understanding of the Western Cape Province's energy-water nexus was gained, and the purpose of a sustainability and technology assessment was discussed. The problem type and required approach can be divulged from this information. This is discussed in the following subsection. Lastly, knowledge of the problem and the approach it requires were used to determine a set of evaluation criteria that were used to select an appropriate modelling tool for modelling the Western Cape Province's energy-water nexus.

2.3.1 Complex systems and systems thinking

Glouberman & Zimmerman (2002) identify and describe three types of problems: simple, complicated and complex. Simple problems involve basic techniques and terminology. Once these are understood they are easy to follow and ensure a high success rate. Complicated problems are large scale problems and require a greater degree of expertise and coordination to solve than simple problems, but once a success has been achieved the steps followed can be repeated and a relatively high success rate can be expected. Complex problems contain subsets of simple and complicated problems, but can't be reduced to either. Complex systems consist of a number of subsystems and each subsystem consists of interacting adaptive components. Complex systems have a degree of uncertainty and ambiguity associated with them. For this reason, formulae have a limited application and the unique local conditions and interdependencies must be understood as well as their non-linearity.

Complex systems theory can be used to represent real-life systems because it studies the many interactions between the various subsystems and the components within the subsystems (Glouberman & Zimmerman, 2002). The Western Cape Province's energy-water nexus can therefore be described as a complex system because of the many subsystems involved including the social, economic and environmental aspects of the water and energy sectors.

According to Aronson (1996) systems thinking studies the interaction between the constituents within a system. Therefore, instead of studying smaller and smaller parts of the system, as is done in traditional analysis, systems thinking expands its view to consider an increasing number of interactions. When the problem that is being analysed is dynamically complex or contains a large amount of feedback, very different conclusions can be drawn from using systems thinking than if a more traditional analysis was performed.

Aronson (1996) lists a number of areas where systems thinking has proven to be effective. Systems thinking can be useful when applied to complex problems so that the entirety of the problem can be understood. It can be used to address problems that affect or are affected by the surrounding environment, whether it's the natural environment or a competitive environment. Lastly, systems thinking can be used when the solution to a problem is not obvious. The energy-water nexus falls within all of these areas, therefore a systems thinking approach is considered applicable to the concerned problem and context of this research inquiry.

Maani & Cavana (2007) suggest seven principles, which are required for systems thinking:

i. Having a holistic view of the situation;
ii. Recognising that both the short-term and long-term perspectives are important and finding a balance between the two;
iii. Taking quantitative and qualitative factors into account;
iv. Realising when the system itself is the cause of the problem;
v. Knowing that cause and effect are not necessarily close in time or space;
vi. Distinguishing between causes and symptoms; and
vii. Using either-or thinking.

Systems thinking, in contrast to linear thinking, recognises that factors are not necessarily independent, causality does not always run one way from cause to effect, and all factors are not necessarily equally important as some have a larger impact on the overall system than others (Maani & Maharaj, 2004).

2.3.2 Model requirements

In the previous subsection, the Western Cape Province's energy-water nexus is defined as a complex system and must therefore be approached using systems thinking. Some of the requirements for the model type that will be used to model the energy-water nexus can be obtained from the systems thinking principles. In addition, the objectives of the model determine the model criteria. The model will need to be able to represent the social, economic and environmental dimensions of the nexus. Since the model will be used for policy making it needs to be transparent to stakeholders and be able to forecast the impact of different scenarios. The evaluation criteria that will be used to select a model type are as follows:

i. Dynamic i.e. indication of behaviour over time;
ii. Quantitative and qualitative modelling;
iii. Transparent and understandable to stakeholders;
iv. Represent the feedback loops within the system;
v. Represent the entire complex system; and
vi. Used to perform medium- to long-term scenario analyses.

This set of evaluation criteria will be used to compare modelling tools that have previously been used for applications similar to the Western Cape Province's energy-water nexus. A review of these efforts is discussed in the next chapter.

CHAPTER 3: MODELLING TOOL SELECTION

The aim of this chapter is to provide a review of the literature that was consulted during the process of selecting an appropriate modelling tool for the Western Cape Province's energy-water nexus. A review of the modelling tools that have been used in the past for applications similar to the energy-water nexus is given. Subsequently, the various modelling tools are compared, given the requirements set out in Section 2.3.2, in order to select the most appropriate tool for this study.

3.1 Literature analysis methodology

A narrative literature review method was used to understand previous efforts that have been made to model systems similar to the Western Cape Province's energy-water nexus. Green, Johnson & Adams (2006) defines narrative literature overviews as "*comprehensive narrative syntheses of previously published information*". A summary of the contents of each article that was selected is generally provided in this type of review method. The advantage of using a narrative review method is that many pieces of information can be consolidated into one document or format, and a broad perspective of the topic can be presented (Green et al., 2006). A summary of a single article, however, may not be sufficient to comprehensively understand a certain tool or methodology as the authors may not have offered such a comprehensive explanation of the tool or methodology. Therefore, additional literature sources were consulted to provide a better understanding of the different modelling tools and methodologies. A drawback of the narrative review method is that the author of the review chooses what information to include, which may result in a biased article (Green et al., 2006).

A systematic search of online literature databases, to which Stellenbosch University subscribes to, was conducted. These include Science Direct, Wiley Online Library, Scopus and ISI Web of Science. Various combinations of the search terms, as shown in Table 3.1, were used.

Table 3.1: Search terms used to conduct the literature review

systems thinking	complex thinking	water
energy	resource	sector
management	energy-water nexus	renewable energy
complex system	desalination	sustainability assessment
technology assessment	modelling approach	modelling methodology
policy making	policy analysis	decision making

The search yielded a large number of papers and journal articles. According to Green et al. (2006), the selection criteria used to include or exclude a study from the review is important to keep the review focussed. The main selection criteria used for deciding whether or not a source should be used was the type of source. Cronin, Ryan & Coughlan (2008) list three types of sources, namely: primary sources, which are usually reports by the original researchers; secondary sources, which are descriptions or summaries by someone other than the original researchers, i.e. a review article; and conceptual/theoretical sources, which are papers concerned with the description of theories associated with the topic. For this review, mainly primary sources were used, but secondary sources were also considered.

3.2 A review of previously used modelling tools and approaches

The search of the available literature yielded a number of studies that aimed to provide policymakers and stakeholders with decision support with regards to water resource management and the implementation of interventions within the water and energy sectors. A review of the previous efforts to model systems similar to the Western Cape Province’s energy-water nexus is provided in this section. The review is presented as summaries of the previous work done by researchers in this field.

3.2.1 The MULINO project

The ‘Multi-sectoral, integrated and operational decision support system for sustainable use of water resources at the catchment scale’ (MULINO) project was financed by the European Commission. The goal of the project was to design a decision support system (DSS) software, called mDSS, which could be used for the sustainable management of water resources at catchment scale (Giupponi, Mysiak, Fassio & Cogan, 2004). Mysiak, Giupponi & Rosato (2005) found that although a high number of DSS programs had already been developed, the risk of these systems failing to address real-life problems was high. One of the main objectives of MULINO was to ensure mDSS could address the complex decision-making challenges dealt with in water resource management (Mysiak et al., 2005).

During the development of mDSS, future users were constantly involved and made valuable contributions to the design of the software to ensure its future success (Mysiak et al., 2005). mDSS was also designed to meet the requirements of the Water Framework Directive, which is a legislative framework for water resource management in the European Union (EU) that had been approved in the early 2000s (Mysiak et al., 2005). The directive set a number of environmental objectives for water systems that had to be met by 2015 (Mysiak et al., 2005).

The Driving force-Pressure-State-Impact-Response framework (DPSIR) was used for the structure of mDSS (Giupponi et al., 2004). The framework identifies the main driving force of the system under consideration and the pressures placed on the system (Giupponi et al., 2004). Certain indicators are used to assess the state of the system. The impact of the driving force is then evaluated and, lastly, possible responses are evaluated to determine what the best course of action would be if any action is needed (Giupponi et al., 2004). The DPSIR framework aims to illustrate the cause-effect relationship between the interacting components of the environment, economic and social systems (Giupponi et al., 2004).

The two main mechanisms used for mDSS were existing hydrological models (for the simulation of water flows in the catchment area), and decision support algorithms (Giupponi et al., 2004). The software, therefore, is able to demonstrate to the user the state of the system when no response is entered and then allow the user to explore various responses, as well as to compare the effects of different decisions (Giupponi et al., 2004). A sensitivity analysis can also be performed on each response (Giupponi et al., 2004).

Mysiak et al. (2005) concluded that the early involvement of the end user in the design of the software was key to its success as end users were able to provide feedback in every phase of the project. It was noted, however, that end users were not familiar with conceptualising decision problems according to cause-effect relationships, and the framework used was not readily understandable to untrained users. Despite this, the researchers state that the mDSS tool has good potential and can be used by middle water management after some training (Mysiak et al., 2005).

When used correctly, the mDSS tool provides valuable insights into water resource management and is detailed in terms of the variables used. However, as Giupponi et al. (2004) stated, the mDSS tool was developed for the management of water catchments and is, therefore, limited to being used for this purpose. It is for this reason that the mDSS tool cannot be used for the entire energy-water nexus. Creating a tool similar to mDSS would be desirable, but that would require extensive research by people who have a reasonable amount of experience in the field, as a multidisciplinary team of researchers was required to develop the mDSS tool (Giupponi et al., 2004). However, it is useful to note how the project was approached. Mysiak et al. (2005) highlights the importance of involving end users in this type of project, and the DPSIR framework could possibly be used for the energy-water nexus model's structure.

3.2.2 Bayesian Networks

While researching the application of Bayesian Networks, Castelletti & Soncini-Sessa (2007) found that there was a growing interest in using graphical models such as Bayesian Networks for environmental and natural resource modelling. According to Castelletti & Soncini-Sessa (2007) this is due to the fact that there is a growing recognition that participation and uncertainty need to be considered in integrated natural resource management; therefore, there is a need for tools and methodologies that are able to handle such complex systems. Castelletti & Soncini-Sessa (2007) researched the advantages and disadvantages of using Bayesian Network for water resource management. Their findings are discussed below.

A Bayesian Network is a graphical model in which reasoning in conditions of uncertainty, or plausible reasoning, are modelled efficiently and consistently by using sound mathematics (Charniak, 1991). The Bayesian Network framework graphically represents the logical relationships between variables. Once the structure of the Bayesian Network is complete, the strength of these relationships is quantified using conditional probabilities (Castelletti & Soncini-Sessa, 2007). Bayesian Networks are directed acyclic graphs meaning there is no way to start at any variable and follow a consistently directed path that leads back to that variable (Charniak, 1991). Each node in the graph represents a random variable, and all root nodes, or nodes with no predecessor, are given prior probabilities (Charniak, 1991). The conditional probabilities of all non-root nodes must be defined so that all possible combinations of their predecessors are accounted for (Charniak, 1991). Each node therefore has a specified conditional probability table in which the probabilities that the variable will assume a particular value is listed, given the values of the variables associated with its predecessors (Castelletti & Soncini-Sessa, 2007). These conditional probabilities are represented by arcs between two nodes. Directional arcs show causality; for example, if there is a directional arc going from node A to node B it can be assumed that A causes B. A lack of arcs means the two variables are independent of one another (Lauritzen & Spiegelhalter, 1988). The conditional probability tables can be populated using derived data, expert opinion or results obtained by simulating other models (Castelletti & Soncini-Sessa, 2007).

If the values of a sufficient number of variables are known, usually those associated with the root nodes, it is possible to determine the values for all the nodes in the network. This process is called belief propagation, and is done by using basic probability calculus and Bayes' Theorem (Castelletti & Soncini-Sessa, 2007). Probabilistic inference, the purpose of Bayesian Networks, is done through the computational tool of belief propagation (Castelletti & Soncini-Sessa, 2007). Bayesian Networks can be used either in a bottom-up or a top-down approach (Castelletti & Soncini-Sessa, 2007). The bottom-up approach is used in diagnostic tasks in which the effect is known, and the most likely cause must be inferred. The top-down approach is used for descriptive purposes in which the probability of an effect is determined if one or more causes are provided. For this approach it is possible to either forecast outcomes as new evidence becomes available or to do scenario testing by updating the network with different sets of values and observing the outcomes (Castelletti & Soncini-Sessa, 2007).

Castelletti & Soncini-Sessa (2007) identified a few selection criteria to consider when selecting which model type to use for the different components in water management. These criteria are as follows:

i. *Ease of identification*: The sub-models must be easily identified so that stakeholders are more willing to participate in the modelling process. The importance of stakeholder participation was already highlighted by Mysiak et al. (2005) as discussed in Section 3.2.1. The model must therefore facilitate understanding of the bigger problem by stakeholders.

ii. *Integration potential*: Integration of the sub-models used for the various components must be technically feasible as this is key in modelling the overall system. A simple solution to this is to use the same model type for all the components. However, some researchers argue that this is unnecessarily rigid.

iii. *Dynamics and parsimoniousness*: The components within water systems are generally dynamic; therefore, the model type needs to be dynamic. The model must also be parsimonious, meaning the observed results require a simple explanation. The model type must therefore be able to concisely capture the most important elements of the components, without the need for advanced mathematics, or losing reliability and transparency for stakeholders.

Castelletti & Soncini-Sessa (2007) found that when the above criteria are applied, Bayesian Networks might not be the most suitable model type for water resource management. Bayesian Networks are well suited for use in representing systems where very little quantitative data is available or in which the knowledge of the system is unstructured or limited (Castelletti & Soncini-Sessa, 2007). Bayesian Networks are thus not adequately applicable to model systems, such as a water catchment area, in which there are a high number of deterministic relationships, or if the number of values each variable can assume is high (Castelletti & Soncini-Sessa, 2007). Bayesian Networks are also not well equipped to be used as dynamic models (Castelletti & Soncini-Sessa, 2007). This is because a

Bayesian Network represents the system at a certain time. Therefore, to simulate a system over a time horizon a cascade of networks must be created (Castelletti & Soncini-Sessa, 2007). Each network represents a different instant in time and has its own set of conditional probability tables. A large amount of data is therefore required to populate all the conditional probability tables. Castelletti & Soncini-Sessa (2007) conclude that Bayesian Networks are unsuitable to model entire water management systems, but suggest that Bayesian Networks only be used for components of the water system that have unstructured knowledge, system variables with a low number of possible values and are static. Bayesian Networks can also be easily integrated with other model types by expressing them as equations (Castelletti & Soncini-Sessa, 2007).

Bayesian Networks have, however, been used for a range of environmental resource systems, including fisheries (Kuikka, Hildén, Gislason, Hansson, Sparholt & Varis, 1999) and the effect of climate change on crop production (Gu, McNicol, Peiris, Crawford, Marshall & Jefferies, 1996). According to Castelletti & Soncini-Sessa (2007), researchers have previously also used Bayesian Networks in water resource modelling. An example is Batchelor & Cain (1999) who used Bayesian Networks for specific water management studies in Zimbabwe and Mauritius. All the studies mentioned, however, mainly focussed on the social systems involved and not the entire system, which would include the environmental and economic systems as well.

It can be concluded that Bayesian Networks are very useful for modelling non-quantitative systems with unstructured knowledge, such as a social system. Bayesian Networks, however, are not suitable for modelling the entire energy-water nexus system because they do not work well as dynamic models and the possible values for each variable is too high. Furthermore, Bayesian Networks are unable to represent feedback loops due to their acyclic nature. The three criteria for model selection listed by Castelletti & Soncini-Sessa (2007) and mentioned above, are, however, useful within the context of modelling the Western Cape Province’s energy-water nexus.

3.2.3 Reference architecture and quantitative approach

Lubega & Farid (2014a) developed a reference system architecture for the energy-water nexus. These researchers found that most previous studies on the energy-water nexus are either discussions of challenges, technologies and policy options or empirical evaluations of the electricity usage of the water sector and water usage of the electricity sector. The aim of Lubega & Farid (2014a) was to develop a reference system architecture that can be used to develop physics-based models of the engineered components in the energy-water nexus. The electricity, water and wastewater systems were modelled together, whereas traditionally they have been modelled in isolation. This enables the effects the systems have on each other and on the environment to become evident.

Lubega & Farid (2014a) used the Systems Modelling Language (SysML) activity diagram to model the flow-based behaviour of the systems. The flows included in the model are energy and matter. A description of the components Lubega & Farid (2014a) included in each of the systems are discussed below:

i. *Electricity system*: Electricity is generated by means of hydroelectric and thermal power as well as wind and photovoltaic generation. The water required for thermal and hydroelectric power is modelled as a withdrawal and not a consumption; therefore, the water is returned to the environment after use. Leakages and evaporated losses are, however, accounted for. Wind and photovoltaic generation require no water. Electricity storage is included in the system so that a constant amount of energy is supplied to the system from the renewable power technologies despite wind and solar power being variable power sources. Pumped hydro storage, which requires water, is used for this.

ii. *Water system*: The water supply options included are artificial reservoir water, river water, surface water, ground water and desalinated seawater, of which desalinated seawater is the most energy intensive. Both the reverse osmosis (RO) and multistage flash (MSF) distillation desalination technologies are included. Energy is required for the pumping of treated and desalinated water. Pipe leakage, which is a major concern, is included, but in the model this water returns to the water table and is therefore not really lost. The brine water from desalination plants is returned to the environment and treated water is distributed to end-users.

iii. *Wastewater system*: Gravity-flow sewers usually transport wastewater; therefore, it requires no energy and is modelled as such. The treatment of the wastewater before it re-enters the environment does, however, require power. After treatment, the water can be discharged into surface water bodies or into the water table to prevent depletion of water close to the surface. Some of the wastewater is recycled and is thus treated for irrigation or industrial use. Recycled water can also be blended into the potable water supply if it is correctly treated. Energy is required for the distribution of the recycled wastewater.

Lubega & Farid (2014b) furthered their work by quantifying the reference architecture and state that "*in this paper, a quantitative, physics-based, engineering systems model of the energy–water nexus is developed as a first of its kind*". Empirical data has been used in previous models, but Lubega & Farid (2014b) used engineering models to determine the energy usage of the water sector and water usage of the energy sector. The functions in the reference architecture were given a set of equations. Bond graphs, a graphical representation of a physical system, were used for the majority of the functions and the final result is a static input-output model.

The graphical models, or reference architecture, can be used for qualitative discussions regarding the interdependence of the demand and supply of energy and water demand (Lubega & Farid, 2014a). The quantitative model can be used to inform decisions regarding the infrastructure of the different systems (Lubega & Farid, 2014b).

The reference architecture provided by Lubega & Farid (2014a) describes the energy-water nexus in great detail and would be very useful for developing a quantitative model of the energy-water nexus. Although the model developed in Lubega & Farid (2014b) is very detailed and could be of great use, it is not dynamic. The model also does not include the social sector.

3.2.4 The EnergyPLAN model

Ostergaard et al. (2014) investigated the sustainability of using desalination for water supply in Jordan by assessing its impact on the energy sector. The study focussed in particular on the impact on the energy systems if large-scale wind power was introduced into the system. Jordan is a semi-arid desert, prone to drought and has strained freshwater resources and is thus contemplating desalination as a source of freshwater supply (Jaber & Mohsen, 2001; Ostergaard et al., 2014). As mentioned before, desalination is an energy intensive practice, therefore, even though it could be used as a freshwater supply, it may have a significant impact on a developing country such as Jordan's energy sector. Jordan is almost completely dependent on imported fossil fuels, therefore the increase in energy demand caused by the implementation will affect the country's security of electricity supply (Ostergaard et al., 2014).

For the assessment of the impact of desalination on Jordan's energy sector , Ostergaard et al. (2014) used the EnergyPLAN model. EnergyPLAN is a freely available energy system analysis model, which is analytically programmed and deterministic (Aalborg University, 2016). Entire energy systems can be modelled including electricity, cooling, heat, transportation and fuel demands (Aalborg University, 2016). EnergyPLAN was developed to enable hourly analyses of energy systems with changing demand and supply (Aalborg University, 2016). The time horizon of the model, however, is limited to a year (Ostergaard et al., 2014).

The impact of both RO and MSF desalination was assessed and compared to a reference energy scenario (Ostergaard et al., 2014). The effects of the different desalination technologies on the Primary Energy Supply for power generation were observed at increasing levels of fluctuating power in terms of electricity generation (Ostergaard et al., 2014). The levels of fluctuating power were increased by increasing the wind power capacity. The Critical Excess Electricity Production is the electricity production that can't be used in the system and was also measured in the study (Ostergaard et al., 2014). It was found that MSF and RO have a similar impact on the Primary Energy Supply, but RO can reduce the Critical Excess Electricity Production, which is relatively high even at moderate wind power capacities (Ostergaard et al., 2014).

EnergyPLAN is not suitable for assessing the long-term impact of a technology system, such as desalination, on the energy-water nexus due to its limited time horizon and because it can only model energy sectors (Aalborg University, 2016). Ostergaard et al. (2014) does, however, provide insight into the short-term impacts of desalination, which might prove to be important to consider when modelling the impact of desalination on the Western Cape Province for a longer time horizon.

3.2.5 The SAHRA multi-resolution model

The United States National Science Foundation founded a science and technology centre for the Sustainability of semi-Arid Hydrology and Riparian Areas (SAHRA) (Wagener, Liu, Gupta, Springer, Brookshire, Franks, Bøgh, Bastidas, Nobre, de Galvão & others, 2005). One of the objectives of SAHRA was to develop a multi-resolution integrated modelling framework of the Rio Grande basin in the southwest of the USA (Wagener et al., 2005). The model were to be used for the water management of this semiarid area (Wagener et al., 2005).

The goal was to achieve sustainable water management, and according to Wagener et al. (2005) the coordination of multiple disciplines was required. An integrated assessment approach was therefore used because it combined the environmental, socio-economic and institutional dimensions of the problem. This approach was implemented by using an integrated modelling system (Wagener et al., 2005).

SAHRA chose to use a multi-resolution modelling framework to address the issues of credibility, scale and communication (Liu, Gupta, Springer & Wagener, 2008). The framework consists of models at three resolutions: fine resolution with units being 100 m grid cells or smaller, medium resolution with units being 1-12 km grid cells and course resolution with units being sub-watersheds (Liu et al., 2008). Each resolution offers its own advantages and disadvantages; therefore, there is strength in their connection and consistency (Wagener et al., 2005). Furthermore, the feedback between the multiple interacting components becomes inherent in the simulations when multiple resolutions are used (Liu et al., 2008). A brief description of each resolution, as discussed by Wagener et al. (2005), is given:

i. *Fine resolution*: This component is high resolution and consists of linked atmosphere-surface-subsurface water and energy balance models. A rigorous mechanistic approach was used to model these physical systems.

ii. *Medium resolution*: This model is based on a combination of a number of land-surface-atmosphere, water and energy balance models. Engineering structures, for example irrigation channels and water controls, as well as behavioural economics were included in this component.

iii. *Coarse resolutions*: This resolution was developed using System Dynamics modelling. System Dynamics is discussed in further detail in Section 3.2.6. This component is intended for decision support and was therefore developed with the focus on the ease of understanding and communicability necessary for scenario testing. Human population growth and the economic evaluation of water use could also be included here in the future.

According to Wagener et al. (2005) this combination of resolutions within the integrated assessment modelling framework allows for a range from high resolution and physically rigorous components to easily understood and communicable components.

Liu et al. (2008) concludes that the multi-resolution integrated modelling framework developed by SAHRA is effective and efficient in achieving the tasks in water management set out by SAHRA. Liu et al. (2008) discuss a number of lessons that were learnt during the development of the model. The first is that the identification of a limited number of questions that address the issue and the problem formulation are very important. Liu et al. (2008) state that this is the first crucial step to any modelling effort. The second lesson is the importance of explicit modelling. A conceptual model is a model of a real system, but with a degree of simplification. Liu et al. (2008) express the importance of modelling explicitly as this aids with communication between the different modellers as well as stakeholders. The third lesson is that the multi-resolution integrated modelling approach could be used to find a balance between the complexities needed to produce a credible model and the simplicity necessary for the use of the model in decision making. The fourth and last lesson is that scenario analysis is a practical way of using models for long-term real-world decision making when many uncertainties exist (Liu et al., 2008).

The course resolution component of the model was developed for decision and policy making, which is what the energy-water nexus model would be used for. System dynamics modelling could therefore potentially be used. The lessons learnt, according to Liu et al. (2008), can also be applied to the energy-water nexus model.

3.2.6 A system dynamics model

A decision support system for integrated water and energy planning in the USA was developed by Tidwell, Kobos, Malczynski, Klise, Hart & Castillo (2009) using system dynamics modelling. Tidwell et al. (2009) note that, in the past, planning and management of energy and water resources were rarely treated in an integrated manner despite the couplings that exist between the two resources. The modelling framework described by the researchers was designed to evaluate competing technical and policy options with regards to the energy-water nexus.

System dynamics is a systems-based modelling methodology and was founded on the idea that the cause and effect relationships present within the structure of the system govern the system behaviour (Sterman, 2000). The behaviour of a system can be simulated over time (Sterman, 2000). However, a thorough understanding of the system is required in order to correctly define the system structure (Sterman, 2000).

Tidwell et al. (2009) selected system dynamics modelling because it met two criteria. The first is that it can integrate the complex physics of resource supply with the social and cultural constructs that create resource demand. The second is that system dynamics modelling is a tool that can be used directly for public participation and education because of its transparency.

The model included the energy sector, water sector, USA demographics and the various links between these elements (Tidwell et al., 2009). The main variables used in the structure of the model therefore include: electrical power production; greenhouse gas production; thermoelectric water use and consumption; water supply; water consumption; water stress; energy use for water; and demography, including population and GDP (Tidwell et al., 2009). The model was populated using high level publicly available data (Tidwell et al., 2009).

After the completion of the model, a baseline case was modelled to compare the model results for various projections, such as water use and GDP, to results presented by other sources (Tidwell et al., 2009). Various scenarios were then tested by Tidwell et al. (2009). In one set of scenarios, alternative mixes of cooling technologies used in newly constructed and recommissioned power plants were tested. Another set considered different mixes of fuel types utilized in future power production. Many other scenarios can also be tested using the model (Tidwell et al., 2009).

A number of indictors can be used in the model, depending on the scenarios that are being tested. The indicator used most often by Tidwell et al. (2009) is one that links the energy and water sectors, i.e. future electricity production water use and consumption. Additionally, water demand and supply ratios were used by Tidwell et al. (2009) as well as installed electricity production capacity and greenhouse gas emissions.

System dynamics modelling has the potential to be used for the energy-water nexus model. The model developed by Tidwell et al. (2009) accounts for the economic, social and environmental aspects of the USA's water and energy sectors. The purpose of the model was to provide assistance to decision makers by forecasting the long-term impacts different scenarios would have on the system. This is similar to the objective of the Western Cape Province's energy-water nexus model.

3.3 Conclusion: Modelling tools

The energy-water nexus of the Western Cape Province is a complex system that requires a systems thinking approach. The correct modelling tool must be chosen to develop a model for this system to ensure that meaningful results will be obtained and that recommendations can be made to policymakers. The purpose of the proposed energy-water nexus model is to investigate the impacts of new technology systems on the energy-water nexus. The evaluation criteria for selecting a modelling tool were identified by considering the objectives of the model while recognising the complexity of the system as discussed in Section 2.3.2.

A number of previous approaches to modelling water sector management and the energy-water nexus have been reviewed. It was found that most of the modelling tools used in previous work could only be used to address specific components of the energy-water nexus and does not account for the entire energy-water nexus system, which consists of the social, economic and environmental sectors. The MULINO project was very successful in providing a decision support system for water resource management. The scope and depth of the project, however, required long-term research and development and significant amounts of funding. Furthermore, the mDSS developed by MULINO cannot be applied directly to the energy-water nexus, because it was specifically developed for use at catchment level only. Bayesian Networks are highly suitable for modelling the social aspects of the problem that is addressed by this research inquiry, but does not address the quantitative components. In contrast to this, the model developed by Lubega & Farid (2014b) focused only on the quantitative aspects of the energy-water nexus, but does not include the qualitative components such as the societal aspects. The reference architecture developed for this model, however, can be expanded to include the social sector. The EnergyPLAN model used by Ostergaard et al. (2014) provides useful insights into the short-term impacts a technology system will have on the energy sector of a country, but cannot be used for long term assessment and excludes the water sector. The SAHRA multi-resolution integrated model consists of various models incorporated at different levels to create a highly quantitative model, which has the necessary qualitative aspects. System dynamics was used for the policy and decision-making component. Tidwell et al. (2009) used system dynamics to develop a decision support system for the integrated planning of the USA's water and energy sectors. This research is of particular interest because the system modelled is similar to the Western Cape Province's energy-water nexus.

A summary of the evaluation of the modelling tools that have been investigated is given in Table 3.2. It can be seen that system dynamics modelling is the only tool that meets all the modelling requirements discussed in Section 2.3.2. Multi-resolution modelling meets most of the requirements, however, the fine resolution sub-models used in multi-resolution modelling are not transparent or easily understandable to all stakeholders.

Table 3.2: Evaluation of modelling tools

	Modelling tools					
Requirement	**MULINO mDSS**	**Bayesian networks**	**SysML**	**EnergyPLAN**	**Multi-resolution modelling**	**System dynamics**
Dynamic	X			X	X	X
Quantitative and qualitative	X		X		X	X
Transparent	X	X		X		X
Represent the feedback loops within the system			X	X	X	X
Represent the entire complex system			X		X	X
Medium- to long term scenario analyses	X		X		X	X

System dynamics is a modelling tool that integrates systems thinking and can therefore be used to represent the feedback loops within the energy-water nexus system. It is a tool specifically designed for the modelling of complex systems (Sterman, 2000). System dynamics models can simulate the quantitative and qualitative components of the energy-water nexus. It is dynamic, can be used for any time horizon and can provide accurate results, assuming the model has been properly validated (Maani & Cavana, 2007). These model types are also transparent, easily understood and designed for scenario analysis, therefore system dynamics can be used for policy and decision making. System dynamics was, thus, selected as the appropriate modelling tool for this research.

CHAPTER 4: MODELLING THE WESTERN CAPE PROVINCE'S ENERGY-WATER NEXUS

In Chapter 2, it was determined that the Western Cape Province's energy-water nexus can be described as a complex system and, consequently, requires a systems thinking approach. In Chapter 3, system dynamics was chosen as an appropriate modelling tool for the nexus because it is specifically designed for modelling complex systems. Furthermore, system dynamics meets the other model criteria as was specified according to the objectives of the model. The purpose of this chapter is to provide a detailed account of the steps involved in the development of the Western Cape Energy-Water Nexus model. The system dynamics modelling method that was used for the modelling process is presented in the first section. The subsequent sections are a discussion of how each step in the described methodology was carried out. Although the modelling process is separated into phases, the process is iterative as the previous phases need to be revised as the development of the model continues.

4.1 System dynamics modelling method

According to Sterman (2000), system dynamics can be used to improve learning in complex systems so that the dynamic complexities can be better understood and more effective policies can be designed. Coyle (1996) describes system dynamics as a tool that "deals with the time dependent behaviour of managed systems with the aim of describing the system, and understanding, through qualitative and quantitative models, how information feedback governs its behaviour, and designing robust information feedback structures and control policy through simulation and optimization". System dynamics can be used to construct integrated models of technical and physical systems, as well as more qualitative systems that fall in the social sector, such as social psychology. It is for this reason that system dynamics can be used to solve real world problems (Sterman, 2000).

System dynamics is most commonly used to determine the impact of the implementation of a policy in a specific context. System dynamics models are descriptive and focus on the causal relations within the system (Bassi, 2014). Musango (2012) notes that system dynamics has not often been used for technology assessments that consider sustainability and the number of studies regarding this are limited. System dynamics is, however, designed for dynamically complex problems and can thus be used for technology assessments within the context of sustainability. It is only in the last 15 years that the benefits of using system dynamics for technology assessments has been recognised. For example, Wolstenholme (2003) used system dynamics as a tool for the evaluation of technologies in three different cases, namely: defence technologies, defence supply chains, and the pharmaceutical industry. Another example is the research conducted by Musango (2012), in which system dynamics was used to determine the sustainability of bioenergy technologies in South Africa. Furthermore, Ness, Urbel-Piirsalu, Anderberg & Olsson (2007) state that an understanding of the complex dynamic interactions between the social, environmental and economic issues is required for a sustainability assessment and lists system dynamics as a possible tool for achieving this.

Bassi (2014) highlights that a potential weakness of system dynamics is that the system's boundaries and causal relations must be correctly defined. This requires knowledge of different fields and a thorough understanding of all the sectors present in the system. Musango (2012) cautions that decision-makers should be aware of the inherent uncertainties that exist in complex open systems and that system dynamics models are unable to provide exact answers. Rather, the purpose of the model is to provide stakeholders with insights into proposed interventions (Maani & Cavana, 2007).

System dynamics modelling has been used for modelling real world problems with the focus on policy and decision making in a number of cases. Xi & Poh (2013) modelled Singapore's water resource management to determine the impact of various long-term investment plans. These plans included desalination and waste water recovery. Problems arising in South Africa and in the Western Cape Province have also been investigated using system dynamics. For example, Musango, Brent, van Niekerk, Jonker, Pienaar, York, Oosthuizen, Duminy & de Kock (2012) analysed the effect a green economy transition would have on the Western Cape Province.

Maani & Cavana (2007) describe five phases for the process of systems thinking and modelling, namely: problem structuring; causal loop modelling; dynamic modelling; scenario planning and modelling; and implementation and organisational learning. Although these phases are distinct, they are interrelated, and it is important to note that the modelling process is iterative. A description of each phase, as defined by Maani & Cavana (2007), is given:

1. *Problem formulation*: The problem identification and definition occur in this phase. Preliminary information and data is collected to ensure a thorough understanding of the problem.

2. *Causal loop modelling*: In this phase, the conceptual model is developed. The dynamics of the system are identified in terms of the endogenous consequences of the system's feedback structure. This is achieved by identifying the system's variables and using these variables to map the causal structure. Causal loop diagrams (CLD) show the cause and effect relationships between the variables present in the system. CLDs can be used to start developing possible intervention strategies.

3. *Dynamic modelling*: The simulation model is developed in this phase. This involves defining the variable types and constructing the stock and flow diagrams (SFD) for the different sectors of the model. The model parameters, boundaries and decision rules are specified in this phase. Detailed historical and statistical data is required to construct the simulation model. After the dynamic model has been developed, it needs to be validated. The model results are compared to reference modes to ensure the model is able to adequately reproduce the problem behaviour. The model's behaviour is tested under extreme conditions to ensure that it still produces realistic results at these conditions. And lastly, the model's sensitivity is tested to observe its behaviour given uncertainty in some parameters.

4. *Scenario planning and modelling*: The model is developed for testing various policies and strategies and that occurs in this phase. Different scenarios are formulated and simulated using the dynamic model. Indicators are used to assess the effects of the different scenarios and the robustness of the different policies can be evaluated. Ideally, all major stakeholders should be involved in this phase.

5. *Implementation and organisational learning*: The purpose of this phase is to present the results of the simulations to stakeholders. Additionally, the model can be adapted so that it

is more user-friendly and interactive, thereby allowing stakeholders to experiment with the model.

The modelling process described by Maani & Cavana (2007) was used to facilitate the development of the Western Cape Province's energy-water nexus model.

4.2 Problem articulation

The purpose of the system dynamics model that was constructed was to determine the sustainability of a desalination technology system in the context of the Western Cape Province's economy and its impact on the energy-water nexus. The Western Cape Province water resource management model constructed by Pienaar (2015) was partly used to model the Western Cape Province's water resources. Additionally, the Western Cape Province electricity sector model constructed by Oosthuizen (2015) was used to model the Western Cape Province's electricity resources. The water and electricity sectors have therefore previously been investigated. This research requires an understanding of the links that exist between the Western Cape Province's water and electricity sectors. The problem articulation phase, which aims to provide a deeper understanding of the context the research is being conducted in, was completed before the modelling tool had been selected and can be seen in Chapter 2.

4.3 Conceptual model

This section details the process of developing the conceptual model. In the problem formulation phase, a better understanding of the Western Cape Province's water and electricity resources was gained. The dynamics that influence the demand and supply of both sectors was explored, as well as how the two sectors influence one another.

In the first subsection, the model boundaries, key variables and time horizon are identified. This is followed by the development of the causal loop structure of the energy-water nexus system. The aim of this is to identify the relationships between the variables that play a role in the system and illustrate the feedback loops that govern the behaviour of the system.

4.3.1 Model boundaries, key variables and time horizon

The aim of the Western Cape Energy-Water Nexus (WeCaEWN) model is to determine the impact and sustainability of various desalination systems on the Western Cape Province's energy-water nexus. For this reason, the Western Cape Province is the geographical boundary of the model. A number of sub-models were developed to determine the Western Cape Province's water demand and supply, electricity demand and supply, and the links between the two sectors. A model of the Western Cape Province's water sector, developed by Pienaar (2015), and a model of the Western Cape Province's electricity sector, developed by Oosthuizen (2015), were used as part of a larger model named the Western Cape Green Economy model (WeCaGEM) (Musango et al., 2012) to determine the implications of a green economy transition in the Western Cape Province. The WeCaEWN model was partially based on these models. Other sub-models that were developed for the WeCaGEM model were also used in the WeCeEWN model. These include sub-models for land usage, population, education and provincial GDP that were built specifically for the Western Cape Province.

The WeCaEWN model was constructed based on an energy-water nexus framework. The water consumption of the electricity sector and the electricity usage of the water sector are important links between the water and electricity sectors. Each sector has its own set of drivers that determine the demand and supply within that sector. In the electricity sector, the demand is driven by economic growth and population growth. On the supply-side, the total installed capacity of the various electricity generation technologies determines the available supply. The electricity supply is what drives the water consumption of the electricity sector. In the water sector, the demand is also driven by economic growth and population growth. The water supply is affected by the Western Cape Province's water supply system and the hydrological cycle. The water sector's electricity use is driven by the water supply.

The key variables are the variables considered essential in determining the impact and sustainability of the installation of a new desalination technology system in the Western Cape Province. These variables were calculated endogenously in the model. The key variables and their direct influences are listed in Table 4.1. It must be noted that various other factors, which are not listed in Table 4.1, influence these variables indirectly.

Table 4.1: WeCaEWN model key variables and their influences

Key variable	Primary influence	Secondary influence
Water supply	Surface water Ground water Recycled water Desalination water supply	Capacity of supply system Depreciation of supply system Western Cape Province runoff Mean annual precipitation Evaporation rate Percolation rate
Water demand	Domestic demand Irrigated agriculture demand Afforestation demand Mining and bulk industries demand Electricity sector water demand	Growth rate of each demand Population growth rate GDP growth rate Electricity supply
Water stress index	Water supply Water demand	All supply and demand sources
Water sector electricity consumption	Electricity requirements for all sources of supply	Capacity of supply system
Electricity supply	Nuclear supply Gas power supply Pumped storage supply Solar PV supply Wind supply	Capacity of supply system Depreciation of system
Electricity demand	Residential demand Industrial demand Commercial demand Transport demand Agricultural demand Water sector electricity demand	Electricity price Population growth rate GDP growth rate Growth rate of demand Water supply
Electricity demand and supply gap i.e. Imported electricity	Electricity demand Electricity supply	All supply and demand sources
Electricity sector water consumption	Water requirements for all sources of supply	Capacity of supply system Imported electricity
Annual air emissions from electricity generation	CO_2 emissions from electricity generation in Western Cape Province CO_2 emissions from electricity imports	All sources of supply Electricity demand and supply gap
Brine stream from desalination	Desalination water supply Desalination recovery	Desalination capacity Desalination technology
Desalination running-cost	Desalination water supply Electricity price	Desalination capacity Desalination technology

The water supply and water demand variables determine the water available and water required. The water stress index is a ratio of the demand against the available supply and is a universally recognised ratio that indicates water scarcity. The water sector electricity demand determines the amount of electricity the water sector requires. The electricity supply and demand determine the amount of electricity generated in the Western Cape Province and how much is required. The electricity demand and supply gap measures the difference between the demand and supply. This gap is also equal to the amount of electricity that is imported from other provinces. The electricity sector water consumption determines the amount of water needed for electricity generated in the Western Cape Province, as well as the amount of water needed to generate the imported electricity. Similarly, the annual air emissions from electricity generation determines the air emissions produced from electricity generated in the Western Cape Province, as well as that from imported electricity, and is expressed in terms of equivalent CO_2 emissions. The brine stream from desalination indicates the amount of brine produced during the desalination process. Brine is a waste product, which requires disposal and must therefore be taken note of. The desalination running-cost determines the operational and maintenance cost of the desalination plant.

There are many variables that impact the energy-water nexus, but it is not possible to model all of them. Table 4.2 lists the variables that were noted as possibly impacting the Western Cape Province's energy-water nexus, but that were excluded from the model due to time constraints and the scope of the problem.

Table 4.2: Excluded variables

Variable	Description
Energy fuel types other than electricity	This includes, but is not limited to: coal, petrol, diesel, natural gas etc.
Limit on the amount of electricity imported from other provinces	It was assumed that the Western Cape Province's electricity demand that cannot be met by locally generated electricity is met by imported electricity and that there is no limit to this.
Climate change	This would impact the hydrological cycle and thereby the amount of precipitation
Employment	The implementation of a desalination system would generate a number of jobs, which impacts the social sphere of the nexus.
GDP as a driver of population growth	An improved GDP would mean that there are more funds available to sustain life. The exact mathematical equation for this, however, is unknown.
Water price	The effect of water price on water demand was not investigated.

The purpose of the model is to assess the sustainability of a desalination system in the Western Cape Province and therefore the medium- to long-term impacts were determined. The model was simulated over a period of 40 years, from the year 2001 to 2040. The years 2001 to 2015 were modelled so that the model results could be compared to historical trends to ensure the model is able to replicate the behaviour of the real system. This time frame was chosen for validation based on the available historical data.

4.3.2 Causal loop modelling basics

This subsection aims to expand on the causal loop modelling concept that was introduced in Section 4.1. Causal loop diagrams (CLD) are used to illustrate the causal relationships that exist between variables and reveal the feedback loops present in the structure of a system (Maani & Cavana, 2007). The purpose of this is to gain a better understanding of the dynamics of the system. An example of a CLD for population size can be seen in Figure 4.1.

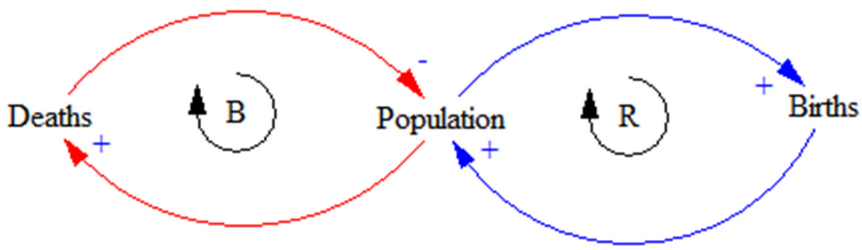

Figure 4.1: CLD for population size

Arrows are used to indicate causal relationships between variables. Each arrow is assigned a polarity, which dictates the type of effect the independent variable has on the dependent variable. A positive sign at an arrow head shows that as the variable from which the arrow starts, the cause, increases, the variable at the arrow's end, the effect, also increases. A negative link indicates the opposite: that as the cause increases, the effect decreases (Sterman, 2000).

The feedback loops in a CLD are labelled either "R" or "B". "R" represents a reinforcing feedback loop. This type of loop is a growing or a declining action (Maani & Cavana, 2007). For example, in Figure 4.1, an increase in population will cause an increase in births. Also, an increase in births will cause an increase in population. A balancing loop is represented by "B". This loop is a goal-seeking or counteracting process, which is seeking balance (Maani & Cavana, 2007). The balancing loop in Figure 4.1 shows that an increase in population will lead to an increase in deaths, but an increase in deaths causes a decrease in population.

A delay is a time lapse between the cause and its effect. Most systems have inherent delays. Delays can mask the underlying causal relationships within a system and the effect of delays can be powerful. It is for this reason that delays need to be included in the mapping of a system's causal structure (Maani & Cavana, 2007). Two parallel lines across an arrow indicate that there is a delay between that particular cause and effect.

4.3.3 Energy-water nexus CLD

Figure 4.2 shows the CLD of the energy-water nexus. More detailed CLDs of each sector are discussed in later sections. The CLD consists of one reinforcing loop, R1, and three balancing loops, B1, B2 and B3. R1 indicates the links between the energy sector and the water sector. If the water stress index becomes too high there will be a need for a greater water supply, therefore investment in the water sector will need to be increased. An increase in investment in the water sector will result in an increase in the investment in the water supply, which would lead to an increase in the total water supply. As the total water supply increases, the amount of electricity used by the water sector will increase and therefore the total electricity demand will increase. The increase in total electricity demand will cause the gap between the electricity demand and supply to increase. A gap between electricity demand and supply would result in a need for increased electricity supply, therefore the investment in electricity capacity will need to be increased. This would result in increased electricity generation. As the electricity generation is increased, the amount of water used by the electricity sector will also increase leading to an increase in total water demand. This will ultimately lead to an increase in the water stress index.

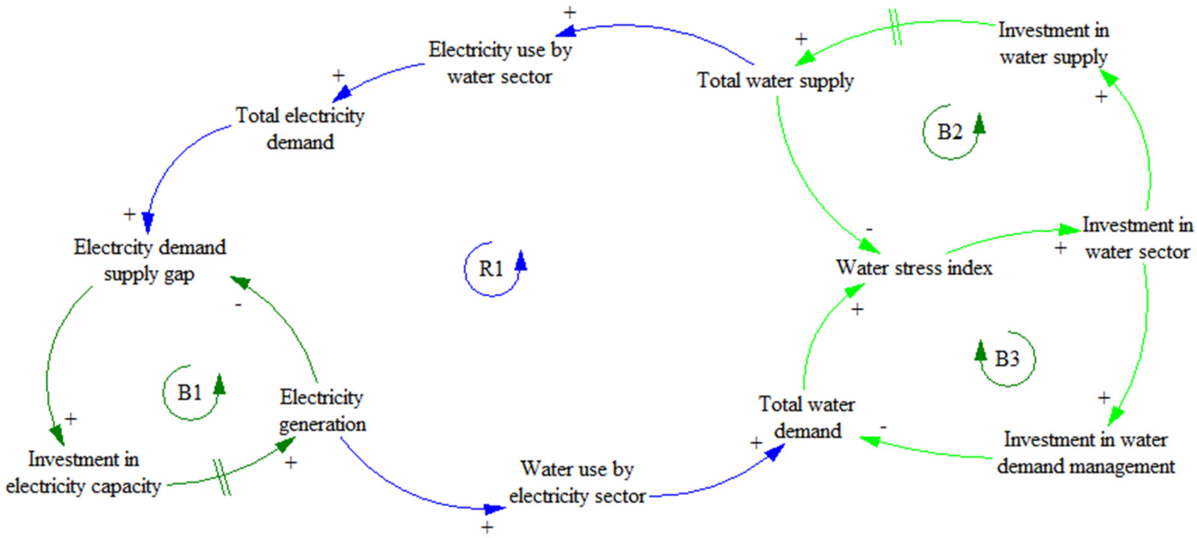

Figure 4.2: Energy-water nexus CLD

B2 presents a simplified view of the interactions between the variables within the water supply subsector and shares most of its variables with loop R1. A high water stress index will result in a need to increase the amount of investment in the water sector, thereby increasing the investment in water supply. An increase in investment in water supply will lead to an increase in total water supply. Ultimately, an increase in total water supply will result in a decrease in the water stress index. Loop B2 can be divided into feedback loops B4, B6, B7 and B8 where each loop presents a different water supply source. These loops are discussed in detail in Section 4.3.4. B1 is discussed in Section 4.3.7 and B3 in Section 4.3.5.

4.3.4 Water supply CLDs

Surface water CLD

The CLD for surface water can be seen in Figure 4.3 and consists of two balancing loops, B4 and B5, and one reinforcing loop, R2. B4 forms part of B2, as was discussed in Section 4.3.3. The connection between the total water supply and water stress index results in a balancing loop. As the water stress index increases, the investment in water supply will need to be increased. The more the available investment in water supply is, the more augmentation of surface water can take place. More augmentation will lead to increased available dam capacity, which will increase the surface water supply and therefore increase the total water supply. This will finally lead to a decrease in the water stress index. This CLD shows that surface water supply is limited by dam capacity. A delay exists between investment and augmentation, as well as between augmentation and available capacity. These delays are caused by the time it takes to plan and construct the new capacity.

B5 shows the feedback loop that exists between evaporation and surface water supply. An increase in surface water supply will lead to an increase in evaporation. Increased evaporation will reduce the surface water supply. There are methods available for reducing evaporation, but these were not considered in this model. Precipitation is an exogenous variable, which affects the surface water supply. More precipitation will result in more surface water supply. As the surface water supply increases, the electricity used for producing surface water also increases. This contributes to the total electricity consumption of the water sector.

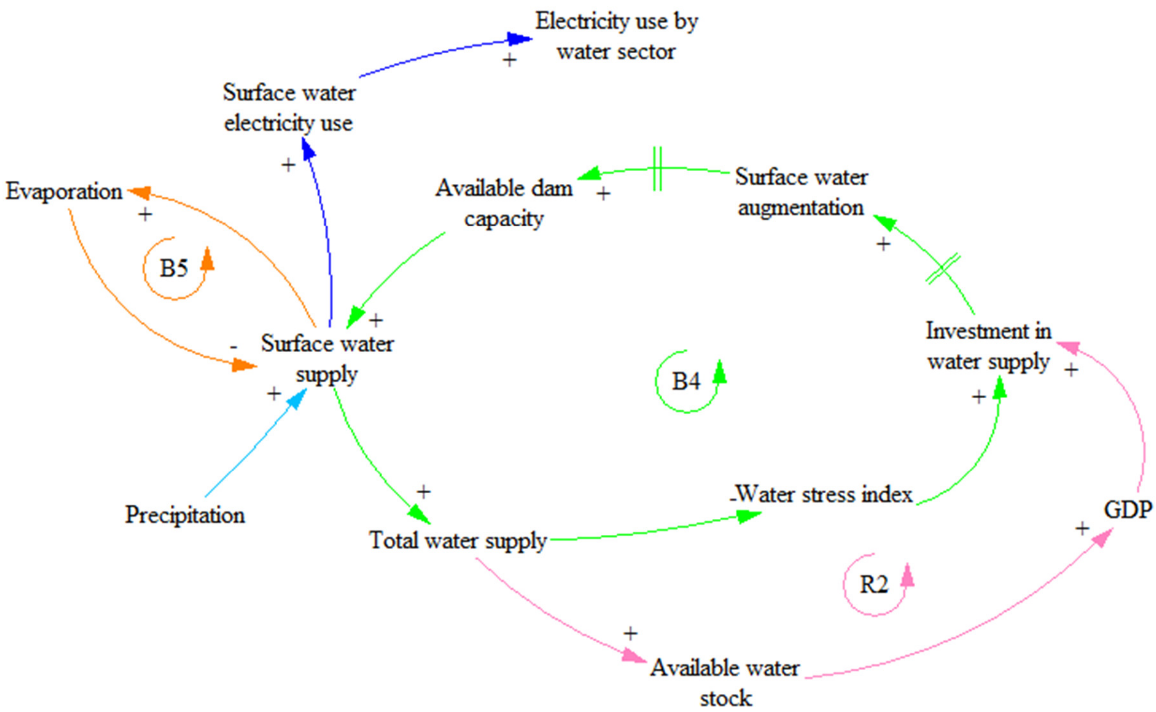

Figure 4.3: Surface water CLD

R2 shares many of its variables with B4 except that total water supply increases available water stock. An increased available water stock is good for the economy and therefore causes an increase in GDP, which then increases the investment in water supply. This ultimately leads to an increase in total water supply.

Groundwater CLD

The CLD for groundwater supply is presented in Figure 4.4 and consists of one balancing loop, B6, and one reinforcing loop R3. B6 forms part of B2, which can be seen in Section 4.3.3. If the water stress index becomes too high, there is a need for investment in water supply, therefore this will need to increase. As the investment in water supply increases, more funds become available for groundwater development and the groundwater pump station capacity will increase. This will lead to an increase in groundwater supply and therefore an increase in total water supply. Ultimately, as the total water supply increases the water stress index decreases. There is a delay between investment and an increase in capacity. It can be seen from Figure 4.4 that the groundwater pump station capacity is limited by the UGEP, which is an exogenous variable. Groundwater supply is increased by precipitation and decreased by evaporation. An increase in groundwater supply causes an increase in the electricity used for groundwater supply, which increases the electricity used by the water sector.

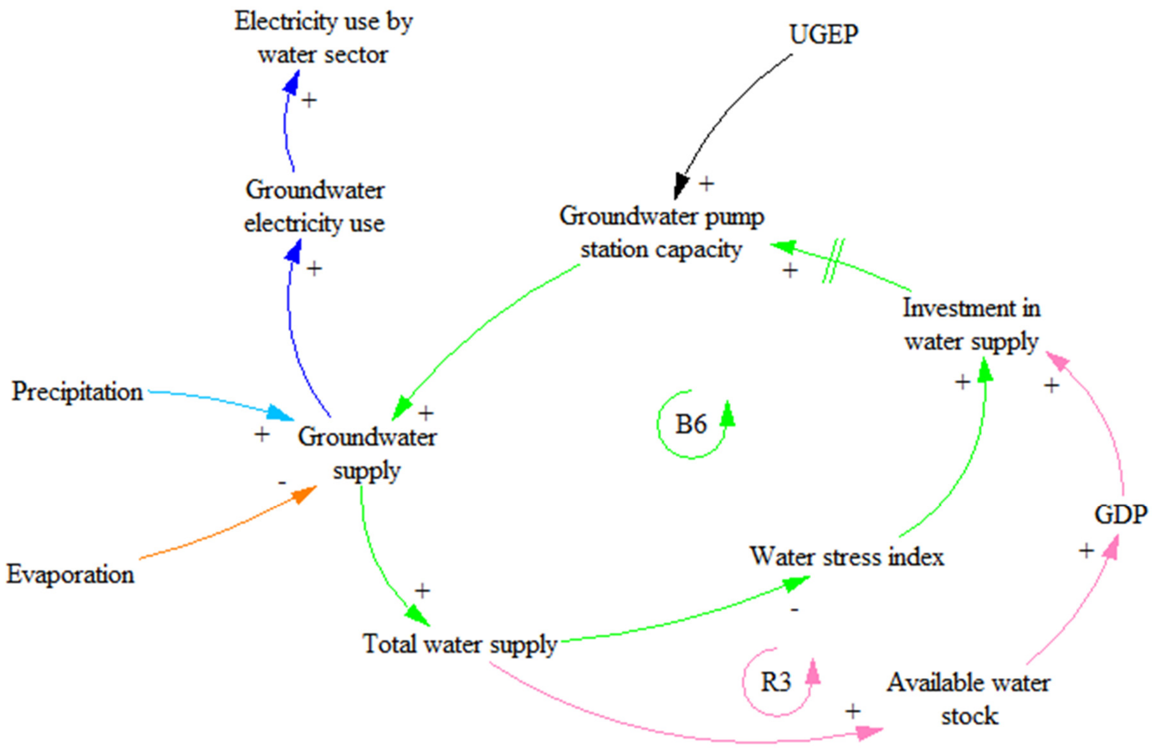

Figure 4.4: Groundwater CLD

R3 shares most of its variables with B6. An increase in total water supply leads to an increase in available water stock and, as was seen with R2 in Figure 4.3, this increases the GDP. The greater the GDP, the greater the investment in water supply, which finally results in an increase in total water water supply.

Recycled water supply

Figure 4.5 presents the CLD of recycled water supply and consists of one balancing loop, B7, and two reinforcing loops, R4 and R5. B7 forms part of B2 given in Section 4.3.3. If the water stress index is too high, the investment in water supply will need to be increased. An increased investment in water supply will result in an increase in available WWTW capacity, although there is a delay before this happens. The greater the WWTW capacity, the greater the potential capacity for treatment. The greater the potential capacity for treatment, the greater the recycled water supply. An increase in recycled water supply leads to an increase in total water supply, which ultimately decreases the water stress index. A greater recycled water supply also increases the electricity used to supply recycled water and therefore increases the water sector's electricity use.

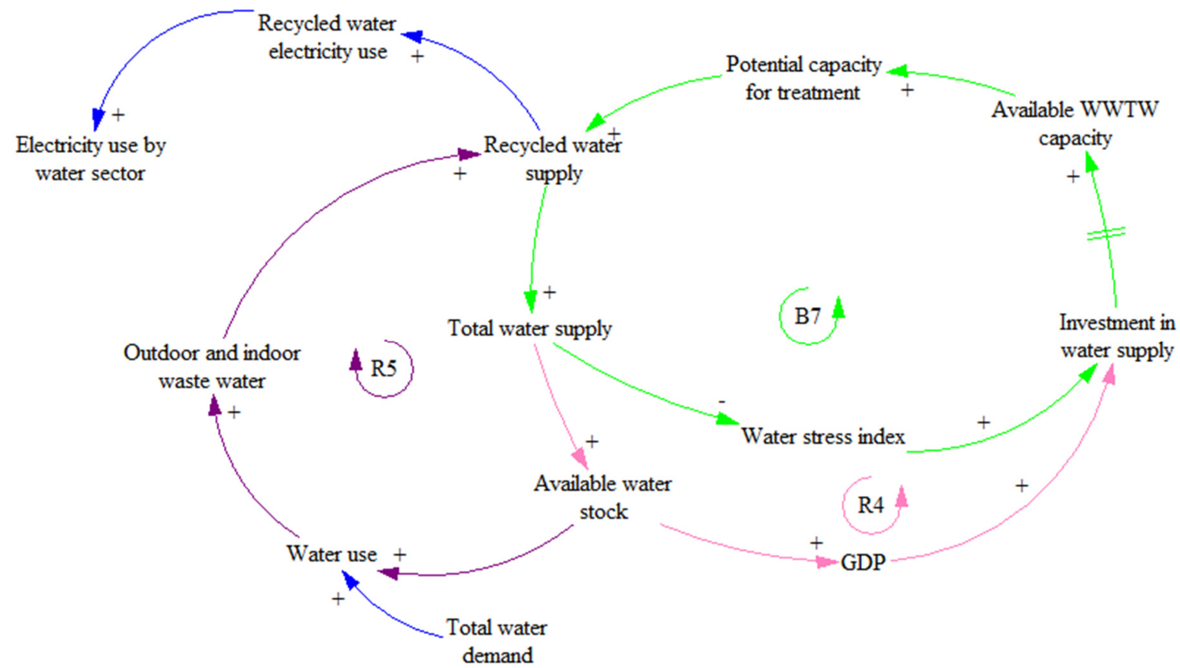

Figure 4.5: Recycled water supply CLD

R4 shares most of its variables with B7 except that the water stress index is replaced with available water stock and GDP. As the total water supply increases, the available water stock increases. The greater the available water stock, the greater the GDP. The greater the GDP, the greater the investment in water supply. An increase in investment in water supply finally results in an increase in total water supply.

R5 is what makes the recycled water supply CLD different from the other water supply CLDs. An increase in total water supply causes an increase in available water stock. Figure 4.5 indicates that an increase in available water stock results in an increase in water use. Water use is equal to the minimum difference between the available water stock and the total water demand, where total water demand is dependent on a number of other variables, as seen in Figure 4.7. The greater the water use, the greater the outdoor and indoor waste water. The more waste water is available, the more the recycled water supply will be. This will lead to an increase in total water supply and, ultimately, an increase in available water stock.

Desalination CLD

The CLD for desalination is presented in Figure 4.6 and consists of one balancing loop, B8, and one reinforcing loop, R6. B8 forms part of B2 given in 4.3.3. At a high water stress index, the amount of investment in water supply will need to increase. This results in more funds being available for the construction of desalination plants and desalination capacity will, after some delay, increase. Greater desalination capacity results in more desalinated water supply, which increases total water supply. Increased total water supply will, ultimately, decrease the water stress index. The greater the desalination supply, the more electricity is used for desalination, and therefore the more electricity is used by the water sector.

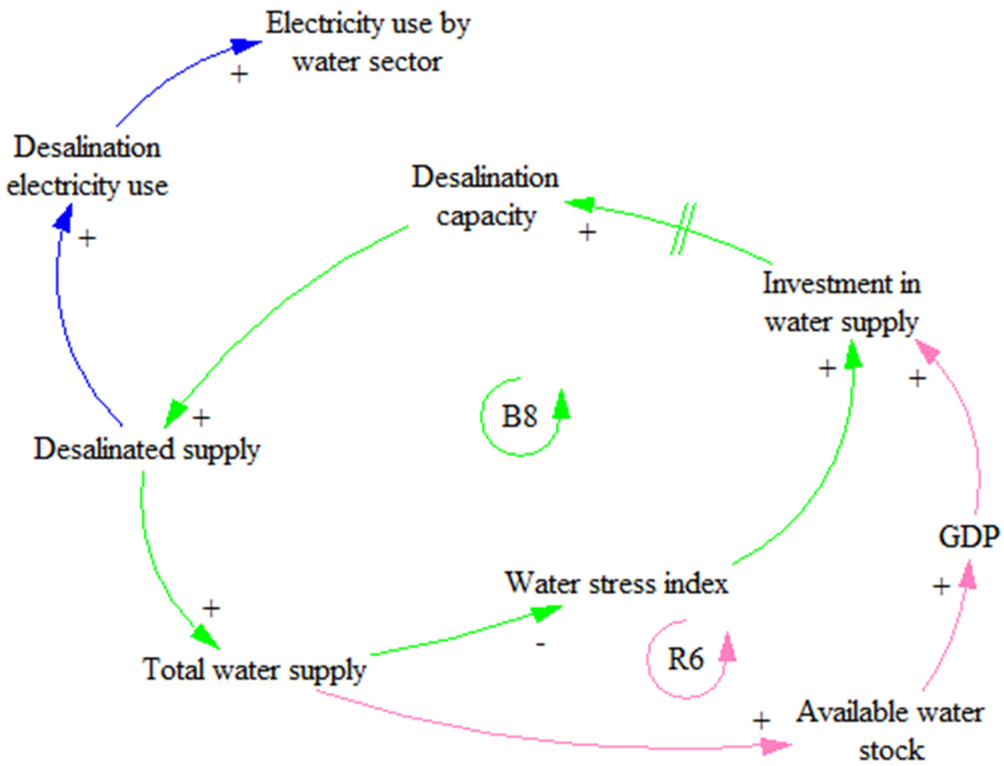

Figure 4.6: Desalination CLD

R6 shares most of its variables with B8. An increase in total water supply results in an increase in available water stock. The greater the available water stock, the greater the GDP will be. This results in more money being available for investment in water supply. More investment will, ultimately, result in an increase in total water supply.

4.3.5 Water demand CLD

The water demand CLD is presented in Figure 4.7 and is made up of four balancing loops, B3, B9, B10 and B11, as well as two reinforcing loops, R7 and R8. As can be seen in Figure 4.7, it is assumed that there are three factors that influence the total water demand, namely GDP, population and investment in water demand management. The simple population CLD presented in Figure 4.7 consists of one balancing loop, B11, and one reinforcing loop, R8. According to R8, as the population increases, the births increase and as the births increase, the population increases. In B11 as the population increases the deaths increase, but as the deaths increase, the population decreases.

B3 represents the water demand management feedback loop, also given in Figure 4.2. As the total water demand increases, the water stress index increases. If the water stress index is too high, investment in water demand management will be required. Investment in water demand management will, ultimately, lead to a decrease in total water demand.

Water is required to sustain economic growth, therefore as the GDP increases, so does the total water demand. This is demonstrated in B10. As the GDP increases, total water demand increases and therefore the water use increases. An increase in water use leads to a decrease in available water stock and the less the available water stock, the less the GDP will be.

B9 represents the causal relationship between available water stock and water use. The greater the water use, the less the available water stock. The less the available water stock, the less the water use.

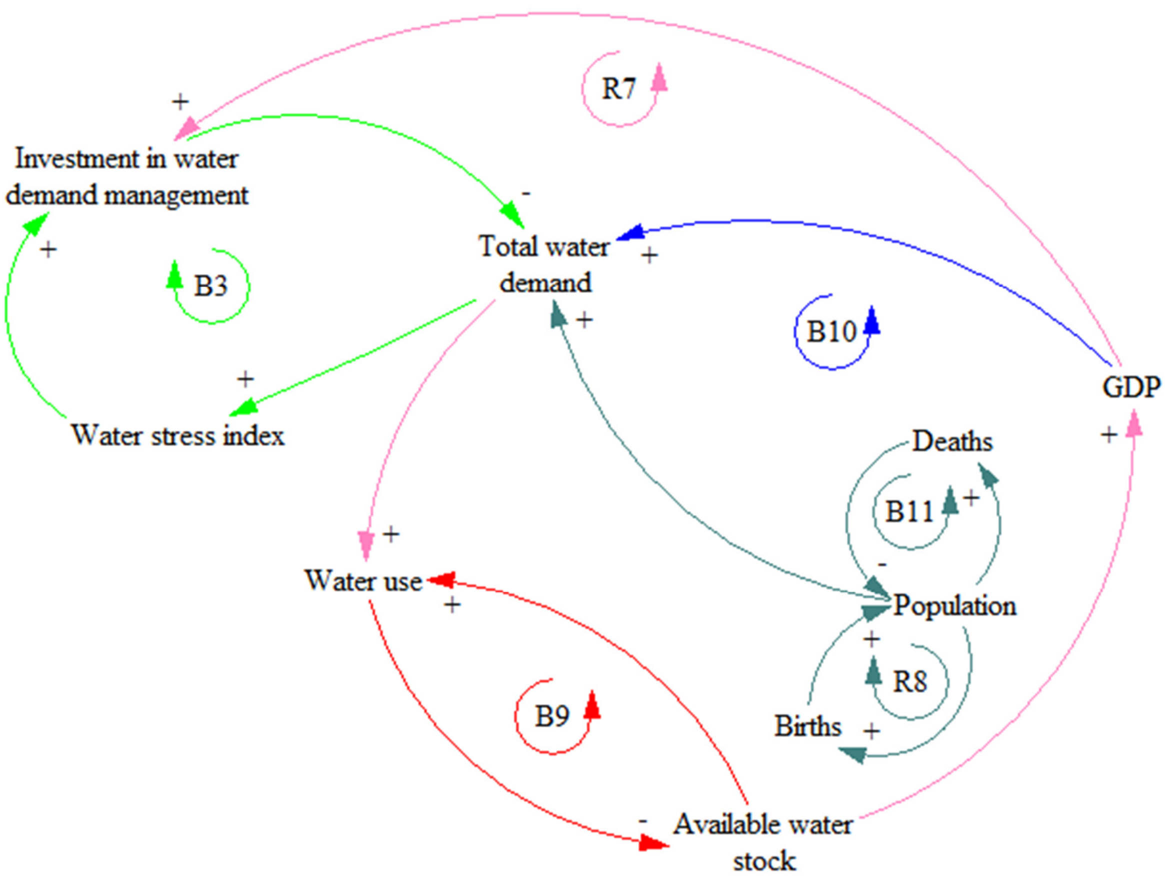

Figure 4.7: Water demand CLD

R7 consists of all of the variables within loop B10, with the addition of investment in water demand management. As the GDP increases, the investment in water demand management will increase. This results in a decrease in total water demand and therefore also in water use. The less the water use, the greater the available water stock will be. And finally, the greater the available water stock, the greater the GDP will be.

Although both water use and water demand are given in the CLD, only water demand was modelled in the dynamic model. The reason water use is included in the CLD is to demonstrate the difference between water demand and water use. The water demand may drive water use, but water use cannot exceed the total water supply, whereas demand can.

4.3.6 Combined water sector CLD

The combined water sector CLD given in Figure 4.8 is a combination of all the CLDs from Figure 4.3 to Figure 4.7. The combined CLD illustrates the interactions between the demand CLD and the supply CLDs. As was discussed in Section 4.3.4, the total water demand is increased by four water sources, namely surface water, groundwater, recycled water and desalinated water.

In Section 4.3.5, it was seen that the main drivers of water demand are population, GDP, investment in water demand management and water used by the electricity sector. Population drives water demand because people require water to survive, therefore more people require more water. Population growth also results in growth in agriculture. Another driver for agriculture, as well as for mining and bulk industries, and afforestation, is GDP because a growing GDP is an indicator of a growing economy, which results in the expansion of these sectors. These sectors require water to operate, therefore an increase in these sectors results in an increase in total water demand. Water demand management reduces the total water demand by educating the population about responsible water use, as well as through the replacement of non-functional water meters and the installation of flow limiting devices. The greater the investment in demand management, the lower the total water demand will be. The water used by the electricity sector, the drivers of which can be seen in Figure 4.12, and the electricity used by the water sector are the key variables that link the water sector and the electricity sector.

The available water stock and the water stress index are both affected by the water supply and demand. The available water stock is the water available for use. Water demand is conceptual in this CLD, whereas water use is the actual amount of water used. This is done to demonstrate that though the total demand can be larger than the total supply, the actual amount of water used cannot be greater than the supply. Only the total water demand is modelled in the dynamic model. The water stress index is an indicator that shows the water stress experienced by the Western Cape Province and is determined by dividing the total water demand by the total water supply. The water stress index will, therefore, increase as the total water demand increases.

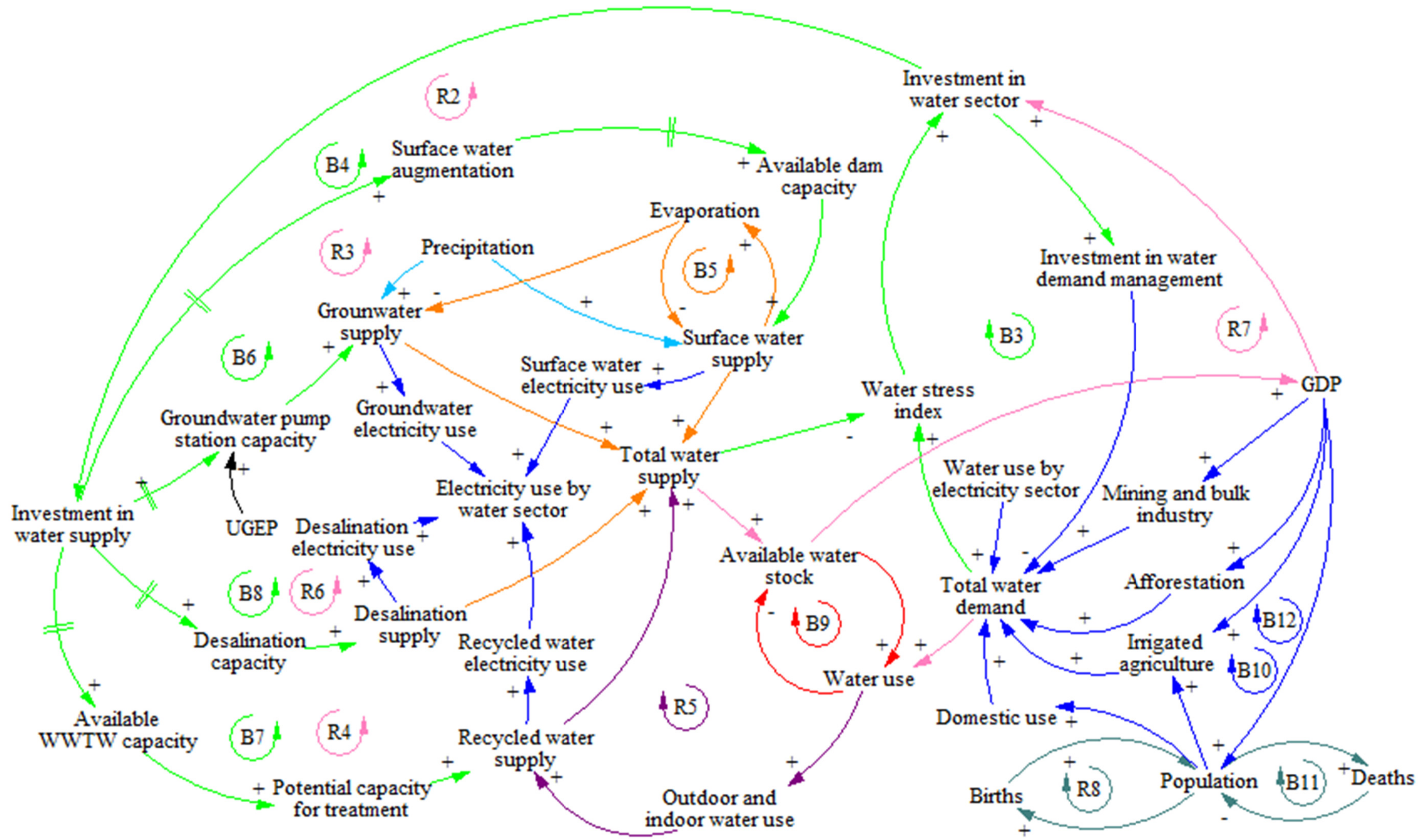

Figure 4.8: Water sector CLD

The combination of the various CLDs results in another balancing loop. B12 indicates that as the GDP increases, the population increases. This is because there would be more funds available to sustain life. The greater the population, the greater the domestic water use and, therefore, the greater the total water demand. The greater the total water demand, the greater the total water use. An increase in water use causes a decrease in available water stock. This finally results in a decrease in GDP. Although the link between GDP and population is given in the CLD, it is not modelled in the dynamic model because the exact mathematical equation to represent this connection is unknown.

4.3.7 Electricity sector CLDs

Electricity generation capacity expansion

The CLD for electricity generation capacity is presented in Figure 4.9 and consists of one balancing loop. B1, which also appears in Figure 4.2, demonstrates how the demand for electricity drives the need for electricity to be generated. The total electricity demand results in a need for electricity generation and therefore increases the gap between electricity demand and supply. As this gap increases, the investment in electricity capacity should increase because more electricity capacity is required to meet the demand. An increased investment in electricity capacity yields an increase in installed electricity capacity. There is, however, a delay between investment and the new capacity supplying power to the grid because of the time it takes to plan and implement these types of projects. The increased electricity capacity results in increased electricity generation. This ultimately results in a decrease in the gap between electricity supply and demand. The short-term solution to closing the demand and supply gap is to import electricity from other provinces. Therefore, until the new electricity generation capacity is commissioned, the amount of imported electricity also increases when the demand and supply gap increases. This is as a result of the delay between investment and commissioning. Importing electricity, although necessary in the short-term, is often expensive and compromises the electricity security of the Western Cape Province because it is dependent on the policies implemented by other local and provincial governments. The total electricity demand is driven by a number of factors as can be seen in Figure 4.11.

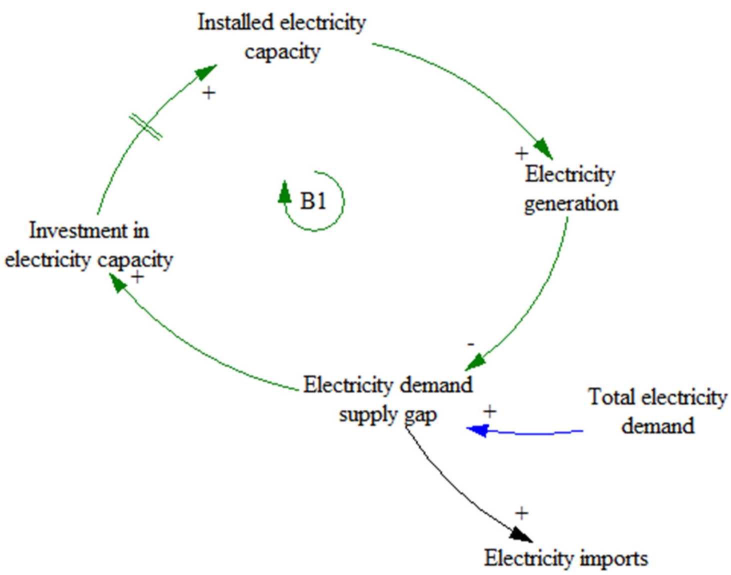

Figure 4.9: Electricity generation capacity expansion CLD

The CLD given in Figure 4.9 is a general CLD for electricity generation capacity and can be applied to all the different electricity generation technologies. In the dynamic model the different technologies were, however, modelled separately.

Electricity generation capacity decommissioning

The installed capacity decreases over time because electricity generation technologies only have a finite operational life. The CLD for the decommissioning of electricity generation capacity is illustrated in Figure 4.10 and consists of one balancing loop. B13 demonstrates how increasing installed electricity capacity results in an increased electricity capacity retirement rate, which reduces the installed electricity capacity. The time delay seen between the installed capacity and the retirement rate is determined by the operational life of the installed capacity.

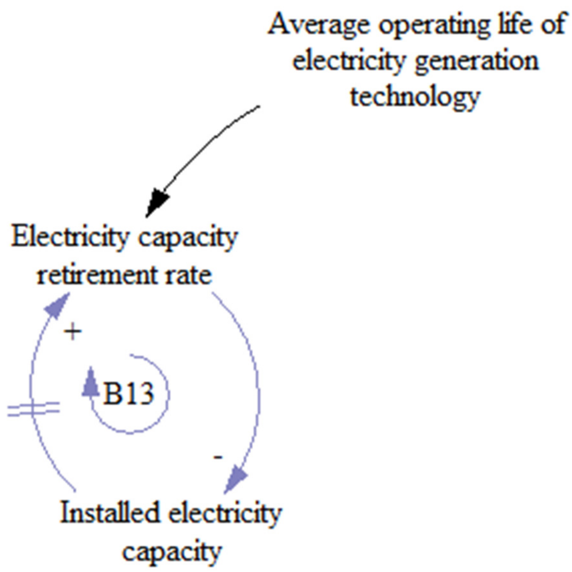

Figure 4.10: Electricity generation capacity decommissioning CLD

As with the CLD in Figure 4.9, this CLD can be applied to various electricity generation technologies. The type of technology will determine the time delay between installation and decommissioning as different technologies will have different average operating lifespans.

Electricity demand

It is assumed that electricity demand is influenced by five main factors, as can be seen in Figure 4.11. As the population increases, the demand for electricity also increases because more people need more electricity. The basic CLD for population is not shown here because it is illustrated in Figure 4.7. An increase in GDP results in an increase in total electricity demand. GDP is an indicator of the strength of the economy, so an increasing GDP indicates a growing economy, which means the various sectors within the economy, such as industries, are growing. As these sectors grow, their electricity demand also increases. An increasing GDP per capita indicates that personal income is on the rise allowing residents to, possibly, increase their electricity usage, thereby increasing the total electricity demand. An increase in electricity price decreases the electricity demand. This is because an increase in electricity price causes an increase in personal and business expenditure, which may result in users lowering their electricity consumption to lower their expenses. Electricity price is presented as an exogenous variable because it is greatly dependent on government policies rather than on a fixed set of variables. An increase in electricity used by the water sector results in an increase in total electricity demand.

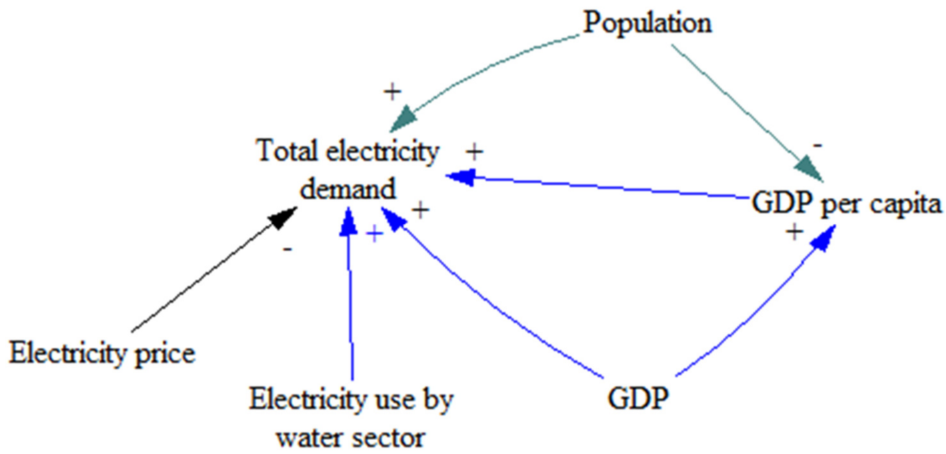

Figure 4.11: Electricity demand CLD

Electricity sector combination CLD

The CLDs discussed in this section thus far can be combined to produce the electricity sector CLD as given in Figure 4.12. The interaction between B1 and B13 is illustrated, as well as the effect of B1 on water use and air emissions. The water used by the electricity sector and the electricity sector air emissions can be used to determine the impact of the electricity sector on the environment.

The greater the electricity generation, the more water is used by the electricity sector. The amount of water used is highly dependent on the types of electricity generation technology installed, as each technology has its own rate of water consumption. An increase in water consumption by the electricity sector has the potential to affect other sectors within the economy. If the electricity sector's water demand were to increase, it could place constraints on water supply, thereby affecting industries that have a lower priority position for water supply than the electricity sector. The total water use for electricity consumption variable is included to demonstrate that electricity imports also require water for generation. This is important to take note of because even if the impact of electricity use in the Western Cape Province on the Province's water resources is not very large, electricity use in the Western Cape Province may have a significant impact on water resources in the rest of South Africa. This variable can be used as an indicator for this impact.

An increase in electricity generation will result in an increase in air emissions. Operating power stations release greenhouse gases and the amount of air emissions depends on the electricity generation technology. A region which uses electricity, in this case the Western Cape Province, is responsible for the greenhouse gases emitted during the generation of that electricity, even if it is generated in a different region. The air emissions in the CLD in Figure 4.12, therefore, include emissions produced by electricity generated in the Western Cape Province, as well emissions produced to generate the imported electricity. Greenhouse gas emissions do not only have an effect locally, but can impact areas far away from the source. Therefore, the total air emissions of the Western Cape Province's electricity consumption need to be accounted for in order to assess the environmental impact of the Province's electricity sector.

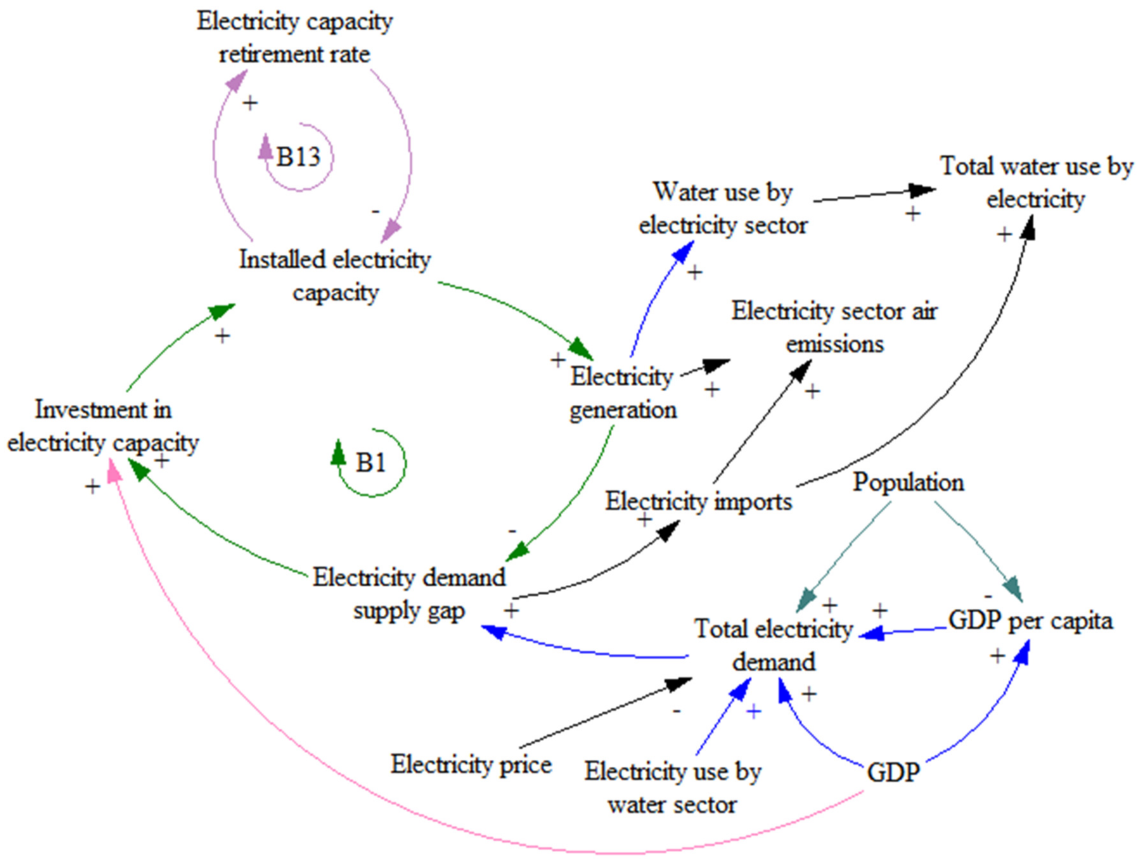

Figure 4.12: Electricity sector CLD

4.4 Dynamic model

The development of the conceptual model was described in the previous section and in this section the development of the dynamic model from the conceptual model is discussed. The WeCaEWN model consists of a number of sub-models, which each represent a sector or component of the energy-water nexus. The purpose of each sub-model is given, as well as a description of the sub-models' structures, including the main variables and relationships that make up the structures. Diagrams of the models can be seen in Appendix A and the equations used for the relationships between variables can be seen in Appendix B. It must be noted that this phase requires accurate historical data and it was found that historical data with regards to the Western Cape Province's energy-water nexus is scarce. However, the data that is available was enough to replicate the historical behaviour of the system, as is discussed in Section 4.5, and predict future trends. The lack of data may result in the answers obtained from the simulations being less exact, but the generated pattern predictions are accurate enough to provide insight into the investigated problem and possible solutions.

4.4.1 Dynamic modelling basics

It is beneficial to develop a dynamic computer simulation model because it allows for the dynamic issues that exist within the system to be further investigated. The simulation model contains more information than the conceptual model and can be used to simulate various model experiments (Maani & Cavana, 2007). It is possible to develop a dynamic model without first constructing the CLDs, but the Western Cape Province's energy-water nexus is a complex problem. It is for this reason that the CLDs in Section 4.3 were constructed and used to develop the dynamic model.

Stock and flow diagrams (SFD) are an essential characteristic of a system dynamics model. Three main variable types exist in SFDs namely: stocks, flows and auxiliary variables. An example of a simple SFD can be seen in Figure 4.13.

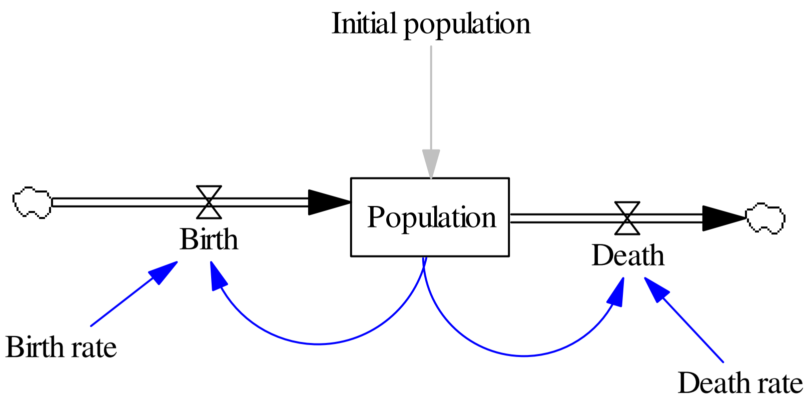

Figure 4.13: Stock and flow diagram for population size

Stocks are accumulated quantities, such as population in Figure 4.13. The flows are the changes that occur to the stock over time. Flows can either increase or decrease a stock. In Figure 4.13, the births (r_b) flow increases the population (P) stock and the deaths (r_d) flow decreases the population stock. The dynamic influence of the flows on the stock can be represented by the following equation:

$$P(t) = P(t_0) + \int_{t_0}^{t_n} [r_b - r_d]dt \qquad (4.1)$$

Auxiliary variables are all other variable types, including constants, graphical relationships and behavioural relationships. The purpose of the auxiliary variables is to break the complex flow equations into simpler components, thus making the model more transparent and easier to understand (Maani & Cavana, 2007). The birth rate and death rate in Figure 4.13 are examples of auxiliary variables.

The dynamic model requires the collection of more detailed information and data. Once the computer simulation model has been developed it must be validated to provide confidence in the model.

4.4.2 Model settings

The software used to construct and simulate the model was Vensim DSS (Ventana Systems, 2013). The time unit specified in the VENSIM model settings was set to years and the Euler method was used for numerical integrations. The model time step was set to 0.0625 years and the results were saved per year. The time step is the delay between iterations of the model's calculations and must be chosen so that the time interval is evenly divisible by the time step. The time horizon for the simulation was 40 years, starting in 2001 and ending in 2040.

4.4.3 Water supply resources

The Western Cape Province's water supply resources are divided into three sub-models. These sub-models are linked in the total water supply and demand sub-model, which is discussed in Section 4.4.4. The water supply resource sub-models are:

i. Surface water and groundwater sub-model
ii. Waste water sub-model
iii. Desalination sub-model

Surface water and groundwater sub-model [9]

The surface water and groundwater resources of the Western Cape Province are presented in this model. Both the surface water supply and the groundwater supply are modelled as auxiliary variables. There are four SFDs present in this sub-model. These are the dam capacity SFD, the additional dam capacity due to investment SFD, the pump station for groundwater capacity SFD and the additional pump station capacity due to investment SFD. These affect the surface water supply and groundwater supply. The dam capacity (DC) stock is dynamically altered by annual dam construction (r_{dc}) and dam depreciation (r_{dd}). The dam capacity SFD can therefore be presented by the following equation:

$$DC(t) = DC(t_0) + \int_{t_0}^{t_n} [r_{dc} - r_{dd}]dt \tag{4.2}$$

The dam capacity limit is equal to the sum of the capacities of the Western Cape Province's dams. If any investment in surface water occurs, the additional dam capacity due to investment is added to the dam capacity limit. The total capacity of the Western Cape Province's dams has changed over time and these changes are included in the model. The Berg River dam was completed in 2009 and added an additional 127.1 million m^3 to the total capacity (Pienaar, 2015). The raising of the Clanwilliam dam wall is a project that has been underway for a number of years and aims to raise the dam wall by 15 m, thereby increasing the dam capacity by 206 million m^3. This project was to be completed by 2016, but a number of setbacks have resulted in the expected date of completion to be moved to 2020 (Engineering News, 2015).

[9] The surface and groundwater sub-model was originally presented as part of WeCaWaRM, but was altered for use here (Pienaar, 2015)

The additional dam capacity due to investment (ADCI) stock is influenced by the increase in dam capacity due to investment (r_{idc}) flow. The increase in dam capacity due to investment is determined by investment in surface water, which is discussed in Section 4.4.5. The equation for the additional dam capacity due to investment SFD is:

$$ADCI(t) = ADCI(t_0) + \int_{t_0}^{t_n} [r_{idc}]dt \qquad (4.3)$$

The surface water supply is a function of the indicated dam capacity and the water that can potentially enter the dams. The potential water to enter the dams is determined by considering the amount of percolation, evaporation and runoff in the Western Cape Province. The runoff is affected by the mean annual precipitation, the total provincial land and the fraction of rainfall that is converted to runoff. Pienaar (2015) determined the average annual precipitation using historical data and used a 12.1% rainfall to runoff conversion. The total provincial land is calculated in the Provincial Land sub-model, described in Section 4.4.7.

The pump station for groundwater capacity (PC) stock is influenced by pump station construction (r_{pc}) and pump station depreciation (r_{pd}). This SFD is given as:

$$PC(t) = PC(t_0) + \int_{t_0}^{t_n} [r_{pc} - r_{pd}]dt \qquad (4.4)$$

The maximum available pump station capacity is set equal to the UGEP of the Western Cape Province, which is 1049.3 million m^3/annum. The UGEP is a management restriction placed on the amount of water that may be extracted and is based on a set maximum permissible water level drawdown. Only approximately 30% of the UGEP in South Africa is being used and it is assumed that this is the same for the Western Cape Province. The pump station capacity limit is therefore set to 30% of the UGEP in the dynamic model. Additional pump station capacity due to investment is added to the pump station capacity limit.

The groundwater supply is calculated using the indicated pump station capacity and the possible available groundwater. It is assumed that if the amount of water entering the dams is greater than the dam capacity, the water that overflows recharges the groundwater. The groundwater is also recharged by rainfall that percolates into the ground. The possible available groundwater is, therefore, the sum of the possible groundwater from dam overflow and the possible rainfall to become groundwater.

The additional pump station capacity due to investment (APCI) stock and the increase in pump station capacity due to investment (r_{ipc}) flow can be represented by the following equation:

$$APCI(t) = APCI(t_0) + \int_{t_0}^{t_n} [r_{ipc}]dt \qquad (4.5)$$

The increase in pump station capacity due to investment is determined by the investment in pump station capacity, which is discussed in Section 4.4.5.

***Waste water sub-model*[10]**

The Western Cape Province's waste water system is presented in this sub-model. Recycled water is produced by treating waste water in the waste water treatment works (WWTW). The recycled water supply is modelled as an auxiliary variable in this sub-model. The indicated WWTW capacity and the amount of available waste water determine the recycled water supply. These are dependent on the WWTW capacity SFD, the additional WWTW capacity due to investment SFD, and the potable water SFD. The WWTW capacity (WC) stock's dynamic behaviour is affected by the annual WWTW construction (r_{wc}) and WWTW depreciation (r_{wd}) flows. The SFD can be represented by the following equation:

$$WC(t) = WC(t_0) + \int_{t_0}^{t_n} [r_{wc} - r_{wd}]dt \tag{4.6}$$

According to GreenCape (2017), the Western Cape Province's total WWTW capacity is 1031 ML/day and this is used for the WWTW capacity limit. In 2012, only 79.13% of the capacity was being used, but by 2017, 87% of this capacity is being utilized (Department of Water Affairs, 2012a; GreenCape, 2017). This is included in the model as the variable "Fraction of WWTW capacity being used".

The additional WWTW capacity due to investment (AWCI) stock is influenced by the increase in WWTW capacity due to investment (r_{iwc}) flow. The additional WWTW capacity is added to the capacity limit. The equation for the additional WWTW capacity due to investment SFD is:

$$AWCI(t) = AWCI(t_0) + \int_{t_0}^{t_n} [r_{iwc}]dt \tag{4.7}$$

The potable water (PW) stock is influenced by the potable water inflow (r_{pwi}), outflow for domestic use (r_{dom}) and unaccounted for water (UAW) in the treatment system (r_{uaw}). The SFD can be presented by the following equation:

$$PW(t) = PW(t_0) + \int_{t_0}^{t_n} [r_{pwi} - r_{dom} - r_{uaw}]dt \tag{4.8}$$

The rate of potable water inflow is dependent on the total water supply. The total water supply is available for potable water, should it be required, because it is assumed potable water would be given the highest priority with regards to water allocation. The UAW refers to water that is lost due to leaks caused by poor maintenance and infiltration, and the average percentage of UAW is 37% (Department of Water Affairs, 2012a, 2013). The outflow for domestic use is dependent on the domestic and municipal water demand. This auxiliary variable is calculated in the water demand and supply sub-model discussed in Section 4.4.4.

Water from sewage treatment facilities or industrial waste water discharge is typically used to produce recycled water. This potential water for treatment is presented in the model as waste water as a result of outdoor and indoor use. On average, 70% of water used by a residential unit becomes

[10] The waste water sub-model was originally presented as part of WeCaWaRM, but was altered for use here (Pienaar, 2015)

waste water and industrial consumers have a waste water producing consumption of 90% (City of Cape Town, 2010).

BAU desalination sub-model

This sub-model represents the desalinated water that is produced in the Business as Usual (BAU) scenario. The existing desalination plants and desalination added as part of scenario testing were separated into different sub-models because the values of the variables associated with the different systems, for example energy use, are not the same. Furthermore, the purpose of this dynamic model is to determine the impact of implementing different desalination technologies in the Western Cape Province, therefore it was deemed appropriate to separate the new desalination system from the existing systems.

For the BAU scenario, very little of the Western Cape Province's water supply is obtained from desalination. Desalination water supply is calculated as an auxiliary variable and is dependent on the desalination capacity SFD. The desalination capacity (DSC) stock is dynamically influenced by the desalination capacity increase (r_{dsc}) inflow and the desalination plant depreciation (r_{dsd}) outflow. The equation for the SFD is:

$$DSC(t) = DSC(t_0) + \int_{t_0}^{t_n} [r_{dsc} - r_{dsd}]dt \tag{4.9}$$

The desalination capacity limit is set equal to the total desalination capacity that exists in the Western Cape Province, which is 24.9 ML/day.

4.4.4 Water supply and demand[11]

This sub-model represents the Western Cape Province's water demand, as well as the total water supply. In Section 4.4.3, the water supply resource sub-models were discussed. The water supplies from each of these sub-models are summed in the water supply and demand sub-model to determine the total water supply, which is an auxiliary variable.

The total water demand is an auxiliary variable, which is dependent on production water demand and domestic water demand. Production water demand is influenced by the following SFDs: the irrigated agriculture water demand (IA); afforestation water demand (AF); and mining and bulk industry water demand (MI). The total water requirement for electricity generation, which is discussed in Section 4.4.10, also impacts the production water demand. The non-domestic demand sectors, not including the electricity sector, are dependent on the growth factor of that sector. The equations for the non-domestic demand SFDs are:

$$IA(t) = IA(t_0) + \int_{t_0}^{t_n} [r_{ia}]dt \tag{4.10}$$

[11] The water supply and demand sub-model was originally presented as part of WeCaWaRM, but was altered for use here (Pienaar, 2015)

$$AF(t) = AF(t_0) + \int_{t_0}^{t_n} [r_{af}]dt \tag{4.11}$$

$$MI(t) = MI(t_0) + \int_{t_0}^{t_n} [r_{mi}]dt \tag{4.12}$$

Pienaar (2015) determined that the growth factor for agriculture and forestry is 1.6 % and the growth factor for mining and bulk industries is -0.17%. These growth factors were determined using the GDP growth of each sector. Other factors, such as climate change and standards of living, may also affect water demand. These, however, were excluded from the model because Pienaar (2015) found that literature confirms that GDP is an appropriate guideline to use for future water demand growth patterns.

Water demand data for the Western Cape Province is scarce, therefore, the initial water demands used in the model are the water requirements for 2000, as it was assumed that these values would be similar for 2001. The water requirements per sector in 2000 are given in Table 4.3.

Table 4.3: Western Cape Province water requirements per sector in 2000 (Department of Water Affairs & Forestry, 2004)

Sector	Water requirement (million kg/year)
Irrigated agriculture	1 488 000
Afforestation	21 000
Mining and bulk industries	9 000
Domestic	529 000

The domestic water demand is dependent on two factors, namely total population and water demand per capita. The total population is calculated in the population sub-model discussed in Section 4.4.14. The water demand per capita (WDC) stock is reduced by the decrease in water demand per capita (r_{dwdc}) flow, which is a result of the implementation of water demand management. The SFD is given as:

$$WDC(t) = WDC(t_0) + \int_{t_0}^{t_n} [-r_{dwdc}]dt \tag{4.13}$$

The Western Cape Province's total population was 4 524 334 in 2001 and the domestic water demand was 529 000 million L/year in 2000 (Department of Water Affairs & Forestry, 2004; City of Cape Town, 2012). Assuming the domestic water demand was similar in 2001, the per capita water demand for 2001 can be calculated and is equal to 320 L/person/day.

A minimum water demand per capita is set to ensure the water demand per capita does not decrease below the minimum amount that can be achieved by water demand management alone. The limit is set to 110 L/person/day, which is the actual average water demand per capita in the Western Cape Province when irresponsible water use and water losses are not taken into account (Department of Water Affairs, 2011).

The water stress index, as well as the water supply demand deficit, are calculated in this sub-model. The supply demand deficit (WSDD), as the name indicates, is the difference between the water supply (WS) and demand (WD). The water stress index (WSI) is used to indicate how stressed a region's water sector is. It is calculated by dividing the demand by the supply. The equations for these calculations are given:

$$WSDD(t) = WS(t) - WD(t) \tag{4.14}$$

$$WSI(t) = \frac{WD(t)}{WS(t)} \tag{4.15}$$

4.4.5 Water sector investments

The water sector investments sub-model determines the amount of money invested in the water sector based on the water stress index. The decisions to invest in water conservation/water demand management (WC/WDM) and in water supply are made independently, although both are based on the water stress index.

A water stress index greater than one indicates that the water demand is greater than the supply. As a result, a high water stress index indicates that intervention in the form of investment in the water sector is required. The water stress index dictates what fraction of the Western Cape Province's GDP (WDMF) is invested in WC/WDM. Consequently, investment in WC/WDM (WDMI) is driven by both the water stress index and the Western Cape Province's GDP (WCGDP). The investment in WC/WDM is then divided by the cost of water savings per capita (CWSC) to calculate the water savings per capita (WSC). This is then used in the water supply and demand sub-model to determine the water demand per capita, as discussed in Section 4.4.4. The equations used for determining the investment in WC/WMD and water savings per capita are:

$$WDMI(t) = WDMF\big(WSI(t)\big) * WCGDP(t) \tag{4.16}$$

$$WSC(t) = \frac{WDMI(t)}{CWSC} \tag{4.17}$$

Values from the WC WSS Reconciliation Strategy Status Report for April 2016 were used to determine the cost of water savings per capita. The total water savings due to WC/WDM from 2007 to 2014 was divided by the total investment in WC/WDM for the same time period. This gives the cost of water savings, which was then divided by the average population for this time period to give an estimate of the cost of water savings per capita. The final value is equal to 127 273 R/kg/person.

The Western Cape Government can invest in water supply and thereby decrease the water stress index. The fraction of the GDP invested in water supply (WSF) would be prescribed according to the water stress index. The investment in water supply (WSI) is a function of the water stress index and the Western Cape Province's GDP. Policies determine the new capacity limit of each supply source (NCL). The required new capacity (RNC) for each source is the difference between the new capacity limit and the additional capacity due to investment (ACI). The required investment in new capacity (RINC) for each supply source is calculated multiplying the required capacity by the capital cost per kilogram of new capacity (CPKG). The capital cost depends on the supply source and technology used. These calculations can be seen in the following equations:

$$WSI(t) = WSF\big(WSI(t)\big) * WCGDP(t) \tag{4.18}$$

$$RNC(t)_i = NCL_i - ACI(t)_i \tag{4.19}$$

$$RINC(t)_i = RNC(t)_i * CPKG_i \tag{4.20}$$

The total required investment in new water supply capacity (TRIWS) is the sum of the required investment in capacity for each supply source. This is used to determine what fraction of the actual investment (IF) will be used for each supply source. The investment fraction and the investment in water supply determine the investment in new capacity for each supply source (INCS). These equations are as follows:

$$TRIWS(t) = \sum RINC(t)_i \tag{4.21}$$

$$IF(t)_i = \frac{RINC(t)_i}{TRIWS(t)} \tag{4.22}$$

$$INCS(t)_i = IF(t)_i * WSI(t) \tag{4.23}$$

The investment in new capacity is used in the appropriate sub-model to determine the increase in capacity due to investment for that supply source.

It must be noted that for the BAU scenario, no investment is made in either WC/WDM nor in water supply. Any changes in the WC/WDM or water supply are introduced using exogenous variables because the decisions to make these changes have already been made and are therefore independent of the model results.

4.4.6 Electricity requirements of the water sector

This sub-model represents the electricity used by the water sector and consists of one SDF, which represents the electricity consumption of water supply. The total electricity requirement for each water supply resource (ERWR) is dependent on the water supplied by the resource (WSR) and the electricity requirement of that resource per kilogram of water supplied (ERWK). This calculation can be seen in the equation below:

$$ERWR(t) = ERWK * WSR(t) \tag{4.24}$$

The different water supply resources have different electricity requirements. Data on what the exact electricity requirements of the water sector in the Western Cape Province is could not be obtained, therefore typical values were used from Marsh (2008). These values compare well with values obtained from Buckely et.al. (2011), who conducted a life cycle analysis on the eThekwini urban water system, which is situated in Durban, South Africa, and recorded the electricity consumption of different water supply resources. It is assumed that similar technology is used in the eThekwini urban water system as is used in the Western Cape Province. The electricity requirements used in the dynamic model can be seen in Table 4.4.

Table 4.4. Electricity requirements for different water supply resources (Marsh, 2008; Buckley, Friedrich & Blottnitz, 2011)

Water supply resource	Electricity requirement (kWh/kL)
Surface water	0.1
Groundwater	0.1
Recycled water	0.4
Desalination	3

The total electricity requirement for water supply is the sum of the electricity requirements for each resource. The accumulated electricity consumption for water supply (ECWS) stock is increased by the annual electricity consumption for water supply (r_{ecws}) flow, which is equal to the total electricity requirement for water supply. This SFD is used as an indicator to assess the impact of the water sector on the electricity sector and can be represented by the following equation:

$$ECWS(t) = ECWS(t_0) + \int_{t_0}^{t_n} [r_{ecws}]dt \qquad (4.25)$$

The total electricity requirement for water supply is used in the electricity demand sub-model discussed in Section 4.4.8.

4.4.7 Provincial land[12]

The Western Cape Province's land use is represented by this sub-model and consists of six SFDs. These stocks are livestock land (LL), settlement land (SL), invasive alien species land (IL), conservation land (CL), agricultural land (AL) and other land (OL). These SFDs are represented by the following equations:

$$LL(t) = LL(t_0) + \int_{t_0}^{t_n} [r_{ol} - r_{lo}]dt \qquad (4.26)$$

$$SL(t) = SL(t_0) + \int_{t_0}^{t_n} [r_{os}]dt \qquad (4.27)$$

$$IL(t) = IL(t_0) + \int_{t_0}^{t_n} [r_{sao} - r_{ro}]dt \qquad (4.28)$$

$$CL(t) = CL(t_0) + \int_{t_0}^{t_n} [r_{oc}]dt \qquad (4.29)$$

[12] The provincial land sub-model was originally presented as part of WeCaGEM (Musango et.al., 2015)

$$AL(t) = AL(t_0) + \int_{t_0}^{t_n} [r_{oa} - r_{ao}]dt \tag{4.30}$$

$$OL(t) = OL(t_0) + \int_{t_0}^{t_n} \left[\left(\sum r_{lo}, r_{ro}, r_{ao}\right) - \left(\sum r_{ol}, r_{os}, r_{sao}, r_{oc}, r_{oa}\right)\right] dt \tag{4.31}$$

Where: r_{ol} represents the rate at which other land becomes livestock land; r_{lo} is the rate at which livestock land becomes other land; r_{os} is the rate at which other land becomes settlement land; r_{sao} is the rate at which invasive species spreads to other land; r_{ro} is the rate at which land affected by invasive alien species is rehabilitated; r_{oc} is the rate at which other land becomes conservation land; r_{oa} is the rate at which other land becomes agricultural land; and r_{oa} is the rate at which agricultural land becomes other land.

4.4.8 Electricity demand[13]

This sub-model represents the electricity demand of the Western Cape Province. The different consumers are divided into five sectors, namely industry, residential, transport, commercial and agricultural. The electricity demand of the water sector is considered separately from these sectors because it is the key link between the water and electricity sectors and is discussed in Section 4.4.6. The demand of each sector is dependent on a number of drivers as was discussed in Section 2.1.3. Oosthuizen (2015) used three main drivers for electricity demand, namely; electricity price, GDP per capita and population. GDP per capita is used as a proxy indicator for personal income, which is a driver for residential electricity demand according to Ziramba (2008). The drivers of each sector's electricity demand are presented in Table 4.5.

Table 4.5: Drivers of electricity demand by sector (Oosthuizen, 2015)

Sector	Drivers
Residential	Electricity price; GDP per capita; Population
Commercial	Electricity price; GDP
Industrial	Electricity price; GDP
Transport	Electricity price; GDP per capita; Population
Agricultural	Electricity price; GDP

The total electricity demand, the main output of this model, is the sum of the sectoral demands, including the total electricity requirements for water supply.

4.4.9 Electricity supply resources[14]

The Western Cape Province's electricity supply technologies are divided into five separate sub-models with each sub-model representing a different technology. The sub-models are:

[13] The electricity demand sub-model was originally presented as part of WeCaGEM, but was altered for use here (Oosthuizen, 2015)

[14] The electricity supply sub-models were originally presented as part of WeCaGEM (Oosthuizen, 2015)

i. Nuclear sub-model
ii. Gas power sub-model
iii. Pumped storage sub-model
iv. Wind (onshore) sub-model
v. Solar PV sub-model

Each sub-model has the same general structure and therefore only the general structure will be discussed. The sub-model consists of four stocks, namely capacity in planning, capacity under construction, operating capacity and decommissioned capacity. The capacity in planning (CIP) is increased by the project start (r_{pr}) flow and decreased by the project construction start (r_{pcs}) flow. The project construction start flow increases the capacity under construction (CUC) stock. The plant commissioning (r_{pc}) flow decreases the capacity under construction stock while increasing the operating capacity (OC) stock. This is then decreased by the plant decommissioning (r_{pd}) flow, which simultaneously increases the decommissioned capacity (DC) stock. The equations for these stocks can be seen below:

$$CIP(t) = CIP(t_0) + \int_{t_0}^{t_n} \left[r_{pr-}\, r_{pcs}\right] dt \tag{4.32}$$

$$CUC(t) = CUC(t_0) + \int_{t_0}^{t_n} \left[r_{pcs-}\, r_{pc}\right] dt \tag{4.33}$$

$$OC(t) = OC(t_0) + \int_{t_0}^{t_n} [r_{pc-}\, r_{dc}] dt \tag{4.34}$$

$$DC(t) = DC(t_0) + \int_{t_0}^{t_n} [r_{pd}] dt \tag{4.35}$$

The installed operating capacity of a technology determines the amount of electricity generated by the technology. This is represented by an auxiliary variable. The specific capacity factor of a technology, which is a measure of the efficiency of the technology, also affects the electricity generation of the technology. The different amounts of electricity generated by each technology is summed together to determine the total electricity supply. This occurs in the electricity technology share sub-model discussed in Section 4.4.12.

4.4.10 Water requirements of electricity sector

This sub-model represents the water required to generate electricity in the Western Cape Province and is very similar to the electricity requirements of the water sector discussed in Section 4.4.6. The water requirements for each electricity generation technology (WRET) is a function of the electricity generated by that technology (EGT) and the amount of water required per kWh of electricity generated (WRETK). This calculation is given in the following equation:

$$WRET(t) = WRETK * EGT(t) \tag{4.36}$$

The total water requirement for electricity generation is the sum of all the water requirements for each technology. A stock is used to measure the accumulated water consumption for electricity generation (WCEG), which is increased by the annual water consumption for electricity generation (r_{wceg}) flow. The SFD is given as:

$$WCEG(t) = WCEG(t_0) + \int_{t_0}^{t_n} [r_{wceg}]dt \tag{4.37}$$

The annual water consumption is the sum of the total water requirements for electricity generated in the Western Cape Province and the water consumption of imported electricity. The water consumption of imported electricity may not affect the Western Cape Province's water sector directly, but it does affect the water resources in other parts of the country. It is, therefore, an important variable to measure to determine the environmental impact of the Western Cape Province's electricity consumption. The total water requirement for electricity generation in the Western Cape Province is used in the water supply and demand sub-model to determine the province's total water demand, as is discussed in Section 4.4.4.

The water consumed for electricity generation in the Western Cape Province is not much and greatly depends on the electricity generation type. According to Eskom (2016a), the Koeberg Nuclear Power station only uses seawater and therefore consumes no freshwater. The gas power plants in the Western Cape Province use open cycle gas turbines (OCGT), which use very little water. These could possibly be converted to combined cycled gas turbines (CCGT), which consume much more water, but this was not considered in the dynamic model. Electricity generated using wind and solar energy currently consume no water. Pumped storage uses water to produce electricity, but its water consumption is negligible. The generation of imported electricity consumes large amounts of freshwater because most imported electricity is generated using coal-fired power stations. The water consumption for each technology type is given in Table 4.6.

Table 4.6: Water consumption of different electricity generation technologies in the Western Cape Province (Eskom, 2008b, 2016a)

Technology type	Freshwater consumption (L/kWh)
Nuclear	0
Gas power	0.00024
Wind	0
Solar	0
Pumped storage	0
Imported	1.26

4.4.11 Electricity air emissions[15]

This sub-model, which determines the air emissions of the Western Cape Province's electricity sector, has the same structure as the water requirements of the electricity sector sub-model

[15] The electricity sector air emissions sub-model was originally presented as part of WeCaGEM (Oosthuizen, 2015)

discussed in Section 4.4.10. The air emissions are expressed in terms of equivalent CO_2 emissions. The CO_2 emissions of each technology is determined by multiplying the electricity generated by each technology by the emissions produced by that technology per kWh of electricity generated. The sum of the emissions of each technology is equal to the total CO_2 emissions from electricity generation in the Western Cape Province. This is added to the CO_2 emissions from electricity imports to determine the total annual air emissions (TAAE) flow, which increases the accumulated air emissions for electricity generation (AAEE) stock. The SFD is given as:

$$AAEE(t) = WCEG(t_0) + \int_{t_0}^{t_n} [r_{wceg}] dt \tag{4.38}$$

4.4.12 Electricity technology share[16]

This sub-model determines the contribution that each electricity generation technology makes to the Western Cape Province's electricity supply and electricity generation capacity. The total electricity generation is calculated, as well as the renewable electricity generation share.

The electricity demand supply gap is calculated in this sub-model. The demand supply gap is equal to the difference between the Western Cape Province's total electricity supply and total electricity demand. The electricity that cannot be met by the Western Cape Province's supply must be imported, therefore the imported electricity is equal to the demand supply gap. The demand supply gap influences the investment decisions in the electricity sector investment sub-model discussed in Section 4.4.13.

4.4.13 Electricity sector investments[17]

The investment allocations to different electricity generation technologies is determined in this sub-model. A new electricity supply factor determines the demand for new electricity supply of each technology, which is the proportion of the electricity demand supply gap that should be filled by that technology type. The required capacity for each technology is calculated using the demand for new electricity supply of that technology, as well as its capacity factor. The required capacity for each technology is then used to determine the cost of installing that capacity.

The total required investment to meet the demand will far exceed the annual amount of capital available for electricity supply investment. The fraction of the total investment in capacity that is invested into each technology annually is, therefore, determined by dividing the total required investment in each technology by the total required investment in electricity generation capacity. It must be noted that the total investment in capacity refers to the annual capital that is available for investment in electricity supply whereas the total required investment in capacity refers to the investment in electricity supply required to meet the total demand. The total investment in capacity is dependent on the Western Cape Province's GPD and the policies that dictate what fraction of the

[16] The electricity technology share sub-model was originally presented as part of WeCaGEM (Oosthuizen, 2015)

[17] The electricity sector investments sub-model was originally presented as part of WeCaGEM (Oosthuizen, 2015)

GDP is invested in electricity supply. The investment made in each technology determines the capacity of each technology entering the planning phase as discussed in Section 4.4.9.

4.4.14 Population[18]

The population of the Western Cape Province is represented in this sub-model. The population (P) stock is increased by the births (r_b) flow and the net migration (r_{nm}) flow and decreased by the deaths (r_d) flow. The population is categorised according to gender and age group, for example child bearing age, school age, adult age etc. The equation for the population SDF is:

$$P(t) = P(t_0) + \int_{t_0}^{t_n} [r_b + r_{nm} - r_d] dt \tag{4.39}$$

Factors that affect the population growth rate include economic growth and urbanisation. The effects of these factors are included in the model through the auxiliary variables "effect of education on proportion using contraceptives" and "effects of economic conditions on fertility rate". The effect of economic growth on life expectancy is also taken into account.

4.4.15 GDP[19]

The Western Cape Province's GDP is calculated in this sub-model. External projections were used to determine the South African GDP over the simulated time horizon and the Western Cape Province's GDP is modelled as a fraction of the national GDP. The Western Cape GDP and the per capita GDP are outputs of this sub-model and are used in a number of the other sub-models.

4.4.16 Education[20]

The purpose of this sub-model is to simulate the movement of the population through the education system. The sub-model consists of three interacting stocks, namely: students, young adult literate population and literate adult population. The students (S) stock is increased by the school entrance rate (r_{er}) flow and decreased by the school drop-out rate (r_{sdo}) flow and the school completion rate (r_{cr}) flow. The completion rate increases the young adult literate population (YLP) stock, which is decreased by the maturation (r_m) flow. The literate adult population (LAP) is increased by maturation and decreased by the literate adult deaths (r_{lad}) flow. The SFDs can be represented by the following equations:

$$S(t) = S(t_0) + \int_{t_0}^{t_n} [r_{er} - r_{sdo} - r_{cr}] dt \tag{4.40}$$

$$YLP(t) = YLP(t_0) + \int_{t_0}^{t_n} [r_{cr} - r_m] dt \tag{4.41}$$

[18] The population sub-model was originally presented as part of WeCaGEM (Musango et.al., 2015)

[19] The GDP sub-model was originally presented as part of WeCaGEM (Musango et.al., 2015)

[20] The Education sub-model was originally presented as part of WeCaGEM (Musango et.al., 2015)

$$LAP(t) = LAP(t_0) + \int_{t_0}^{t_n} [r_m - r_{lad}]dt \tag{4.42}$$

The school entrance rate is mainly affected by government expenditure on the schooling system and household income. Additionally, government expenditure has an effect of the school drop-out rate. The purpose of this sub-model is to determine the level of adult literacy, which is used in the population sub-model.

4.4.17 Scenario testing

The scenario testing sub-model consists of the five SFDs required as part of policy analysis, namely: additional desalination capacity limit; additional desalination capacity in planning; additional desalination capacity due to investment; accumulated desalination running costs; and accumulated brine produced by desalination. The additional desalination capacity limit (ADSCL) stock is dynamically influenced by the increase in desalination capacity limit (r_{idscl}). The additional desalination capacity in planning (ADSCP) stock is influenced by the increase in desalination capacity due to investment (r_{idsc}) and is decreased by the additional desalination construction (r_{adc}) flow. This increases the additional desalination capacity due to investment (ADSC) stock. The accumulated desalination running costs (ADRC) stock is increased by the annual running costs for desalination (r_{rcd}) flow and the accumulated brine produced by desalination (AB) stock is increased by the annual brine produced by desalination (r_b) flow. The SFDs can be represented by the following equations:

$$ADSCL(t) = ADSCL(t_0) + \int_{t_0}^{t_n} [r_{idscl}]dt \tag{4.43}$$

$$ADSCPc(t) = ADSCP(t_0) + \int_{t_0}^{t_n} [r_{idsc} - r_{adc}]dt \tag{4.44}$$

$$ADSC(t) = ADSC(t_0) + \int_{t_0}^{t_n} [r_{iadc}]dt \tag{4.45}$$

$$ADRC(t) = ADRC(t_0) + \int_{t_0}^{t_n} [r_{rcd}]dt \tag{4.46}$$

$$AB(t) = AB(t_0) + \int_{t_0}^{t_n} [r_b]dt \tag{4.47}$$

This sub-model is described in further detail in Chapter 5, which covers scenario planning and testing.

4.5 Validation

Validation is an important part of any modelling process as it ensures confidence in the “soundness and usefulness” of the model with respect to its purpose (Forrester & Senge, 1979). According to Barlas (1996), no single definition of model validity has been established and system dynamics models, in particular, are often criticised for relying on subjective and qualitative validation methods. The process of establishing confidence in a system dynamics model is dispersed throughout the modelling process, but the majority of the validation tests are performed after the construction of the model, before the policy analysis (Barlas, 1994).

Currently, no formal validation methodology exists for system dynamics modelling (Barlas, 1996; Musango, 2012). Barlas (1996) found that the validity of a system dynamics model relies greatly on the validity of its internal structure and that, once this has been established, the ability of the model to reproduce the behaviour of the real system must also be evaluated. The validation process, therefore, requires a combination of quantitative and qualitative tests and Barlas (1996) separates the required tests into two types, namely structural tests and behaviour tests.

4.5.1 Structural validity tests

Forrester & Senge (1979) suggest five tests that can be performed to ensure the validity of the model's internal structure. The aim of these tests is to determine whether the model's structure accurately represents the structure of the real system. These same tests are included in the formal model validation process suggested by Barlas (1996). The five tests are:

i. Structure verification test
ii. Parameter verification test
iii. Extreme conditions test
iv. Boundary adequacy test
v. Dimensional consistency test

Structure verification

In order to verify the model's structure, it must be compared with the structure of the system it represents. To pass this test, the model's structure cannot contradict what is known about the real system's structure (Forrester & Senge, 1979). Each relationship that exists within the model must be taken individually and compared to the real system. Maani & Cavana (2007) suggest first comparing the CLDs of the conceptual model to the real system to ensure that they correspond with the real system's structure. One should then ensure that the dynamic model structure corresponds with the conceptual model structure.

The problem articulation phase, discussed in Section 2.1 and Section 4.2, ensured that valuable insight was gained into the Western Cape Province's energy-water nexus. This was done using a review of the available literature and various government documents. The conceptual model was constructed using the available data and was then used to construct the dynamic computer simulation model. The model's structure is similar to the structure of the model that was constructed by Tidwell et al. (2009) for decision support for integrated water-energy planning. The model's structure was further verified by being reviewed by people who have experience in building system dynamics models, including the author's supervisors.

Parameter verification test

This test requires that the model parameters be verified against observations of the real system and is done in the same way that the model structure is compared to the system's structure (Forrester, 1994). The parameter must be evaluated against knowledge of the real system, both numerically and conceptually. Conceptual confirmation is the ability to identify elements in the real system that correspond to the model parameters and numerical confirmation ensures that the value of the parameter is estimated with enough accuracy that it falls within a plausible range (Forrester, 1994; Barlas, 1996).

The parameter values that were used in the Western Cape Energy-Water Nexus model were obtained from documents that contain knowledge of the system, including numerical data. If exact values for a certain parameter could not be found, plausible values were obtained from other sources of literature.

Extreme conditions test

For this test, the model equations are subjected to certain extreme conditions and the plausibility of the results are assessed using the anticipated outcomes of the real system under the same conditions (Barlas, 1996). There are two purposes for performing this test. The first is to uncover flaws that exist in the model structure and reveal variables that may have been omitted. Often, a proposed formulation may look plausible until it is subjected to the extreme conditions test and it is found that the system does not respond as expected. The second purpose is to enhance the model so that it is more useful for analysing policies. A model that only behaves plausibly under normal conditions can only be used for policies that will not cause the system to operate outside historical ranges of behaviour and thus limits the usefulness of the model. A model that has been subjected to numerous extreme conditions tests can, however, be used confidently for polices that will cause the system to behave outside the range of historical behaviour.

A number of extreme conditions tests were conducted on the model, but only four of the tests are discussed here. These tests ensure that the water and electricity sectors interact as expected. For the first test, the dam capacity was increased by tenfold. As expected, this resulted in a decrease in the water stress index, but an increase in the water sector electricity requirement. The impacts of the change in dam capacity on the water stress index and water sector electricity requirement have the correct magnitudes. In the second test, the water requirement of the gas power supply was increased from that of OCGT to that of CCGT, which requires almost 7000 times more water. This caused the expected increase in the electricity sector water requirement. In the third test, a tenfold increase in the water sector electricity requirement was introduced. This was done by applying a step function, which multiplies the water sector electricity requirement between the years 2021 and 2030. This caused an increase in the total electricity requirement and an increase in the electricity demand and supply gap for the time the step function was introduced (i.e. between 2021 and 2030). The magnitudes of these increases were correct. A similar test was conducted on the electricity sector water requirement, except a 100 000 times increase was introduced. A step of this magnitude was required in order to see an effect on the total water demand. The result, as expected, was an increase in the total water demand and an increase in the water stress index for the time period for which the step function was introduced (i.e. between 2021 and 2030). The magnitudes of these increases were what would be expected from the real system. The conclusion is therefore that the results of extreme condition tests are similar to what would be expected from the real system under the same conditions. The figures that illustrate the results of these tests can be seen in Appendix C.

Boundary adequacy test

The purpose of this test is to ensure that all relevant structures are included in the model and that the model aggregation is appropriate. The model boundary must be chosen according to the purpose of the model. Therefore, the model must contain the structures that enable it to serve its purpose. This test requires that the criticisms of the model boundary must be able to unify with criticisms of the model purpose (Forrester, 1994).

The model boundaries and key variables, discussed in Section 4.3.1, were chosen so that the model could serve its purpose. Furthermore, the model boundary was reviewed by the author's supervisors, who have experience in the field of system dynamics.

Dimensional consistency test

This simple test requires dimensional analysis of the model's rate equations and entails checking that the dimensions of the rights-hand side and the left-hand side of each equation are consistent (Forrester, 1994; Barlas, 1996). A check for dimensional consistency is included in the Vensim software. When this function is used, any equations that have inconsistent dimensions are highlighted. This function was used throughout the construction of the Western Cape Energy-Water Nexus model to ensure that all equations have dimensional consistency.

4.5.2 Model behaviour tests

Once the model structure has been verified and validated, it is necessary to investigate the model behaviour results to ensure that the model sufficiently replicates the behaviour of the real system. Model behaviour tests are a further evaluation of the adequacy of the model structure (Forrester, 1994). Maani & Cavana (2007) suggest that the following model behaviour tests be used:

i. Behaviour reproduction test
ii. Behaviour anomaly test
iii. Behaviour sensitivity test

The same tests are described by Barlas (1996) and Forrester (1994).

Behaviour reproduction test

Barlas (1996) stresses that emphasis must be placed on pattern prediction rather than point prediction when conducting behaviour reproduction tests. This is because the purpose of system dynamics models is to conduct long-term policy analysis. These models are unable to produce accurate point predictions. For this test, the model results are compared to the available historical data.

Data for most of the system variables is scarce, therefore it was difficult to perform this test effectively. Some historical data does exist for total electricity demand, total electricity capacity and total water supply. The total electricity demand and electricity capacity was compared to data obtained from Statistics South Africa (2017b). The total water demand was also compared to data obtained from Statistics South Africa (2010). The model results for these variables correspond well to the available data and the output graphs can be seen in Appendix C. Only a limited number of variables could be tested like this due to the unavailability of data, which is a possible weakness of the model.

Behaviour anomaly test

During the construction and evaluation of a system dynamics model, the modeller may find that the model behaviour conflicts with the behaviour of the real system. The behavioural anomaly can be traced to the components of the model structure that are causing the behaviour. The model assumptions made with regards to this component can then be reviewed and altered to eliminate the anomaly (Forrester, 1994). Any anomalies that were found during the development of the model were eliminated and all assumptions that were made were reviewed by the author's supervisors to ensure the assumptions are valid. According to Forrester (1994), the behaviour anomaly test can also be used to justify particular model assumptions. This is done by showing that anomalous behaviour arises if the assumption is changed.

Behaviour sensitivity test

The purpose of this test is to determine how sensitive the model is to changes in parameter values. Confidence in the model is enhanced by ensuring it does not fail behaviour tests that were previously passed if a plausible change is made to model parameter values. If the model is sensitive to changes in certain parameters, it does not necessarily invalidate the model. It does, however, highlight possible weaknesses in the model (Forrester, 1994).

The behaviour sensitivity test was used to investigate the impact of parameters for which exact values for the system could not be found. The electricity requirements for the various water supply sources are an example of this. The values used in the model were not specifically for the Western Cape Province's water system, but were typical values from literature. Another parameter that was tested is the cost of water savings per capita. The behaviour sensitivity tests were conducted through the use of Monte Carlo simulations, which is a function that is available on Vensim. Maximum and minimum bounds for the variable are specified by the modeller and the results are given in confidence bounds. The model results are sensitive to changes in the electricity requirement of surface water, but not so sensitive to changes in the electricity requirements of the other water supply sources. This would be because the majority of the Western Cape Province's water is supplied from surface water. It was found that the model results are also sensitive to changes in the cost of water savings per capita. This indicates that the effectiveness of water demand management is highly dependent on the cost of water savings per capita. The graphs that are a result of the sensitivity tests can be seen in Appendix C.

4.6 Conclusion: Modelling

This chapter describes the process of developing the Western Cape Energy-Water Nexus model. The modelling methodology was described, followed by the development of the conceptual and dynamic models. Lastly, the model validation and verification were described. Chapter 5 will discuss the development of the scenarios that were simulated using the energy-water nexus model, as well as the analysis of the results obtained from the simulations.

CHAPTER 5: SCENARIO PLANNING AND MODELLING

This chapter represents the fourth phase of the system dynamics methodology in which the scenario planning and modelling occurs. In the first section, the development of the different scenarios is discussed. The purpose of the Western Cape Energy-Water Nexus model is to investigate the impact of different desalination technology systems on the nexus. Therefore, a different desalination technology system is implemented in each scenario. The discussion of the scenario development is followed by an analysis of the results of the scenario simulations. First, the BAU results are discussed in order to understand the predicted behaviour of the system when no intervention is implemented. This is followed by a comparison of the impact of each intervention scenario on the water sector and the electricity sector, as well as a comparison of the costs of each scenario.

5.1 Scenario development

It has been established that the Western Cape Province requires additional water supply to ensure that the growing water demand can be met. Desalination is considered a possible solution, but the Western Cape Government has stalled the implementation of a large-scale desalination system, because the process is energy-intensive, and the capital cost of a desalination plant is high. Advances in the research of desalination processes and technologies have resulted in a considerable decrease in the capital cost of the systems, as well as the development of technologies that are more energy efficient. The aim of simulating the different scenarios was to determine the impact different desalination systems would have on the Western Cape Province's energy-water nexus, and determine the costs associated with the different systems. The scenario development, therefore, required researching the available desalination technology types and the potential to combine desalination with renewable energy sources to improve energy efficiency.

Desalination is the process of producing freshwater from a saline source, in this case seawater. There are three categories of desalination technologies, namely: thermal technologies, membrane technologies, and ion exchange technologies (Voutchkov, 2012). There are a number of technology types that fall under each category, but for the purpose of this research only mature, commercially used technology types were considered.

5.1.1 Thermal desalination

Thermal desalination technologies use distillation to produce freshwater. The source water is heated to produce water vapour, which is then condensed into freshwater. This technology type has been widely used because the energy needed for water evaporation is not dependent on the salinity of the water, therefore this process is suitable for high-salinity water, such as seawater (Voutchkov, 2012).

Multi-stage flash (MSF) distillation is the most commonly used desalination technology type. The source water is fed to the system and is heated to a temperature of 90 ºC to 115 ºC then passed through a series of chambers, or stages. In each stage, a fraction of the water is flashed, which is the sudden evaporation of water due to a decreased pressure. Pure water evaporates, leaving the salt in the remaining liquid. The pressure is lower in each successive stage, resulting in further flashing and the system can have up to 45 stages (Ali, Fath & Armstrong, 2011). The resulting water vapour is condensed to product water on heat transfer tubes. Source water flows through the tubes and is heated by the transfer of latent heat from the condensing vapour. The brine stream, which is the high-salinity water that remains after successive flashes, is discharged from the system (Ali et al., 2011). A simple process flow diagram for MSF can be seen in Figure 5.1.

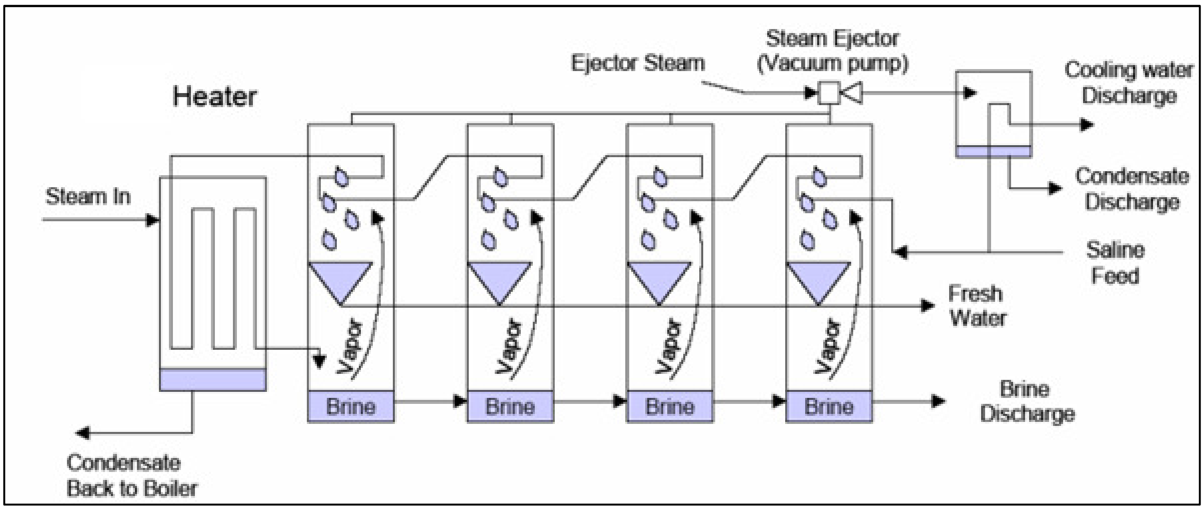

Figure 5.1: Multi-stage flash distillation process (German Aerospace Centre, 2007)

Multi-effect distillation (MED) is another thermal desalination technology and is gaining popularity over MSF because it is more energy efficient (German Aerospace Centre, 2007). In the MED process, source water is preheated in the upper sections of different chambers, or effects, to a temperature of 55 °C to 70 °C and sprayed onto the evaporator surface, usually heat exchanger tubes, of the effect to promote evaporation. The evaporation tubes in the first effect are heated using steam from a boiler. The vapour produced in the first effect is condensed to product water in the evaporation tubes of the second effect. The evaporation surface of each consequent effect is heated using the vapour produced in the previous effect. Each effect has a lower pressure than the preceding effect to promote evaporation and the process may consist of up to 16 effects. The vapour produced in the last chamber is condensed in a heat exchanger called the final condenser and is cooled using incoming source water (Wade, 2001; German Aerospace Centre, 2007; Voutchkov, 2012). The brine is discharged from the bottom of each chamber. The MED process can be seen in Figure 5.2.

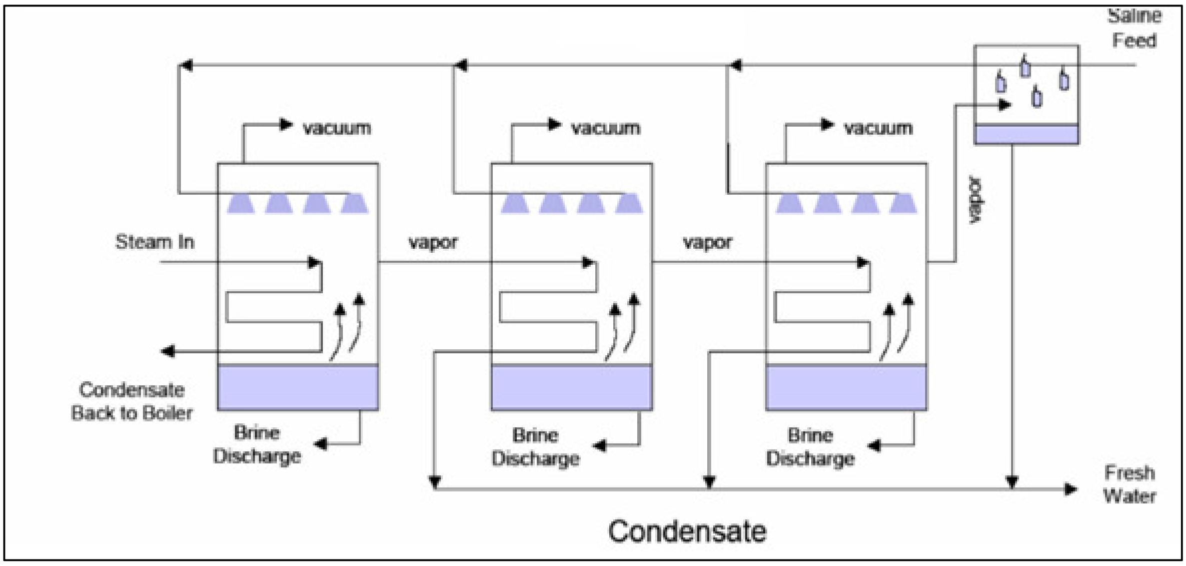

Figure 5.2: Multi-effect distillation process (German Aerospace Centre, 2007)

5.1.2 Membrane desalination

In membrane desalination, a semipermeable membrane is used to separate minerals from source water. Reverse Osmosis (RO) is the most commonly used membrane technology. Osmosis is the natural tendency of water to pass through a semipermeable membrane from a less concentrated to a more concentrated solution until osmotic equilibrium is attained. In RO, the process is reversed by applying pressure, using a high-pressure pump, to the more concentrated solution so that the osmotic pressure is overcome and water is forced through the semipermeable membrane to the less concentrated solution (German Aerospace Centre, 2007; Voutchkov, 2012). The semipermeable membrane allows water to pass through at a much higher rate than the constituents contained in the water, thus the salt ions are retained on the feed side. The salt is rejected from the system at a high pressure as a brine stream. A diagram of the RO process can be seen in Figure 5.3. RO membranes are sensitive to particulate accumulation and fouling and therefore pre-treatment of the feed water is required. Pre-treatment involves the removal of particulates from the feed water before it reaches the RO membranes. Post-treatment of the pure water is also required to adjust the pH levels of the water and return minerals that have been lost during the RO process (German Aerospace Centre, 2007; Voutchkov, 2012). Most of the energy consumed during the RO process is used for pressurising the feed water and the osmotic pressure that needs to be overcome is directly related to the salinity of the feed water. Therefore, the higher the salinity of the water, the higher the energy consumption of the process. Seawater desalination requires an operating pressure between 50 and 80 bar. This is high compared to the operating pressure of brackish water, which ranges from 10 to 15 bar, thus RO has been the preferred desalination method for brackish water (German Aerospace Centre, 2007). Important improvements in RO systems, however, have resulted in a continuous increase in the use of RO technology for seawater desalination (Ghaffour, Missimer & Amy, 2013).

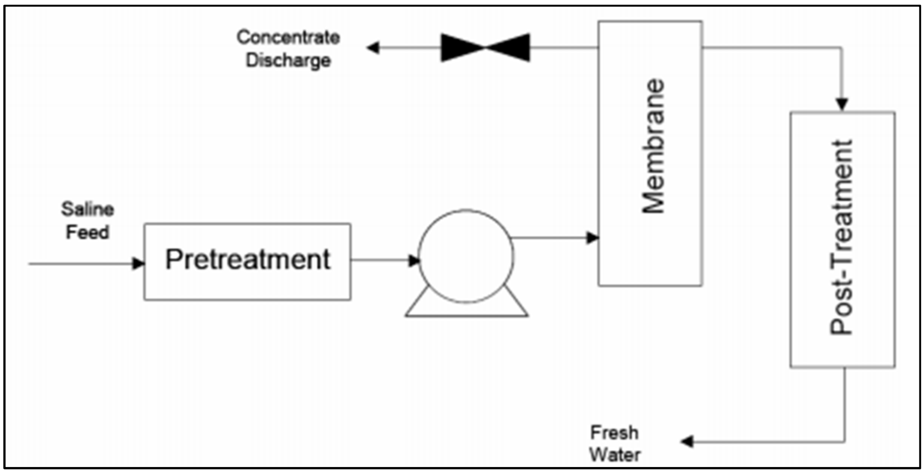

Figure 5.3: Reverse osmosis process (German Aerospace Centre, 2007)

5.1.3 Solar desalination

The commercial desalination technologies that have been described in the previous subsections all have the potential to be operated using indirect solar energy. The operating principle of indirect solar collection systems involves implementing the solar technology and the desalination plant as two separate sub-systems (Kalogirou, 2005). MSF and MED are thermal desalination technologies and therefore require solar thermal collectors as their energy source. Table 5.1 lists the different solar thermal collector types that have been used for desalination, including their operating temperatures and motion. RO is a mechanically driven technology. Therefore, it can be operated using solar thermal collectors combined with a heat engine that uses steam to drive the pump. RO can also be powered using solar energy that is converted to electricity (Ali et al., 2011).

Table 5.1: Solar thermal collector types (Ali et al., 2011)

Motion	Collector type	Indicative temperature range (°C)
Stationary	Flat plate collector (FPC)	30-80
	Evacuated tube collector (ETC)	50-200
	Compound parabolic collector (CPC)	60-240
Single-tracking	Compound parabolic collector (CPC)	60-300
	Parabolic trough collector (PTC)	60-300

Examples of solar thermal collectors that have been used commercially to provide the thermal energy required for the operation of an MSF desalination plant include FPC and PTC (Ali et al., 2011). Figure 5.4 shows how solar thermal collectors can be combined with the MSF process. The seawater feed is first preheated using the latent heat transferred from the condensing of the vapour to form product water. The feed water is then further heated in the solar collector before entering the first MSF stage. The solar collectors, therefore replace the feed heater seen in Figure 5.1. A disadvantage of MSF is that it requires precise pressure levels in each stage. Therefore, some transient time is required to establish steady state operating conditions. This makes MSF relatively unsuitable for operation using solar energy, unless a storage tank is used for thermal buffering (Kalogirou, 2005).

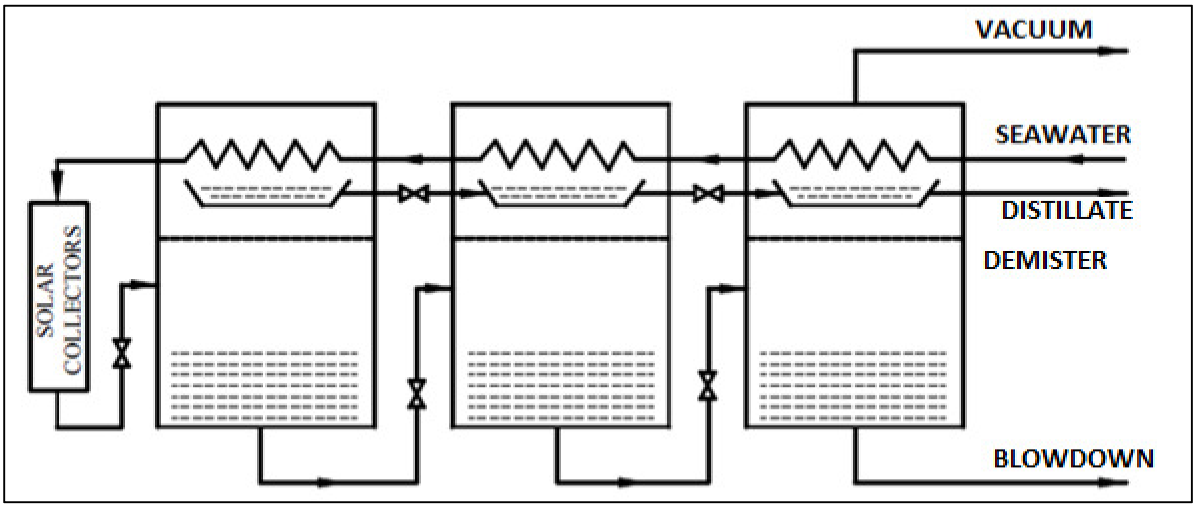

Figure 5.4: MSF process with solar collectors (Kalogirou, 2005)

Most commercial solar thermal desalination plants are based on MED. This is because the feed stream in MED is heated to a lower temperature than in MSF and MED consumes less energy (Ali et al., 2011). The majority of solar MED desalination plants are combined with either FPC, ETC, PTC or CPC (Kalogirou, 2005; Ali et al., 2011). It can be seen from Figure 5.5 that the solar collectors replace the boiler that is used to generate the steam needed to heat the evaporation tubes in the first effect. A type of MED technology called the multi-effect stack type operates at steady state between virtually 0% and 100% output. Unlike the MSF process, it therefore has no transient state, which makes it more suitable for solar energy applications (Kalogirou, 2005).

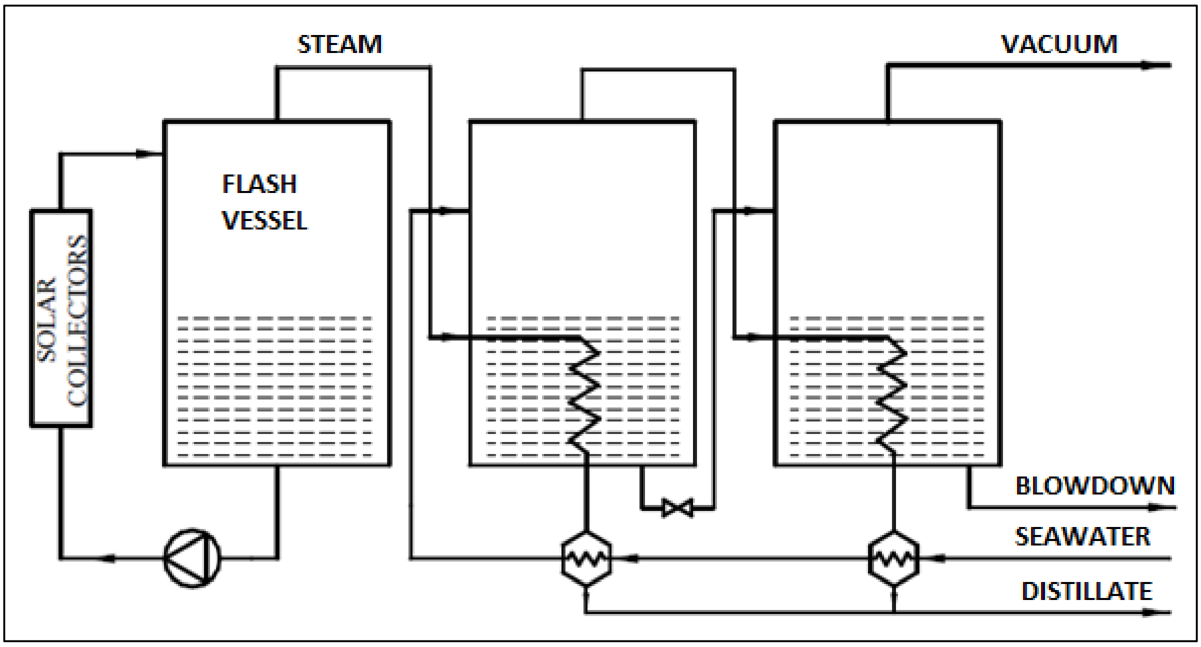

Figure 5.5: MED with solar collectors (Kalogirou, 2005)

RO systems can be operated using FPC combined with a heat engine, but the majority of commercial systems use photovoltaics (PV) panels. The high-pressure pumps are operated using electricity that is generated using solar energy through the use of PV panels (Kalogirou, 2005). Batteries can also be included in the system, but one study in Greece found that this did not significantly increase production. The cost of adding batteries can therefore not be justified (Ali et al., 2011).

5.1.4 Thermal desalination using waste heat

Many industrial processes produce vast quantities of waste heat that is not being utilised. This waste heat can provide the thermal energy required in thermal desalination processes. Maheswari, Murugavel & Esakkimuthu (2015) utilised the heat energy in the exhaust gas of an internal combustion engine for thermal desalination in an experimental analysis. Shih & Shih (2007) describe methods for using waste heat for thermal desalination. They used the waste heat in sulfuric acid produced in a sulphuric acid plant as their heat source. In their first configuration, the thermal energy from the sulphuric acid is used to heat water to a temperature of 97 °C. This hot water is then transferred to a flashing chamber and flashed to produce steam, which is used to evaporate the saline water in the first effect of the MED process. In the second configuration, the water that was heated using the sulphuric acid is used in the MSF process to heat the feed water in the feed water heater. The problem with using thermal waste heat for desalination is that the desalination plant must be constructed within close proximity of the plant that produces the waste heat.

5.1.5 Scenarios

The scenarios were used to determine the impact of different desalination systems on the Western Cape Province's energy-water nexus. A business as usual (BAU) scenario was simulated to determine the state of the nexus up until 2040; if no intervention is made and to provide a reference to which the intervention scenarios can be compared. Each intervention scenario represents the implementation of a different desalination system. It was decided that the difference between installing a thermal desalination technology and a membrane desalination technology should be investigated. Furthermore, it was decided that the impact of combining these desalination technologies with the available renewable energy sources must be investigated. For each scenario, investment in water supply is required.

Desalination technologies

The first step was to decide which desalination technologies to use for the scenarios. MED was chosen for the thermal technology because it has been used commercially and has been growing in popularity compared to MSF. Additionally, MED is more suited to solar energy applications than MSF. RO was chosen for the membrane technology because it is the only membrane technology that is available for large-scale use.

Energy sources

Once the desalination technologies had been chosen, the next step was to decide on the energy sources that would be used for desalination. MED and RO can be operated using electricity from the national grid. These scenarios were simulated to determine the impact of these technologies on the Western Cape Province's electricity sector and to provide a reference for comparison with the utilisation of renewable energy sources for desalination. MED is a thermal technology and can therefore use solar thermal collectors as an energy source. ETC is the most commonly used solar collector for MED and was therefore chosen for scenario testing. Waste heat can also be used as an energy source for MED. Furthermore, it is possible to use both solar energy and waste heat together for MED. RO can be operated using electricity generated from solar energy through the use of PV panels.

Location

The location of the desalination plant has to meet a number of requirements, namely: close proximity to the ocean; high solar radiation, if using solar technology; a source of waste heat, if using waste heat; close proximity to users; and large open plots of land. Saldanha Bay, located 105 km from Cape Town, meets all these requirements. This harbour town has an annual solar radiation that is similar to the rest of the Western Cape Province and is suited to PV applications. The *Arcelor Mittal Saldanha Works* is a steel plant situated close to Saldanha and can provide waste heat for the desalination plant. It was assumed that the steel works would still be operating by 2040. The flue gas from one of the steel plant's processes has a volume flow rate of 65 000 m^3/ h at a temperature of approximately 400 °C (Cohen, 2016).

Scenarios' descriptions

A summary of the scenarios that were investigated using the Western Cape Energy-Water Nexus model can be seen in Table 5.2. The scenarios that were simulated are: the business as usual scenario (BAU); implementing MED only (MED); implementing MED using thermal energy from the waste heat obtained from the *Arcelor Mittal Saldanha Works* (MED+WH); implementing MED using solar energy from ETCs (MED+ETC); implementing MED using waste heat and ETCs (MED+WH+ETC); implementing RO only (RO); and implementing RO with solar PV (RO+PV).

Table 5.2: Scenarios summary

Scenario	Investment in water supply	Desalination technology type	Thermal energy from waste heat	Solar energy
BAU	No	-	-	-
MED	Yes	MED	No	None
MED+WH	Yes	MED	Yes	None
MED+ETC	Yes	MED	No	ETC
MED+WH+ETC	Yes	MED	Yes	ETC
RO	Yes	RO	No	None
RO+PV	Yes	RO	No	PV

The following assumptions were made for all the intervention scenarios:

- The desalination plant capacity is equal to 205 000 m^3/day of freshwater produced.
- The fraction of the Western Cape GDP that is invested in water supply is dependent on the water stress index.
- 100% of the investment in water supply is invested in desalination.
- The additional investment in water supply starts in 2017.
- Maximum possible recovery is achieved for both desalination processes. The maximum recovery rate is equal to 50% for both processes, according to Mezher, Fath, Abbas & Khaled (2011).

All the variables associated with the different scenarios are in the scenario testing sub-model, which was briefly described in Section 4.4.17. The sub-model consists of five SFDs, namely: additional desalination capacity limit; additional desalination capacity in planning; additional desalination capacity due to investment; accumulated desalination running costs; and accumulated brine produced by desalination. The sub-model is set-up to produce accurate pattern predictions rather than point predictions because system dynamics models are unable to provide exact answers due to the uncertainties that exist in complex open systems. The additional desalination capacity limit stock is influenced by the increase in desalination capacity limit flow. This is dependent on the investment in desalination capacity and the capital cost of desalination per kilogram of capacity. The capital cost is different for each scenario and is given in Table 5.3.

Table 5.3: Capital cost of different scenarios (Ghaffour et al., 2013; Cohen, 2016; Open Energy Information, 2017)

Scenario	Capital cost for desalination technology (R/tonne desalination capacity)	Capital cost for thermal waste heat recovery (R/tonne desalination capacity)	Capital cost for solar technology (R/tonne desalination capacity)	Total capital cost for scenario (R/tonne desalination capacity)
MED	50.89	0	0	50.89
MED+WH	50.89	0.07	0	50.96
MED+ETC	50.89	0	2.69	53.58
MED+WH+ETC	50.89	0.07	2.69	53.65
RO	59.67	0	0	59.67
RO+PV	59.67	0	23.3	82.97

The additional desalination capacity in planning is influenced by the increase in desalination capacity due to investment, which is dependent on the investment in desalination. The additional desalination construction flow decreases the additional desalination capacity in planning stock while increasing the additional desalination capacity due to investment stock. This flow is influenced by the desalination commissioning delay, which is assumed to be equal to one year. The additional desalination capacity due to investment determines the water supply from additional desalination, which is added to the total water supply in the water supply and demand sub-model. The annual running costs for desalination increases the accumulated desalination running costs and is dependent on the water supply for additional desalination, the additional desalination electricity cost and the other operation and maintenance (O&M) costs, which can be seen in Table 5.4. The annual brine produced from desalination flow is dependent on the water supply from additional desalination and the water recovery of the desalination process. This flow adds to the accumulated brine produced by desalination stock. The capital costs and O&M costs were calculated using data from a number of sources and the calculations can be seen in Appendix D.

Table 5.4: Operation and maintenance cost of scenarios excl. electricity cost

Scenario	O&M cost for desalination technology (R/tonne water supplied)	O&M cost for solar technology (R/tonne water supplied)	Total O& M cost for scenario (R/tonne water supplied)
MED	3.17	0	3.17
MED+WH	3.17	0	3.17
MED+ETC	3.17	0.02	3.19
MED+WH+ETC	3.17	0.02	3.19
RO	4.36	0	4.36
RO+PV	4.36	0.02	4.38

The electricity requirement for additional desalination is calculated and is highly dependent on the desalination technology system. The thermal energy and electrical energy required is determined separately and the effect of the renewable energy sources is also included. The energy requirements for the different desalination technologies is given in Table 5.5. The energy requirements were obtained from Ghaffour et al. (2013) and the units were converted from kWh/m^3 to GWh/kg. A sample calculation can be seen in Appendix D.

Table 5.5: Energy requirements of desalination technology types (Ghaffour et al., 2013)

Desalination technology	Thermal energy (GWh/kg water supplied)	Electrical energy (GWh/kg water supplied)	Total energy (GWh/kg water supplied)
MED	5.5×10^{-9}	1.75×10^{-9}	7.25×10^{-9}
RO	0	3.5×10^{-9}	3.5×10^{-9}

The energy that can be obtained from each renewable energy source is presented in Table 5.6. The calculations for the determining these values can be seen in Appendix D. The energy from the solar sources is given in units of GWh/kg water supplied because the size of the solar field is dependent on the desalination plant capacity. The energy from waste heat, however, is given in units of GWh/year because the amount of waste heat is independent of the size of the desalination plant.

Table 5.6: Energy output of renewable energy sources

Source	Energy type	Energy	Unit
Solar ETC	Thermal	1.229×10^{-10}	GWh/kg water supplied
Waste heat	Thermal	28.215	GWh/year
Solar PV	Electrical	7.822×10^{-10}	GWh/kg water supplied

Additional model equations for scenario testing can be seen in Appendix D.

5.2 Scenario analyses results

The Western Cape Province needs additional water supply capacity to meet a growing water demand. Currently, the Western Cape Province's main source of water is surface water, but climate change could result in a decrease in the Western Cape Province's annual rainfall. This means that augmentation of the Western Cape Province's surface water supply system is not a feasible option. Seawater desalination is the main water supply source for many arid countries and has been considered as a possible supply source in the Western Cape Province for a number of years. The sustainability of a large-scale desalination system in the Western Cape Province must, however, be investigated. Seven scenarios – BAU, MED, MED+WH, MED+ETC, MED+WH+ETC, RO, and RO+PV – were simulated to determine the impact of different desalination systems on the Western Cape Province's water sector and electricity sector. A cost comparison of the scenarios was also completed.

The results of the scenarios are discussed in four subsections. The first subsection is an analysis of the BAU scenario, which was developed to investigate what would happen if desalination is not implemented. The results of this scenario were also used as basis to compare the results of the other scenarios. The second subsection analyses the impact of the various intervention scenarios on the water sector. This is followed by an analysis of the impact of the interventions on the electricity sector in the third subsection. The costs involved in each of the interventions are analysed in the fourth subsection. In each subsection, the key indicators for the sector discussed in that subsection are used to compare the different scenarios. Results are given in the form of graphs and tables. Additional results that may be relevant can be seen in Appendix E.

5.1.6 BAU scenario results

The BAU scenario assumes that no additional investment will be made in the water sector. The only interventions included in this simulation are from existing policies. Climate change is not considered in this scenario because it is an excluded variable, but it is something that should be considered in future research. The BAU scenario can be used to predict the growth in various areas of the Western Cape Province's energy-water nexus. The key variables discussed in this subsection are the water stress index, the electricity sector demand supply gap and the air emission from the Western Cape Province's electricity consumption. Figure 5.6 illustrates the predicted water stress index for the BAU scenario. The water stress index is dependent on two variables, namely total water demand and total water supply, both of which are also illustrated in Figure 5.6.

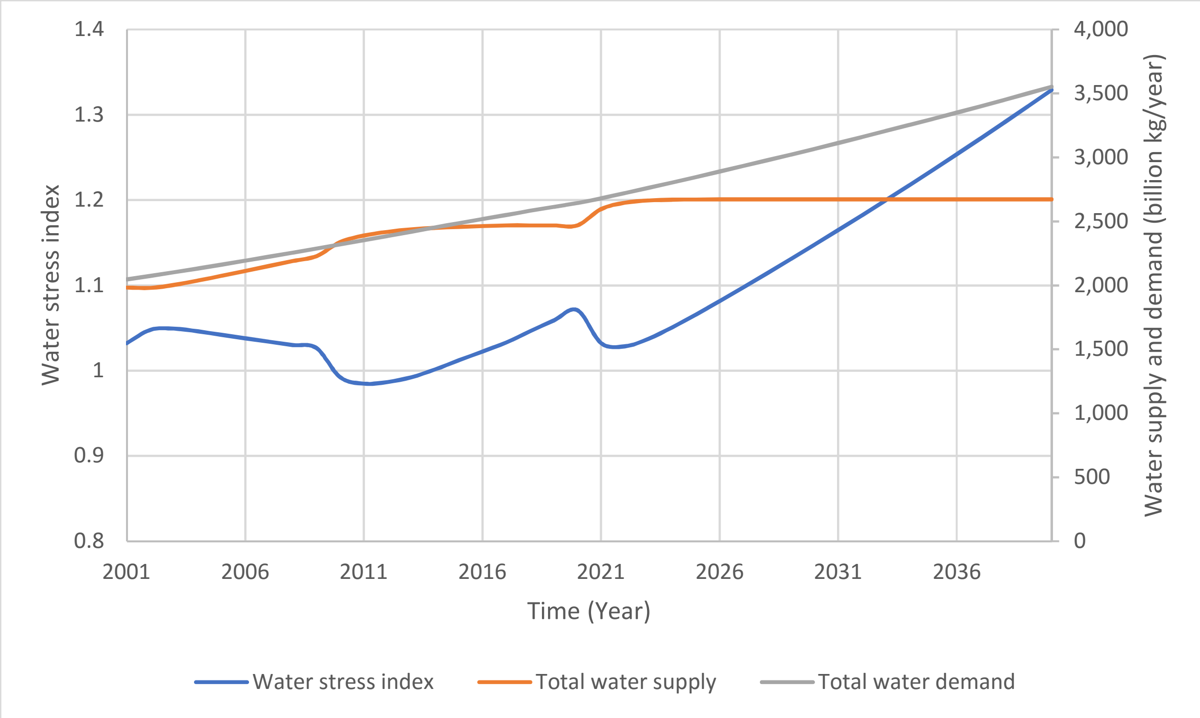

Figure 5.6: BAU scenario water demand and supply

Ideally, the water stress index should be equal to or less than one, meaning the available water supply is sufficient to meet the total water demand. It is important to note that the water demand represents the amount of water the Western Cape Province desires to use and not the actual water consumption. A water stress index above one therefore does not necessarily indicate that the Western Cape Province will be without water, but only that the Western Cape Province would like to use more water than is currently available. The higher the water stress index is, however, the more water stressed the area is and the more likely there is to be a water shortage.

It can be seen from Figure 5.6 that the water stress index has increased since 2001 and is expected to continue increasing in the future. This is due to a 34.8% growth in water demand between 2001 and 2040, which is caused by population growth and economic growth. For the instances where the water supply capacity increases, the water stress index sharply decreases. This happened in 2010 and is expected to happen again in 2020 when the Clan William dam wall raising is expected to be completed. After this, the water supply is not expected to increase further, resulting in a high water stress index of 1.33 by 2040. This is caused by a supply demand deficit of 880 billion kg of water. Unless the water supply capacity is increased, the Western Cape Province will experience extreme water shortages in the future. This is without considering the effects of climate change, which is likely to reduce the available surface water supply in the future.

Figure 5.7 illustrates the electricity demand and supply, as well as the resulting electricity demand supply gap, as predicted for the BAU scenario.

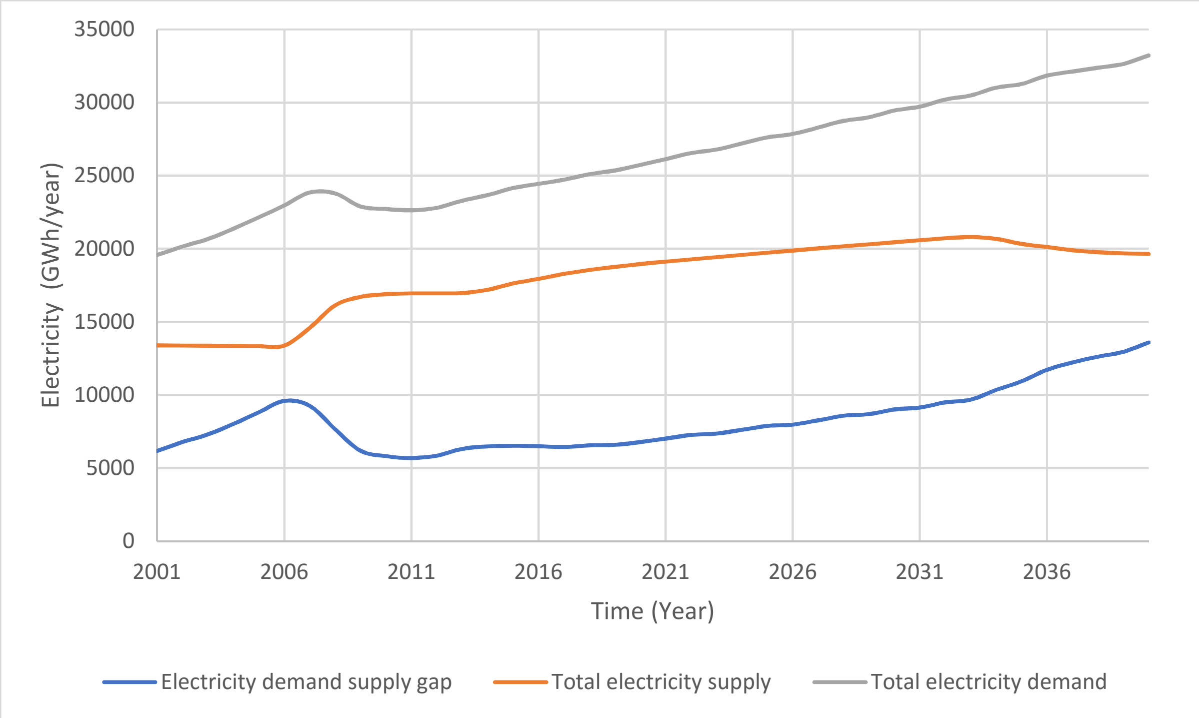

Figure 5.7: BAU scenario electricity demand and supply

Figure 5.7 shows that the electricity supply is expected to grow by 47% between 2001 and 2040. The majority of this growth, however, occurred in 2007 when the gas power plants were commissioned. The growth, caused mainly by an increase in renewable energy generation, is slower from 2007 onwards. The electricity demand, however, is expected to grow by 70% between 2001 and 2040 as a result of population growth and economic growth. This is a much higher growth rate than the growth rate for electricity supply. The result is an increasing electricity demand supply gap, and therefore an increasing amount of imported electricity. By 2040 the deficit between the demand and supply is expected to be 13 590 GWh. This is despite the Western Cape Government's intentions to reduce the Western Cape Province's dependency on imported electricity through the addition of renewable electricity generation capacity. The current plans to increase electricity generation capacity, as demonstrated by the BAU scenario, are not sufficient to reduce the demand supply gap.

Figure 5.8 illustrates the annual air emissions produced as a result of the Western Cape Province's electricity consumption as predicted for the BAU scenario. The air emissions are expressed in terms of equivalent CO_2 emissions. Figure 5.8 shows the plots for air emissions as a result of locally generated electricity, air emissions produced by the generation of the imported electricity and the total air emissions that result from the Western Cape Province's electricity consumption. The Western Cape Province is responsible for the air emissions released during the generation of the imported electricity even though the electricity is generated outside the Western Cape Province's borders.

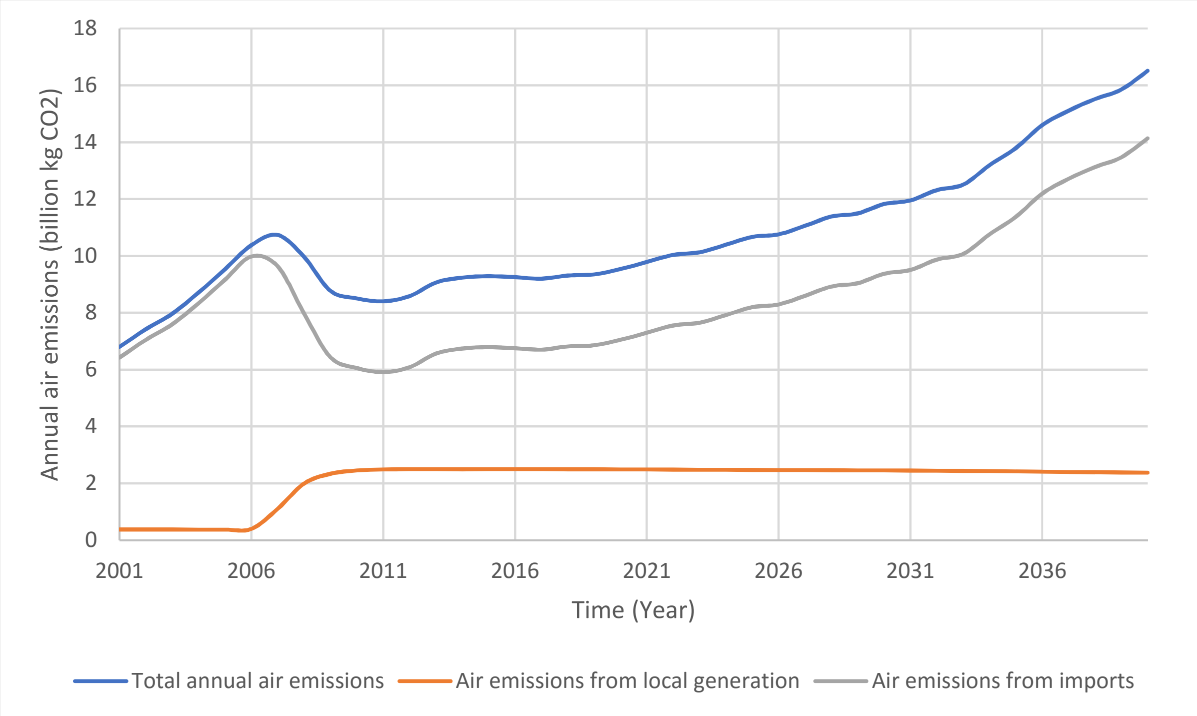

Figure 5.8: BAU scenario annual air emissions from electricity consumption

The majority of the total annual air emissions is caused by the imported electricity, as can be seen in Figure 5.8. This is because the imported electricity is mainly generated using coal-fired power stations, which produce large quantities of greenhouse gases. It can be seen that the emissions from locally generated electricity increase in 2007 with the commissioning of the gas power plants. The total air emissions, however, decrease significantly, which indicates that the gas power plants produce less greenhouse gases than is produced during the generation of the imported electricity. The emissions from local electricity generation is not expected to increase in the future. This is because, according to Western Cape Government's current plans, all additional electricity generation capacity will be from renewable energy technologies, which do not emit greenhouse gases. The total annual air emissions, however, is still expected to increase because of the increasing amount of imported electricity. The total annual air emissions could be reduced by further increasing the renewable energy generation capacity in the Western Cape Province. This, however, is not investigated in this research.

5.1.7 Water sector results

The purpose of implementing desalination is to increase the Western Cape Province's water supply. The scenarios must therefore be analysed to determine whether or not a single large-scale desalination plant is enough to ensure the future water demand can be met. Desalination is an energy intensive process, therefore the impact of desalination on the water requirement for electricity generation is also investigated. This is done to ensure the additional water consumption is not so significant as to render the implementation of a desalination plant unreasonable.

The predicted water supply from additional desalination for all the scenarios is illustrated in Figure 5.9. For all the scenarios, except the BAU scenario, it is assumed that the additional investment in water supply starts in 2017 and that the investment is only used for additional desalination capacity. The investment amount is a fraction of the Western Cape GDP and the fraction is determined by the water stress index. Therefore, the higher the water stress index, the greater the investment.

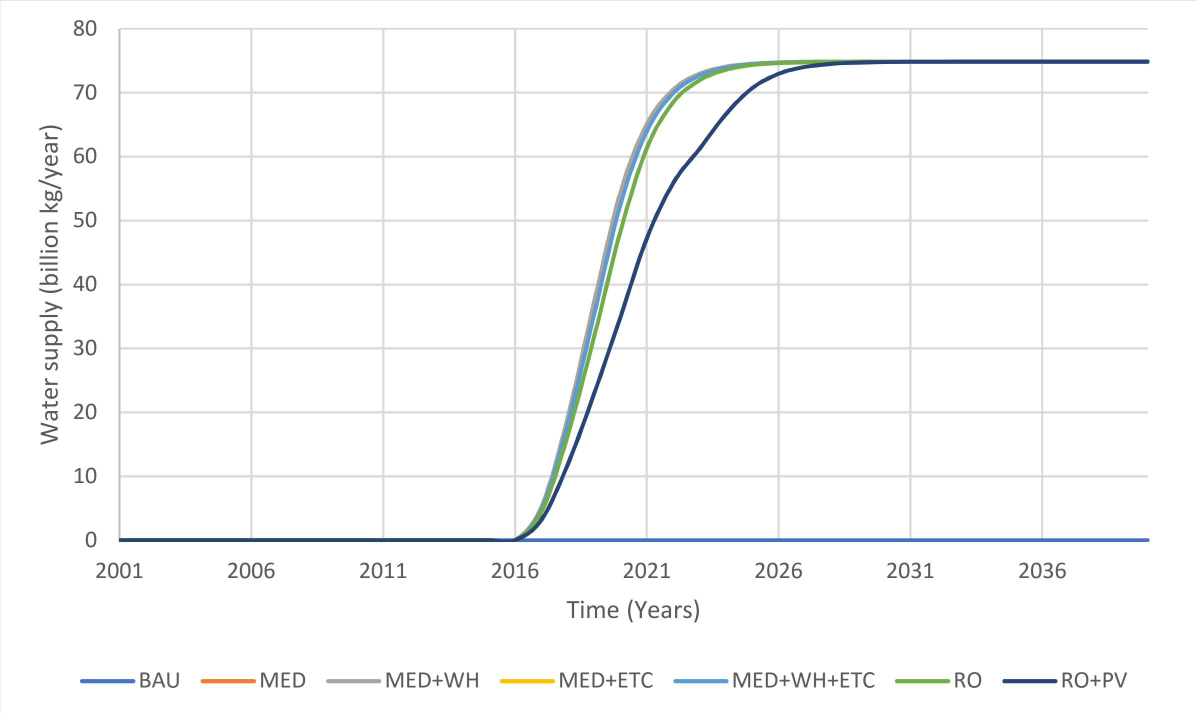

Figure 5.9: Annual water supply from additional desalination

There is no additional desalination implemented in the BAU scenario, as can be seen in Figure 5.9. For the rest of the scenarios, it was assumed that the desalination capacity limit is the same, therefore the water supply from additional desalination levels out at a water supply of 74.9 billion kg/year. The rate at which the maximum water supply is reached is dependent on the time taken to invest enough to meet the capital cost of the desalination system. Therefore, the higher the capital cost of the desalination system, the longer it takes to attain the maximum water supply. It must be noted that in real-life the desalination system would not supply water until enough capital has been invested and the system has been commissioned. For the purpose of this model, however, it was assumed that construction would start as soon as the first investment is made and water supply from additional desalination is used to indicate the progress of the project. This is a valid assumption because the purpose of system dynamics models is not to provide accurate point predictions, but rather to provide insight into proposed interventions using the resulting pattern predictions. Oosthuizen (2015) used a similar method to determine the impact of installing different electricity generation technologies on the electricity sector of the Western Cape Province. In Figure 5.9, it can be seen that the rates at which the MED, MED+WH, MED+ETC, MED+WH+ETC and RO scenarios' water supply increases are very similar and that the maximum water supply is reached by 2024. The RO+PV scenario, however, has a higher capital cost and therefore only reaches the maximum water supply by 2028. It will therefore take significantly longer to invest enough to commission the RO+PV system. The slight change in the rate of water supply increase for the RO+PV scenario seen at time equals to 2022 is a delayed reaction to a decrease in investment in water supply in 2021. The decrease in investment is caused by a decrease in the water stress index, which can be attributed to the increase in water supply after the completion of the Clan William dam wall raising, as discussed in Section 5.1.6. The results of the investment in water supply for all the scenarios is included in Appendix E along with other additional results.

The forecasted annual water consumption for the generation of the electricity used in the Western Cape Province is given in Figure 5.10. These results include water consumption for electricity generated in the Western Cape Province, as well as the water consumed by the generation of imported electricity. The water consumed outside the Western Cape Province does not directly affect the Western Cape Province's water sector, but it is an important environmental impact that should be taken note of.

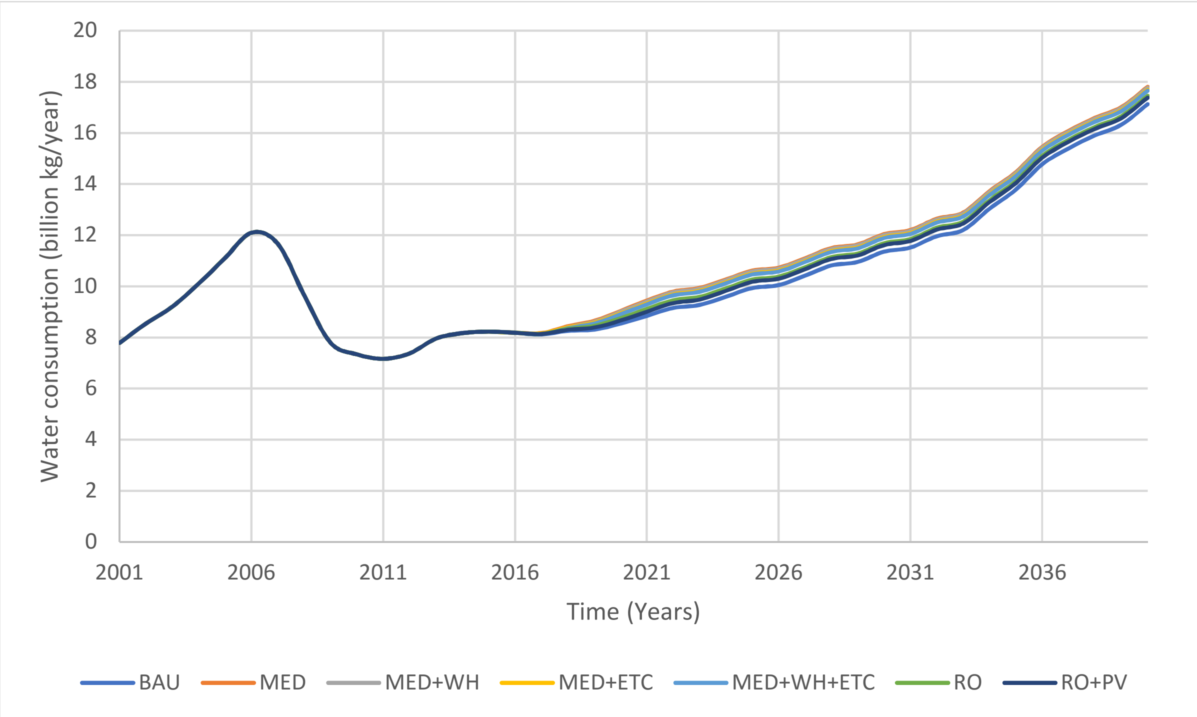

Figure 5.10: Annual water consumption for electricity generation

In Figure 5.10 it can be seen that all the intervention scenarios result in an increase in water consumption for electricity generation when compared to the BAU scenario. This is because desalination results in an increase in electricity demand, as will be discussed in Section 5.1.8. An increase in electricity demand causes an increase in the electricity demand supply gap, and therefore an increase in imported electricity. The majority of the imported electricity is generated using coal-fired power stations, which consume large amounts of freshwater. Therefore, the implementation of a desalination system ultimately results in an increase in the water consumption for electricity generation. Table 5.7 presents the water consumption for electricity generation values predicted for 2040 for each scenario and the percentage that it increases by compared to the BAU scenario. The MED scenario results in the greatest increase in water consumption and the RO+PV scenario results in the smallest increase.

Table 5.7: Water consumption for electricity generation in 2040

Scenario	Water consumption (billion kg/ year)	Difference between BAU and scenario (billion kg/year)	% increase from BAU scenario
BAU	17.124	-	-
MED	17.808	0.684	3.99
MED+WH	17.772	0.648	3.79
MED+ETC	17.692	0.568	3.32
MED+WH+ETC	17.657	0.533	3.11
RO	17.454	0.330	1.93
RO+PV	17.380	0.256	1.50

The MED scenario causes an increase in water consumption of 0.684 billion kg/year. This is 0.91% of the total water supplied by the desalination system. The increase in water consumption due to the implementation of a desalination system is, therefore, insignificant in comparison to the amount of water supplied by the desalination system and is not a concern.

Figure 5.11 illustrates the water stress index predicted for every scenario. The water stress index is dependent on the total water supply and total water demand. The total water demand is the same for all the scenarios, therefore, the difference seen in the water stress index plots for each scenario is caused by changes in the total water supply.

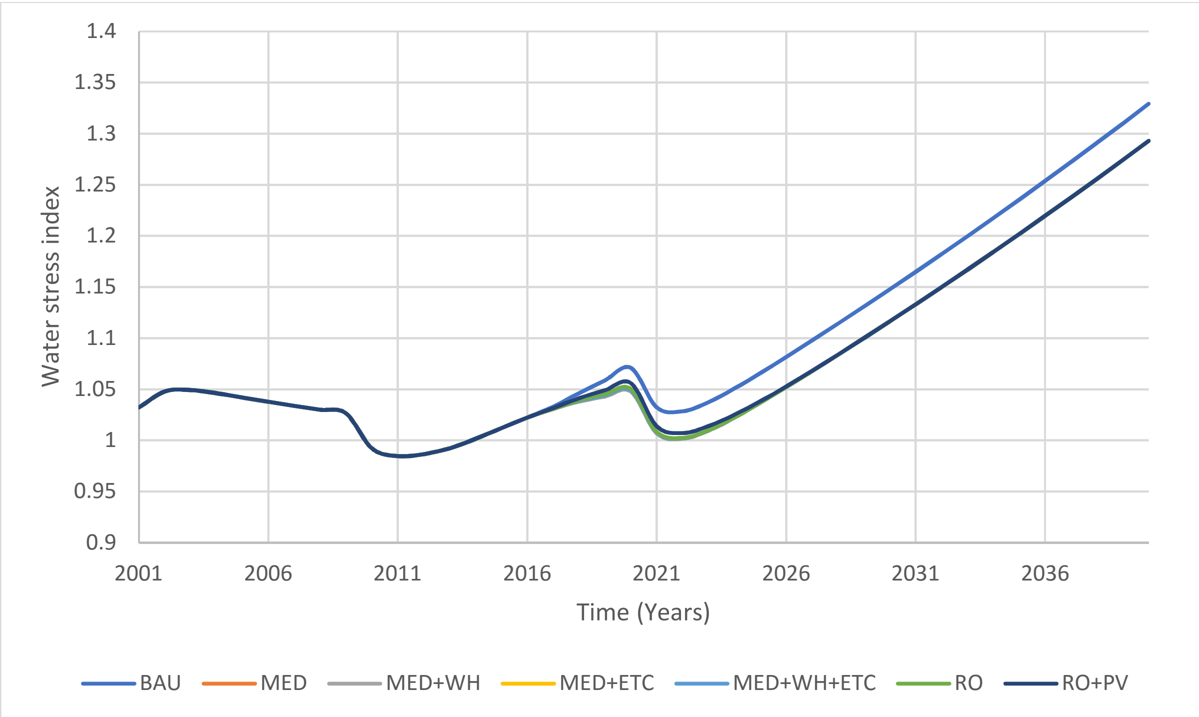

Figure 5.11: Water stress index

The different intervention scenarios have a similar effect on the water stress index when compared to the BAU scenario. From Figure 5.11, it can be seen that the implementation of a large-scale desalination plant will significantly reduce the water stress index, but at 1.29 the water stress index is still far higher than 1.00 by 2040. Although a large-scale desalination plant will alleviate the predicted water shortage, additional interventions are required to prevent water shortages.

5.1.8 Electricity sector results

Concerns regarding the high electricity consumption of the desalination process, among other concerns, have so far prevented the Western Cape Government from investing in and commissioning a large-scale desalination plant. The impact of the different desalination systems on the Western Cape Province's electricity sector must therefore be analysed for each intervention scenario. First, the annual electricity requirements for the desalination systems implemented in each scenario are compared. This is followed by an analysis of the impact each scenario's system has on the Western Cape Province's electricity demand supply gap. Lastly, the impact on the air emissions from electricity consumption was considered.

The electricity requirements for the implemented desalination system as predicted for each intervention scenario are illustrated in Figure 5.12. The electricity requirements are determined by the thermal and electrical energy required for the desalination plants and the thermal and electrical energy provided by the renewable energy sources.

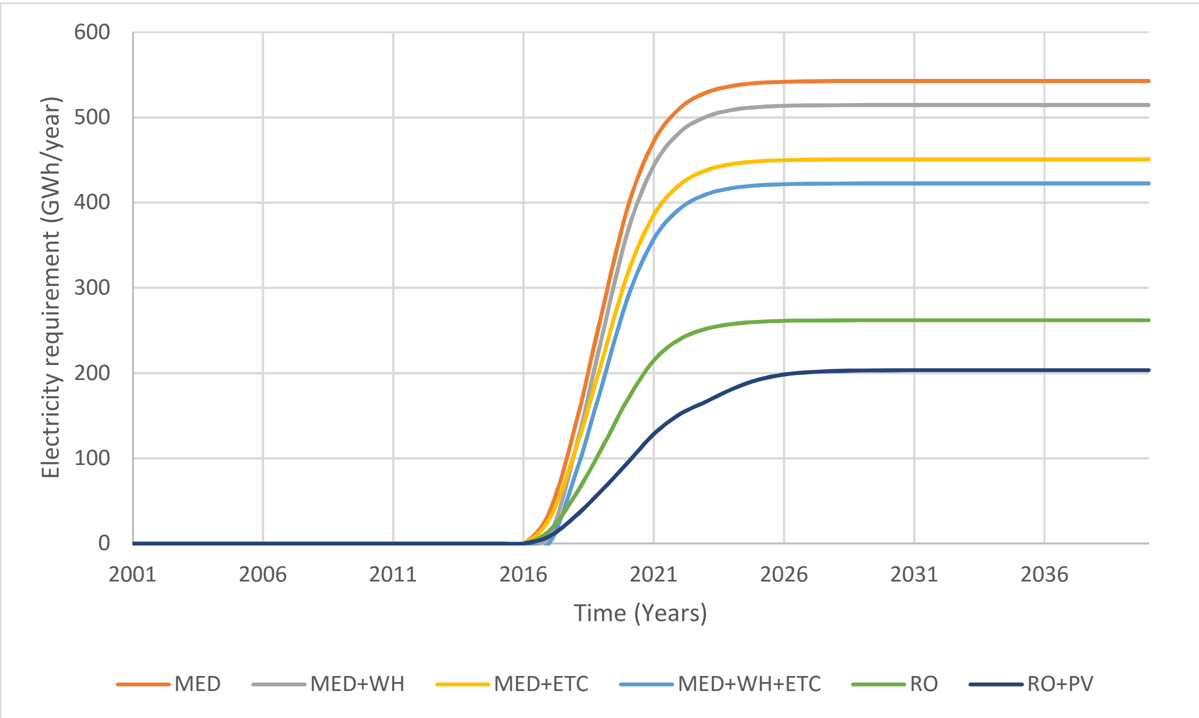

Figure 5.12: Annual electricity requirements for desalination system

From Figure 5.12, the MED system requires the most electricity and the RO+PV system requires the least electricity. The use of thermal energy from waste heat and solar ETC reduces the electricity requirements for MED, but even then, the system is not nearly as energy efficient as an RO system with the RO system requiring 160.55 GWh/year less than the MED+WH+ETC system in 2040. This means the RO system uses 38% less electricity than the MED+WH+ETC system. The RO system's energy efficiency can be further improved by the addition of solar PV to the system. Table 5.8 presents the electricity requirements for each desalination system in 2040, as well as the reduction in the requirements due to the addition of renewable energy sources. This is the difference between the requirements when only the desalination technology is implemented i.e. the MED or RO scenarios, and the requirements when a renewable energy source is included in the system.

Table 5.8: Annual electricity requirements for desalination system in 2040

Scenario	Annual electricity requirement (GWh/year)	Reduction in requirement due to renewables (GWH/year)	% reduction due to renewables
MED	542.85	-	-
MED+WH	514.64	28.22	5.20
MED+ETC	450.83	92.02	16.95
MED+WH+ETC	422.61	120.24	22.15
RO	262.07	-	-
RO+PV	203.50	58.57	10.79

Table 5.8 shows that the addition of renewable energy sources to the desalination systems significantly reduces the electricity required by the systems. Solar energy is particularly effective in reducing the system's energy requirements. It must be noted that the waste heat, however, is sourced from only one of *Arcelor Mittal Saldanha Work's* processes and that the steel works may be able to supply additional thermal energy from process waste heat. This possibility can be investigated in the future.

Figure 5.13 illustrates the electricity demand supply gap as predicted for each scenario. The gap also represents the amount of electricity that must be imported from other provinces to meet the Western Cape Province's demand. The gap should be minimised to ensure the electricity security of the Western Cape Province.

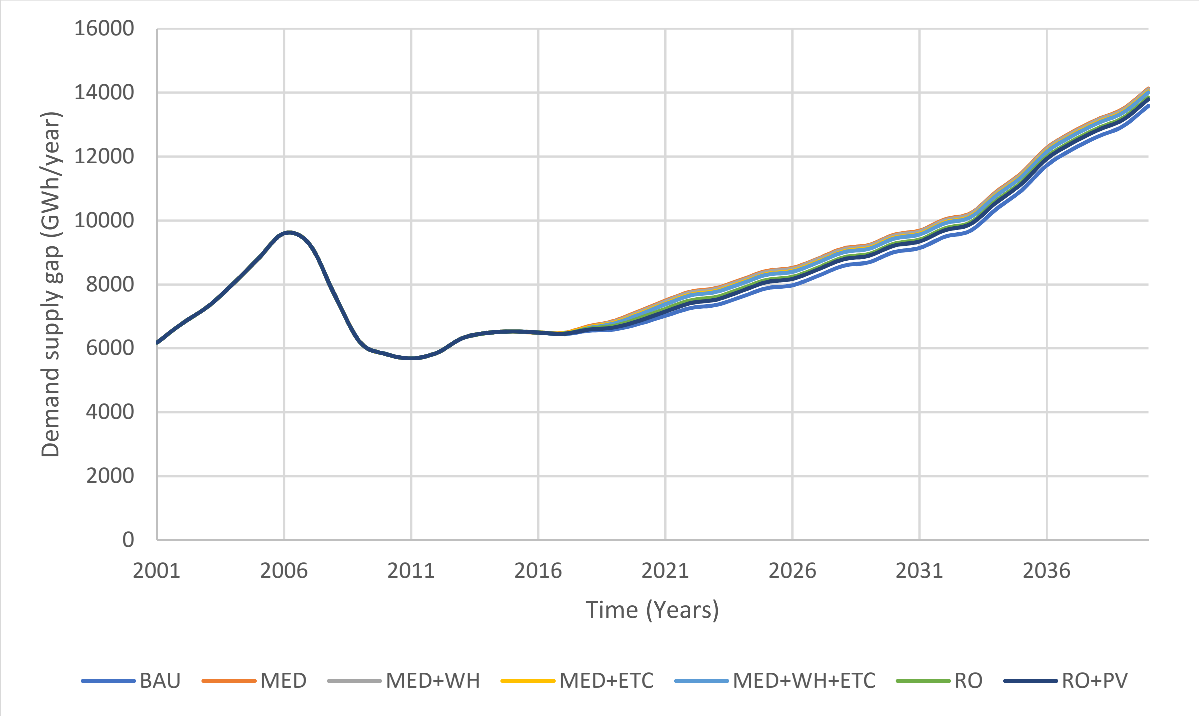

Figure 5.13: Electricity demand supply gap

From Figure 5.13 it can be seen that the implementation of a desalination system causes an increase in the electricity demand supply gap for all the intervention scenarios when compared to the BAU scenario. This is because the desalination process requires electricity and increases the electricity demand, resulting in an increase in the electricity demand supply gap. Table 5.9 presents the electricity demand supply gap predicted for 2040 for each scenario, as well as the increase in the gap compared to the BAU scenario.

Table 5.9: Electricity demand supply gap for 2040

Scenario	Electricity demand supply gap (GWh/year)	Difference between BAU and scenario (GWh/year)	% increase from BAU scenario
BAU	13589.7		
MED	14132.6	542.9	3.99
MED+WH	14104.4	514.7	3.64
MED+ETC	14040.6	450.9	3.20
MED+WH+ETC	14012.3	422.6	3.01
RO	13851.8	262.1	1.87
RO+PV	13793.2	203.5	1.47

At 3.99% the MED system causes the greatest increase in the electricity demand supply gap and at 1.47% the RO+PV system causes the smallest increase in the electricity demand supply gap. This is because, as seen in Figure 5.12, the MED system is the least energy efficient and the RO+PV system is the most energy efficient. Desalination causes an increase in the electricity demand supply gap, which will make it more difficult for the Western Cape Government to reduce electricity imports. As

seen from the BAU scenario results, reducing electricity imports is already difficult without the implementation of desalination. This means the Western Cape Government will have to enforce additional policies to further increase the Western Cape Province's electricity generation capacity.

The predicted annual air emissions from electricity consumption for each scenario is presented in Figure 5.14. The air emissions are from electricity generated in the Western Cape Province, as well as the emissions from generating the imported electricity.

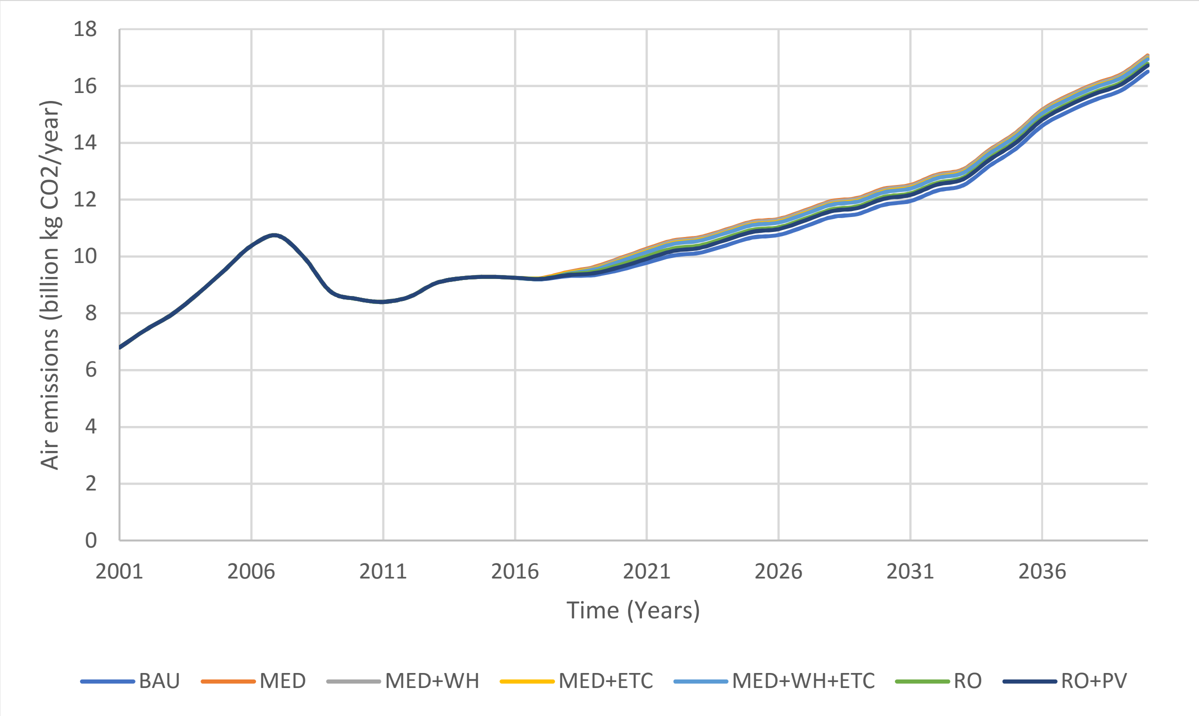

Figure 5.14: Annual air emissions from electricity consumption

As can be seen in Figure 5.14, similar to the energy demand supply gap, the implementation of any desalination system causes an increase in the air emissions from electricity consumption when compared to the BAU scenario. This is because the desalination system causes an increase in electricity consumption. The increase caused by each scenario in 2040 when compared to the BAU scenario can be seen in Table 5.10.

Table 5.10: Air emissions from electricity consumption for 2040

Scenario	Annual air emissions from electricity consumption (billion kg CO_2/year)	Difference between BAU and scenario (billion kg CO_2/year)	% increase from BAU scenario
BAU	16.510	-	-
MED	17.074	0.565	3.42
MED+WH	17.045	0.535	3.24
MED+ETC	16.979	0.469	2.84
MED+WH+ETC	16.949	0.440	2.66
RO	16.782	0.273	1.65
RO+PV	16.721	0.212	1.28

The MED scenario, at 3.42%, causes the largest increase and the RO+PV scenario, at 1.28%, causes the smallest increase. The majority of the air emissions are a result of the generation of the imported electricity, but, as has already been discussed, the Western Cape Province is still responsible for those emissions. The Western Cape Government aims to reduce the Western Cape Province's greenhouse gas emissions and the implementation of desalination would make this more difficult.

5.1.9 Economic impacts

The capital and operating costs of a desalination system are another concern the Western Cape Government has regarding the implementation of a large-scale desalination plant. The capital and running costs of the desalination systems implemented in each scenario were analysed to determine the economic effect of the systems. The total cost of implementing each scenario's desalination system is presented in Table 5.11. The initial capital costs, the annual O&M costs at full capacity including electricity costs and the accumulated O&M costs until 2040 are given. The total cost is equal to the sum of the capital cost and the accumulated O&M cost. These costs do not depict the actual project costs and do not include the effects of inflation or electricity prices changes. Rather, these values were used to provide an indication of the possible cost of each intervention so that the interventions could be compared.

Table 5.11: Cost of desalination system

Scenario	Capital cost (billion R)	Annual O&M cost incl. electricity (billion R)	Accumulated O&M cost incl. electricity up to 2040 (billion R)	Total accumulated cost up to 2040 (billion R)
MED	3.81	0.99	20.62	24.43
MED+WH	3.82	0.95	19.68	23.50
MED+ETC	4.01	0.87	17.91	21.92
MED+WH+ETC	4.03	0.83	16.97	20.99
RO	4.47	0.69	14.15	18.62
RO+PV	6.21	0.61	11.87	18.08

The MED scenario is the most expensive intervention scenario because of its high O&M costs. The cost of the electricity required by the MED system contributes significantly to its O&M costs. The RO+PV scenario is the least expensive scenario, despite the system having the highest capital cost by a considerable amount. This is because the system uses substantially less electricity than the other scenarios' systems, which greatly reduces the electricity costs and thereby the O&M costs. These results show the importance of regarding not only the immediate effect of implementing a technology, but also the long-term impacts. If only the initial capital costs were used to assess the economic effect of the desalination system, MED would appear to be the best option. However, if the total O&M costs over a significant time period are also considered, the RO+PV system becomes the least expensive option.

Another economic impact that should be considered is brine disposal. For all the intervention scenarios, a brine stream of 74.9 billion kg/year is produced when the desalination plant operates at full capacity. This brine requires safe disposal to ensure the impact on the environment is negligible. The cost of brine disposal is not investigated in this research, but must be considered in the planning of a desalination system. For the purpose of this research, it is assumed that the brine disposal cost would be the same for all the scenarios because the same amount of brine is produced in each scenario. The brine disposal cost, therefore, has no effect on the comparison of the different desalination systems.

5.3 Conclusion: Scenario simulations

The development of different simulation scenarios and the results of those scenarios was discussed in this chapter. In Chapter 6, these results will be used to make recommendations to policymakers with regards to the implementation of a desalination system in the Western Cape Province.

CHAPTER 6: RECOMMENDATIONS AND CONCLUSIONS

The Western Cape Government recognises the need to reconcile the Western Cape Province's predicted future water requirements with the supply available from the Western Cape Province's water supply system. The WCWSS Reconciliation Strategy was commissioned in 2005 to facilitate this. Since the commissioning of the strategy, the Western Cape Government has increased the available water supply through the augmentation of surface water sources and reduced water requirements through its Water Conservation/Water Demand Management (WC/WDM) programme. Additional non-surface water supply interventions have been in the feasibility study phase since 2007. The strategy has been successful thus far, but further surface water supply augmentation may not be feasible in the future because climate change is likely to reduce the Western Cape Province's annual rainfall, resulting in an unreliable surface water supply. Furthermore, WC/WDM can only reduce the Western Cape Province's water requirements up until a certain point. With a water demand that is growing rapidly due to population growth and economic growth, the Western Cape Government must start implementing non-surface water supply options. Seawater desalination has been considered a possible water supply option since the WCWSS Reconciliation Strategy was commissioned, but implementation of a large-scale desalination plant has been delayed due to concerns regarding the high capital cost of such a project and the potential impacts desalination would have on the electricity sector and the environment.

One of the main objectives of this research was to determine the impact of different desalination systems on the Western Cape Province's energy-water nexus. Seven scenarios were simulated and the results were compared. The BAU scenario was used as a baseline to which the intervention scenarios could be compared and gives an indication of what the behaviour of the energy-water nexus will be if large-scale desalination is not implemented. The MED and RO scenarios were used to compare the impact of these two different desalination technologies. The MED+WH, MED+ETC, MED+WH+ETC and RO+PV scenarios compared the effect that the addition of renewable energy sources to the desalination system would have. The different desalination systems were analysed in terms of the effects on the water sector and the electricity sector. A cost comparison of the systems was also performed.

It is important to be aware that the results from the simulations are not intended to be numerically accurate. System dynamics models are unable to produce accurate point results because of the inherent uncertainties that exist in an open complex system, such as the energy-water nexus. Rather, the results give an indication of the development of trends and the changes that occur over time. The pattern predictions produced by system dynamics models give stakeholders insights into the proposed interventions. The focus of the results discussion is therefore on the changes seen in variables over time. Point predictions, however, are used as an indication of how extreme the changes in the variables are.

6.1 A need for intervention

The results of the BAU scenario clearly show that the water sector interventions that the Western Cape Government has implemented, and has absolute plans to implement in the near future are not sufficient to ensure that the future water supply will be able to meet the future water demand. Water shortages can be expected in the future and this is without considering the effect climate change may have on the Western Cape Province's water supply.

As discussed in Section 2.1.1, the Western Cape Province's economy is dependent on a secure water supply to ensure continued growth. All economic sectors require water to operate and sectors that are heavily dependent on water, such as the agricultural sector, may experience negative growth if the water supply is insufficient to meet the demand. Poor economic growth endangers the jobs and livelihoods of members of the population. Water shortages will also have further impacts on the social sector. Negative growth in the agriculture sector may inhibit food security and the population may, therefore, not only face a shortage of water, which is essential for life, but may also experience inflated food prices or even food shortages. As discussed in Section 1.2.1, the drought that affected large parts of South Africa in 2016 demonstrated the effect water shortages can have on cereal prices. Furthermore, as discussed by Wang (2013), the decreased water levels and poor water quality that are a result of water shortages negatively impact the environment, particularly aquatic habitats. Thus, it is prudent that interventions are made to ensure water security and prevent the ramifications of a water shortage on the economic, social and environmental sectors.

6.2 Water sector context

The simulation results predict that the Western Cape Province's water demand will grow by 34.8% between 2001 and 2040. Population growth and economic growth are the main drivers of water demand. Investment in the water sector is required to ensure the future demand can be met. In each intervention scenario, a fraction of the Western Cape GDP is allocated to investment in water supply. It was assumed that the fraction of the GDP that is invested depends on the water stress index, therefore a higher water stress index, which indicates that intervention is required, results in a higher investment fraction. It was also assumed that the investment would only be used for desalination.

For all the intervention scenarios, the size of the desalination plant capacity was set to 205 000 m^3/day, which is equal to an annual water supply of 74.9 billion L when the desalination plant is operated at full capacity. The effect of the different desalination systems on the water stress index is, therefore, similar. It was seen that the implementation of a large-scale desalination system will improve the predicted water stress index, but that it is not enough to lower the water stress index to below one, which is when the available supply can meet the demand. A single, large capacity desalination plant can therefore meet some of the future water demand, but the intervention scenarios that have been investigated are alone not enough to prevent water shortages in the future. Additional water supply-side interventions will be required to reconcile the Western Cape Province's available water supply with the projected future water demand.

It was seen that the implementation of a desalination system would cause an increase in the water consumed for electricity generation. This is due to an increase in imported electricity, which is generated using coal-fired power stations that consume large amounts of freshwater. This water may be consumed outside of the Western Cape Province, but it is still an important impact to consider to ensure that the increase in water consumption caused by the desalination system is not significant when compared to the increase in water supply. However, it was found that for all the intervention scenarios the increase in water consumption for electricity generation is negligible in comparison to the increase in water supply from the additional desalination.

The various intervention scenarios have a similar effect on the Western Cape Province's water sector. A large-scale desalination system would greatly improve the Western Cape Province's water supply and reduce the water stress index. However, in order to determine which desalination system would be better to implement, the impact of the intervention scenarios on the electricity sector must be investigated and the costs of each scenario must be compared.

6.3 Electricity sector context

The BAU scenario predicts that the electricity demand supply gap will increase in the future and is expected to be equal to 13 590 GWh by 2040. This is because the Western Cape Province's electricity demand is expected to grow more rapidly than the electricity supply. The result is that the Western Cape Province will become more reliant on imported electricity. The implementation of any desalination system will increase the electricity demand and supply gap.

The MED scenario has the highest electricity requirement and therefore causes the largest increase in the electricity demand supply gap. The MED electricity requirement can be reduced through the addition of renewable energy sources to the desalination system. The use of waste heat from the *Arcelor Mittal Saldanha Works* can reduce the electricity requirement by 5.20% and the use of solar energy through ETC further reduces the requirement by 16.95%. This results in a combined reduction of 22.15%.

The RO scenario, however, requires 37.99% less electricity than the MED+WH+ETC and is therefore much more energy efficient than the MED system, even when renewable energy sources are used. Combining RO with PV causes a further 10.7% reduction in the electricity requirement of the desalination system. The RO and RO+PV scenarios, therefore, have the smallest impacts on the electricity sector and are the best options for minimising the effect on the electricity demand supply gap. These scenarios will increase the water supply without greatly affecting the Western Cape Government's goal of reducing electricity imports.

The increase in the electricity demand supply gap that will result if any of the considered interventions are implemented will undermine the aims of the Western Cape Government's Green is Smart Green Economy Framework, discussed in Section 1.3. One of the aims is to increase the province's electricity security by decreasing its dependence on other provinces for electricity and installing sustainable electricity generation technologies. An increase in the demand supply gap will mean an increase in the amount of imported electricity, which will counteract some of the effects of the Green Economy Framework.

An increase in the Western Cape Province's electricity demand results in an increase in the air emissions from electricity consumption, which is an important environmental impact to consider.

Furthermore, an increase in air emissions would oppose another of the Green Economy Framework's aims; to reduce the Western Cape Province's carbon footprint. The air emissions are directly proportional to the electricity demand. The MED scenario, therefore, causes the greatest increase in air emissions and the RO+PV scenario causes the smallest increase, followed closely by the RO scenario. Thus, these two scenarios will have the smallest effect on the Western Cape Government's plans to reduce greenhouse gas emissions.

6.4 Cost comparison

When comparing the cost of the different scenarios, it is important to consider both the initial capital cost as well as the accumulated operation and maintenance (O&M) cost for some time period. Often, a project may have a higher capital cost than its alternatives, but the higher capital cost may mean the technology is more efficient resulting in a lower O&M cost. This was true for the simulated intervention scenarios.

The MED scenario has the lowest capital cost, making it a desirable option to implement. The cost of electricity, however, contributes largely to the O&M cost of each system. The MED scenario requires the most electricity and therefore has the highest O&M cost. The result is that the accumulated cost of the MED scenario by 2040 is the highest of all the intervention scenarios. The addition of waste heat and ETC to the system does improve the O&M cost by reducing the electricity requirement, but not enough to compete with the RO and RO+PV scenarios.

The capital cost of the RO+PV scenario is 40% higher than the RO scenario and almost twice the capital cost of the MED scenario. The RO+PV scenario, however, results in such significant electricity savings, when compared to the MED scenario, that its O&M cost is much lower resulting in the lowest accumulated cost by 2040. The RO scenario's accumulated cost is only slightly higher than the RO+PV. The deciding factor between these two scenarios would probably be whether the smaller impact of the RO+PV scenario on the electricity sector justifies its higher initial capital cost. RO+PV may have a smaller impact than RO, in terms of electricity requirements, air emission and O&M cost, but the higher capital cost of RO+PV requires a larger initial investment. The funds for a larger initial investment may not be available or may require the diversion of funds from other sectors, which would negatively impact those sectors. Conversely, smaller investments could be made over a period of time, but that would increase the time it takes to implement the scenario, which may not be desirable if the Western Cape Province is experiencing water stress. The lower capital cost of the RO scenario means that this would not be as serious a problem. However, the implementation of any if the intervention scenarios would require the diversion of funds from other economic sectors, which may negatively impact those sectors. The extent of the impact cannot be determined without knowing where the exactly the required investment would be obtained.

6.5 Model limitations and recommendations for future research

The Western Cape Province was selected as the geographical boundary for this model. It was therefore assumed that the Western Cape Province's water sector and electricity sector are independent and isolated from the national water sector and electricity sector. In reality, this is mostly true for the water sector, though the National Government does have influence over it, but the Western Cape Province's electricity sector is highly dependent on the national electricity sector. The model could be improved by defining this dependency more clearly and expanding on how the Western Cape Province links to the other eight provinces.

In the validation section it was seen that the one of the possible limitations of the model is a lack of detailed historical data for a number of the parameters. The accuracy of the model could be improved if more data was available. The model, therefore, cannot be relied upon to provide exact answers, but can be used to give insight into the proposed interventions by analysing the pattern predictions generated. Furthermore, point predictions still provide an indication of the difference in magnitude the impacts of the various scenarios will have.

Only six desalination systems were investigated in this research. There are, however, a number of other system configurations that could also be explored. For example, if additional waste heat was available for the MED+WH scenario, the scenario would be more energy efficient and could possibly compete with the RO+PV system. Furthermore, other energy sources, such as gas power plants or wind energy, could be used for the desalination plant.

For the scenario simulations, it was assumed that climate change would not have an effect on the water supply. Various scientists have, however, predicted the Western Cape Province will become increasingly drier, thereby reducing the available surface water supply (Western Cape Government, 2014). In 2017 the Western Cape Province is facing one of the worst droughts in years (Western Cape Government, 2017a). Decreased dam levels have forced the Western Cape Government to implement severe water restrictions. This drought has not been included in the model simulations, but it is further evidence that the Western Cape Province needs to invest in additional non-surface water supply. The simulation results showed that the implementation of a large-scale desalination plant would not be enough to ensure the security of water supply and that was without considering climate change and droughts. More scenarios could be simulated to determine the impact of climate change and to test the effectiveness of additional non-surface water supply interventions. Some concepts that can be investigated are the impact of droughts on the water supply, the effect of water restrictions as a result of water shortages on water demand and the effect of investing in groundwater and waste water treatment.

The effect of water price on the water sector was excluded from the model. It would be beneficial to include water price in the model structure because it would influence the water demand. The water price would be dependent on the water supply methods and their costs. The addition of a more expensive supply method, such as desalination, would increase the water price and therefore possibly decrease water demand. Investigating these interactions could provide a better understanding of the effect of implementing desalination.

The brine produced by the desalination process was determined in the model, but brine disposal was not. The method of brine disposal used would need to meet certain environmental regulations. Furthermore, brine disposal would increase the costs involved in implementing a desalination system and the cost would greatly depend on the disposal method. Including brine disposal in the model structure and investigating different disposal methods would provide additional insights into the environmental impacts of the scenarios and the costs of the scenarios. Methods for processing the brine to produce valuable products are improving. If products from the brine could be sold, it would improve the profitability of the desalination process. This is another aspect of brine disposal that can be investigated.

In the intervention scenarios, funds were allocated to investment in desalination. The model, however, does not specify the source of those funds nor does it investigate the impact allocating those funds to desalination would have on other sectors of the economy. The local government, national government and private investors could all be sources of the required investment. The model structure could be expanded to include the investment sources and to investigate the eventual effect of the investment in desalination on the Western Cape GDP. The effect of population growth on the GDP could also be included.

GDP was used as the main driver for growth in the sectoral water and electricity demands. The model accuracy could be improved by developing sub-models to determine the growth in each sector and thereby determine the water and electricity demand of each sector. This would require expanding the model boundaries to include, not only the energy-water nexus, but all of the Western Cape Province's economic sectors. This expanded model could be used to investigate different scenarios types other than only the implementation of a desalination system.

6.6 Recommendations for policymakers

The purpose of system dynamics modelling is to model complex systems and provide decision makers, such as governments and institutions, with some insights into proposed policies and interventions. The Western Cape Province's electricity sector and water sector are critical to the economy. The links that exist between the sectors, which form the energy-water nexus, are not currently of great concern because the sectors are not very dependent on one another. This is mainly due to the technologies being used in each sector. However, it is important to note that as other technologies and systems are implemented in each sector to increase electricity and water supply, the sectors may grow more dependent on one another. It is therefore still important to consider these links when implementing changes in either the electricity or water sector. New electricity generation capacity may require more water and more water supply may require more electricity. The Western Cape Province needs to increase its water supply and desalination is a viable option. However, a number of factors need to be considered before a desalination system can be implemented. The purpose of this research was to investigate the impact of different desalination systems on the energy-water nexus and the economy.

The model predictions show that the current available water supply will not be able to meet the future water demand and that the Western Cape Province will experience severe water shortages if no interventions are made. This was the result without taking climate change into account and it is highly probable that climate change will aggravate the situation. Up until 2016, the Western Cape Government has mostly invested in water demand management to delay the need for investment in supply-side interventions. From the model results it can be seen that this has helped, but that it is no longer enough. The Western Cape Government must, therefore, take the necessary steps to invest in additional water supply and start implementing supply-side interventions as soon as possible.

If climate change causes the Western Cape Province to become increasingly drier, the surface water supply will become unreliable. Investment in non-surface water supply is, thus, needed. Seawater desalination, which is being used as the main water supply method in many drought-prone countries, is one possible solution. The construction and commissioning of a single large-scale desalination plant will significantly improve the available water supply and greatly reduce the future water shortages. This intervention alone is not enough to ensure future water security, but it will help. Additional interventions will need to be made, such as increasing the groundwater supply and expanding the waste water treatment capacity. Furthermore, once a desalination plant has been designed, commissioned and optimised, it will be easier to implement additional, similar desalination plants because more knowledge about the system and its impacts will be available.

MED and RO are widely used commercial desalination technologies. MSF is also popular, but is being surpassed by MED because it is more energy efficient. MED, however, is more energy intensive than RO and therefore would increase the Western Cape Province's electricity demand by a significant amount. This would also result in increased air emissions from electricity consumption. MED has the lowest capital cost and it would be desirable to use this process if the thermal energy it requires could be obtained from a renewable energy source. The model simulations show that the use of some waste heat, as well as ETC would make an improvement, but not enough to compete with RO. Using MED with only waste heat would be the most cost-effective solution, therefore, MED could still be considered if a large enough waste heat source could be found.

RO performs better than MED with regards to electricity consumption and the resulting air emissions. The initial capital cost of RO is higher than that of MED, but the electricity cost savings more than makes up for this. Furthermore, the RO system can be further improved through the addition of PV panels to provide the electricity required for desalinisation. This significantly increases the initial capital cost of the system, but reduces the electricity cost, making it more cost-effective in the long run. If the funds for a combined RO and PV system are not immediately available, it is possible to first invest in the RO plant and add the PV panels to reduce the operation and maintenance cost of the system later, when more funds become available.

6.7 Concluding remarks

The Western Cape Province needs to increase its available water supply to ensure that the future water demand can be met. Seawater desalination is one possible solution, but the desalination process is energy intensive and the capital cost of a desalination plant is high. The aim of this research was to investigate the appropriateness of desalination used in conjunction with renewable energy as a possible water supply-side intervention. The sustainability of this technology, its effect on the Western Cape Province's energy-water nexus and the costs involved were determined.

The current state of the Western Cape Province's energy-water nexus was investigated to gain a deeper understanding of the problem and to provide the context within which the research was conducted. It was determined that the energy-water nexus can be classified as a complex system because of the many subsystems and components that are contained within the nexus, as well as the uncertainty and ambiguity associated with the nexus. A set of evaluation criteria for the modelling tool that would be used to model the nexus was developed using the problem context and the principles of systems thinking, which is an appropriate approach to use for a complex system.

A literature survey was conducted to fully understand the previous efforts that had been made to model systems similar to the Western Cape Province's energy-water nexus and to evaluate the modelling tools that had been used. It was found that system dynamics modelling was the only modelling tool that had been investigated that met all of the modelling requirements. It integrates systems thinking and is therefore the appropriate modelling tool to use for a complex system.

The five phases for the process of systems thinking and modelling, as described by Maani & Cavana (2007), were used to develop the Western Cape Energy-Water Nexus model. The problem formulation had already been completed to determine the model requirements. The conceptual model was developed to determine the dynamics of the system. This was achieved by constructing a number of causal loop diagrams. Next, the dynamic computer simulation model was developed, verified and validated.

Once confidence in the dynamic model had been established, a number of scenarios were developed and simulated to determine the effect of the desalination technology system on the Western Cape Province. Seven scenarios were simulated, namely: BAU; MED only; MED with waste heat; MED with ETC; MED with waste heat and ETC; RO only; and RO with PV. It was seen that the Western Cape Province's water supply would be unable to meet the future water demand if no intervention was made. The installation of large-scale desalination would help to mitigate the predicted water shortages, but would still not provide enough water supply for the future water demand. Therefore, additional intervention would be required. MED is more energy intensive than RO, resulting in a greater increase in the electricity demand supply gap and the air emissions from water consumption. The addition of waste heat and ETC to the MED does improve its energy efficiency, but not enough to compete with the RO system. The RO with PV system would be the most sustainable in terms of electricity requirements, air emissions and cost. The system may have the highest initial capital cost, but it has the lowest O&M cost due to its low electricity requirements. Therefore, the system's life cycle cost up until 2040 is lowest of all the simulated systems.

A number of recommendations were made to policymakers. Investment in water supply is crucial to ensure the future water security of the Western Cape Province and investing in only one large-scale desalination plant will not be enough. Additional interventions, such as investment in groundwater and waste water treatment, will be required. The MED system had the lowest initial capital cost, making it a desirable option, but for it to be sustainable it would need to be operated using mostly solar energy and waste heat. This would only be possible if a large enough waste heat source is available. RO is the better technology to invest in because it is more sustainable than MED. The inclusion of solar energy from PV improves its sustainability, but greatly increases its initial capital cost. If the funds for a RO with PV system is not available, it may be possible to first invest in the RO plant and add the PV panels later, when more funds become available. Before the desalination system can be implemented, however, brine disposal must be investigated.

This research provides a better understanding of the complexities involved in the installation of a new technology system, such as desalination, in the Western Cape Province’s energy-water nexus. This research can be used as a platform to further explore the impacts of a desalination system or to investigate the sustainability of other technology systems that will affect the nexus.

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APPENDICES

APPENDIX A: DYNAMIC MODEL STRUCTURE

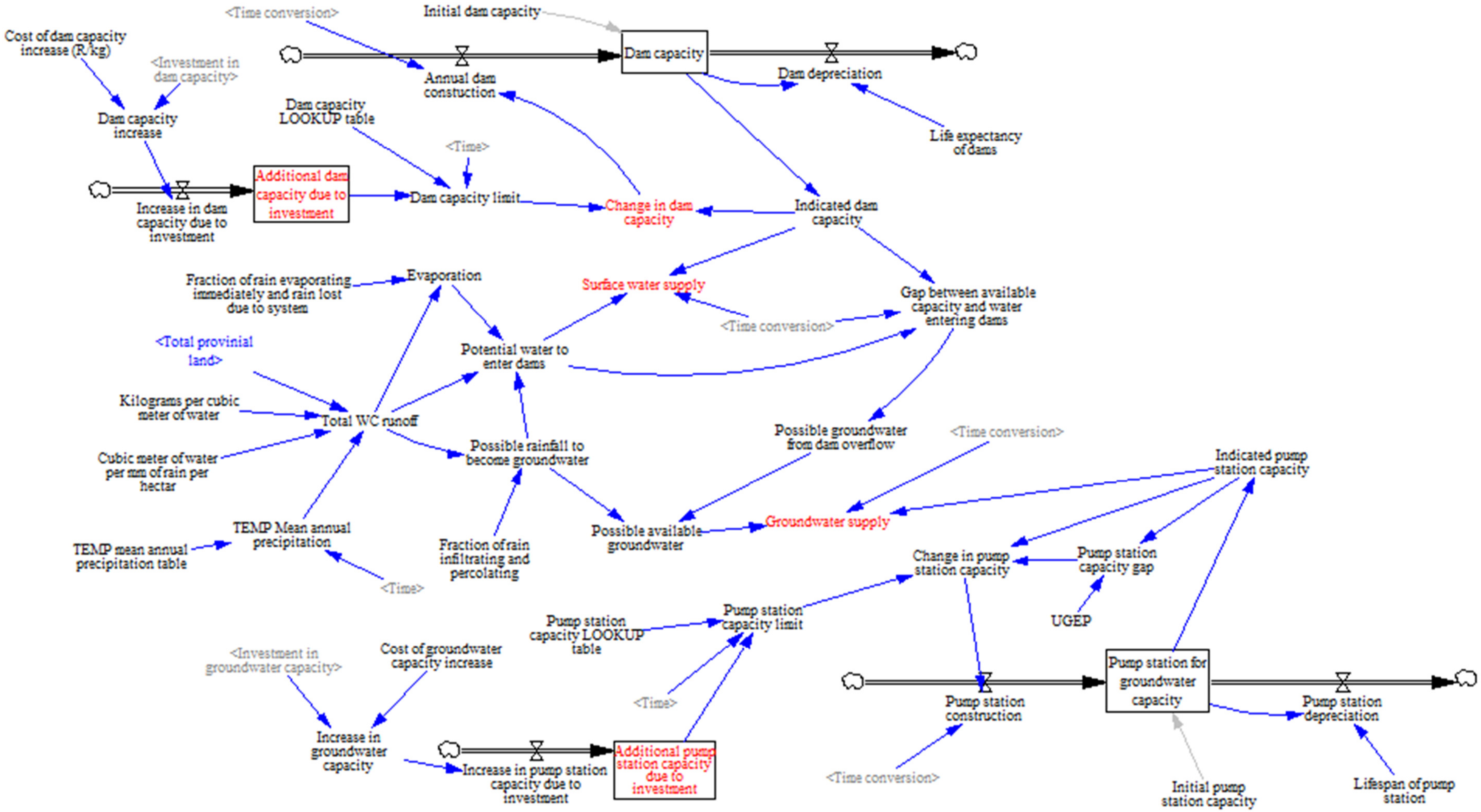

Figure A.1: Surface water and groundwater sub-model

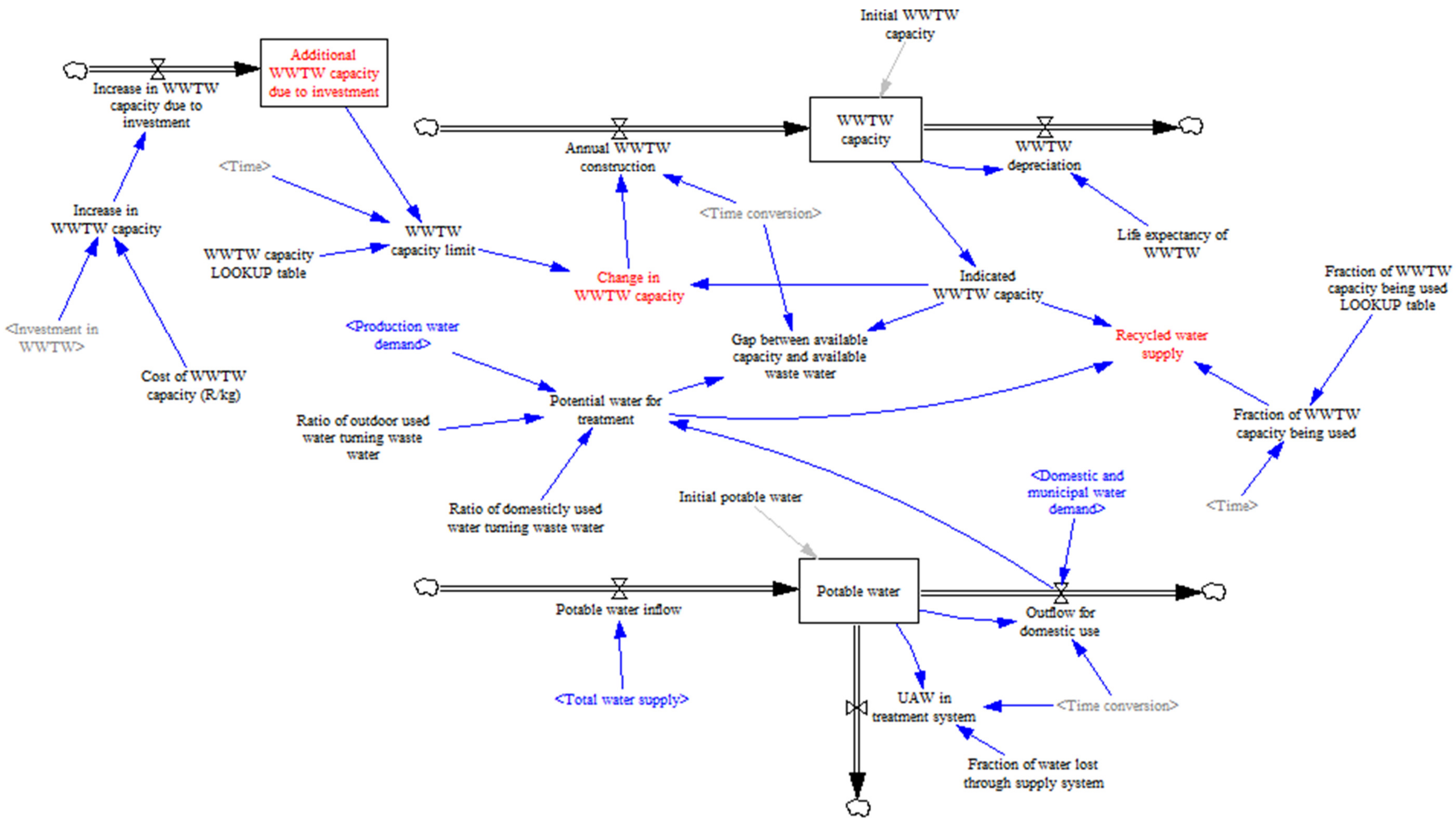

Figure A.2: Waste water sub-model

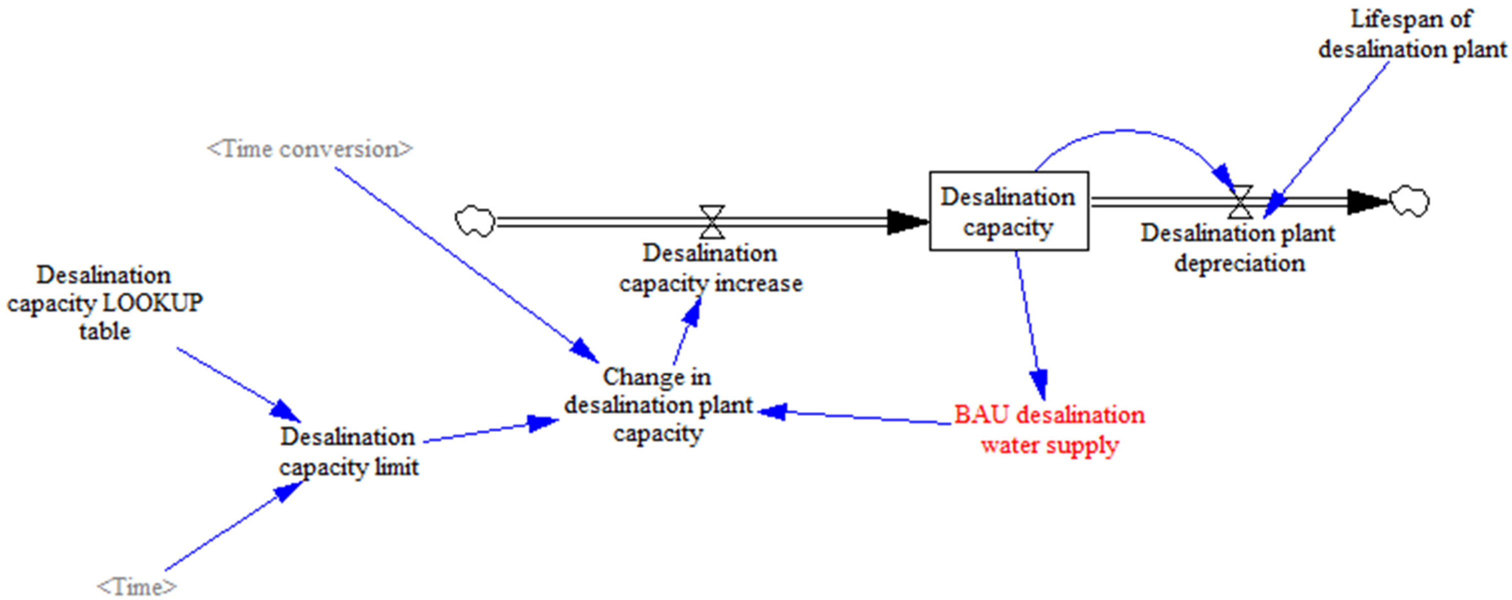

Figure A.3: BAU desalination sub-model

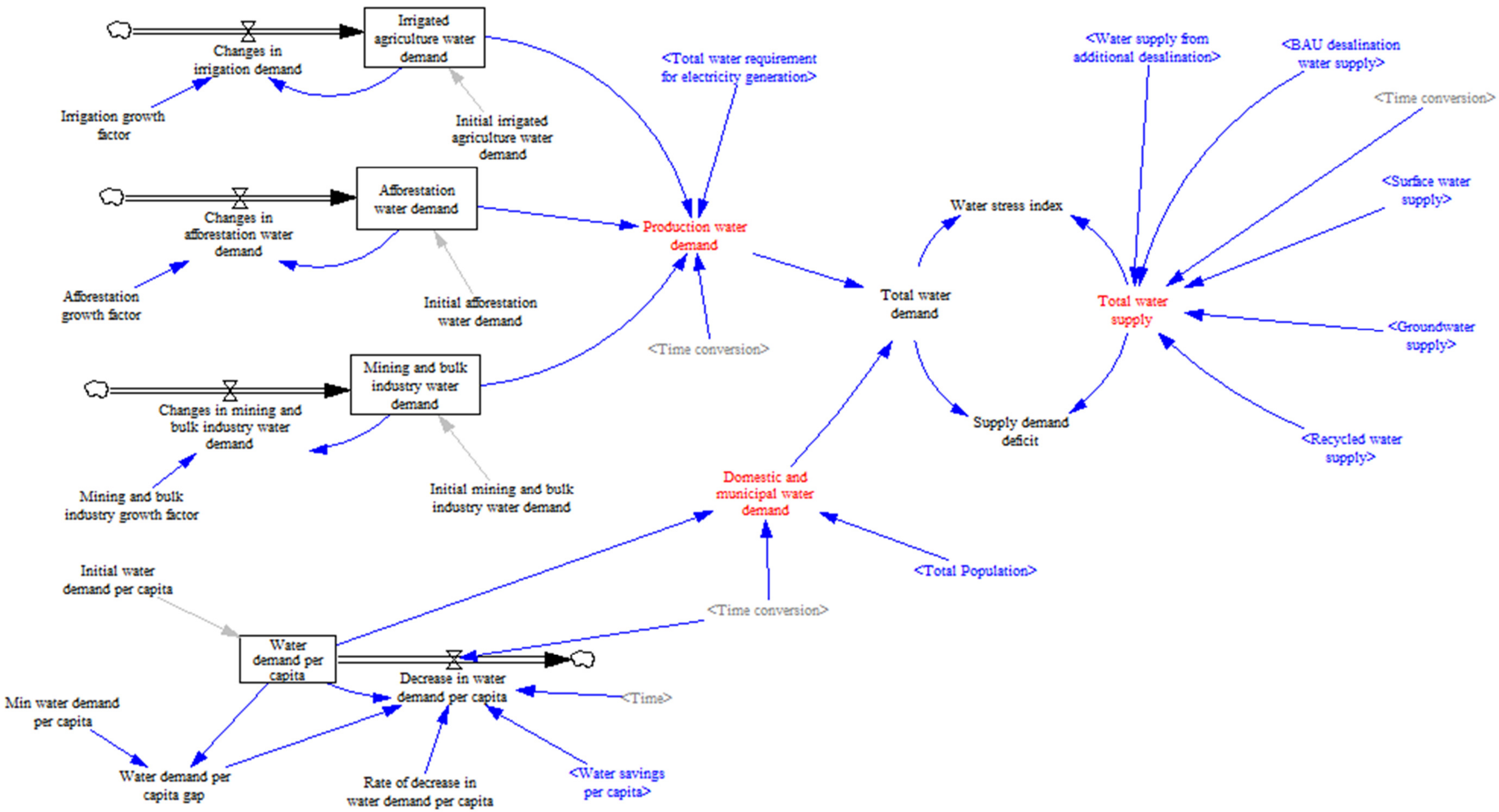

Figure A.4: Water supply and demand sub-model

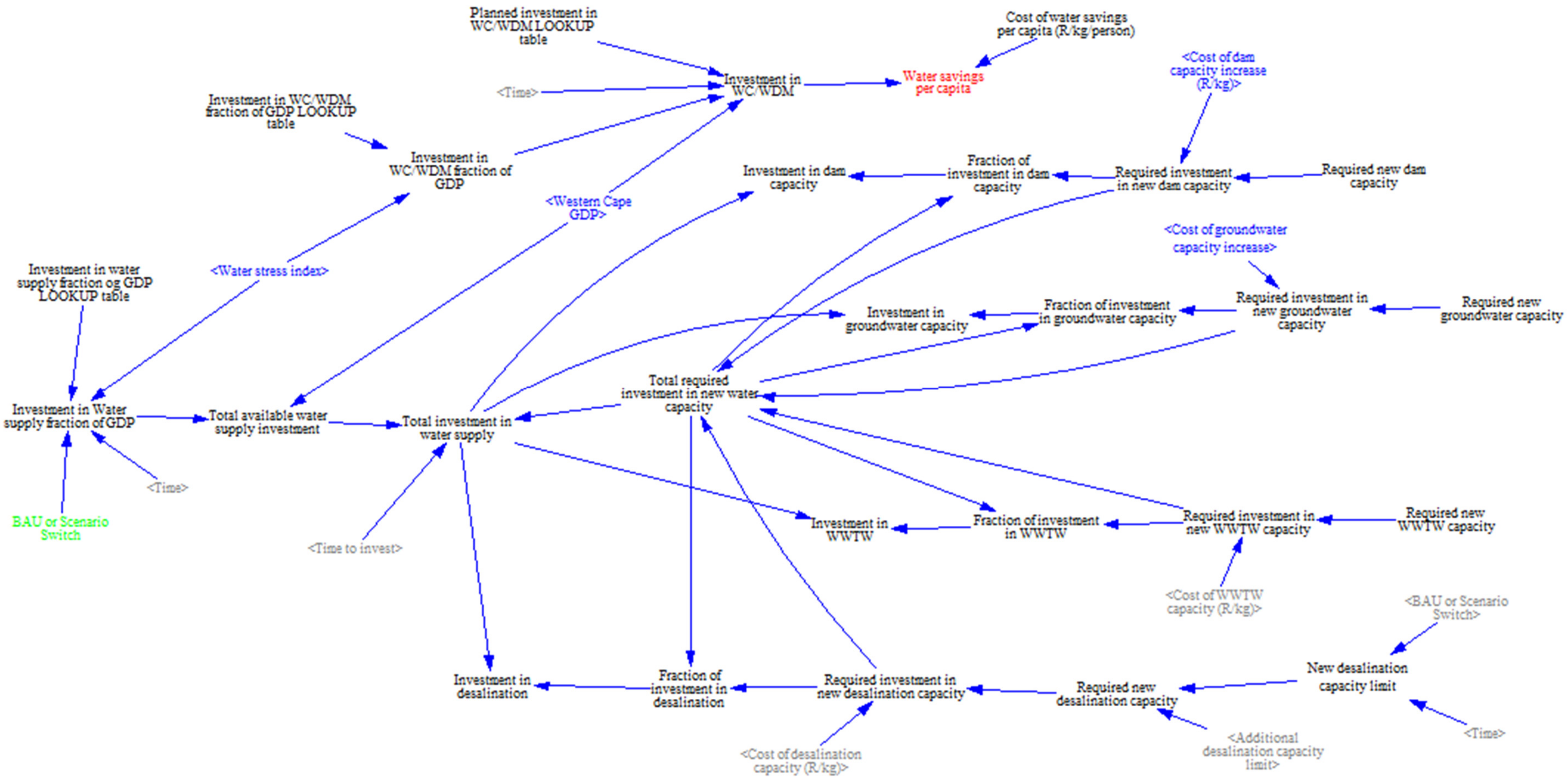

Figure A.5: Water sector investments sub-model

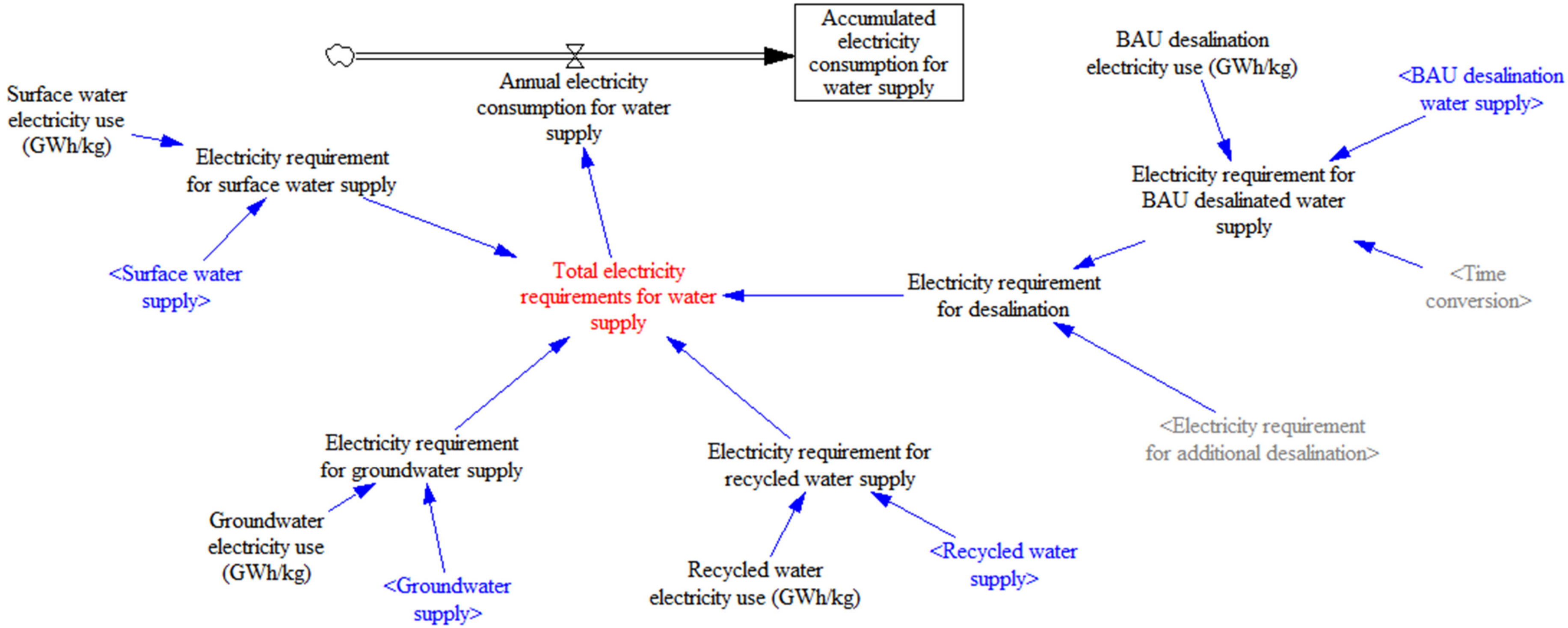

Figure A.6: Electricity requirements of the water sector sub-model

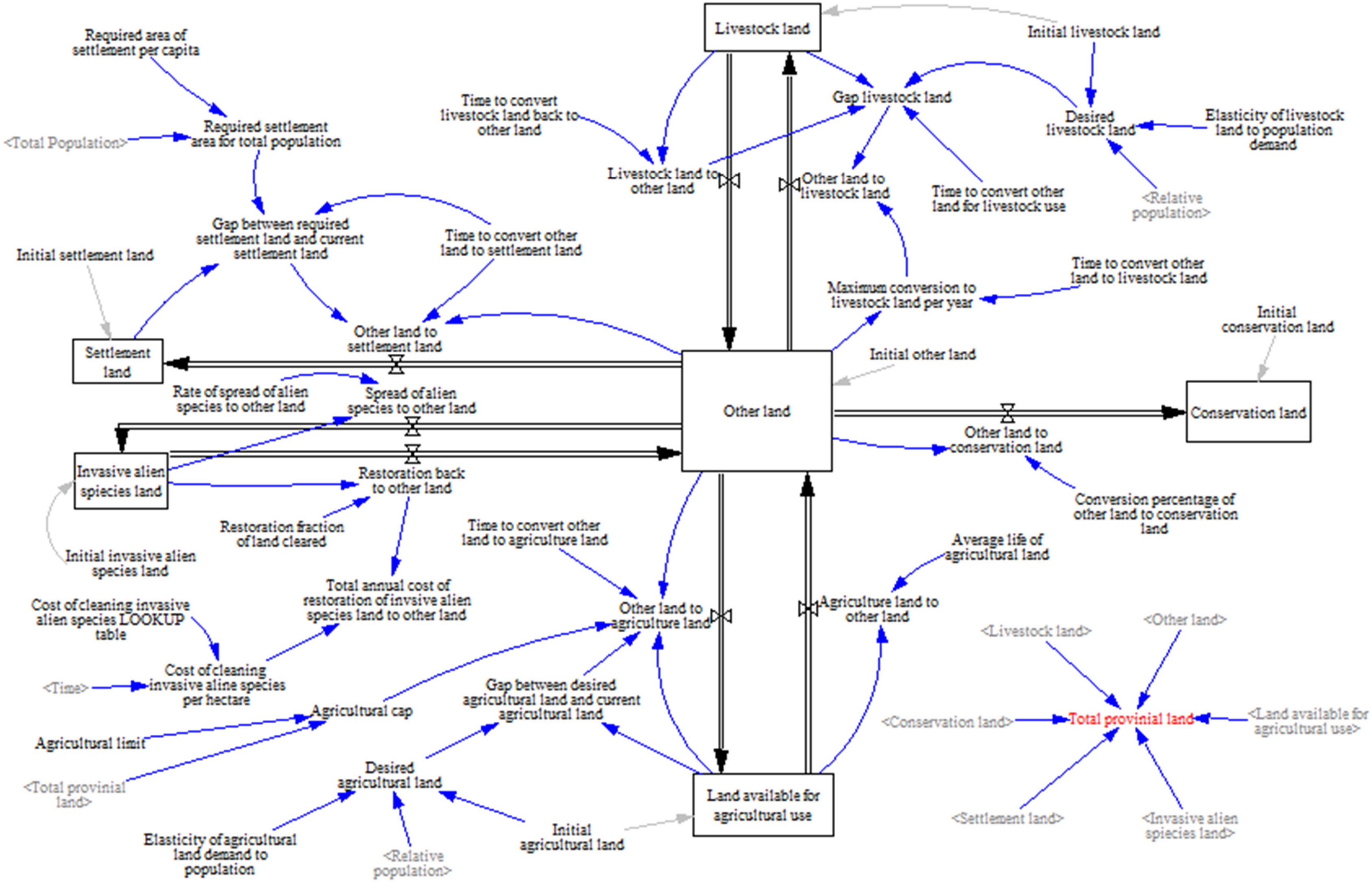

Figure A.7: Provincial land sub-model

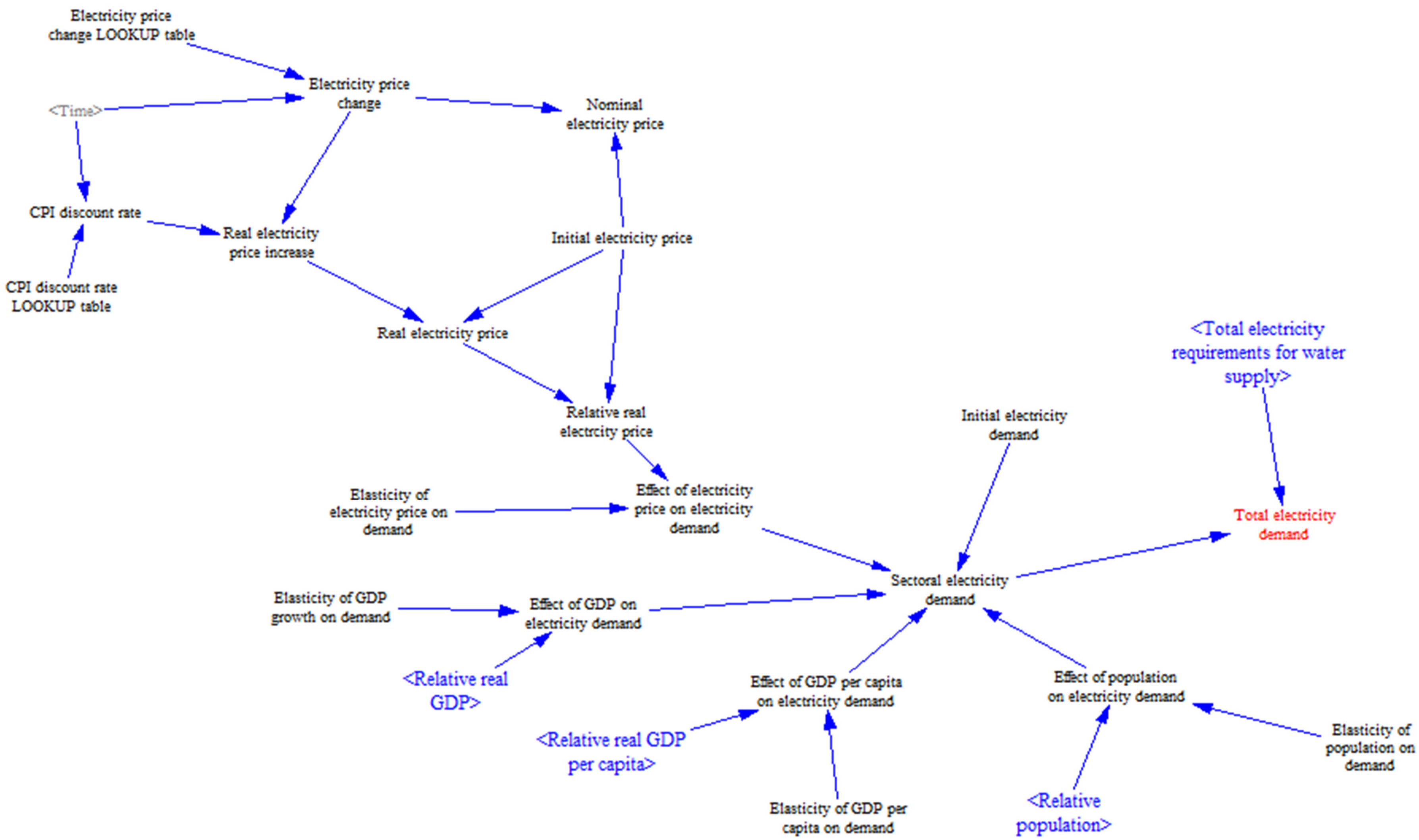

Figure A.8: Electricity demand sub-model

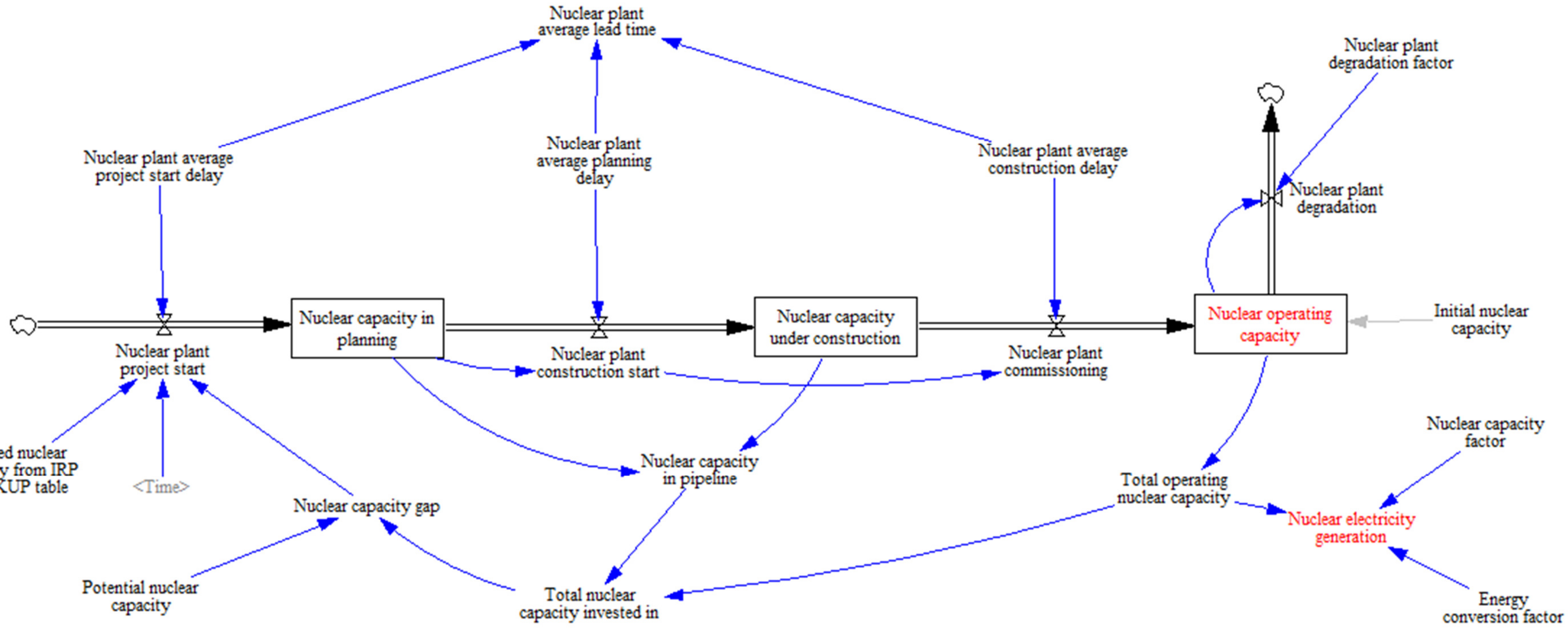

Figure A.9: Nuclear sub-model

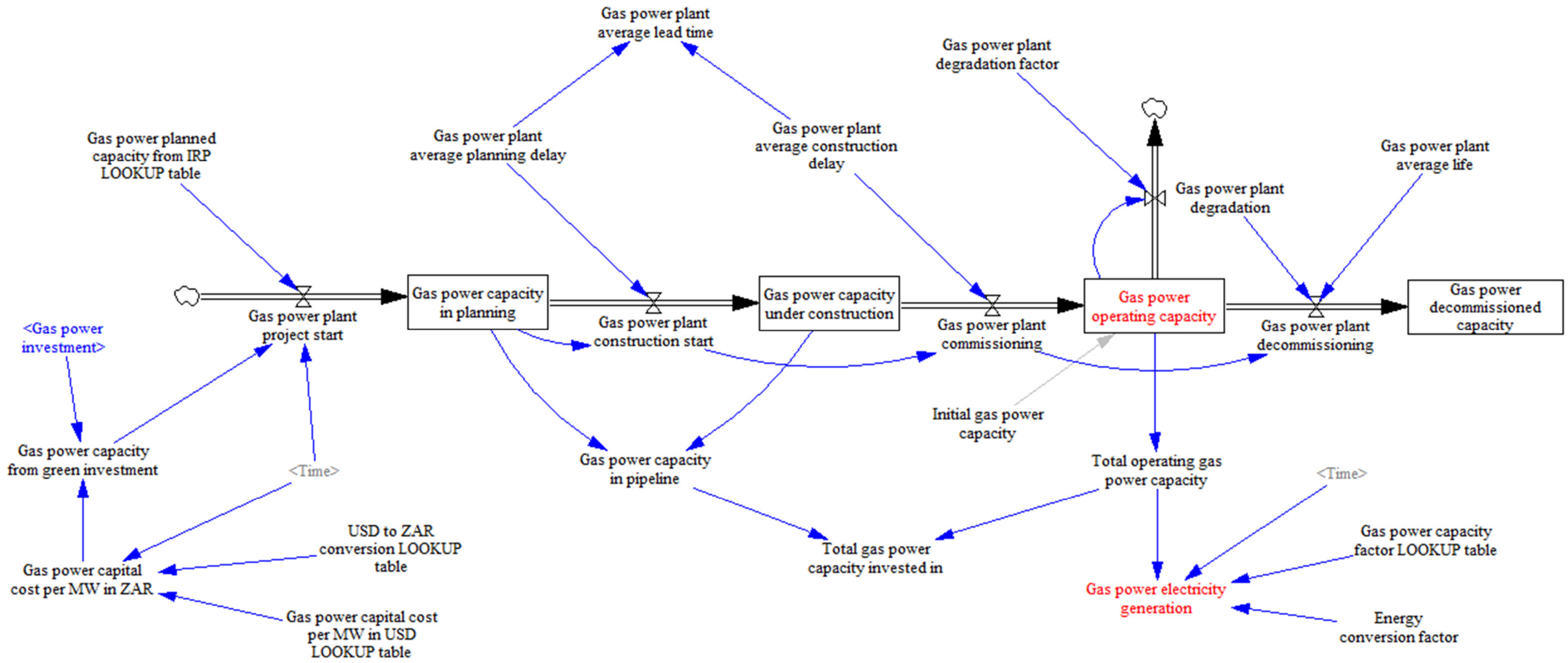

Figure A.10: Gas power sub-model

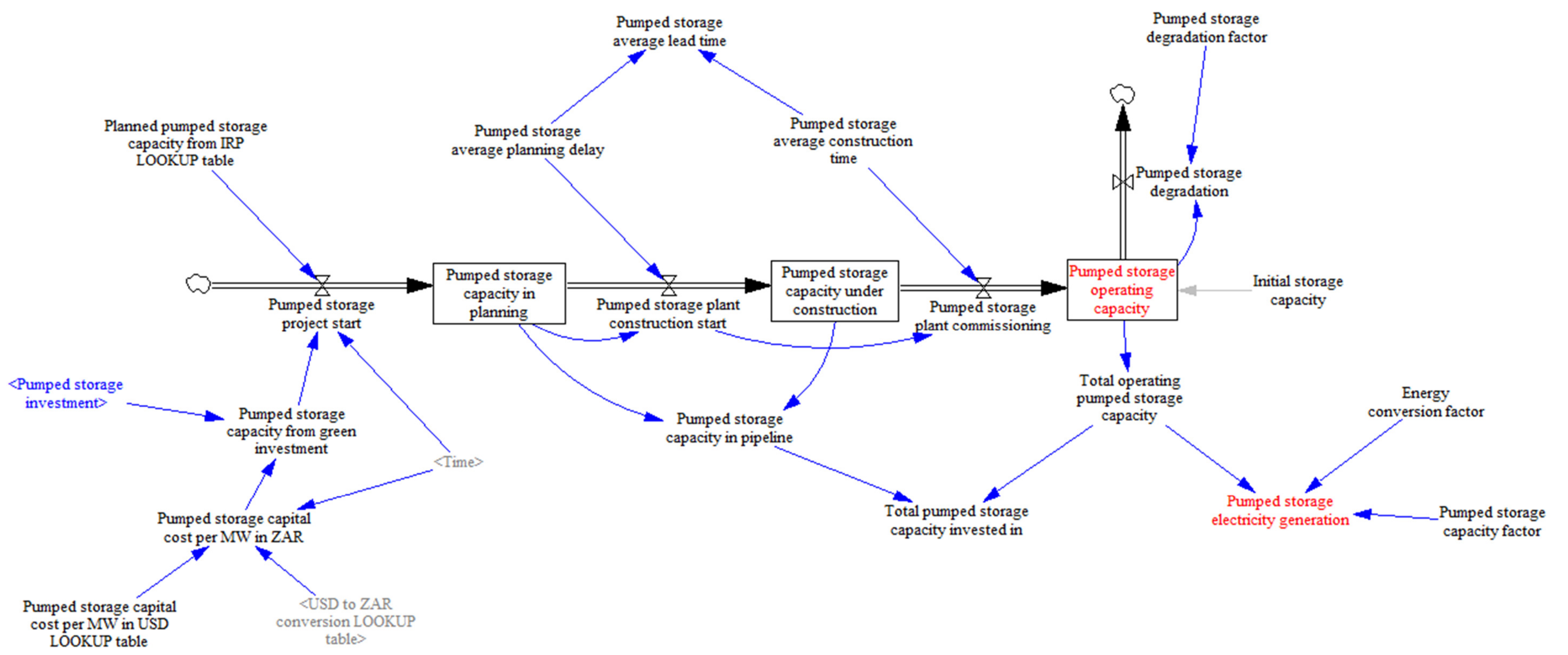

Figure A.11: Pumped storage sub-model

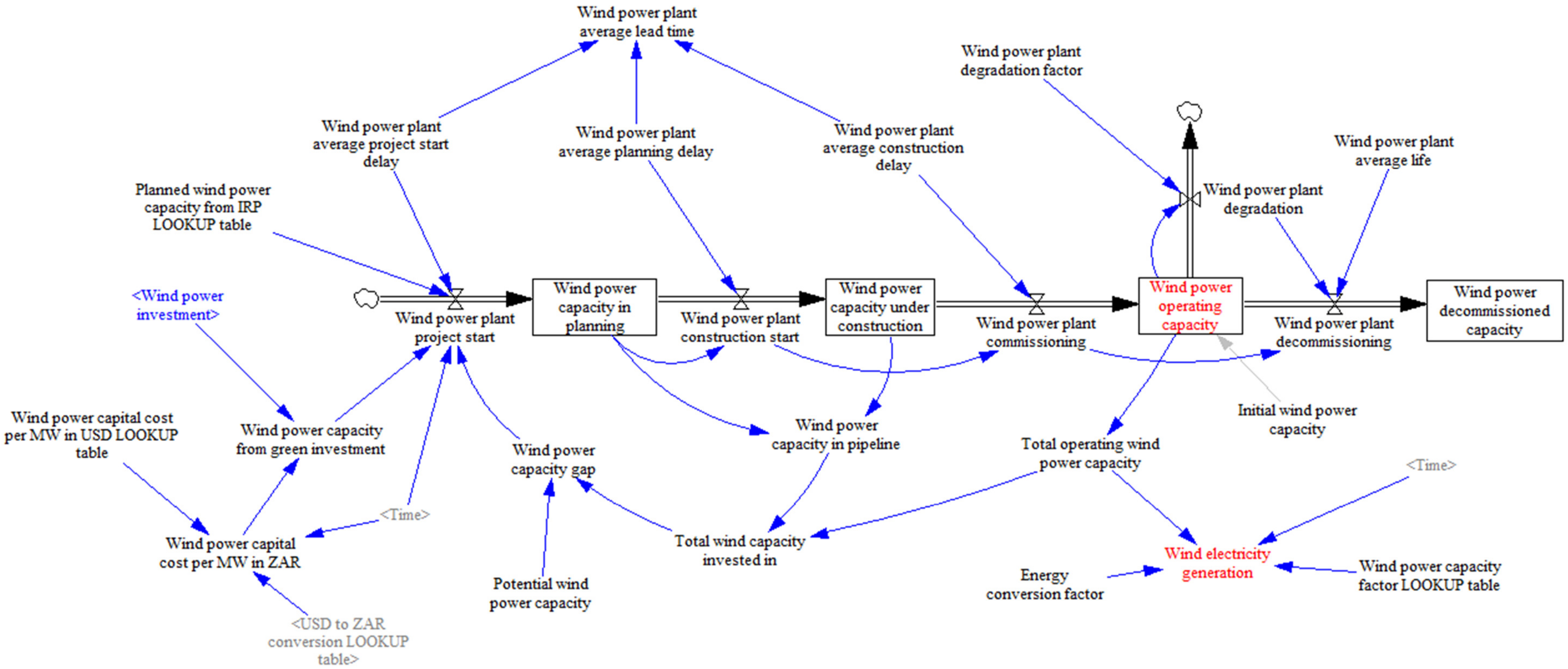

Figure A.12: Wind (onshore) sub-model

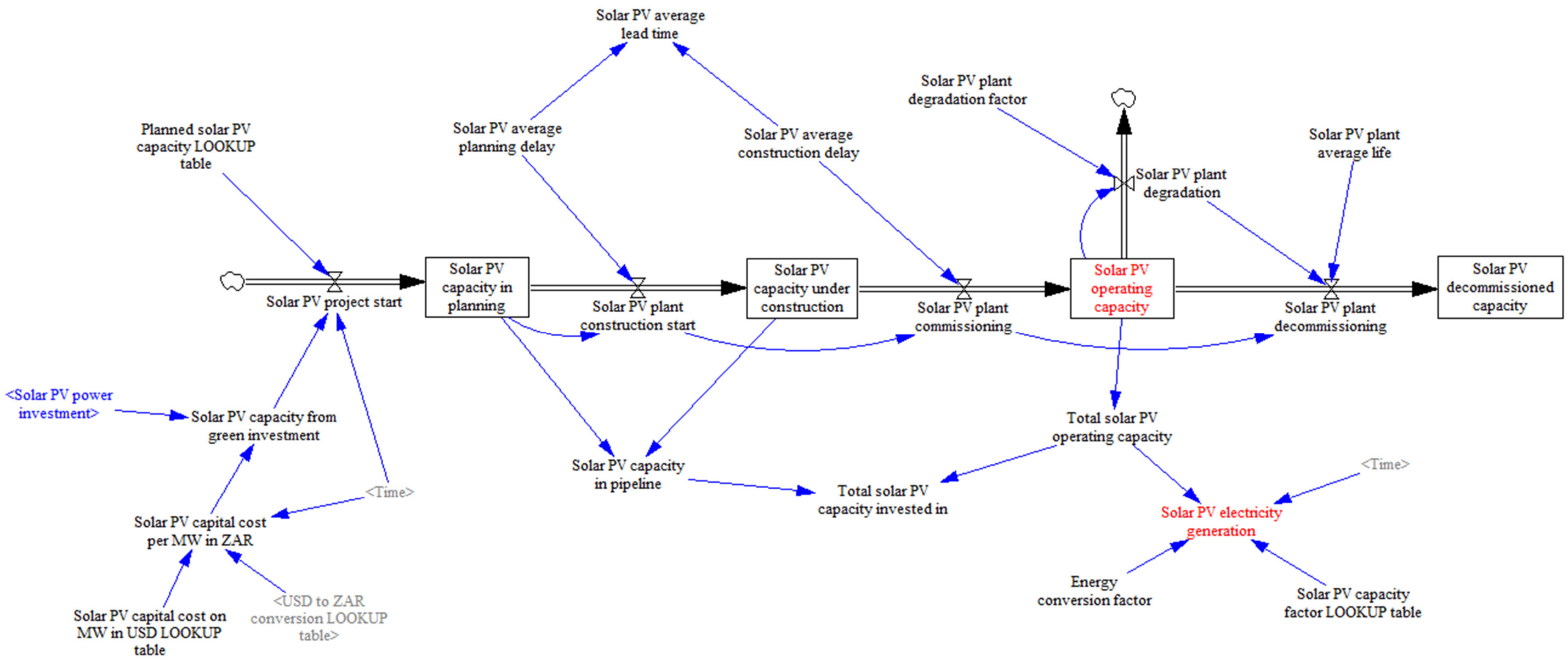

Figure A.13: Solar PV sub-model

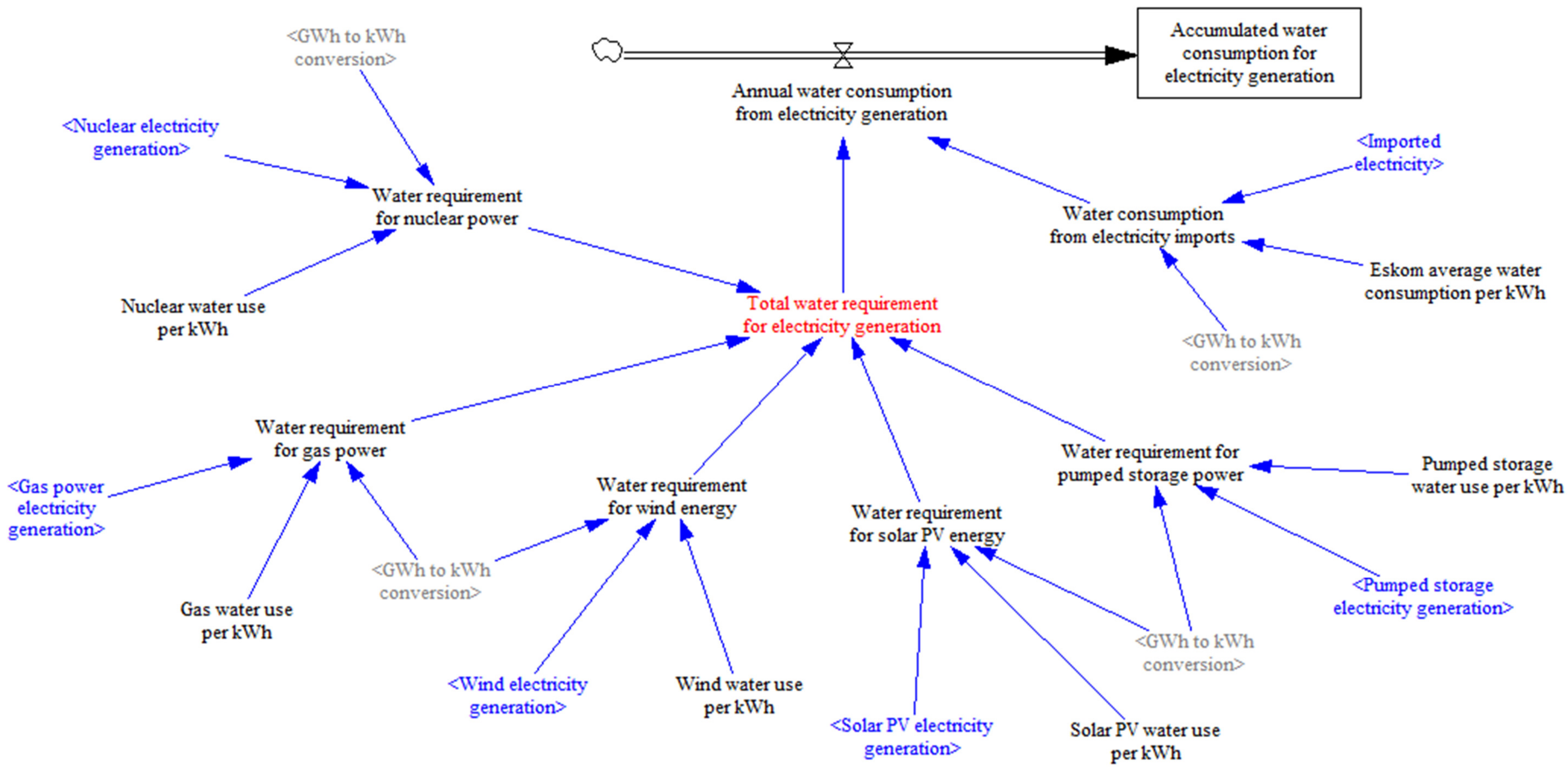

Figure A.14: Water requirements of electricity sector sub-model

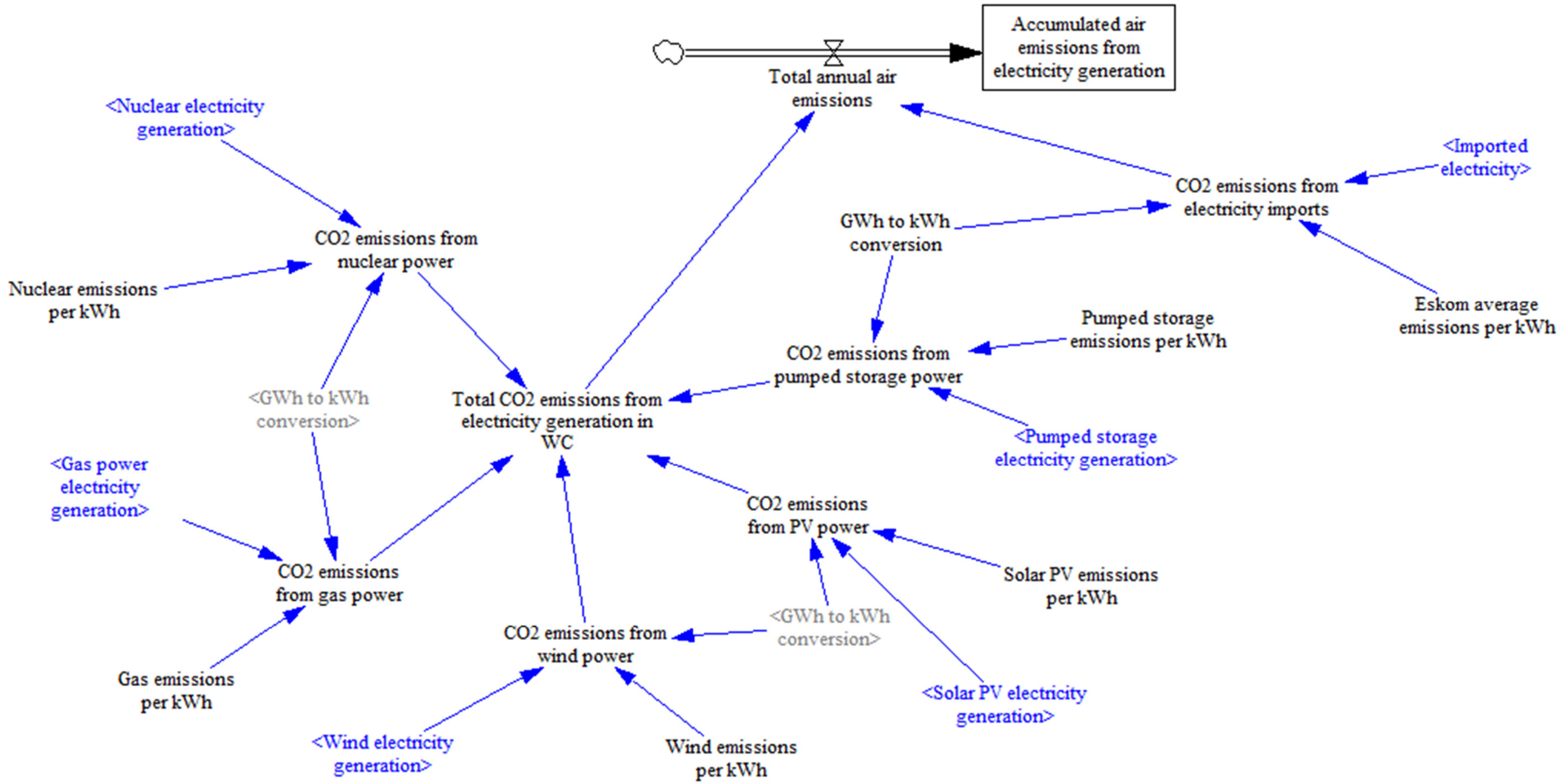

Figure A.15: Electricity air emissions

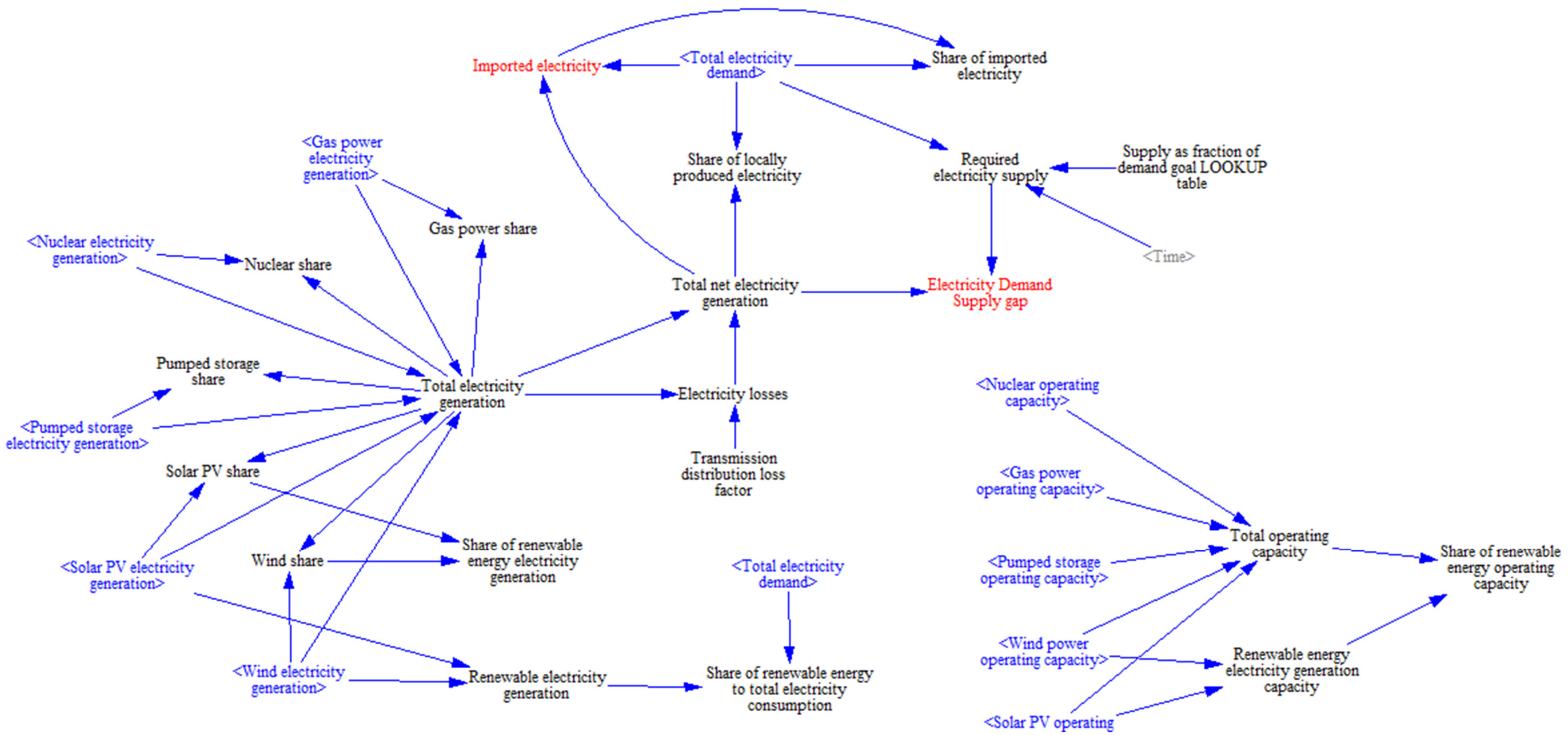

Figure A.16: Electricity technology share sub-model

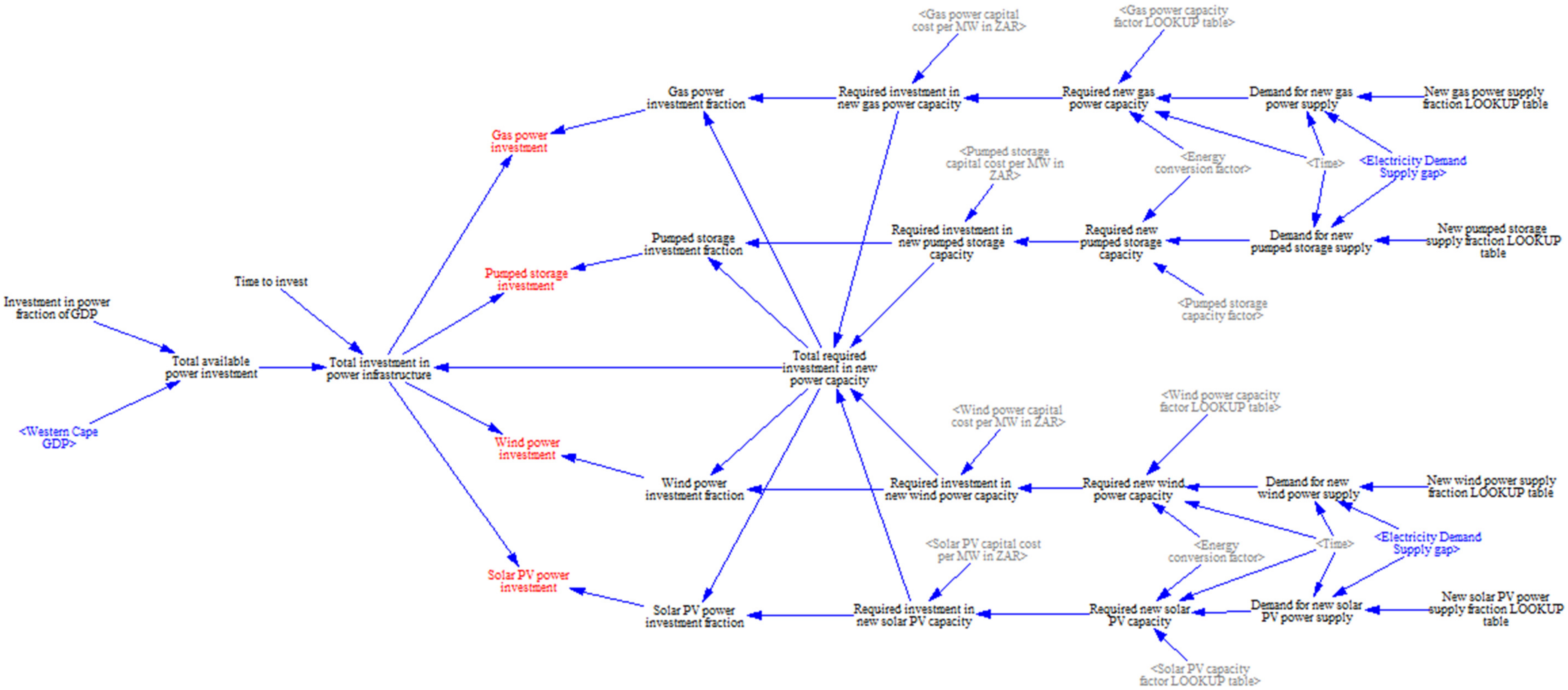

Figure A.17: Electricity sector investments

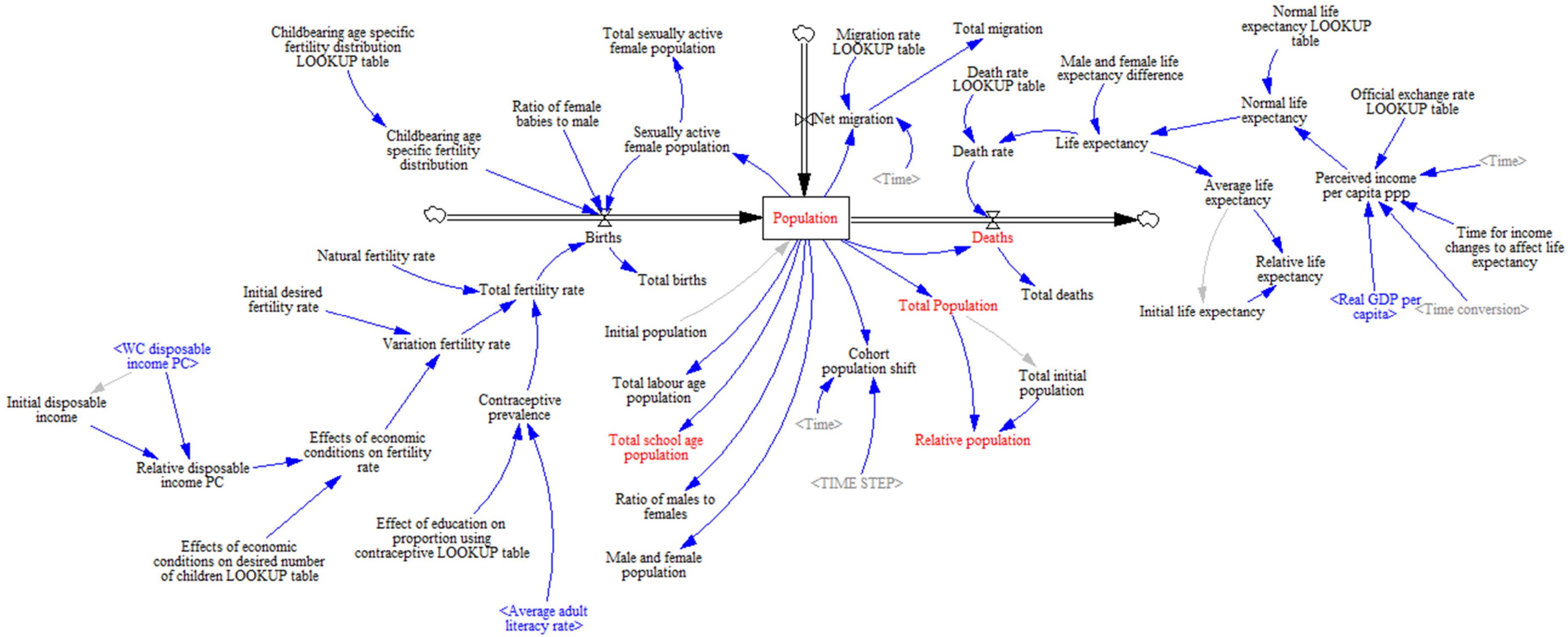

Figure A.18: Population sub-model

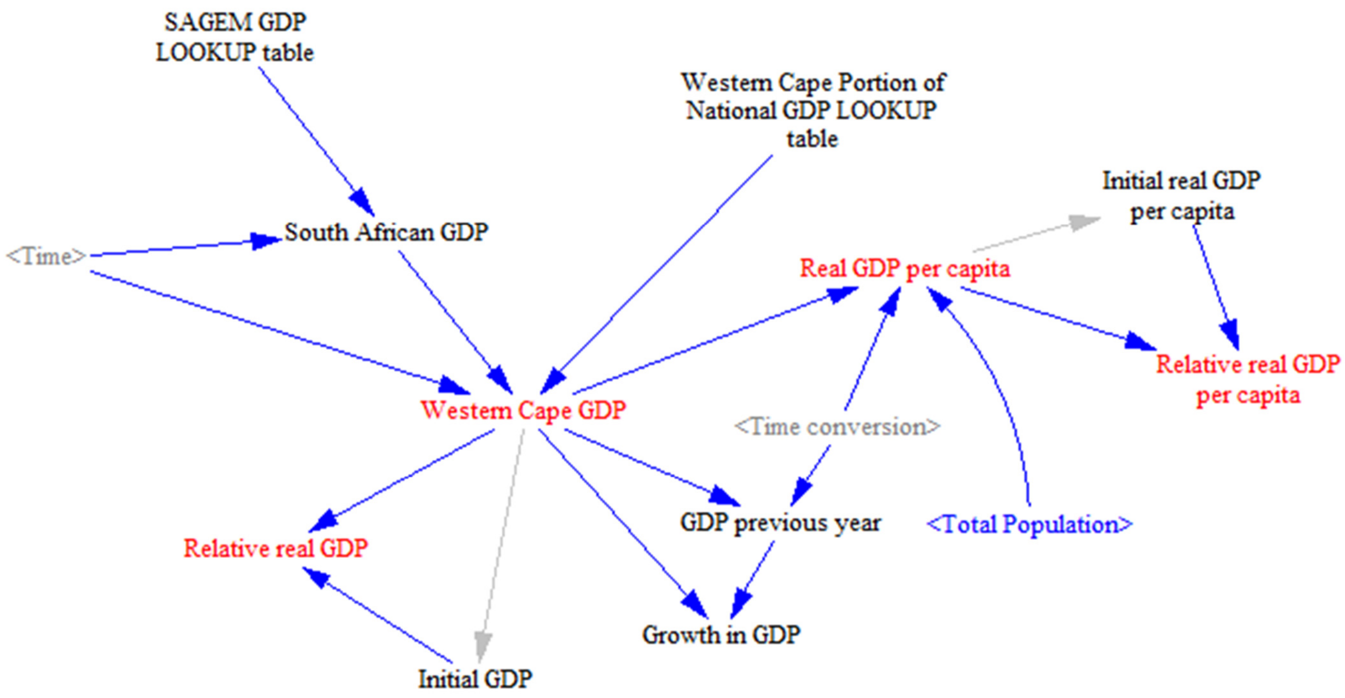

Figure A.19: GDP sub-model

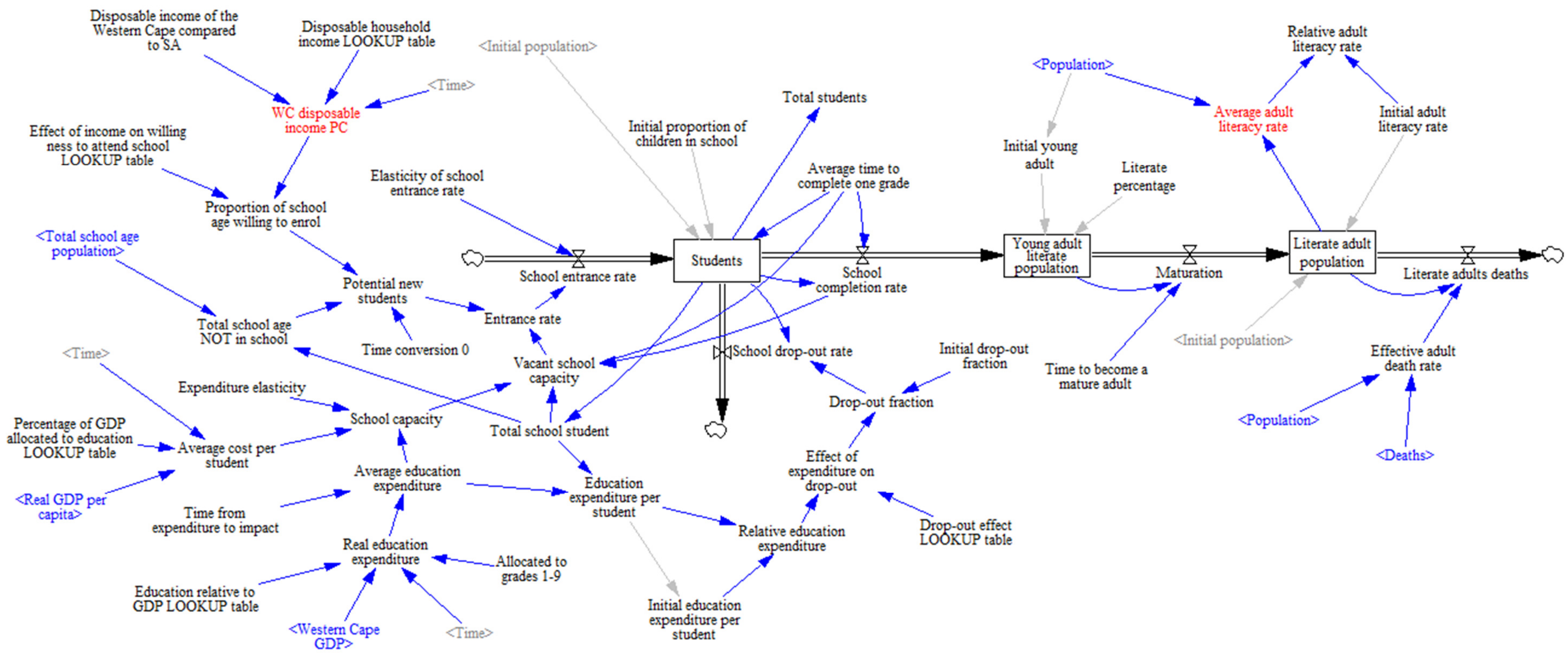

Figure A.20: Education sub-model

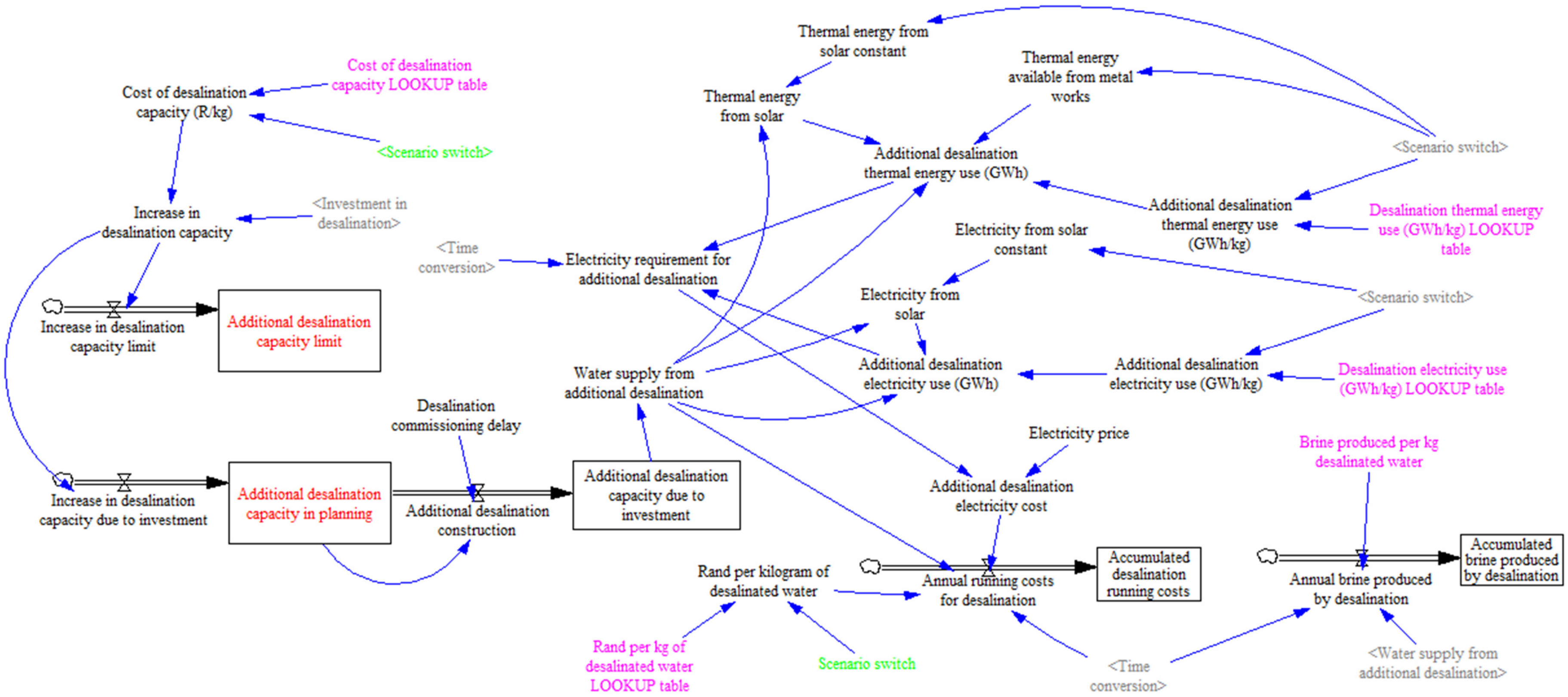

Figure A.21: Scenario testing sub-model

APPENDIX B: MODEL EQUATIONS

B.1 Surface water and groundwater sub-model

Additional dam capacity due to investment= INTEG (Increase in dam capacity due to investment, 0)

Units: kg

Additional pump station capacity due to investment= INTEG (Increase in pump station capacity due to investment, 0)

Units: kg

Annual dam construction= Change in dam capacity/Time conversion

Units: kg/Year

Change in dam capacity= Dam capacity limit-Indicated dam capacity

Units: kg

Change in pump station capacity= MIN(Pump station capacity limit-Indicated pump station capacity, Pump station capacity gap)

Units: kg

"Cost of dam capacity increase (R/kg)"= 1000

Units: Rand/kg

Comment: Actual value is not used because it did not affect the model results.

Cost of groundwater capacity increase= 1000

Units: Rand/kg

Comment: Actual value is not used because it did not affect the model results.

Cubic meter of water per mm of rain per hectare= 10

Units: cubic meter/mm/ha

Dam capacity= INTEG (Annual dam construction-Dam depreciation, Initial dam capacity)

Units: kg

Dam capacity increase= Investment in dam capacity/"Cost of dam capacity increase (R/kg)"

Units: kg/Year

Dam capacity limit= Dam capacity LOOKUP table(Time) + Additional dam capacity due to investment

Units: kg

Dam capacity LOOKUP table([(2001,1e+012) (2040,3e+012)],(2001,1.547e+012),(2009,1.726e+012),(2009,1.853e+012),(2020,1.853e+012),(2020,2.059e+012),(2040,2.059e+012))

Units: kg

Dam depreciation= Dam capacity/Life expectancy of dams
Units: kg/Year

Evaporation= Total WC runoff*Fraction of rain evaporating immediately and rain lost due to system
Units: kg/Year

Fraction of rain evaporating immediately and rain lost due to system= 0.88
Units: Dmnl

Fraction of rain infiltrating and percolating= 0.02
Units: Dmnl

Gap between available capacity and water entering dams= Potential water to enter dams - Indicated dam capacity/Time conversion
Units: kg/Year

Groundwater supply= IF THEN ELSE(Possible available groundwater < Indicated pump station capacity/Time conversion, Possible available groundwater , Indicated pump station capacity /Time conversion)
Units: kg/Year

Increase in dam capacity due to investment= Dam capacity increase
Units: kg/Year

Increase in groundwater capacity= Investment in groundwater capacity/Cost of groundwater capacity increase
Units: kg/Year

Increase in pump station capacity due to investment= Increase in groundwater capacity
Units: kg/Year

Indicated dam capacity= Dam capacity
Units: kg

Indicated pump station capacity= Pump station for groundwater capacity
Units: kg

Initial dam capacity= 1.547e+012
Units: kg

Initial pump station capacity= 2.736e+011
Units: kg

Investment in dam capacity= Fraction of investment in dam capacity*Total investment in water supply

Units: Rand/Year

Investment in groundwater capacity= Fraction of investment in groundwater capacity*Total investment in water supply

Units: Rand/Year

Kilograms per cubic meter of water= 1000

Units: kg/cubic meter

Life expectancy of dams= 100

Units: Year

Comment: This variable indicates the lifespan of a dam. it influences the rate of depreciation on an existing dam. Source: Department of Water Affairs (2012b)

Lifespan of pump station= 20

Units: Year

Source: Department of Water Affairs (2012b)

Possible available groundwater= Possible groundwater from dam overflow + Possible rainfall to become groundwater

Units: kg/Year

Possible groundwater from dam overflow= IF THEN ELSE(Gap between available capacity and water entering dams>0, Gap between available capacity and water entering dams, 0)

Units: kg/Year

Possible rainfall to become groundwater= Total WC runoff*Fraction of rain infiltrating and percolating

Units: kg/Year

Potential water to enter dams= Total WC runoff-Evaporation-Possible rainfall to become groundwater

Units: kg/Year

Pump station capacity gap= UGEP-Indicated pump station capacity

Units: kg

Pump station capacity limit= Pump station capacity LOOKUP table(Time) + Additional pump station capacity due to investment

Units: kg

Pump station capacity LOOKUP table([(2001,2e+011)-(2040,4e+011)],(2001,2.837e+011),(2010,3.298e+011),(2040,3.298e+011))

Units: kg

Comment: Groundwater supply in 2000 was 275000e+006 kg Source: Department of Water Affairs (2013)

According to the Department of Water Affairs (2010), approximately 30% of the groundwater is currently being used therefore 30% of the UGEP value was used. These values were then adjusted to account for pump station depreciation to determine the pump station capacity that would produce the indicated supply

Pump station construction= Change in pump station capacity/Time conversion

Units: kg/Year

Pump station depreciation= Pump station for groundwater capacity/Lifespan of pump station

Units: kg/Year

Pump station for groundwater capacity= INTEG (Pump station construction-Pump station depreciation, Initial pump station capacity)

Units: kg

"Required supply reduction through WC/WSS"= (Required per capita water savings*Total Population)

Units: kg

Surface water supply= MIN(Indicated dam capacity/Time conversion, Potential water to enter dams)

Units: kg/Year

TEMP Mean annual precipitation= TEMP mean annual precipitation table(Time)

Units: mm/Year

TEMP mean annual precipitation table([(2001,0)-(2040,2000)],(2001,907.6),(2002,486.9),(2003,787.9),(2004,239.1),(2005,462.9),(2006,1135),(2007,489),(2008,480.4),(2009,530.1),(2010,826.3),(2011,421.8),(2012,497.5),(2013,507.3),(2014,362.9),(2015,758),(2016,363.6),(2017,641.8),(2018,406.7),(2019,508.7),(2020,719),(2021,267),(2022,387.7),(2023,423.4),(2024,440.2),(2025,309.1),(2026,595.8),(2027,544.1),(2028,688),(2029,1114),(2030,1020),(2031,590),(2032,714.5),(2033,518.9),(2034,333.7),(2035,354.8),(2036,808),(2037,400.7),(2038,710.8),(2039,217.7),(2040,488.2))

Units: mm/Year

Time conversion= 1

Units: Year

Total provincial land= Conservation land + Invasive alien species land + Land available for agricultural use + Livestock land + Other land + Settlement land

Units: ha

Total WC runoff= TEMP Mean annual precipitation*Cubic meter of water per mm of rain per hectare *Kilograms per cubic meter of water*Total provincial land

Units: kg/Year

UGEP= 1.0439e+012

Units: kg

Comment: DWA Gouritz = 279.3Mm^3/a Olifants/Doring = 157.5Mm^3/a Breede = 362.6Mm^3/a Berg = 249Mm^3/a This is the UGEP under normal conditions, it decreases by approximately 25% in drought conditions The UGEP presents a management restriction on the volumes of water that may be abstracted based on a defined maximum allowable water level drawdown. Source: Department of Water Affairs (2010)

****

B.2 Waste water sub-model

Additional WWTW capacity due to investment= INTEG (Increase in WWTW capacity due to investment, 0)

Units: kg

Annual WWTW construction= Change in WWTW capacity/Time conversion

Units: kg/Year

Change in WWTW capacity= WWTW capacity limit - Indicated WWTW capacity

Units: kg

"Cost of WWTW capacity (R/kg)"= 1000

Units: Rand/kg

Comment: Actual value is not used because it did not affect the model results.

Domestic and municipal water demand= Water demand per capita*Total Population/Time conversion

Units: kg/Year

Fraction of water lost through supply system= 0.37

Units: Dmnl

Source: GreenCape (2017)

Fraction of WWTW capacity being used= Fraction of WWTW capacity being used LOOKUP table(Time)

Units: Dmnl/Year

Fraction of WWTW capacity being used LOOKUP table([(2001,0)(2040,1)],(2001,0.7913),(2012,0.7913),(2017,0.87),(2040,0.87))

Units: Dmnl/Year

Source: GreenCape (2017)

Gap between available capacity and available waste water= Potential water for treatment - Indicated WWTW capacity/Time conversion

Units: kg/Year

Increase in WWTW capacity= MAX(Investment in WWTW/"Cost of WWTW capacity (R/kg)", 1e-006)

Units: kg/Year

Increase in WWTW capacity due to investment= Increase in WWTW capacity

Units: kg/Year

Indicated WWTW capacity= WWTW capacity

Units: kg

Initial potable water= 5.29e+011

Units: kg

Initial WWTW capacity= 2.04726e+011

Units: kg

Investment in WWTW= Fraction of investment in WWTW*Total investment in water supply

Units: Rand/Year

Life expectancy of WWTW= 20

Units: Year

Source: Güereca, Musharrafie, Mart'\inez, Padilla, Morgan & Noyola Robles (2011)

Outflow for domestic use= MIN(Potable water/Time conversion, Domestic and municipal water demand)

Units: kg/Year

Potable water= INTEG (Potable water inflow-Outflow for domestic use-UAW in treatment system, Initial potable water)

Units: kg

Potable water inflow= Total water supply

Units: kg/Year

Potential water for treatment= Production water demand*Ratio of outdoor used water turning waste water + Outflow for domestic use*Ratio of domestically used water turning waste water

Units: kg/Year

Production water demand= (Afforestation water demand + Irrigated agriculture water demand + Mining and bulk industry water demand)/Time conversion + Total water requirement for electricity generation

Units: kg/Year

Ratio of domestically used water turning waste water= 0.7

Units: Dmnl

Source: City of Cape Town (2010)

Ratio of outdoor used water turning waste water= 0.95

Units: Dmnl

Source: City of Cape Town (2010)

Recycled water supply= MIN(Indicated WWTW capacity*Fraction of WWTW capacity being used, Potential water for treatment)

Units: kg/Year

Time conversion= 1

Units: Year

Total water supply= Surface water supply + Groundwater supply + BAU desalination water supply/ Time conversion + Recycled water supply + Water supply from additional desalination /Time conversion

Units: kg/Year

UAW in treatment system= (Potable water/Time conversion)*Fraction of water lost through supply system

Units: kg/Year

WWTW capacity= INTEG(Annual WWTW construction-WWTW depreciation, Initial WWTW capacity)

Units: kg

WWTW capacity limit= WWTW capacity LOOKUP table(Time) + Additional WWTW capacity due to investment

Units: kg

WWTW capacity LOOKUP table([(2001,2e+011)-(2040,4e+011)],(2001,2.04726e+011), (2012,3.766e+011),(2040,3.766e+011))

Units: kg

Source: GreenCape (2017)

WWTW depreciation= WWTW capacity/Life expectancy of WWTW
Units: kg/Year

****

B.3 BAU desalination sub-model

BAU desalination water supply= Desalination capacity
Units: kg

Change in desalination plant capacity= Desalination capacity limit/Time conversion - BAU desalination water supply/Time conversion
Units: kg/Year

Desalination capacity= INTEG(Desalination capacity increase-Desalination plant depreciation, 0)
Units: kg

Desalination capacity increase= Change in desalination plant capacity
Units: kg/Year

Desalination capacity limit= Desalination capacity LOOKUP table(Time)
Units: kg

Desalination capacity LOOKUP table([(2001,0)-(2040,9e+009)],(2001,0),(2009,0),(2009,5.475e+008),(2010,5.475e+008),(2010,1.278e+009),(2011,1.278e+009),(2011,6.752e+009),(2012,6.752e+009),(2012,8.0665e+009),(2013,8.067e+009),(2013,8.687e+009),(2040,8.687e+009))
Units: kg
Source: Blersch (2014; 2017)

Desalination plant depreciation= Desalination capacity/Lifespan of desalination plant
Units: kg/Year

Lifespan of desalination plant= 10
Units: Year
Source: Veolia (2017)

Time conversion= 1
Units: Year

****

B.4 Water supply and demand sub-model

Afforestation growth factor= 0.016

Units: Dmnl/Year

Comment: These growth factors are determined by using the 2004 and 2013 GDP values of the specific sector (based on 2010 prices). ((Present-past)/past)/number of years) as was determined by Pienaar (2015)

Afforestation water demand= INTEG (Changes in afforestation water demand, Initial afforestation water demand)

Units: kg

BAU desalination water supply= Desalination capacity

Units: kg

Changes in afforestation water demand= Afforestation water demand*Afforestation growth factor

Units: kg/Year

Changes in irrigation demand= Irrigated agriculture water demand*Irrigation growth factor

Units: kg/Year

Changes in mining and bulk industry water demand= Mining and bulk industry water demand*Mining and bulk industry growth factor

Units: kg/Year

Decrease in water demand per capita= MIN(Water demand per capita gap/Time conversion, IF THEN ELSE(Time > 2015, Water savings per capita , Rate of decrease in water demand per capita*Water demand per capita))

Units: kg/(Year*person)

Domestic and municipal water demand= Water demand per capita*Total Population/Time conversion

Units: kg/Year

Groundwater supply= IF THEN ELSE(Possible available groundwater < Indicated pump station capacity/Time conversion, Possible available groundwater , Indicated pump station capacity /Time conversion)

Units: kg/Year

Initial afforestation water demand= 2.1e+010

Units: kg

Source: Statistics South Africa (2010)

Initial irrigated agriculture water demand= 1.488e+012

Units: kg

Source: Department of Water Affairs & Forestry (2004)

Initial mining and bulk industry water demand= 9e+009

Units: kg

Source: Department of Water Affairs & Forestry (2004)

Initial water demand per capita= 116800

Units: kg/person

Source: Department of Water Affairs & Forestry (2004)

Irrigated agriculture water demand= INTEG (Changes in irrigation demand, Initial irrigated agriculture water demand)

Units: kg

Irrigation growth factor= 0.016

Units: Dmnl/Year

Comment: These growth factors are determined by using the 2004 and 2013 GDP values of the specific sector (based on 2010 prices). ((Present-past)/past)/number of years) as was determined by Pienaar (2015)

Min water demand per capita= 40177

Units: kg/person

Comment: According to the Department of Water Affairs & Forestry (2004; 2012), the average per capita water demand of the Western Cape is 110 kg/person/day. The actual value is much higher because of water losses and irresponsible use therefore the aim of the WC/WDM is to prevent these losses therefore the minimum water demand per capita is set to 110 kg/person/day or 40177 kg/person/year

Mining and bulk industry growth factor= -0.0017

Units: Dmnl/Year

Comment: These growth factors are determined by using the 2004 and 2013 GDP values of the specific sector (based on 2010 prices). ((Present-past)/past)/number of years) as was determined by Pienaar (2015)

Mining and bulk industry water demand= INTEG (Changes in mining and bulk industry water demand, Initial mining and bulk industry water demand)

Units: kg

Per capita water demand= Per capita water demand LOOKUP table(Time)

Units: kg/(Year*person)

Per capita water demand LOOKUP table([(2001,70000)-(2040,200000)],(2001,116800),(2040,73000))

Units: kg/person/Year

Production water demand= (Afforestation water demand + Irrigated agriculture water demand + Mining and bulk industry water demand)/Time conversion + Total water requirement for electricity generation

Units: kg/Year

Rate of decrease in water demand per capita= 0.01026

Units: Dmnl/Year

Comment: Known values: Demand for 2001 = 116800 kg/person (Department of Water Affairs & Forestry, 2004) Predicted demand for 2015 = 101100 kg/person (Statistics South Africa, 2010) Then solve for r using goal seek in excel

Recycled water supply= MIN(Indicated WWTW capacity*Fraction of WWTW capacity being used, Potential water for treatment)

Units: kg/Year

Supply demand deficit= Total water supply - Total water demand

Units: kg/Year

Surface water supply= MIN(Indicated dam capacity/Time conversion, Potential water to enter dams)

Units: kg/Year

Time conversion= 1

Units: Year

Total Population= SUM(Population[sex!,age!])

Units: person

Total water demand= Domestic and municipal water demand + Production water demand

Units: kg/Year

Total water requirement for electricity generation= (Water requirement for nuclear power + Water requirement for gas power + Water requirement for pumped storage power + Water requirement for solar PV energy + Water requirement for wind energy)

Units: kg/Year

Total water supply= Surface water supply + Groundwater supply + BAU desalination water supply/ Time conversion + Recycled water supply + Water supply from additional desalination/Time conversion

Units: kg/Year

Water demand per capita= INTEG (-Decrease in water demand per capita, Initial water demand per capita)

Units: kg/person

Water demand per capita gap= Water demand per capita - Min water demand per capita

Units: kg/person

Water savings per capita= "Investment in WC/WDM"/"Cost of water savings per capita (R/kg/person)"

Units: kg/person/Year

Water stress index= Total water demand/Total water supply

Units: Dmnl

Water supply from additional desalination= Additional desalination capacity due to investment

Units: kg

****

B.5 Water sector investments sub-model

Additional desalination capacity due to investment= INTEG (Additional desalination construction, 0)

Units: kg

Additional desalination capacity in planning= INTEG (Increase in desalination capacity due to investment-Additional desalination construction, 0)

Units: kg

Additional desalination capacity limit= INTEG (Increase in desalination capacity limit, 0)

Units: kg

BAU or Scenario Switch= 0

Units: Dmnl

"Cost of dam capacity increase (R/kg)"= 1000

Units: Rand/kg

Comment: Actual value is not used because it did not affect the model results.

"Cost of desalination capacity (R/kg)"= Cost of desalination capacity LOOKUP table(Scenario switch)

Units: Rand/kg

Cost of groundwater capacity increase= 1000

Units: Rand/kg

Comment: Actual value is not used because it did not affect the model results.

"Cost of water savings per capita (R/kg/person)"= 127273
Units: Rand/(kg/person)
Source: Department of Water & Sanitation (2016)

"Cost of WWTW capacity (R/kg)"= 1000
Units: Rand/kg
Comment: Actual value is not used because it did not affect the model results.

Fraction of investment in dam capacity= IF THEN ELSE(Total required investment in new water capacity = 0, 0 , Required investment in new dam capacity/Total required investment in new water capacity)
Units: Dmnl

Fraction of investment in desalination= IF THEN ELSE(Total required investment in new water capacity = 0, 0 , Required investment in new desalination capacity/Total required investment in new water capacity)
Units: Dmnl

Fraction of investment in groundwater capacity= IF THEN ELSE(Total required investment in new water capacity = 0, 0 , Required investment in new groundwater capacity/Total required investment in new water capacity)
Units: Dmnl

Fraction of investment in WWTW= IF THEN ELSE(Total required investment in new water capacity = 0, 0 , Required investment in new WWTW capacity/Total required investment in new water capacity)
Units: Dmnl

Investment in dam capacity= Fraction of investment in dam capacity*Total investment in water supply
Units: Rand/Year

Investment in desalination= Fraction of investment in desalination*Total investment in water supply
Units: Rand/Year

Investment in groundwater capacity= Fraction of investment in groundwater capacity*Total investment in water supply
Units: Rand/Year

Investment in Water supply fraction of GDP= IF THEN ELSE(Time > 2016, Investment in water supply fraction of GDP LOOKUP table(Water stress index)*BAU or Scenario Switch , 0)
Units: Dmnl

Investment in water supply fraction og GDP LOOKUP table([(0,0)-(10,10)],(1,0),(1.031,0.003))

Units: Dmnl

Comment: Policy decision

"Investment in WC/WDM fraction of GDP LOOKUP table"([(0.9,0)-(1.1,0.002)],(0.9,0),(1,0),(1.1,0))

Units: Dmnl

"Investment in WC/WDM fraction of GDP"="Investment in WC/WDM fraction of GDP LOOKUP table"(Water stress index)

Units: Dmnl

"Investment in WC/WDM"= "Investment in WC/WDM fraction of GDP"*Western Cape GDP + "Planned investment in WC/WDM LOOKUP table"(Time)

Units: Rand/Year

Investment in WWTW= Fraction of investment in WWTW*Total investment in water supply

Units: Rand/Year

New desalination capacity limit= IF THEN ELSE(BAU or Scenario Switch = 0, 0 , IF THEN ELSE(Time > 2016, 7.4876e+010 , 0))

Units: kg

Comment: Policy intervention

Per capita water savings LOOKUP table([(2015,0)-(2040,30000)],(2015,28100),(2040,0))

Units: kg/person

Source: Department of Water & Sanitation (2016)

"Planned investment in WC/WDM LOOKUP table"([(2016,0)-(2040,3e+008)],(2016,1.75e+008),(2017,1.5e+008),(2018,1.5e+008),(2019,2.4e+008),(2020,1.8e+008),(2021,0),(2040,0))

Units: Rand/Year

Source: Department of Water & Sanitation (2016)

Required investment in new dam capacity= Required new dam capacity*"Cost of dam capacity increase (R/kg)"

Units: Rand

Required investment in new desalination capacity= Required new desalination capacity*"Cost of desalination capacity (R/kg)"

Units: Rand

Required investment in new groundwater capacity= Required new groundwater capacity*Cost of groundwater capacity increase

Units: Rand

Required investment in new WWTW capacity= Required new WWTW capacity*"Cost of WWTW capacity (R/kg)"
Units: Rand

Required new dam capacity= 0
Units: kg

Required new desalination capacity= New desalination capacity limit - Additional desalination capacity limit
Units: kg

Required new groundwater capacity= 0
Units: kg

Required new WWTW capacity= 0
Units: kg

Required per capita water savings= IF THEN ELSE(Time <2015, 0, IF THEN ELSE(Water stress index>0.95, Per capita water savings LOOKUP table(Time) , 0))
Units: kg/person

Scenario switch= 0
Units: Dmnl

Time to invest= 1
Units: Year

Total available water supply investment= Investment in Water supply fraction of GDP*Western Cape GDP
Units: Rand/Year

Total investment in water supply= MIN(Total available water supply investment, Total required investment in new water capacity/Time to invest)
Units: Rand/Year

Total required investment in new water capacity= Required investment in new dam capacity + Required investment in new groundwater capacity + Required investment in new WWTW capacity + Required investment in new desalination capacity
Units: Rand

Water savings per capita= "Investment in WC/WDM"/"Cost of water savings per capita (R/kg/person)"

Units: kg/person/Year

Water stress index= Total water demand/Total water supply

Units: Dmnl

Western Cape GDP= South African GDP*Western Cape Portion of National GDP LOOKUP table(Time)

Units: Rand/Year

****

B.6 Electricity requirement of water sector sub-model

Accumulated electricity consumption for water supply= INTEG (Annual electricity consumption for water supply, 0)

Units: GWh

Annual electricity consumption for water supply= Total electricity requirements for water supply

Units: GWh/Year

"BAU desalination electricity use (GWh/kg)"= 3e-009

Units: GWh/kg

Comment: According to Marsh (2008), this ranges from 3 to 5 kWh/kL. This has been converted to GWh/kg by multiplying with 10^-9

BAU desalination water supply= Desalination capacity

Units: kg

Electricity requirement for additional desalination= ("Additional desalination electricity use (GWh)"+"Additional desalination thermal energy use (GWh)")/Time conversion

Units: GWh/Year

Electricity requirement for BAU desalinated water supply= "BAU desalination electricity use (GWh/kg)"*BAU desalination water supply/Time conversion

Units: GWh/Year

Electricity requirement for desalination= Electricity requirement for BAU desalinated water supply + Electricity requirement for additional desalination

Units: GWh/Year

Electricity requirement for groundwater supply= "Groundwater electricity use (GWh/kg)" *Groundwater supply

Units: GWh/Year

Electricity requirement for recycled water supply= "Recycled water electricity use (GWh/kg)" *Recycled water supply

Units: GWh/Year

Electricity requirement for surface water supply= "Surface water electricity use (GWh/kg)"*Surface water supply

Units: GWh/Year

"Groundwater electricity use (GWh/kg)"= 1e-010

Units: GWh/kg

Groundwater supply= IF THEN ELSE(Possible available groundwater < Indicated pump station capacity/Time conversion, Possible available groundwater , Indicated pump station capacity /Time conversion)

Units: kg/Year

"Recycled water electricity use (GWh/kg)"= 4e-010

Units: GWh/kg

Comment: According to Marsh (2008), this ranges from 0.4 to 0.5kWh/kL. This has been converted to GWh/kg by multiplying with 10^-9

Recycled water supply= MIN(Indicated WWTW capacity*Fraction of WWTW capacity being used, Potential water for treatment)

Units: kg/Year

"Surface water electricity use (GWh/kg)"= 1e-010

Units: GWh/kg

Comment: According to Marsh (2008), this ranges from 0.1 to 0.6kWh/kL. This has been converted to GWh/kg by multiplying with 10^-9

Surface water supply= MIN(Indicated dam capacity/Time conversion, Potential water to enter dams)

Units: kg/Year

Time conversion= 1

Units: Year

Total electricity demand= SUM(Sectoral electricity demand[Sectors!]) + Total electricity requirements for water supply

Units: GWh/Year

Total electricity requirements for water supply= (Electricity requirement for desalination+Electricity requirement for groundwater supply+Electricity requirement for recycled water supply+Electricity requirement for surface water supply)

Units: GWh/Year

****

B.7 Electricity demand sub-model

CPI discount rate= CPI discount rate LOOKUP table(Time)

Units: Dmnl

CPI discount rate LOOKUP table([(2001,0)-(2040,20)],(2001,0.057),(2002,0.1521),(2003,0.2209) ,(2004,0.2403),(2005,0.2844),(2006,0.3452),(2007,0.4183),(2008,0.6007),(2009,0.8647), (2010,1.162),(2011,1.545),(2012,1.92),(2013,2.222),(2014,2.55),(2015,2.908),(2016,3.298), (2017,3.722),(2018,4.109),(2019,4.519),(2020,4.953),(2021,5.414),(2022,5.902),(2023,6.419), (2024,6.968),(2025,7.549),(2026,8.166),(2027,8.819),(2028,9.511),(2029,10.25),(2030,11.02), (2031,11.85),(2032,12.72),(2033,13.65),(2034,14.63),(2035,15.67),(2036,16.78),(2037,17.95), (2038,19.19),(2039,20.5),(2040,21.89))

Units: Dmnl

Source: Oosthuizen (2015)

Effect of electricity price on electricity demand[Residential]= Relative real electrcity price^Elasticity of electricity price on demand[Residential]

Effect of electricity price on electricity demand[Industrial]= Relative real electrcity price^Elasticity of electricity price on demand[Industrial]

Effect of electricity price on electricity demand[Commercial]= Relative real electrcity price^Elasticity of electricity price on demand[Commercial]

Effect of electricity price on electricity demand[Transport]= Relative real electrcity price^Elasticity of electricity price on demand[Transport]

Effect of electricity price on electricity demand[Agricultural]= Relative real electrcity price^Elasticity of electricity price on demand[Agricultural]

Units: Dmnl

Effect of GDP on electricity demand[Residential]= Relative real GDP^Elasticity of GDP growth on demand[Residential]

Effect of GDP on electricity demand[Industrial]= Relative real GDP^Elasticity of GDP growth on demand[Industrial]

Effect of GDP on electricity demand[Commercial]= Relative real GDP^Elasticity of GDP growth on demand[Commercial]

Effect of GDP on electricity demand[Transport]= Relative real GDP^Elasticity of GDP growth on demand[Transport]

Effect of GDP on electricity demand[Agricultural]= Relative real GDP^Elasticity of GDP growth on demand[Agricultural]

Units: Dmnl

Effect of GDP per capita on electricity demand[Residential]= Relative real GDP per capita^Elasticity of GDP per capita on demand[Residential]
Effect of GDP per capita on electricity demand[Industrial]= Relative real GDP per capita^Elasticity of GDP per capita on demand[Industrial]
Effect of GDP per capita on electricity demand[Commercial]= Relative real GDP per capita^Elasticity of GDP per capita on demand[Commercial]
Effect of GDP per capita on electricity demand[Transport]= Relative real GDP per capita^Elasticity of GDP per capita on demand[Transport]
Effect of GDP per capita on electricity demand[Agricultural]= Relative real GDP per capita^Elasticity of GDP per capita on demand[Agricultural]

Units: Dmnl

Effect of population on electricity demand= Relative population^Elasticity of population on demand

Units: Dmnl

Elasticity of electricity price on demand[Residential]= -0.04
Elasticity of electricity price on demand[Industrial]= -0.3
Elasticity of electricity price on demand[Commercial]=-0.05
Elasticity of electricity price on demand[Transport]= -0.01
Elasticity of electricity price on demand[Agricultural]= -0.05

Units: Dmnl

Comment: According to Oosthuizen (2015), Zirumba(2008) stated that residential price elasticities are elastic at -0.04. Lotz & Blignaut(2011) stated that industrial price elasticities are at -0.869, also stating that the industrial sector is the only sector with a significant price elasticity. Price elasticity in SA is not very significant because users do not have the option of switching to other sources of power, or other providers of electricity.

Elasticity of GDP growth on demand[Residential]= 0
Elasticity of GDP growth on demand[Industrial]= 0.8
Elasticity of GDP growth on demand[Commercial]= 0.42
Elasticity of GDP growth on demand[Transport]= 0
Elasticity of GDP growth on demand[Agricultural]= 0.42

Units: Dmnl

Comment: According to Oosthuizen (2015), GDP only shows effects on non-residential sectors. Deloitte(2012) states GDP elasticity to be roughly 1.2 or between 0.8 and 1.1. Inglesi(2010) states GDP elasticity to be 0.42.

Elasticity of GDP per capita on demand[Residential]= 0.31
Elasticity of GDP per capita on demand[Industrial]= 0
Elasticity of GDP per capita on demand[Commercial]= 0
Elasticity of GDP per capita on demand[Transport]= 0.31

Elasticity of GDP per capita on demand[Agricultural]= 0

Units: Dmnl

Comment: According to Oosthuizen (2015), Ziramba(2008) stated that the income elasticity for households is 0.31. Other sectors depend on the GDP and not on GDP per capita.

Elasticity of population on demand= 1

Units: Dmnl

Comment: Population has unitary elasticity on electricity demand

Electricity price change= Electricity price change LOOKUP table(Time)

Units: Dmnl

Electricity price change LOOKUP table([(2001,0)-(2040,30)],(2001,0.052),(2002,0.1172),(2003,0.2114),(2004,0.2417),(2005,0.2926),(2006,0.3585),(2007,0.4387),(2008,0.8343),(2009,1.408),(2010,2.006),(2011,2.781),(2012,3.386),(2013,3.737),(2014,4.116),(2015,4.525),(2016,4.967),(2017,5.445),(2018,5.831),(2019,6.241),(2020,6.676),(2021,7.136),(2022,7.625),(2023,8.142),(2024,8.691),(2025,9.272),(2026,9.888),(2027,10.54),(2028,11.23),(2029,11.97),(2030,12.75),(2031,13.57),(2032,14.45),(2033,15.37),(2034,16.35),(2035,17.4),(2036,18.5),(2037,19.67),(2038,20.91),(2039,22.22),(2040,23.62))

Units: Dmnl

Initial electricity demand[Residential]= 5713.3
Initial electricity demand[Industrial]= 9030.7
Initial electricity demand[Commercial]= 2194.08
Initial electricity demand[Transport]= 937
Initial electricity demand[Agricultural]= 1435.6

Units: GWh/Year

Comment: From Western Cape Government (2013b) without water sector energy demand

Initial electricity price= 0.132

Units: Rand

Nominal electricity price= Initial electricity price*Electricity price change

Units: Rand

Real electricity price= (1+Real electricity price increase)*Initial electricity price

Units: Rand

Real electricity price increase= Electricity price change-CPI discount rate

Units: Dmnl

Relative population= Total Population/Total initial population

Units: Dmnl

Relative real electrcity price= Real electricity price/Initial electricity price

Units: Dmnl

Relative real GDP= Western Cape GDP/Initial GDP

Units: Dmnl

Relative real GDP per capita= Real GDP per capita/Initial real GDP per capita

Units: Dmnl

Sectoral electricity demand[Residential]= Initial electricity demand[Residential]*Effect of electricity price on electricity demand[Residential]*Effect of GDP per capita on electricity demand[Residential]*Effect of population on electricity demand

Sectoral electricity demand[Industrial]= Initial electricity demand[Industrial]*Effect of electricity price on electricity demand[Industrial]*Effect of GDP on electricity demand[Industrial]

Sectoral electricity demand[Commercial]= Initial electricity demand[Commercial]*Effect of electricity price on electricity demand[Commercial]*Effect of GDP on electricity demand[Commercial]

Sectoral electricity demand[Transport]= Initial electricity demand[Transport]*Effect of electricity price on electricity demand[Transport]*Effect of GDP per capita on electricity demand[Transport]*Effect of population on electricity demand

Sectoral electricity demand[Agricultural]= Initial electricity demand[Agricultural]*Effect of electricity price on electricity demand[Agricultural]*Effect of GDP on electricity demand [Agricultural]

Units: GWh/Year

Comment: Electricity for transport is mostly from the passenger rail sector.

Total electricity demand= SUM(Sectoral electricity demand[Sectors!]) + Total electricity requirements for water supply

Units: GWh/Year

Total electricity requirements for water supply= (Electricity requirement for desalination+Electricity requirement for groundwater supply+Electricity requirement for recycled water supply+Electricity requirement for surface water supply)

Units: GWh/Year

****

B.8 Nuclear sub-model

Energy conversion factor= 8.76

Units: GWh/(MW*Year)

Initial nuclear capacity= 1840

Units: MW

Comment: Initial installed capacity at Koeberg Nuclear Power Station

Nuclear capacity factor= 0.8

Units: Dmnl

Comment: Koeberg average Or 0.92 in IRP for electricity

Nuclear capacity gap= MAX(Potential nuclear capacity-Total nuclear capacity invested in, 0)

Units: MW

Nuclear capacity in pipeline= Nuclear capacity in planning + Nuclear capacity under construction

Units: MW

Nuclear capacity in planning= INTEG (Nuclear plant project start-Nuclear plant construction start, 0)

Units: MW

Nuclear capacity under construction= INTEG (Nuclear plant construction start-Nuclear plant commissioning, 0)

Units: MW

Nuclear electricity generation= Total operating nuclear capacity*Energy conversion factor*Nuclear capacity factor

Units: GWh/Year

Nuclear operating capacity= INTEG (Nuclear plant commissioning-Nuclear plant degradation, Initial nuclear capacity)

Units: MW

Nuclear plant average construction delay= 5

Units: Year

Nuclear plant average lead time= Nuclear plant average project start delay + Nuclear plant average planning delay + Nuclear plant average construction delay

Units: Year

Nuclear plant average planning delay= 2

Units: Year

Nuclear plant average project start delay= 1

Units: Year

Nuclear plant commissioning= DELAY FIXED (Nuclear plant construction start, Nuclear plant average construction delay, 0)

Units: MW/Year

Nuclear plant construction start= Nuclear capacity in planning/Nuclear plant average planning delay
Units: MW/Year

Nuclear plant degradation= Nuclear operating capacity*Nuclear plant degradation factor
Units: MW/Year

Nuclear plant degradation factor= 0.001
Units: Dmnl/Year
Comment: According to Oosthuizen (2015), degradation for steam turbines was considered here, and not for the entire nuclear power plant. Figures for degradation range between 0.1%/year and 0.8%/year. From "Steam turbine efficiency degradation"

Nuclear plant project start= MIN(Nuclear capacity gap/Nuclear plant average project start delay ,Planned nuclear capacity from IRP LOOKUP table(Time))
Units: MW/Year

Planned nuclear capacity from IRP LOOKUP table([(2001,0)-(2040,10000)],(2001,0),(2020,0),(2030,0),(2040,0))
Units: MW/Year
Source: IRP for electricity 2010 - energyramblings.com

Potential nuclear capacity= 5400
Units: MW
Comment: Based on the fact that only two sites have been set out for nuclear use in the Western Cape. The first is the expansion of Koeberg, the second is Bantemsklip. Koeberg is 1800MW and a new nuclear power station will not exceed a capacity of 3600 MW, thus limits capacity to 5400MW

Total nuclear capacity invested in= Nuclear capacity in pipeline + Total operating nuclear capacity
Units: MW

Total operating nuclear capacity= Nuclear operating capacity
Units: MW

****

B.9 Gas power sub-model

Energy conversion factor= 8.76
Units: GWh/(MW*Year)

Gas power capacity factor LOOKUP table([(2001,0)-(2040,1)],(2001,0.22),(2010,0.22),(2020,0.22),(2035,0.22),(2040,0.22))
Units: Dmnl

Comment: 22% based on peak demand hours between 06:00-08:00 and 17:00-20:00

Gas power capacity from green investment= Gas power investment/Gas power capital cost per MW in ZAR

Units: MW/Year

Gas power capacity in pipeline= Gas power capacity in planning + Gas power capacity under construction

Units: MW

Gas power capacity in planning= INTEG (Gas power plant project start-Gas power plant construction start, 0)

Units: MW

Gas power capacity under construction= INTEG (Gas power plant construction start-Gas power plant commissioning, 0)

Units: MW

Gas power capital cost per MW in USD LOOKUP table([(2001,300000)-(2040,700000)],(2001,400000),(2010,700000),(2020,700000),(2035,700000),(2040,700000))

Units: USD/MW

Source: IEA World Energy Outlook 2011

Gas power capital cost per MW in ZAR= USD to ZAR conversion LOOKUP table(Time)*Gas power capital cost per MW in USD LOOKUP table(Time)

Units: Rand/MW

Gas power decommissioned capacity= INTEG (Gas power plant decommissioning, 0)

Units: MW

Gas power electricity generation= Total operating gas power capacity*Gas power capacity factor LOOKUP table(Time)*Energy conversion factor

Units: GWh/Year

Gas power investment= Total investment in power infrastructure*Gas power investment fraction

Units: Rand/Year

Gas power operating capacity= INTEG (Gas power plant commissioning-Gas power plant decommissioning-Gas power plant degradation, Initial gas power capacity)

Units: MW

Gas power planned capacity from IRP LOOKUP table([(2001,0)-(2040,10000)],(2001,0),(2004,0),(2005,2084),(2006,0),(2020,0),(2030,0),(2040,0))

Units: MW/Year

Source: Department of Energy (2013)

Gas power plant average construction delay= 1.5

Units: Year

Gas power plant average lead time= Gas power plant average planning delay + Gas power plant average construction delay

Units: Year

Gas power plant average life= 60

Units: Year

Gas power plant average planning delay= 1

Units: Year

Gas power plant commissioning= DELAY FIXED (Gas power plant construction start, Gas power plant average construction delay, 0)

Units: MW/Year

Gas power plant construction start= Gas power capacity in planning/Gas power plant average planning delay

Units: MW/Year

Gas power plant decommissioning= DELAY FIXED (Gas power plant commissioning - Gas power plant degradation, Gas power plant average life, 0)

Units: MW/Year

Gas power plant degradation= Gas power operating capacity*Gas power plant degradation factor

Units: MW/Year

Gas power plant degradation factor=0.003

Units: Dmnl/Year

Comment: According to Oosthuizen (2015), between 0.3%/year and 2%/year for gas turbines. From "GE gas turbine performance characteristics'

Gas power plant project start= Gas power capacity from green investment + Gas power planned capacity from IRP LOOKUP table(Time)

Units: MW/Year

Initial gas power capacity= 171

Units: MW

Total gas power capacity invested in= Gas power capacity in pipeline + Total operating gas power capacity

Units: MW

Total operating gas power capacity= Gas power operating capacity

Units: MW

USD to ZAR conversion LOOKUP table([(2001,9)-(2040,10)],(2001,10),(2002,10),(2003,10),(2004,10),(2005,10),(2006,10),(2007,10),(2008,10),(2009,10),(2010,10),(2011,10),(2012,10),(2013,10),(2014,10),(2015,10),(2016,10),(2017,10),(2018,10),(2019,10),(2020,10),(2021,10),(2022,10),(2023,10),(2024,10),(2025,10),(2026,10),(2027,10),(2028,10),(2029,10),(2030,10),(2031,10),(2032,10),(2033,10),(2034,10),(2035,10),(2036,10),(2037,10),(2038,10),(2039,10),(2040,10))

Units: Rand/USD

****

B.10 Pumped storage sub-model

Energy conversion factor= 8.76

Units: GWh/(MW*Year)

Initial storage capacity= 580

Units: MW

Comment: Palmiet (400MW) + Steenbras (180MW)

Planned pumped storage capacity from IRP LOOKUP table([(2001,0)-(2040,5e+006)],(2001,0),(2020,0),(2030,0),(2040,0))

Units: MW/Year

Source: Department of Energy (2013)

Pumped storage average construction time= 3

Units: Year

Pumped storage average lead time= Pumped storage average planning delay + Pumped storage average construction time

Units: Year

Pumped storage average planning delay= 1.5

Units: Year

Pumped storage capacity factor= 0.2

Units: Dmnl

Pumped storage capacity from green investment= Pumped storage investment/Pumped storage capital cost per MW in ZAR

Units: MW/Year

Pumped storage capacity in pipeline= Pumped storage capacity in planning + Pumped storage capacity under construction

Units: MW

Pumped storage capacity in planning= INTEG (Pumped storage project start-Pumped storage plant construction start, 0)

Units: MW

Pumped storage capacity under construction= INTEG (Pumped storage plant construction start-Pumped storage plant commissioning, 0)

Units: MW

Pumped storage capital cost per MW in USD LOOKUP table([(2001,0)-(2040,5e+006)],(2001,2.33e+006),(2020,2.13e+006),(2035,1.98e+006),(2040,1.98e+006))

Units: USD/MW

Source: IEA World Energy Outlook 2011

Pumped storage capital cost per MW in ZAR= USD to ZAR conversion LOOKUP table(Time)*Pumped storage capital cost per MW in USD LOOKUP table(Time)

Units: Rand/MW

Pumped storage degradation= Pumped storage degradation factor*Pumped storage operating capacity

Units: MW/Year

Pumped storage degradation factor= 0.001

Units: Dmnl/Year

Comment: Estimate

Pumped storage electricity generation= Total operating pumped storage capacity*Pumped storage capacity factor*Energy conversion factor

Units: GWh/Year

Pumped storage investment= Total investment in power infrastructure*Pumped storage investment fraction

Units: Rand/Year

Pumped storage operating capacity= INTEG (Pumped storage plant commissioning-Pumped storage degradation, Initial storage capacity)

Units: MW

Pumped storage plant commissioning= DELAY FIXED (Pumped storage plant construction start, Pumped storage average construction time, 0)

Units: MW/Year

Pumped storage plant construction start=Pumped storage capacity in planning/Pumped storage average planning delay

Units: MW/Year

Pumped storage project start= Pumped storage capacity from green investment + Planned pumped storage capacity from IRP LOOKUP table(Time)

Units: MW/Year

Total operating pumped storage capacity= Pumped storage operating capacity

Units: MW

Total pumped storage capacity invested in= Total operating pumped storage capacity + Pumped storage capacity in pipeline

Units: MW

USD to ZAR conversion LOOKUP table([(2001,9)-(2040,10)],(2001,10),(2002,10),(2003,10),(2004,10),(2005,10),(2006,10),(2007,10),(2008,10),(2009,10),(2010,10),(2011,10),(2012,10),(2013,10),(2014,10),(2015,10),(2016,10),(2017,10),(2018,10),(2019,10),(2020,10),(2021,10),(2022,10),(2023,10),(2024,10),(2025,10),(2026,10),(2027,10),(2028,10),(2029,10),(2030,10),(2031,10),(2032,10),(2033,10),(2034,10),(2035,10),(2036,10),(2037,10),(2038,10),(2039,10),(2040,10))

Units: Rand/USD

****

B.11 Wind (onshore) sub-model

Energy conversion factor= 8.76

Units: GWh/(MW*Year)

Initial wind power capacity= 3.16

Units: MW

Comment: 3.16 = Klipheuwel wind farm

Planned wind power capacity from IRP LOOKUP table([(2001,0)-(2040,1000)],(2001,0),(2011,0),(2012,92),(2013,226),(2014,0),(2015,140),(2016,55),(2017,55),(2023,55),(2030,55),(2031,55),(2040,55))

Units: MW/Year

Potential wind power capacity= 3600
Units: MW

Total operating wind power capacity= Wind power operating capacity
Units: MW

Total wind capacity invested in= Total operating wind power capacity + Wind power capacity in pipeline
Units: MW

USD to ZAR conversion LOOKUP table([(2001,9)-(2040,10)],(2001,10),(2002,10),(2003,10),(2004,10),(2005,10),(2006,10),(2007,10),(2008,10),(2009,10),(2010,10),(2011,10),(2012,10),(2013,10),(2014,10),(2015,10),(2016,10),(2017,10),(2018,10),(2019,10),(2020,10),(2021,10),(2022,10),(2023,10),(2024,10),(2025,10),(2026,10),(2027,10),(2028,10),(2029,10),(2030,10),(2031,10),(2032,10),(2033,10),(2034,10),(2035,10),(2036,10),(2037,10),(2038,10),(2039,10),(2040,10))
Units: Rand/USD

Wind electricity generation= Total operating wind power capacity*Wind power capacity factor LOOKUP table(Time)*Energy conversion factor
Units: GWh/Year

Wind power capacity factor LOOKUP table([(2001,0)-(2040,1)],(2001,0.35),(2010,0.35),(2020,0.4),(2035,0.4),(2040,0.4))
Units: Dmnl
Source: http://www.sanea.org.za/CalendarOfEvents/2013/SANEALecturesCT/Feb 13/KilianHagemann-G7RenewableEnergiesAndSAWEA.pdf
http://awsassets.wwf.org.za/downloads/a16369_wwf_reip_report_online.pdf

Wind power capacity from green investment= Wind power investment/Wind power capital cost per MW in ZAR
Units: MW/Year

Wind power capacity gap= MAX(Potential wind power capacity - Total wind capacity invested in, 0)
Units: MW

Wind power capacity in pipeline= Wind power capacity in planning + Wind power capacity under construction
Units: MW

Wind power capacity in planning= INTEG (Wind power plant project start-Wind power plant construction start, 0)
Units: MW

Wind power capacity under construction= INTEG (Wind power plant construction start-Wind power plant commissioning, 0)

Units: MW

Wind power capital cost per MW in USD LOOKUP table([(2001,0)-(2040,5e+006)],(2001,1.47e+006),(2020,1.37e+006),(2035,1.37e+006),(2040,1.37e+006))

Units: USD/MW

Source: IEA Word Energy Outlook 2011

Wind power capital cost per MW in ZAR= USD to ZAR conversion LOOKUP table(Time)*Wind power capital cost per MW in USD LOOKUP table (Time)

Units: Rand/MW

Wind power decommissioned capacity= INTEG (Wind power plant decommissioning, 0)

Units: MW

Wind power investment= Total investment in power infrastructure*Wind power investment fraction

Units: Rand/Year

Wind power operating capacity= INTEG (Wind power plant commissioning-Wind power plant decommissioning-Wind power plant degradation, Initial wind power capacity)

Units: MW

Wind power plant average construction delay= 1

Units: Year

Wind power plant average lead time= Wind power plant average project start delay + Wind power plant average planning delay + Wind power plant average construction delay

Units: Year

Wind power plant average life= 20

Units: Year

Wind power plant average planning delay= 1

Units: Year

Wind power plant average project start delay= 1

Units: Year

Wind power plant commissioning= DELAY FIXED (Wind power plant construction start, Wind power plant average construction delay, 0)

Units: MW/Year

Wind power plant construction start= Wind power capacity in planning/Wind power plant average planning delay

Units: MW/Year

Wind power plant decommissioning= DELAY FIXED (Wind power plant commissioning - Wind power plant degradation, Wind power plant average life, 0)

Units: MW/Year

Wind power plant degradation= Wind power operating capacity*Wind power plant degradation factor

Units: MW/Year

Wind power plant degradation factor= 0.015

Units: Dmnl/Year

Source: According to Oosthuizen (2015), from "How does wind farm performance decline with age?"

Wind power plant project start= MIN(Wind power capacity from green investment + Planned wind power capacity from IRP LOOKUP table(Time),Wind power capacity gap/Wind power plant average project start delay)

Units: MW/Year

****

B.12 Solar PV sub-model

Energy conversion factor= 8.76

Units: GWh/(MW*Year)

Planned solar PV capacity LOOKUP table([(2001,0)-(2040,1000)],(2001,0),(2011,0),(2012,41),(2013,18),(2014,75),(2015,18),(2016,18),(2017,18),(2023,18),(2030,18),(2030,18),(2040,18))

Units: MW/Year

Comment: Figures represent the REIPP contracts that have been signed

Source: Energy Project Database (2017)

Solar PV average construction delay= 1

Units: Year

Solar PV average lead time= Solar PV average planning delay + Solar PV average construction delay

Units: Year

Solar PV average planning delay= 1

Units: Year

Solar PV capacity factor LOOKUP table([(2001,0)-(2040,1)],(2001,0.2),(2010,0.2),(2020,0.22),(2035,0.22),(2040,0.22))

Units: Dmnl

Source: WWF (2014)

Solar PV capacity from green investment= Solar PV power investment/Solar PV capital cost per MW in ZAR

Units: MW/Year

Solar PV capacity in pipeline= Solar PV capacity in planning + Solar PV capacity under construction

Units: MW

Solar PV capacity in planning= INTEG (Solar PV project start-Solar PV plant construction start, 0)

Units: MW

Solar PV capacity under construction= INTEG (Solar PV plant construction start-Solar PV plant commissioning, 0)

Units: MW

Solar PV capital cost on MW in USD LOOKUP table([(2001,0)-(2040,5e+006)],(2001,3.23e+006),(2020,2.14e+006),(2035,1.63e+006),(2040,1.63e+006))

Units: USD/MW

Source: IEA World Energy Outlook 2011

Solar PV capital cost per MW in ZAR= USD to ZAR conversion LOOKUP table(Time)*Solar PV capital cost on MW in USD LOOKUP table(Time)

Units: Rand/MW

Solar PV decommissioned capacity= INTEG (Solar PV plant decommissioning, 0)

Units: MW

Solar PV electricity generation= Total solar PV operating capacity*Energy conversion factor*Solar PV capacity factor LOOKUP table(Time)

Units: GWh/Year

Solar PV operating capacity= INTEG (Solar PV plant commissioning-Solar PV plant decommissioning-Solar PV plant degradation, 0)

Units: MW

Solar PV plant average life= 20

Units: Year

Solar PV plant commissioning= DELAY FIXED (Solar PV plant construction start, Solar PV average construction delay, 0)

Units: MW/Year

Solar PV plant construction start= Solar PV capacity in planning/Solar PV average planning delay

Units: MW/Year

Solar PV plant decommissioning= DELAY FIXED (Solar PV plant commissioning - Solar PV plant degradation, Solar PV plant average life, 0)

Units: MW/Year

Solar PV plant degradation= Solar PV operating capacity*Solar PV plant degradation factor

Units: MW/Year

Solar PV plant degradation factor= 0.005

Units: Dmnl/Year

Comment: This is the rate at which the individual PV modules degrade every year, leading to a loss in system performance, and hence, power output. 0.5%/year average as claimed by the report "PV degradation rates - An analytical review"

Solar PV power investment= Total investment in power infrastructure*Solar PV power investment fraction

Units: Rand/Year

Solar PV project start= Solar PV capacity from green investment + Planned solar PV capacity LOOKUP table(Time)

Units: MW/Year

Total solar PV capacity invested in= Total solar PV operating capacity + Solar PV capacity in pipeline

Units: MW

Total solar PV operating capacity= Solar PV operating capacity

Units: MW

USD to ZAR conversion LOOKUP table([(2001,9)-(2040,10)],(2001,10),(2002,10),(2003,10),(2004,10),(2005,10),(2006,10),(2007,10),(2008,10),(2009,10),(2010,10),(2011,10),(2012,10),(2013,10),(2014,10),(2015,10),(2016,10),(2017,10),(2018,10),(2019,10),(2020,10),(2021,10),(2022,10),(2023,10),(2024,10),(2025,10),(2026,10),(2027,10),(2028,10),(2029,10),(2030,10),(2031,10),(2032,10),(2033,10),(2034,10),(2035,10),(2036,10),(2037,10),(2038,10),(2039,10),(2040,10))

Units: Rand/USD

****

B.13 Water requirements of electricity sector sub-model

Accumulated water consumption for electricity generation= INTEG (Annual water consumption from electricity generation, 0)

Units: kg

Annual water consumption from electricity generation= Total water requirement for electricity generation + Water consumption from electricity imports

Units: kg/Year

Eskom average water consumption per kWh= 1.26

Units: kg/kWh

Comment: According to Eskom average water consumption ranges from 1.26 to 1.32L/kWh

Source: Eskom (2017b)

Gas power electricity generation= Total operating gas power capacity*Gas power capacity factor LOOKUP table(Time)*Energy conversion factor

Units: GWh/Year

Gas water use per kWh= 2.4*10^-4

Units: kg/kWh

Comment: Potable water is only used for cleaning of turbine blades.

According to the EIA of Gourikwa, the plant consumes 30kl/month. This was used to obtain the above value. Source: The Environmental Partnership (2005)

GWh to kWh conversion= 10^6

Units: kWh/GWh

Imported electricity= Total electricity demand - Total net electricity generation

Units: GWh/Year

Nuclear electricity generation= Total operating nuclear capacity*Energy conversion factor*Nuclear capacity factor

Units: GWh/Year

Nuclear water use per kWh= 0

Units: kg/kWh

Comment: Koeberg does not use freshwater - Eskom

Pumped storage electricity generation= Total operating pumped storage capacity*Pumped storage capacity factor*Energy conversion factor

Units: GWh/Year

Pumped storage water use per kWh= 0
Units: kg/kWh

Solar PV electricity generation= Total solar PV operating capacity*Energy conversion factor*Solar PV capacity factor LOOKUP table (Time)
Units: GWh/Year

Solar PV water use per kWh= 0
Units: kg/kWh

Total water requirement for electricity generation= (Water requirement for nuclear power+Water requirement for gas power+Water requirement for pumped storage power+Water requirement for solar PV energy+Water requirement for wind energy)
Units: kg/Year

Water consumption from electricity imports= Eskom average water consumption per kWh*GWh to kWh conversion*Imported electricity
Units: kg/Year

Water requirement for gas power= Gas power electricity generation*GWh to kWh conversion*Gas water use per kWh
Units: kg/Year

Water requirement for nuclear power= Nuclear electricity generation*GWh to kWh conversion*Nuclear water use per kWh
Units: kg/Year

Water requirement for pumped storage power= Pumped storage electricity generation*GWh to kWh conversion*Pumped storage water use per kWh
Units: kg/Year

Water requirement for solar PV energy= Solar PV electricity generation*GWh to kWh conversion*Solar PV water use per kWh
Units: kg/Year

Water requirement for wind energy= Wind electricity generation*GWh to kWh conversion*Wind water use per kWh
Units: kg/Year

Wind electricity generation= Total operating wind power capacity*Wind power capacity factor LOOKUP table(Time)*Energy conversion factor
Units: GWh/Year

Wind water use per kWh= 0

Units: kg/kWh

****

B.14 Electricity air emissions sub-model

Accumulated air emissions from electricity generation= INTEG (Total annual air emissions, 0)

Units: kg CO2

CO2 emissions from electricity imports= MAX(0, Imported electricity*GWh to kWh conversion *Eskom average emissions per kWh)

Units: kg CO2/Year

CO2 emissions from gas power= Gas power electricity generation*GWh to kWh conversion*Gas emissions per kWh

Units: kg CO2/Year

CO2 emissions from nuclear power= Nuclear electricity generation*GWh to kWh conversion*Nuclear emissions per kWh

Units: kg CO2/Year

CO2 emissions from pumped storage power= Pumped storage electricity generation*GWh to kWh conversion*Pumped storage emissions per kWh

Units: kg CO2/Year

CO2 emissions from PV power= Solar PV electricity generation*GWh to kWh conversion*Solar PV emissions per kWh

Units: kg CO2/Year

CO2 emissions from wind power= Wind electricity generation*GWh to kWh conversion*Wind emissions per kWh

Units: kg CO2/Year

Eskom average emissions per kWh= 1.04

Units: kg CO2/kWh

Gas emissions per kWh= 0.54

Units: kg CO2/kWh

Source: NREL Report Evans et.al. (Assessment of sustainability indicators for renewable energy technologies)

Gas power electricity generation= Total operating gas power capacity*Gas power capacity factor LOOKUP table(Time)*Energy conversion factor

Units: GWh/Year

GWh to kWh conversion= 10^6

Units: kWh/GWh

Imported electricity= Total electricity demand - Total net electricity generation

Units: GWh/Year

Nuclear electricity generation= Total operating nuclear capacity*Energy conversion factor*Nuclear capacity factor

Units: GWh/Year

Nuclear emissions per kWh= 0.012

Units: kg CO2/kWh

Source: NREL Report

Pumped storage electricity generation= Total operating pumped storage capacity*Pumped storage capacity factor*Energy conversion factor

Units: GWh/Year

Pumped storage emissions per kWh= 0.041

Units: kg CO2/kWh

The value for Hydro power was used here Evans et.al. (Assessment of sustainability indicators for renewable energy technologies)

Solar PV electricity generation= Total solar PV operating capacity*Energy conversion factor*Solar PV capacity factor LOOKUP table(Time)

Units: GWh/Year

Solar PV emissions per kWh= 0.046

Units: kg CO2/kWh

Source: NREL report

Total annual air emissions= Total CO2 emissions from electricity generation in WC + CO2 emissions from electricity imports

Units: kg CO2/Year

Total CO2 emissions from electricity generation in WC= CO2 emissions from gas power+CO2 emissions from nuclear power+CO2 emissions from pumped storage power+CO2 emissions from PV power+CO2 emissions from wind power

Units: kg CO2/Year

Wind electricity generation=Total operating wind power capacity*Wind power capacity factor LOOKUP table(Time)*Energy conversion factor

Units: GWh/Year

Wind emissions per kWh= 0.011

Units: kg CO2/kWh

Source: NREL report

****

B.15 Electricity technology share sub-model

Electricity Demand Supply gap= Required electricity supply - Total net electricity generation

Units: GWh/Year

Electricity losses= Total electricity generation*Transmission distribution loss factor

Units: GWh/Year

Gas power electricity generation= Total operating gas power capacity*Gas power capacity factor LOOKUP table(Time)*Energy conversion factor

Units: GWh/Year

Gas power operating capacity= INTEG (Gas power plant commissioning-Gas power plant decommissioning-Gas power plant degradation, Initial gas power capacity)

Units: MW

Gas power share= Gas power electricity generation/Total electricity generation

Units: Dmnl

Imported electricity= Total electricity demand - Total net electricity generation

Units: GWh/Year

Nuclear electricity generation= Total operating nuclear capacity*Energy conversion factor*Nuclear capacity factor

Units: GWh/Year

Nuclear operating capacity= INTEG (Nuclear plant commissioning-Nuclear plant degradation, Initial nuclear capacity)

Units: MW

Nuclear share= Nuclear electricity generation/Total electricity generation

Units: Dmnl

Pumped storage electricity generation= Total operating pumped storage capacity*Pumped storage capacity factor*Energy conversion factor

Units: GWh/Year

Pumped storage operating capacity= INTEG (Pumped storage plant commissioning-Pumped storage degradation, Initial storage capacity)

Units: MW

Pumped storage share= Pumped storage electricity generation/Total electricity generation

Units: Dmnl

Renewable electricity generation= Solar PV electricity generation + Wind electricity generation

Units: GWh/Year

Renewable energy electricity generation capacity= Solar PV operating capacity + Wind power operating capacity

Units: MW

Required electricity supply= Total electricity demand*Supply as fraction of demand goal LOOKUP table(Time)

Units: GWh/Year

Share of imported electricity= Imported electricity/Total electricity demand

Units: Dmnl

Share of locally produced electricity= Total net electricity generation/Total electricity demand

Units: Dmnl

Share of renewable energy electricity generation= Solar PV share + Wind share

Units: Dmnl

Share of renewable energy operating capacity= Renewable energy electricity generation capacity/Total operating capacity

Units: Dmnl

Share of renewable energy to total electricity consumption= Renewable electricity generation/Total electricity demand

Units: Dmnl

Solar PV electricity generation= Total solar PV operating capacity*Energy conversion factor*Solar PV capacity factor LOOKUP table(Time)

Units: GWh/Year

Solar PV operating capacity= INTEG (Solar PV plant commissioning-Solar PV plant decommissioning-Solar PV plant degradation, 0)
Units: MW

Solar PV share= Solar PV electricity generation/Total electricity generation
Units: Dmnl

Supply as fraction of demand goal LOOKUP table([(2001,0)-(2040,3)],(2001,1),(2010,1),(2020,1),(2035, 1), (2040, 1))
Units: Dmnl

Total electricity demand= SUM(Sectoral electricity demand[Sectors!]) + Total electricity requirements for water supply
Units: GWh/Year

Total electricity generation= Gas power electricity generation + Nuclear electricity generation + Pumped storage electricity generation + Solar PV electricity generation + Wind electricity generation
Units: GWh/Year

Total net electricity generation= Total electricity generation - Electricity losses
Units: GWh/Year

Total operating capacity= Nuclear operating capacity + Gas power operating capacity + Pumped storage operating capacity + Wind power operating capacity + Solar PV operating capacity
Units: MW

Transmission distribution loss factor= 0.06
Units: Dmnl

Wind electricity generation= Total operating wind power capacity*Wind power capacity factor LOOKUP table(Time)*Energy conversion factor
Units: GWh/Year

Wind power operating capacity= INTEG (Wind power plant commissioning-Wind power plant decommissioning-Wind power plant degradation, Initial wind power capacity)
Units: MW

Wind share= Wind electricity generation/Total electricity generation
Units: Dmnl

APPENDIX C: VALIDATION TESTS

C.1 Extreme condition tests

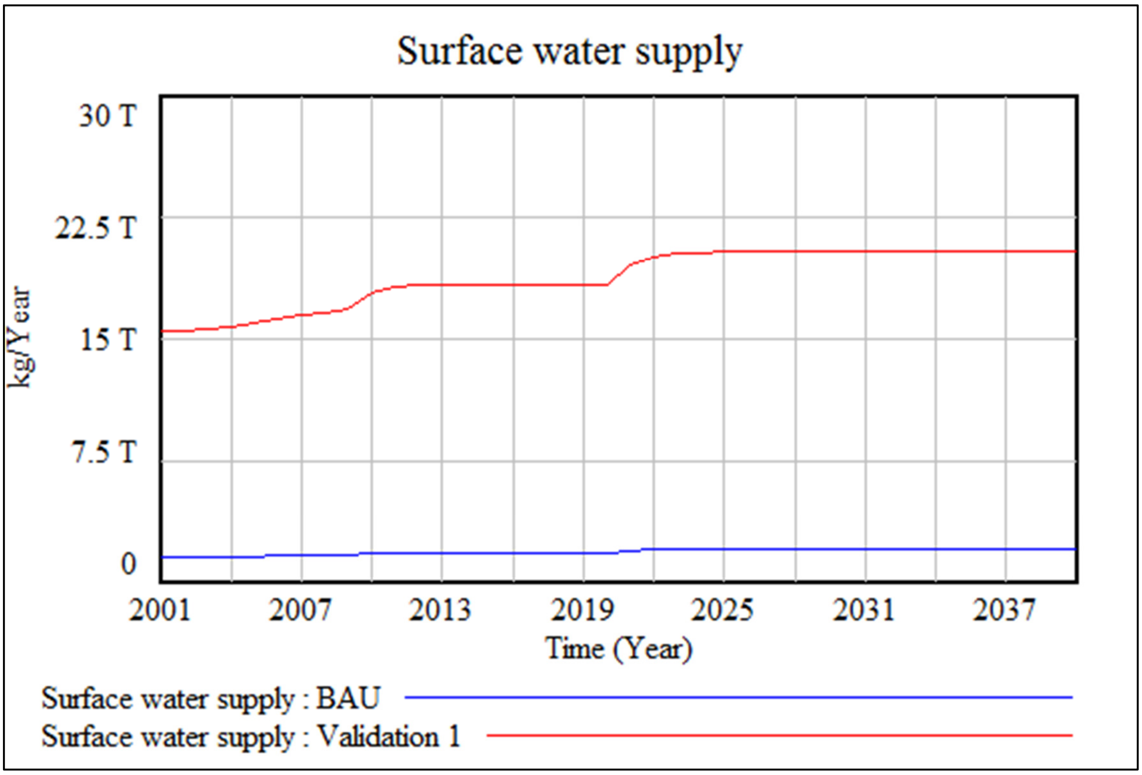

Figure C.1: Effect of a tenfold increase in dam capacity on surface water supply

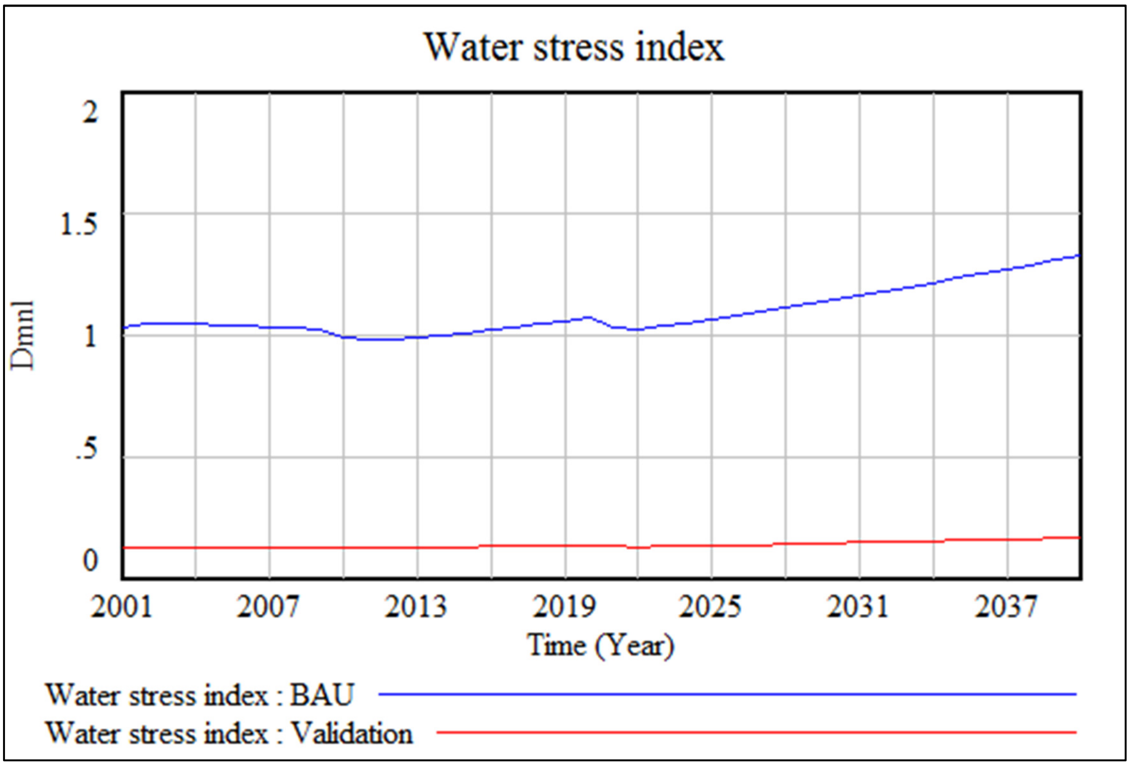

Figure C.2: Effect of tenfold increase in dam capacity on water stress index

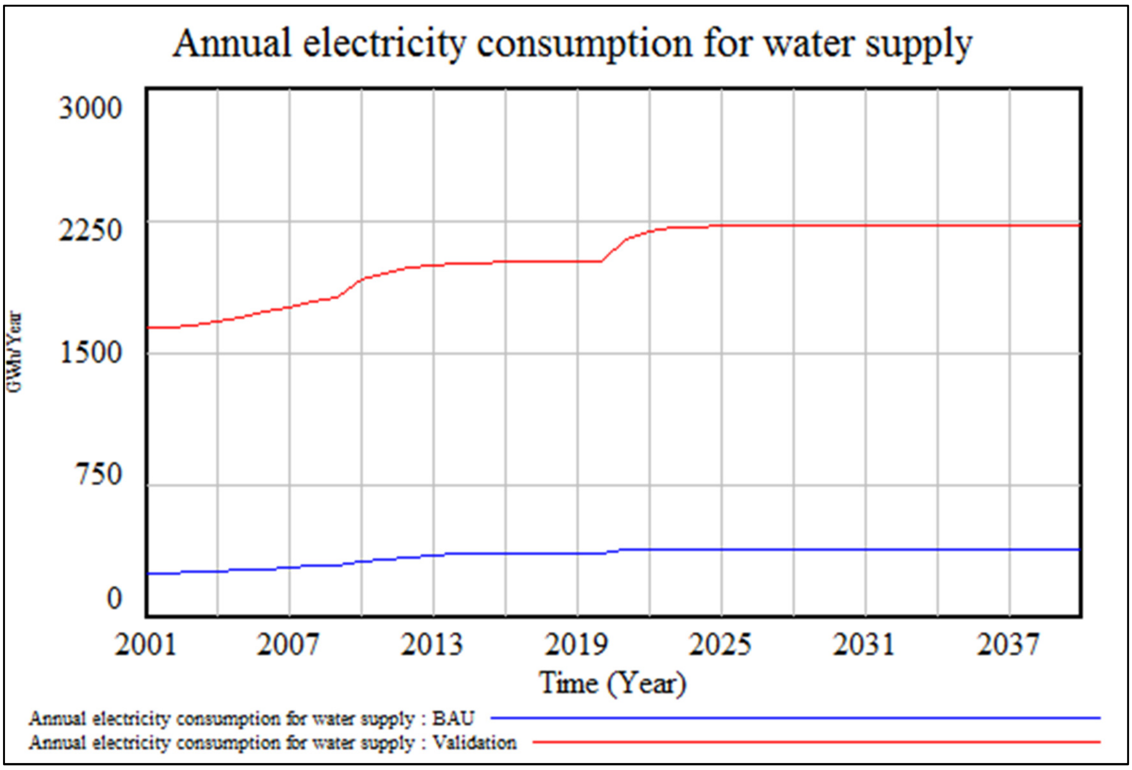

Figure C.3: Effect of tenfold increase in dam capacity on electricity consumption for water sector

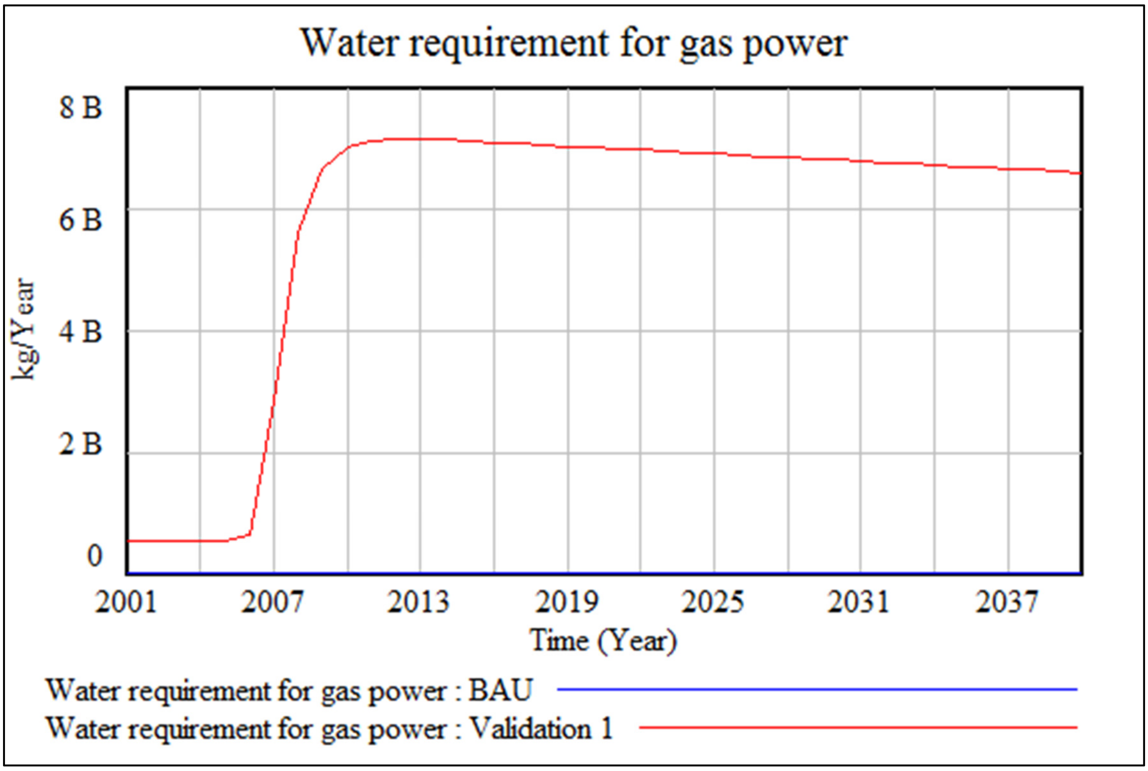

Figure C.4: Effect of changing gas power water requirement from OCGT to CCGT

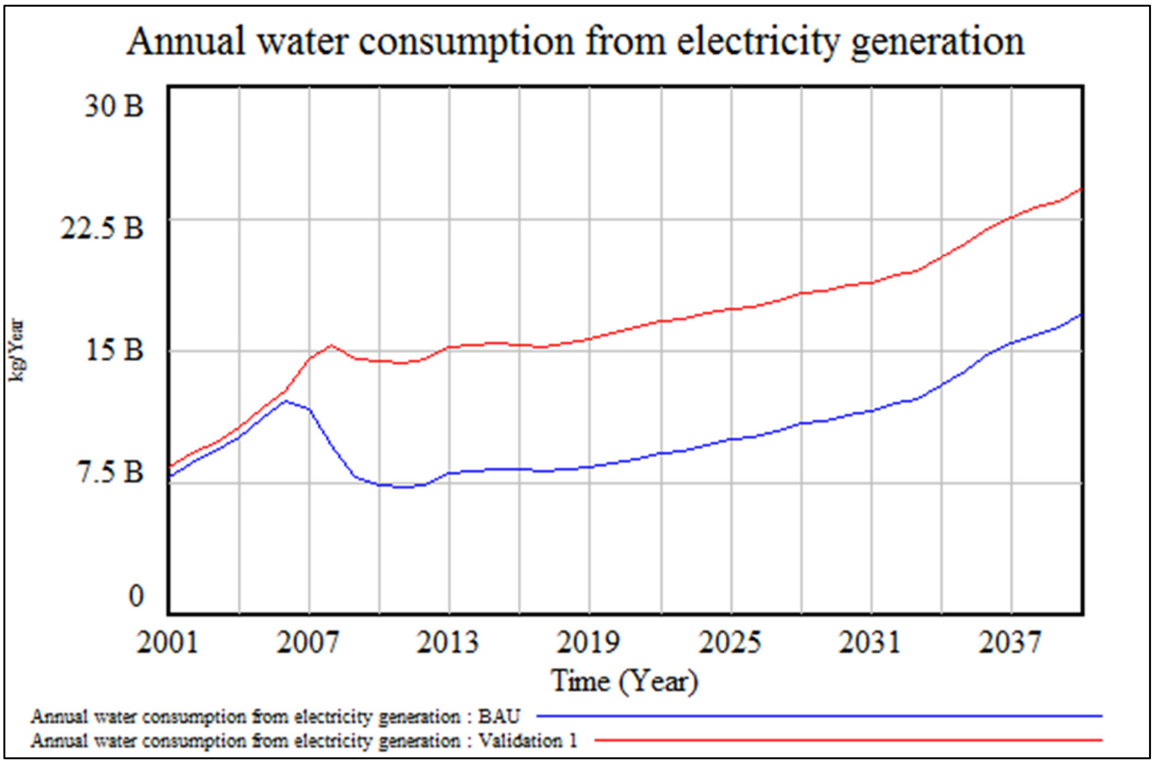

Figure C.5: Effect of changing gas power water requirement from OCGT to CCGT on electricity sector water consumption

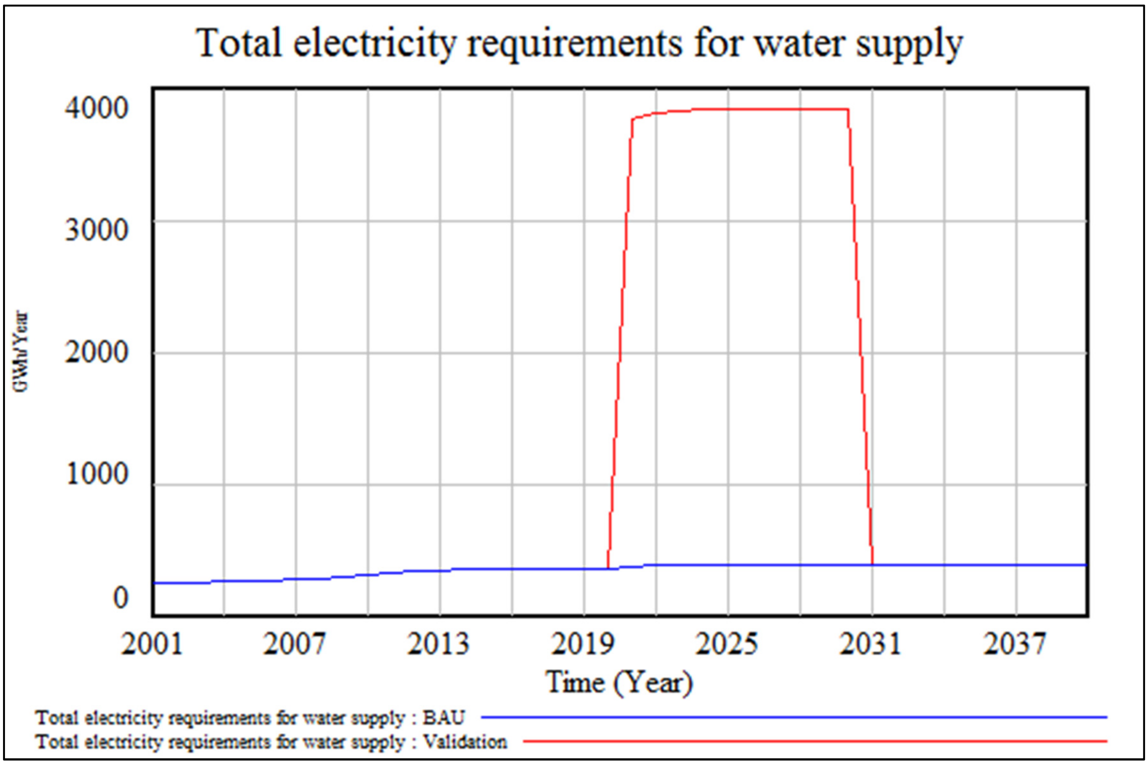

Figure C.6: Tenfold step in total electricity requirement for water supply

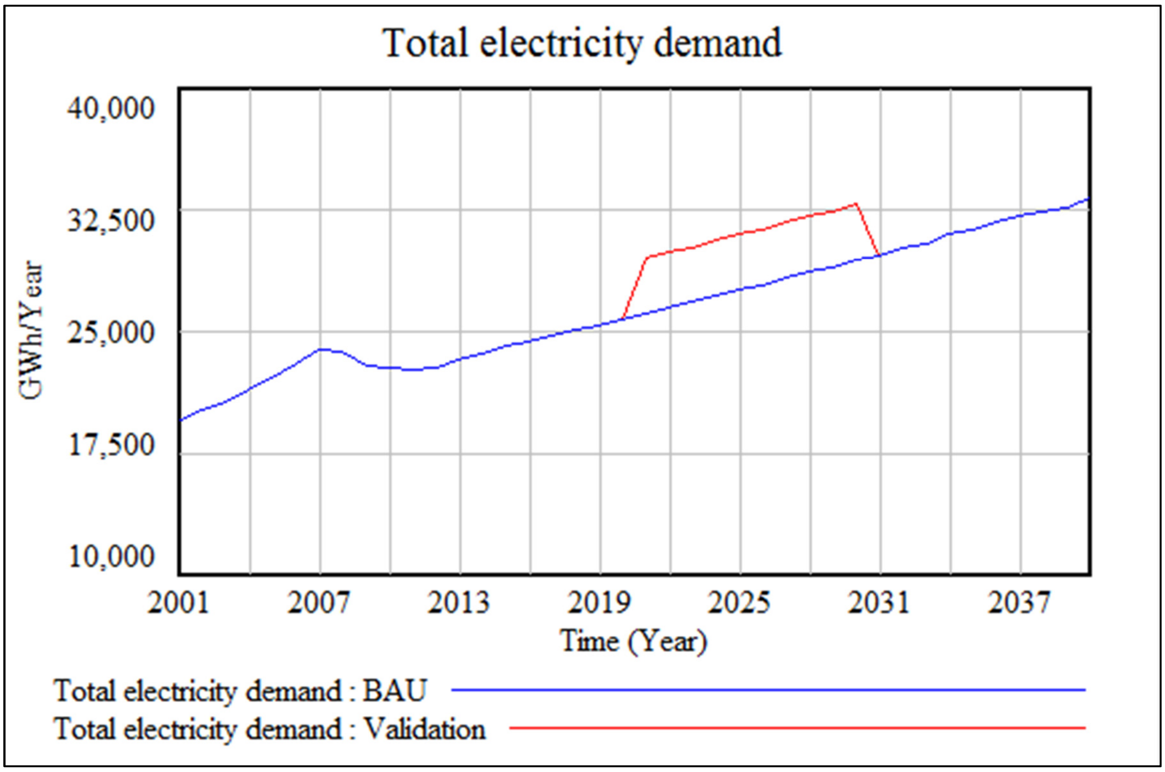

Figure C.7: Effect of tenfold step total water sector electricity requirement on total electricity demand

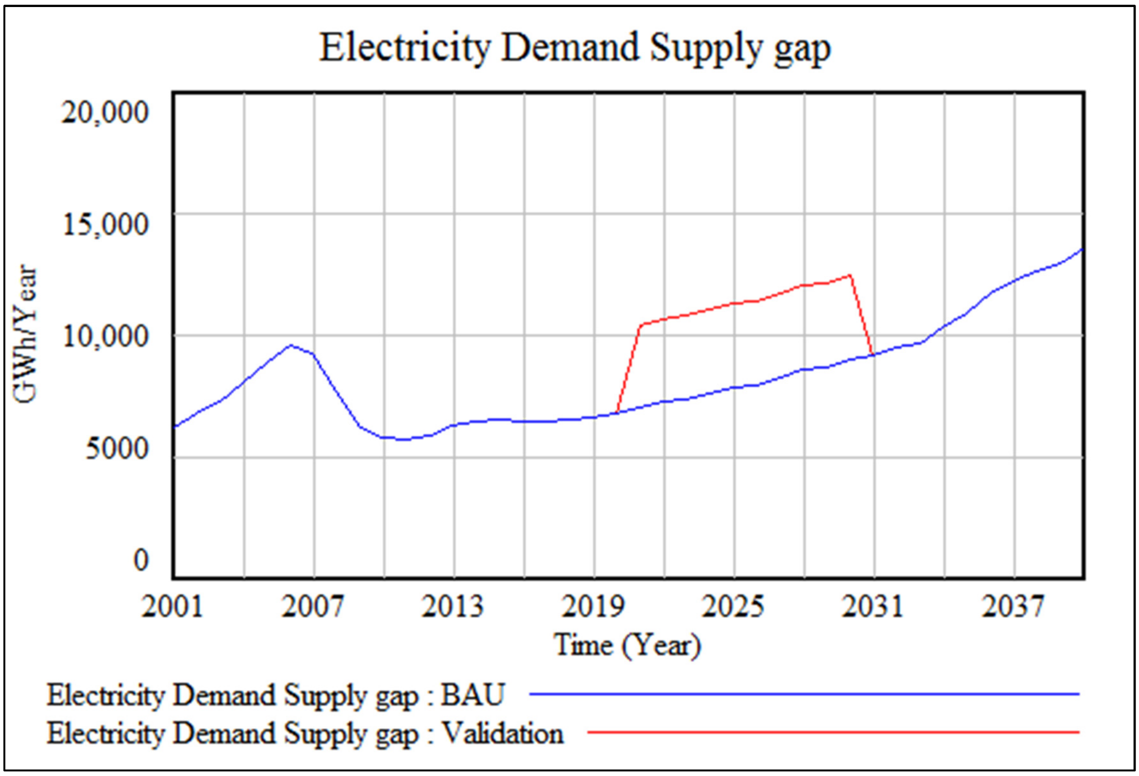

Figure C.8: Effect of tenfold step total water sector electricity requirement on electricity demand supply gap

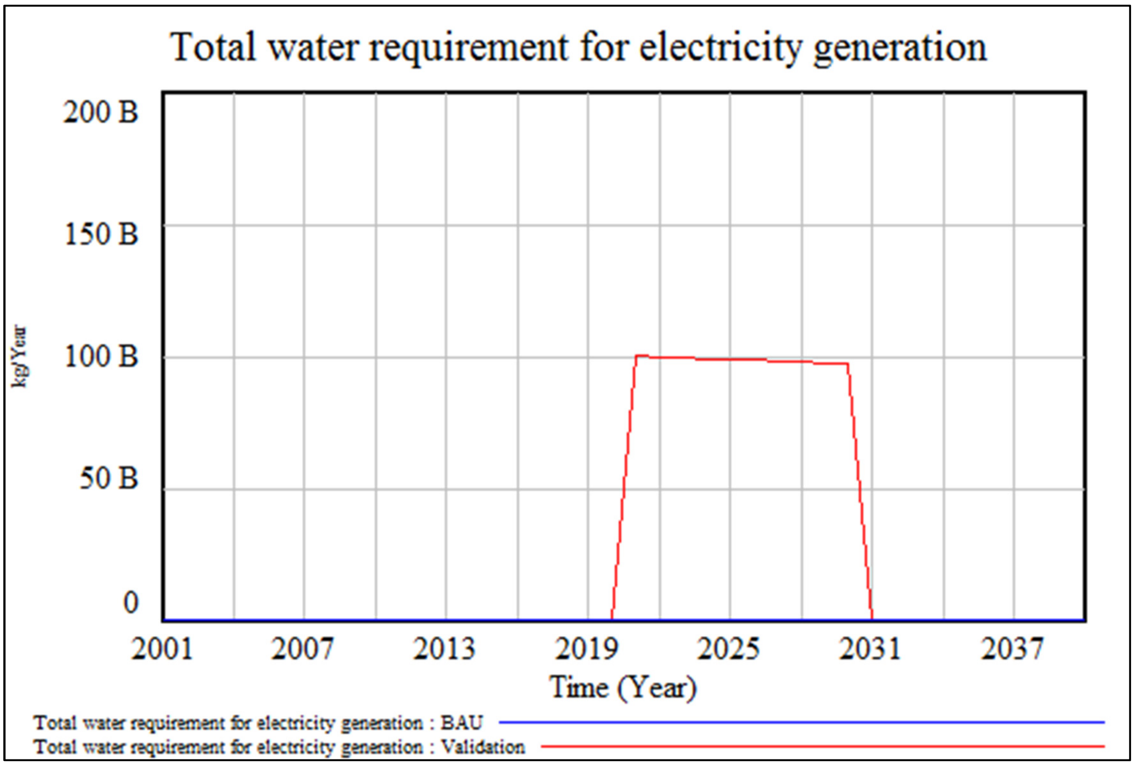

Figure C.9: 100000 times step increase in total water requirement for electricity generation

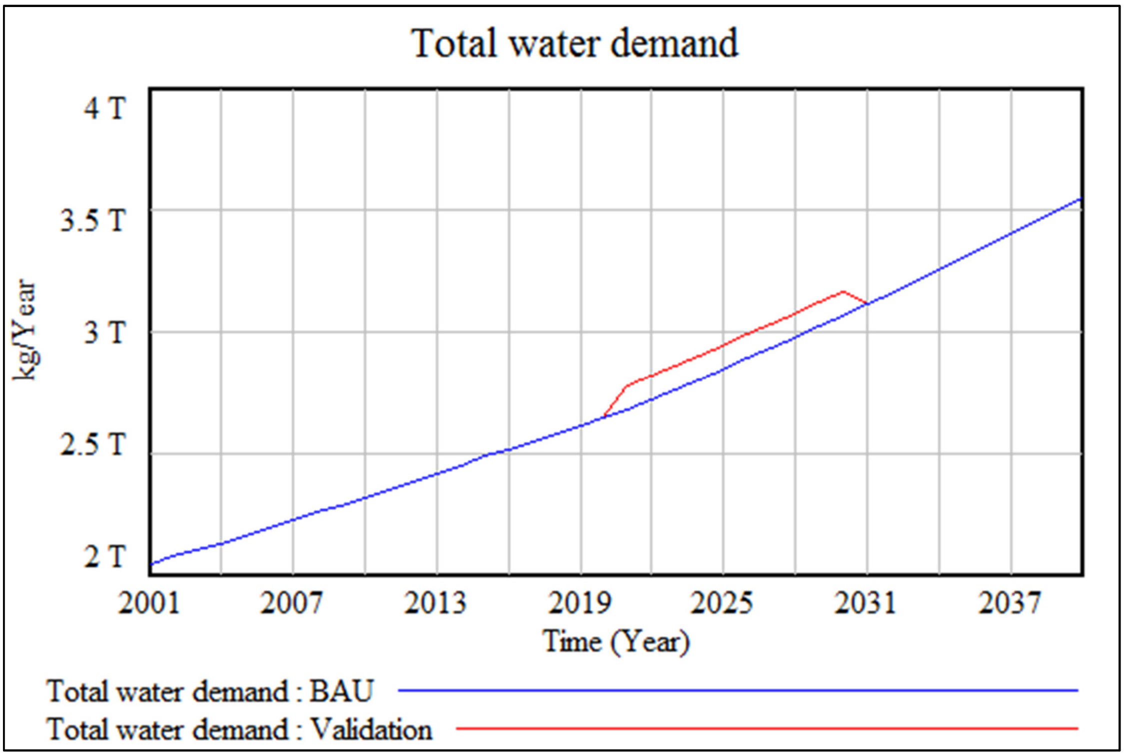

Figure C.10: Effect of 100000 times step increase in total water requirement for electricity generation on total water demand

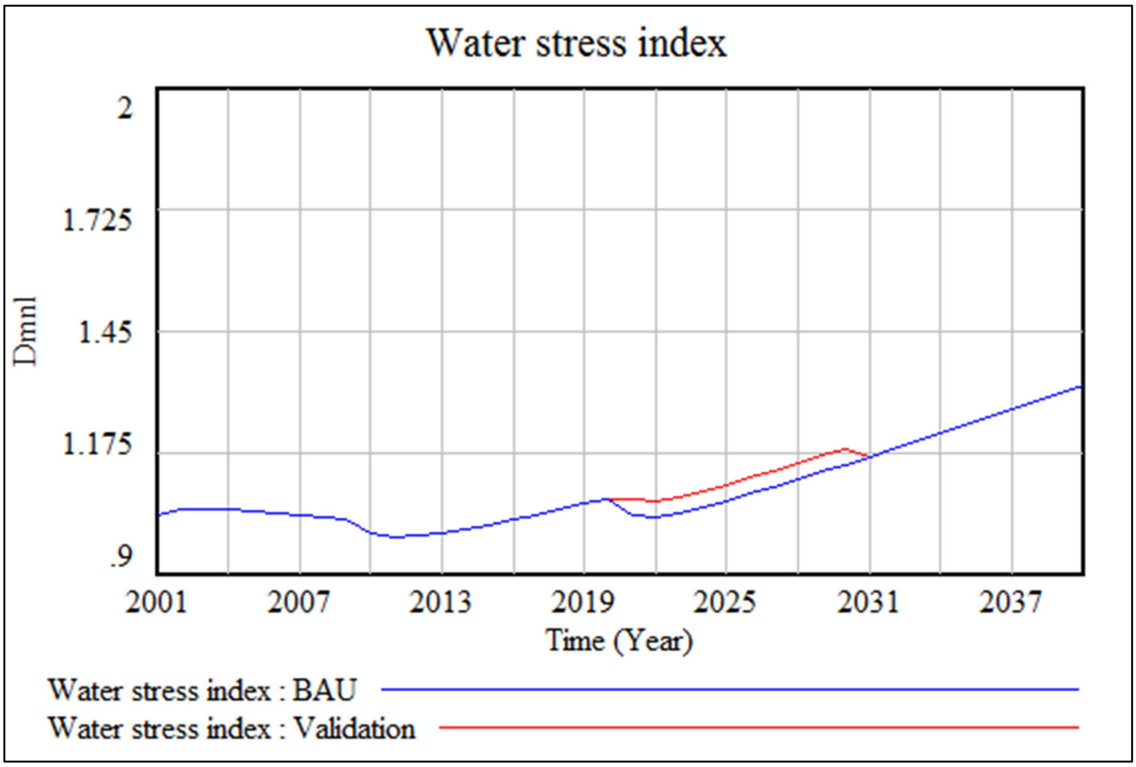

Figure C.11: Effect of 100000 times step increase in total water requirement for electricity generation on water stress index

C.2 Behaviour reproduction tests

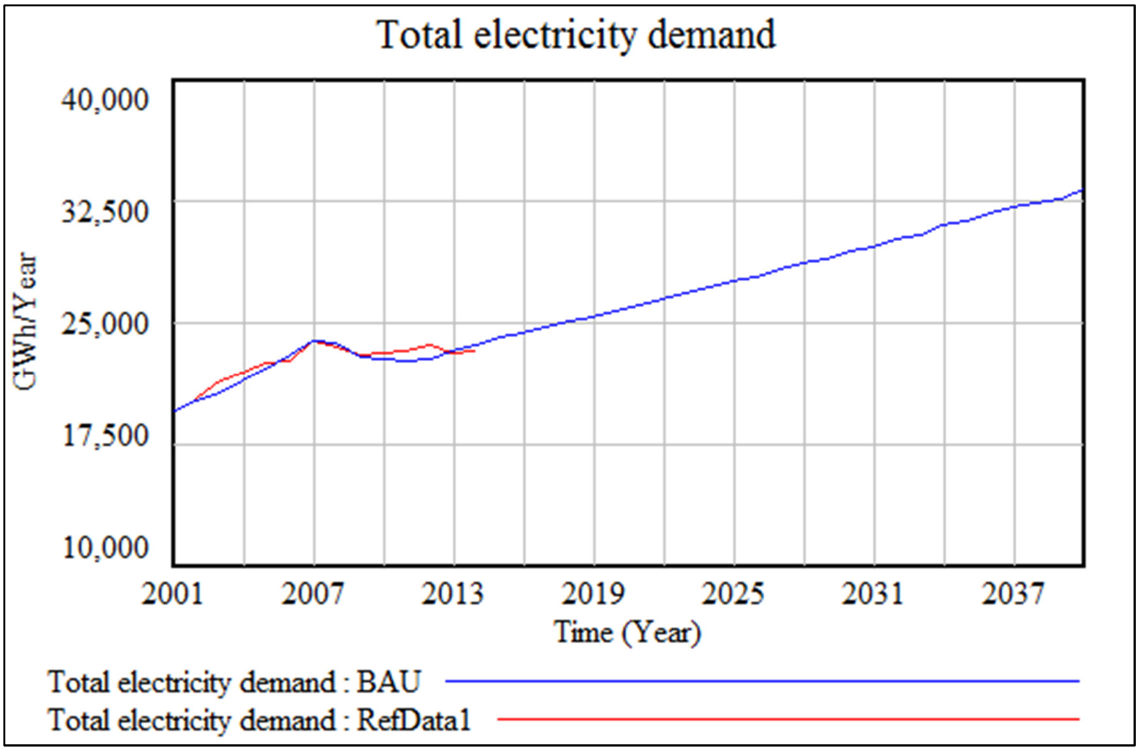

Figure C.12: Reference data for total electricity demand

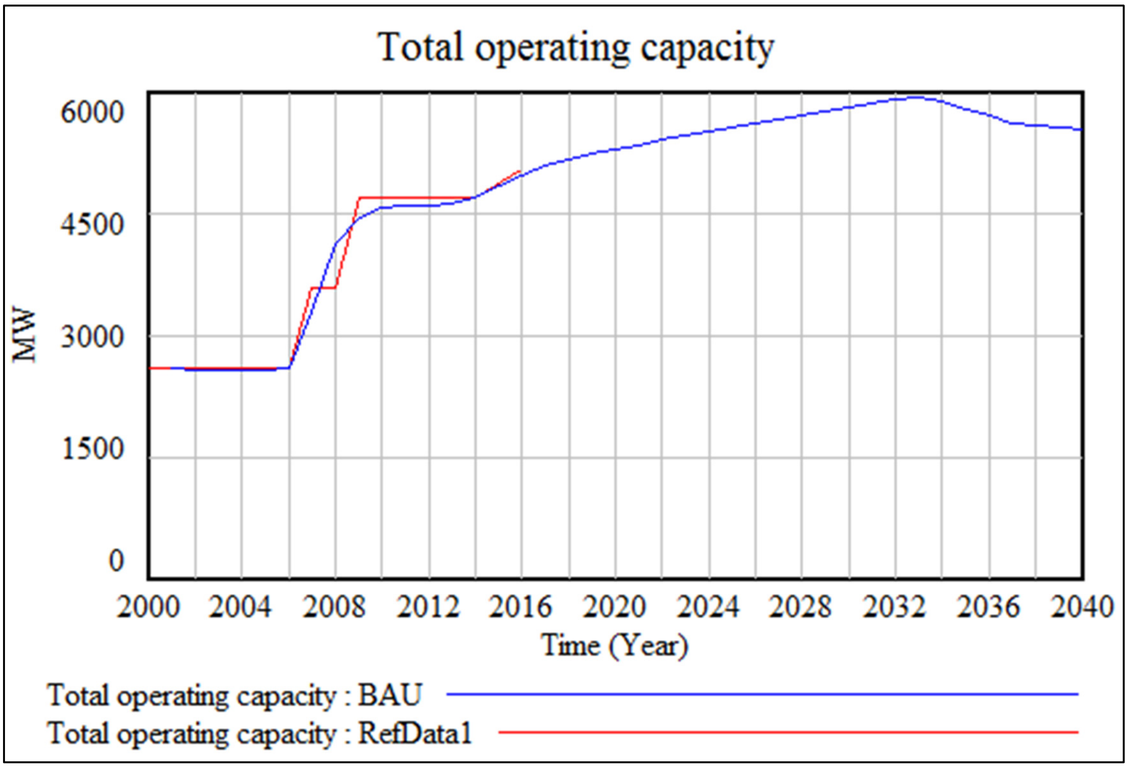

Figure C.13: Reference data for total electricity sector operating capacity

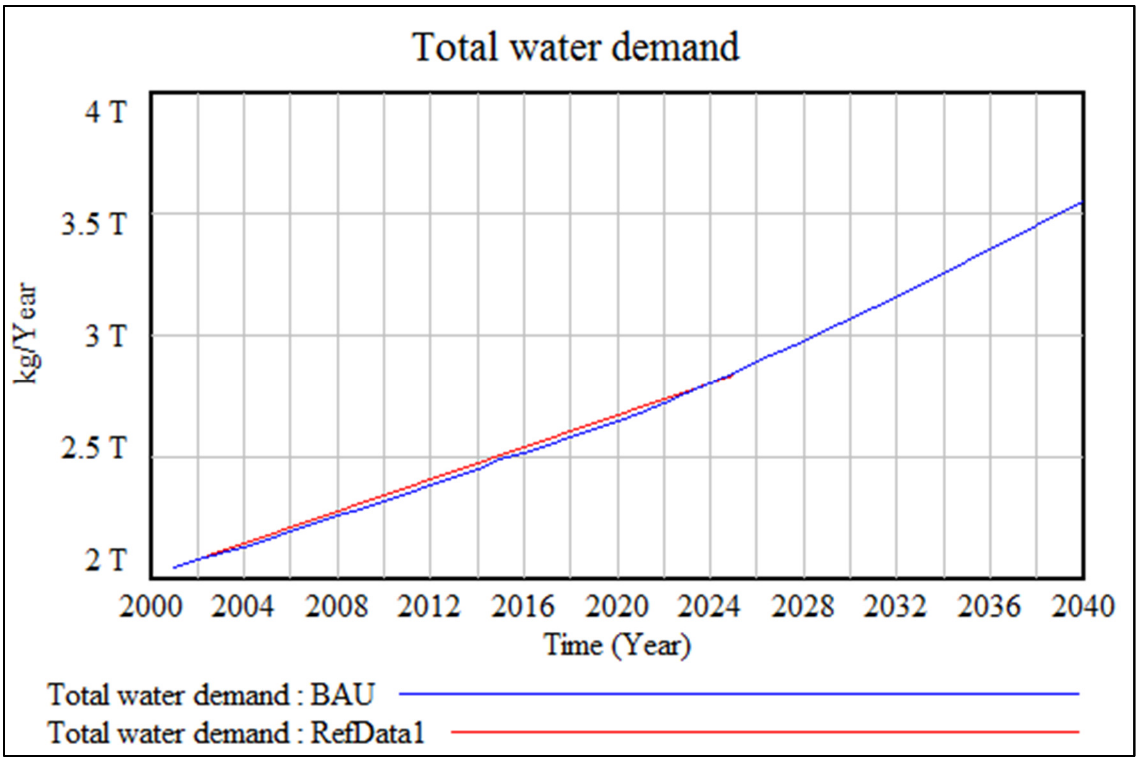

Figure C.14: Reference data for predicted growth in total water demand

C.3 Behaviour sensitivity test

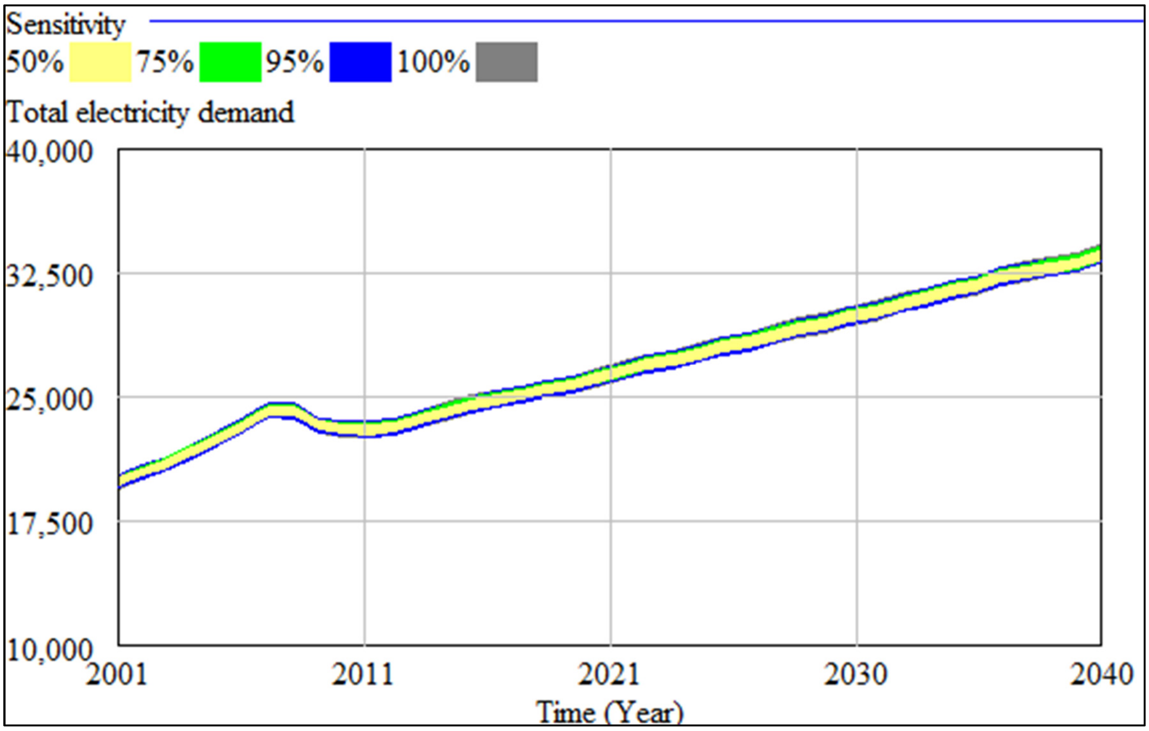

Figure C.15: Effect of varying surface water supply electricity requirement between 0.5 x 10^{-10} GWh/kg and 6 x 10^{-10} GWh/kg on total electricity demand

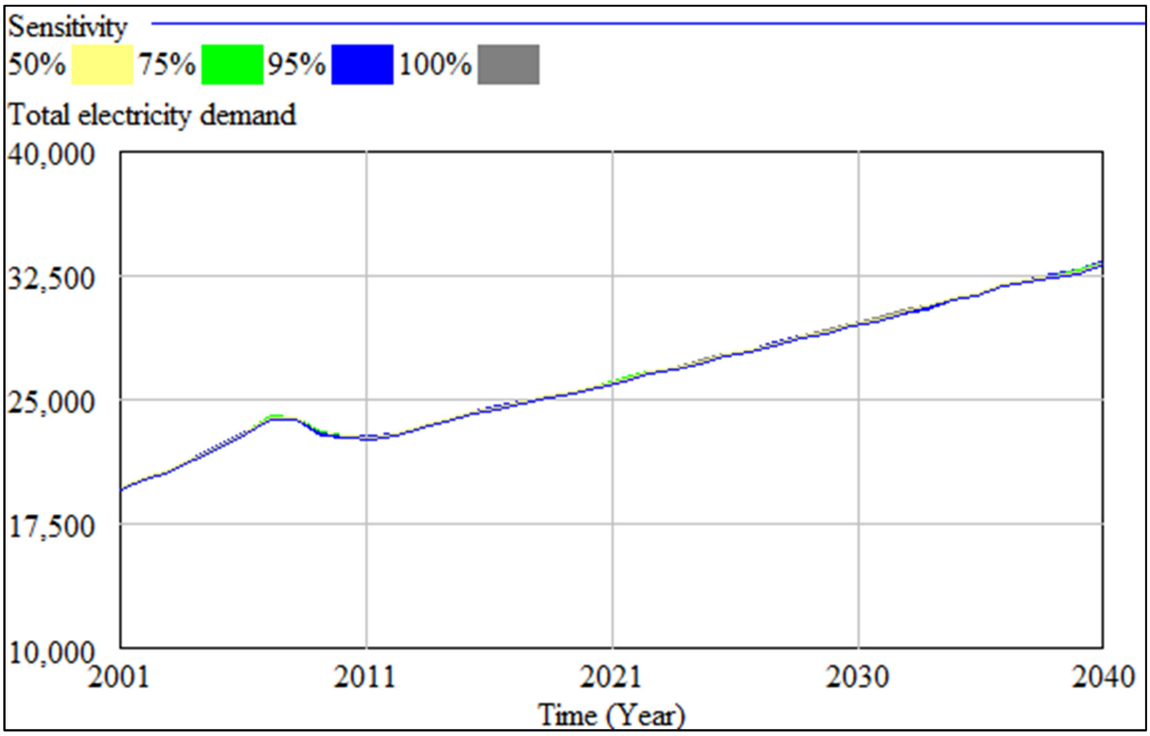

Figure C.16: Effect of varying groundwater supply electricity requirement between 0.5 x 10^{-10} GWh/kg and 6 x 10^{-10} GWh/kg on total electricity demand

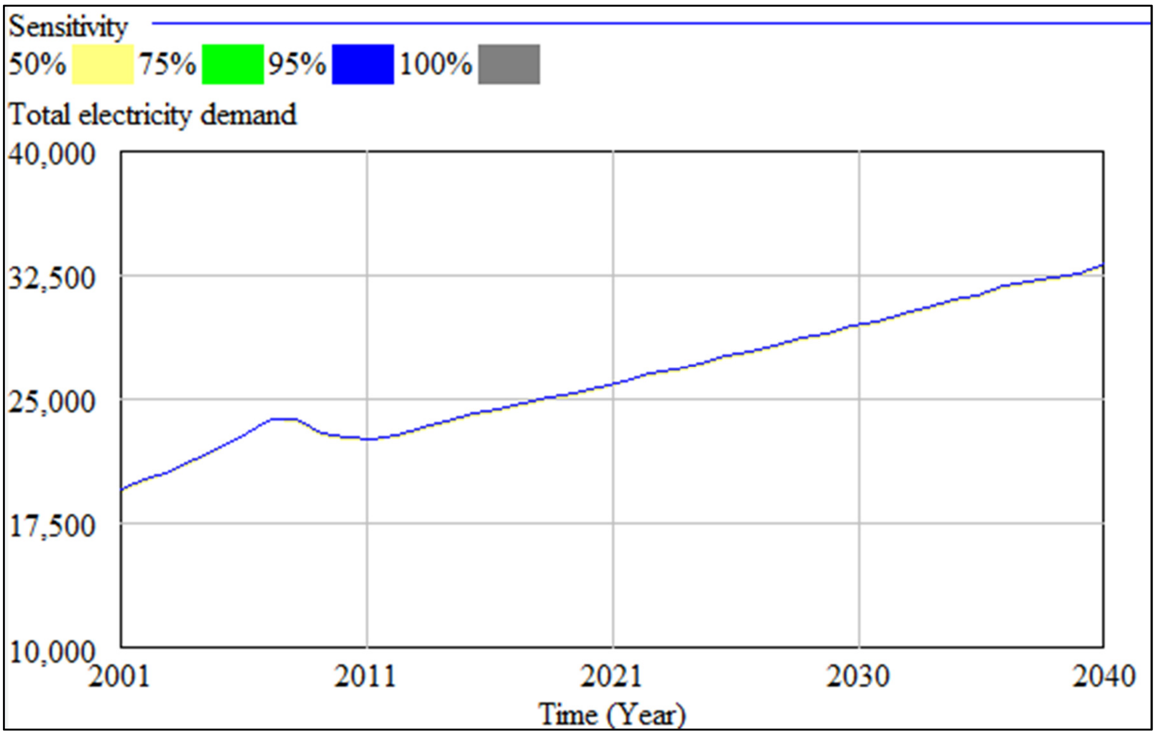

Figure C.17: Effect of varying recycled water supply electricity requirement between 3×10^{-10} GWh/kg and 5×10^{-10} GWh/kg on total electricity demand

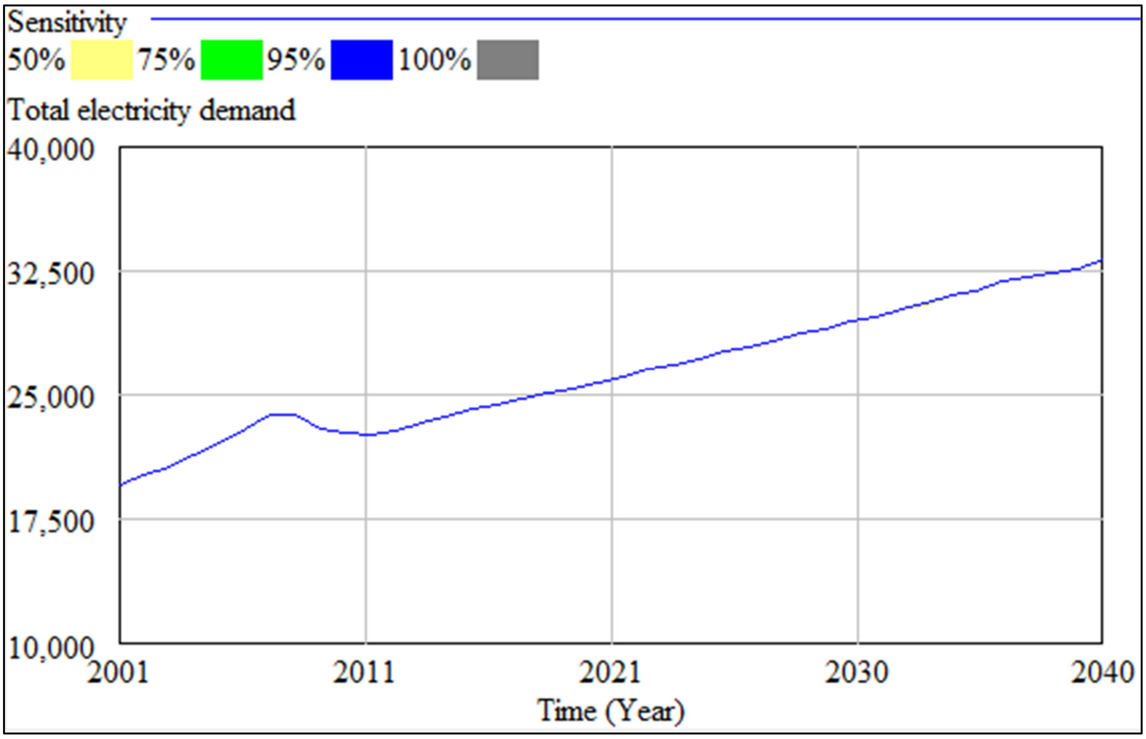

Figure C.18: Effect of varying BAU desalination water supply electricity requirement between 2×10^{-9} GWh/kg and 5×10^{-9} GWh/kg on total electricity demand

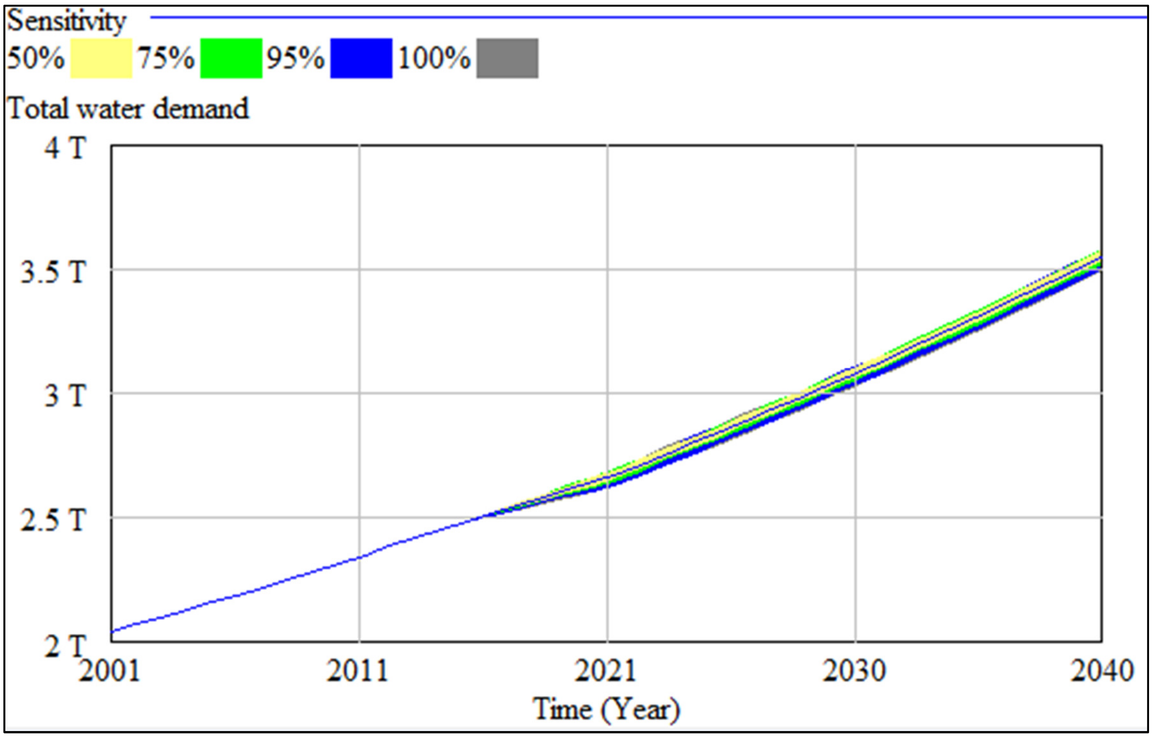

Figure C.19: Effect of varying cost of water savings per capita between 63500 R/kg/person and 255000 R/kg/person on total water demand

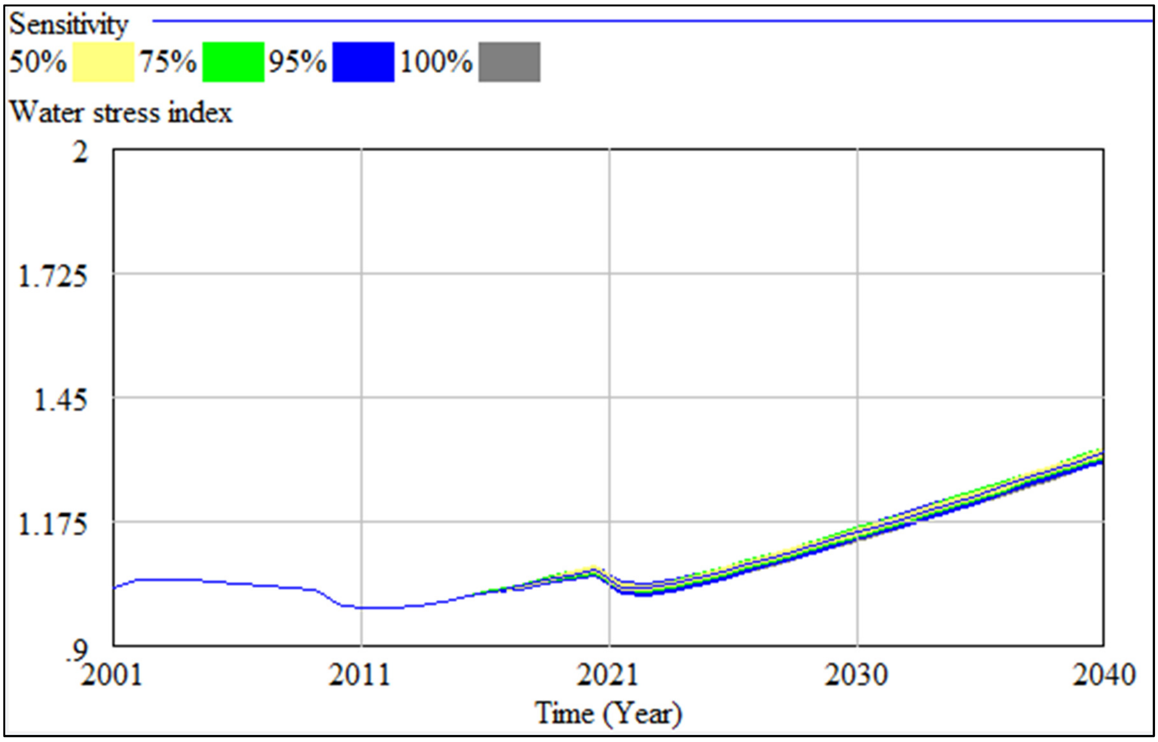

Figure C.20: Effect of varying cost of water savings per capita between 63500 R/kg/person and 255000 R/kg/person on water stress index

APPENDIX D: SCENARIO DATA AND CALCULATIONS

D.1 MED

Capital cost

Capital cost = 900 to 2000 $\$/m^3/day$ Source: Ghaffour et al. (2013)

Mean capital cost = 1450 $\$/m^3/day$

Sample calculation 1: convert units from $\$/m^3/day$ to Rand/kg/year

$$\frac{(mean\ capital\ cost) \times (USD\ to\ ZAR\ conversion)}{(number\ of\ days\ in\ year) \times (density\ of\ water)}$$

$$= \frac{\frac{1450\$}{m^3/day} \times \frac{R12.82}{\$}}{\frac{365.25\ days}{year} \times \frac{1000kg}{m^3}}$$

$$= 0.05089 \frac{R}{kg}/year$$

O&M cost

The O&M cost excluding the cost of electricity must be determined.

Total water cost = 0.7 to 1.2 $\$/m^3$ Source: Ghaffour et al. (2013)

Mean total water cost = 0.95 $\$/m^3$

According to Ghaffour et al. (2013), 45% of this is due to the initial capital cost, 22% is for steam production and 7% is for additional electricity.

Sample calculation 2: Determine O&M cost excluding the cost of electricity

$$O\&M\ excl.\ electricity$$

$$= total\ water\ cost \times (1 - capital\ cost\ fraction - steam\ fraction - power\ fraction$$

$$= \frac{0.95\ \$}{m^3} \times (1 - 0.45 - 0.22 - 0.07)$$

$$= \frac{0.247\ \$}{m^3} \times \frac{12.82\ R}{\$} \times \frac{1000\ m^3}{kg}$$

$$= \frac{0.00317\ R}{kg}$$

D.2 RO

Capital cost

Capital cost = 900 to 2500 $\$/m^3/day$ Source: Ghaffour et al. (2013)

Mean capital cost = 1700 $/m^3$/day
= 0.0596 R/kg/day (using sample calculation 1)

O&M cost

Total water cost = 0.5 to 1.2 $/m^3$

Mean total water cost = 0.85 $/m^3$

According to Ghaffour et al. (2013), 41% of this is due to the initial capital cost and 19% is for electricity.

Similar to sample calculation 2:

O&M cost excl. electricity = 0.00436 R/kg

D.3 ETC

Energy output

ETC efficiency = 0.55 Source: Zambolin & Del Col (2010)

Average GHI of Saldanha = 232.42 W/m^2 Source: SAURAN (2017)

Peak GHI = 1040 W/m^2 Source: SAURAN (2017)

Specific thermal energy required for MED = 5.5 Wh/kg Source: Ghaffour et al. (2013)

Assume a desalination capacity of 1000 kg/year

Sample calculation 3: calculate total energy required for capacity

$$Total\ thermal\ energy = Specific\ thermal\ energy\ \times desalination\ capacity$$
$$= 5.5\frac{Wh}{kg} \times 1000\frac{kg}{year}$$
$$= 5500\ Wh$$

Sample calculation 4: convert energy required from Wh to W

$$\frac{Total\ energy\ required}{Hours\ in\ a\ year}$$
$$= \frac{5500\ Wh}{\frac{8760\ hours}{year}}$$
$$0.62785\ W$$

Sample calculation 5: determine the required collector area

$$Collector\ area = \frac{Total\ energy\ required}{Peak\ GHI\ \times efficiency}$$

$$= \frac{0.62785\ W}{\frac{1040\ W}{m^2} \times 0.55}$$
$$= 0.0011\ m^2$$

Sample calculation 6: determine the thermal energy output

$$Energy\ output = collector\ area\ \times average\ GHI\ \times efficiency$$
$$= 0.0011\ m^2 \times \frac{232.42\ W}{m^2} \times 0.55$$
$$= 0.1406\ W$$

Reverse sample calculations 3 and 4 to determine the energy output in Wh per kg of water produced:

Energy output = 1.229 Wh/kg = 1.229 x 10^{-9} GWh/kg

Capital cost

Capital cost = 190 $/m^2 = 2436 R/m^2 Source: Open Energy Information (2017)

Capital cost is given per m^2 of the collector area, but for the model the cost must be related to the desalination plant capacity. This is done as follows:

Sample calculation 7: convert capital cost from R/m^2 of collector area to R/kg/year of desalination capacity

$$\frac{capital\ cost \times collector\ area}{desalination\ capacity}$$
$$= \frac{\frac{2436R}{m^2} \times 0.0011\ m^2}{\frac{1000\ kg}{year}}$$
$$= \frac{0.00269\ R}{kg/year}$$

O&M cost

O&M cost = 0.5 to 1 % of initial capital cost Source: Open Energy Information (2017)
Mid O&M cost = 0.75 % of initial capital cost

Sample calculation 8: determine O&M cost for ETC

$$ETC\ O\&M\ cost$$
$$= O\&M\ fraction\ of\ capital\ cost\ \times capital\ cost$$

$$= (0.0075)(\frac{0.0269\ R}{kg/year}$$

$$= 2.0175 \times 10^{-5} \frac{R}{kg/year}$$

D.4 PV

Energy output

PV efficiency = 0.178 Source: Open Energy Information (2017)

Specific electrical energy required = 3.5 Wh/kg Source: Ghaffour et al. (2013)

Similar to determining the thermal energy output of ETC per kg of water produced:

PV electrical energy output = 7.822 x 10^{-10} GWh/kg/year

Capital cost

PV capital cost = 4550 \$/kW/year = 58300 R/kW/year Source: Open Energy Information (2017)

It must be noted that this capital cost is in terms of the peak electricity output.

The capital cost of PV must also be related to the desalination plant capacity.

Sample calculation 9: determine the peak electrical output

Assume a desalination plant capacity of 1000 kg/year

$$Peak\ electricity\ output$$

$$= specific\ energy\ required\ \times desalination\ capacity \times conversion\ factor$$

$$= \frac{3.5\ Wh}{kg} \times \frac{1000\ kg}{year} \times \frac{1\ W}{8760\ Wh}$$

$$= 0.3995\ W/\text{year}$$

Sample calculation 10: determine the capital cost in terms of the desalination plant capacity

$$capital\ cost\ in\ terms\ of\ desalination\ plant\ capacity$$

$$= \frac{capital\ cost \times peak\ PV\ electrical\ energy\ output \times conversion\ factor}{desalination\ plant\ capacity}$$

$$= \frac{\frac{58300\ R}{kW/year} \times \frac{0.3995\ W}{year} \times \frac{1\ kW}{1000\ W}}{\frac{1000\ kg}{year}}$$

$$= 0.0233 \frac{R}{kg/year}$$

O&M cost

O&M cost = 16 $/kW Source: Open Energy Information (2017)

Sample calculation 11: determine O&M cost for PV in terms of water production

$$O\&M\ cost\ in\ terms\ of\ water\ production$$
$$= O\&M\ cost\ \times PV\ electrical\ energy\ output \times conversion\ factors$$
$$= \frac{16\ \$}{kW} \times \frac{7.822 \times 10^{-10} GWh}{kg/year} \times \frac{1000000\ kWh}{1\ GWh} \times \frac{1\ kW}{8760\ kWh} \times \frac{12.82\ R}{\$}$$
$$= 1.832 \times 10^{-5} \frac{R}{kg/year}$$

D.5 Waste heat

Capital cost = 0.00007 R/kg/year Source: Cohen (2016)

Thermal energy output

Flue gas volumetric flow rate = 65000 m^3/h
Gas temperature = 400 °C = 673.15 K

Sample calculation 12: determine the mass flow rate

Assumes the gas density = 0.525 kg/m^3 Source: Calculations (2017)

$$mass\ flow\ rate$$
$$= volumetric\ flow\ rate\ \times density$$
$$= \frac{65000\ m^3}{h} \times \frac{0.525\ kg}{m^3}$$
$$= 34125\ kg/h$$

Sample calculation 13: determine the energy available for the gas in a year

Assume the minimum allowable gas temperature is 373.15 K.
Assume the gas heat capacity = 1.151 kJ/kg·K Source: Calculations (2017)

$$Energy\ available$$
$$= mass\ flow\ rate\ \times heat\ capacity \times change\ in\ temperature\ \times conversion\ factors$$
$$= \frac{65000\ m^3}{h} \times \frac{1.151\ kJ}{kg \cdot K} \times (673.15\ K - 373.15\ K) \times \frac{3600\ s}{h} \times \frac{kW \cdot s}{kJ} \times \frac{8620\ kWh}{kW} \times \frac{1\ kW}{10^6\ GWh}$$
$$= 28.215\ GWh$$

D.6 Scenario testing sub-model equations

Accumulated brine produced by desalination= INTEG (Annual brine produced by desalination, 0)
Units: kg salt

Accumulated desalination running costs= INTEG (Annual running costs for desalination, 0)
Units: Rand

Additional desalination capacity due to investment= INTEG (Additional desalination construction, 0)
Units: kg

Additional desalination capacity in planning= INTEG (Increase in desalination capacity due to investment-Additional desalination construction, 0)
Units: kg

Additional desalination capacity limit= INTEG (Increase in desalination capacity limit, 0)
Units: kg

Additional desalination construction= Additional desalination capacity in planning/Desalination commissioning delay
Units: kg/Year

Additional desalination electricity cost= Electricity requirement for additional desalination * Electricity price
Units: Rand/Year

"Additional desalination electricity use (GWh)"= IF THEN ELSE(Water supply from additional desalination > 0, "Additional desalination electricity use (GWh/kg)"*Water supply from additional desalination - Electricity from solar, 0)
Units: GWh

"Additional desalination electricity use (GWh/kg)"= "Desalination electricity use (GWh/kg) LOOKUP table"(Scenario switch)
Units: GWh/kg

"Additional desalination thermal energy use (GWh)"= IF THEN ELSE(Water supply from additional desalination > 0, "Additional desalination thermal energy use (GWh/kg)"*Water supply from additional desalination - Thermal energy available from metal works - Thermal energy from solar, 0)
Units: GWh

"Additional desalination thermal energy use (GWh/kg)"= "Desalination thermal energy use (GWh/kg) LOOKUP table"(Scenario switch)
Units: GWh/kg

Annual brine produced by desalination= Water supply from additional desalination*Brine produced per kg desalinated water/Time conversion

Units: kg salt/Year

Annual running costs for desalination= Water supply from additional desalination*Rand per kilogram of desalinated water/Time conversion + Additional desalination electricity cost

Units: Rand/Year

Brine produced per kg desalinated water= 0.5

Units: kg salt/kg

"Cost of desalination capacity (R/kg)"= Cost of desalination capacity LOOKUP table(Scenario switch)

Units: Rand/kg

Cost of desalination capacity LOOKUP table([(0,0)-(6,1)],(0,1),(1,0.05089),(2,0.05096),(3,0.05358),(4,0.05365),(5,0.05967),(6,0.10527))

Units: Rand/kg

Desalination capacity LOOKUP table([(2001,0)-(2040,9e+009)],(2001,0),(2009,0),(2009,5.475e+008),(2010,5.475e+008),(2010,1.278e+009),(2011,1.278e+009),(2011,6.752e+009),(2012,6.752e+009),(2012,8.0665e+009),(2013,8.067e+009),(2013,8.687e+009),(2040,8.687e+009))

Units: kg

Desalination commissioning delay= 1

Units: Year

"Desalination electricity use (GWh/kg) LOOKUP table"([(0,0)-(6,4)],(0,0),(1,1.75e-009),(2,1.75e-009),(3,1.75e-009),(4,1.75e-009),(5,3.5e-009),(6,3.5e-009))

Units: GWh/kg

"Desalination thermal energy use (GWh/kg) LOOKUP table"([(0,0)-(6,6e-009)],(0,0),(1,5.5e-009),(2,5.5e-009),(3,5.5e-009),(4,5.5e-009),(5,0),(6,0))

Units: GWh/kg

Electricity from solar= Electricity from solar constant*Water supply from additional desalination

Units: GWh

Electricity from solar constant= IF THEN ELSE(Scenario switch = 6,7.822e-010 , 0)

Units: GWh/kg

Electricity price= 1.39e+006

Units: Rand/GWh

Source: Cohen (2016)

Electricity requirement for additional desalination= ("Additional desalination electricity use (GWh)"+"Additional desalination thermal energy use (GWh)")/Time conversion

Units: GWh/Year

Increase in desalination capacity= Investment in desalination/"Cost of desalination capacity (R/kg)"

Units: kg/Year

Increase in desalination capacity due to investment= Increase in desalination capacity

Units: kg/Year

Increase in desalination capacity limit= Increase in desalination capacity

Units: kg/Year

Investment in desalination= Fraction of investment in desalination*Total investment in water supply

Units: Rand/Year

Rand per kg of desalinated water LOOKUP table([(0,0)-(6,0.01)],(0,0),(1,0.00317),(2,0.00317),(3,0.00319),(4,0.00319),(5,0.00436),(6,0.00438))

Units: Rand/kg

Rand per kilogram of desalinated water= Rand per kg of desalinated water LOOKUP table(Scenario switch)

Units: Rand/kg

Scenario switch= 4

Units: Dmnl

Thermal energy available from metal works= IF THEN ELSE(Scenario switch = 2 :OR: Scenario switch = 4, 28.215 , 0)

Units: GWh

Thermal energy from solar= Thermal energy from solar constant*Water supply from additional desalination

Units: GWh

Thermal energy from solar constant= IF THEN ELSE(Scenario switch = 3 :OR: Scenario switch = 4, 1.229e-009 , 0)

Units: GWh/kg

Time conversion= 1

Units: Year

Water supply from additional desalination= Additional desalination capacity due to investment

Units: kg

APPENDIX E: ADDITIONAL SIMULATION RESULTS

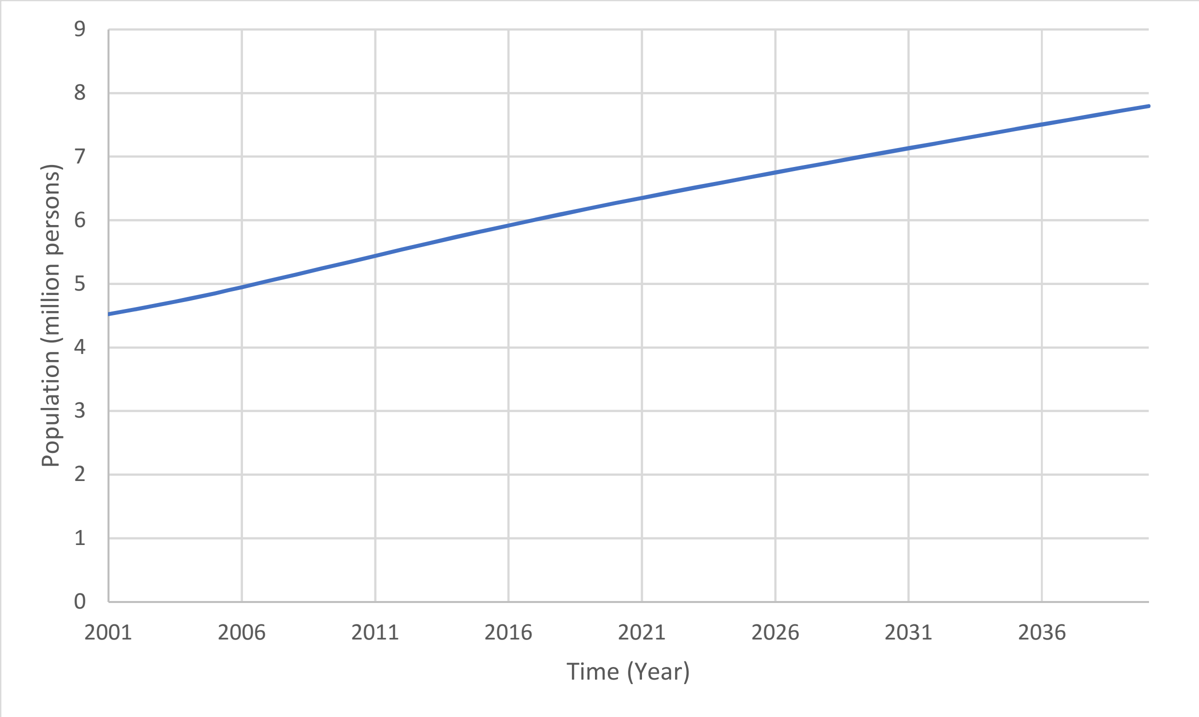

Figure E.1: Total population for all scenarios

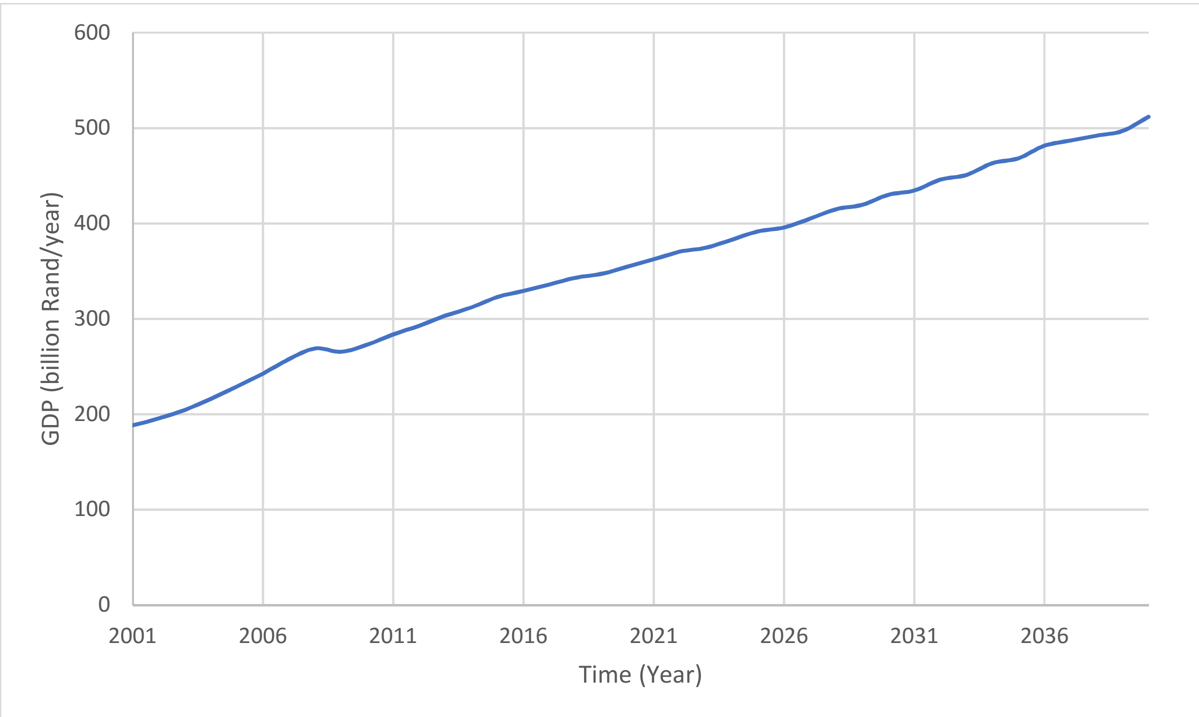

Figure E.2: Western Cape GDP for all scenarios

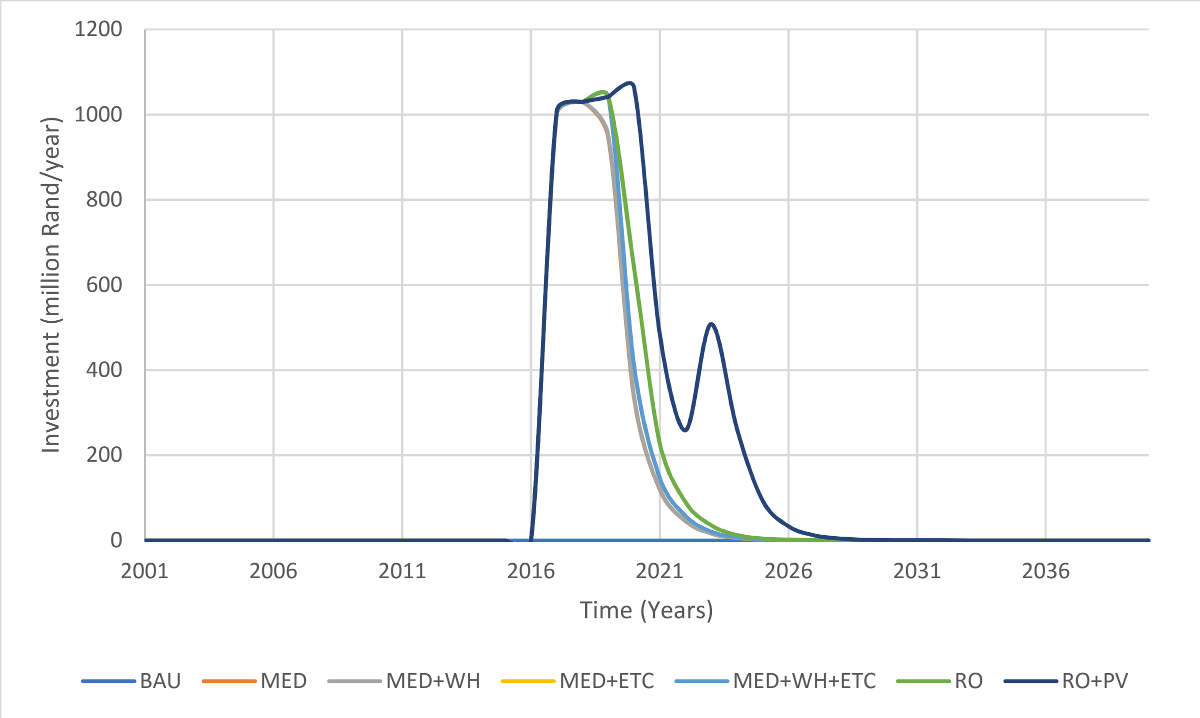

Figure E.3: Investment in water supply