Assessing the energy implications of exploiting stormwater, through artificial aquifer recharge, as an alternative water source in the Cape Flats, South Africa.

19th January 2018

Prepared by:

Aumashvini Gobin

Supervised by:

Dr Debbie Sparks

Fadiel Ahjum

Professor Neil P Armitage

Dissertation has been submitted in partial fulfilment of the requirements for the degree of Master of Science in Sustainable Energy Engineering at the University of Cape Town

Plagiarism Declaration

I know the meaning of plagiarism and declare that all the work in the document, save for that which is properly acknowledged, is my own. This dissertation has been submitted to the Turnitin module and I confirm that my supervisor has seen my report and any concerns revealed by such have been resolved with my supervisor.

Signature: Signed by candidate

Name: Aumashvini Gobin

Date: 19th January 2018

Acknowledgement

I would like to acknowledge and express my appreciation and gratitude to the organisations who have provided the financial support for the research, the National Research Foundation (NRF) and the John Davidson Educational Trust, and to the following persons who have contributed their time and knowledge for the completion of this dissertation:

My supervisors, Dr Debbie Sparks, Fadiel Ahjum and Professor Neil Armitage for their guidance, advice and feedback throughout the research work. Dr Debbie Sparks had made herself available for all queries that I had, reading and reviewing several drafts of the dissertation from the beginning to guide me in the right direction. Professor Neil Armitage and Fadiel Ahjum provided indispensable guidance and assistance in the difficult aspects of the study, bringing in their expertise from two different fields,

John Okedi, from the Urban Water Management research unit, has allowed me to use his research work as a basis for this study. He furthermore offered essential inputs and recommendations on the methods and potential relevant outputs to shape the dissertation as it is,

Richard Larmour, from the Energy Research Centre, who provided valuable insights for energy aspects and validating the relevant research methods of the study,

Nicholas Lindenberg from the UCT GIS labs who made available the relevant DEM and shapefiles,

Mr Hilton Southgate and the City of Cape Town for organising visits to the water treatment plants and making available information necessary for the purposes of this study,

And finally, to my family and friends for encouraging me throughout the year and patiently reading the drafts.

Abstract

South Africa has been facing challenges in both its energy and water sectors over the past few years. They are heavily dependent on each other and a better understanding of the linkages between the two sectors is crucial for sustainable development and planning in both sectors. While the water-energy nexus has been widely explored in developed countries, there is a limited amount of literature found on the significance of the nexus in South Africa. With the current critical drought in the region, alternative water sources are being considered by the City of Cape Town including seawater desalination, water re-use and abstraction of groundwater, to increase potable water supplies. The Cape Flats Aquifer represents a significant water resource for Cape Town and its yield can be further augmented by using artificial recharge with stormwater. Due to the location and water quality of the resource, several possible approaches have been identified for its exploitation.

This study investigates quantitatively the energy implications of the three selected approaches in order to exploit the Cape Flats Aquifer as an alternative water source for Cape Town and further provides the potential carbon emissions from their respective energy usages. The three approaches consist of a Centralised Approach to treat the abstracted water for potable uses at two existing Water Treatment Plants (Blackheath and Faure); a Decentralised Approach to supply neighbouring suburbs with minimally treated water for non-potable uses through four proposed treatment plants and a Desalination Approach to treat brackish groundwater to potable quality at a proposed desalination plant.

The energy implications of the approaches were evaluated using both direct energy usage during the abstraction, conveyance and treatment stages and the embodied energy of the consumables used during the treatment processes. These were then used to compare the shares of direct electricity intensities and embodied energy intensities of the alternatives at each stage to determine their viability. The individual stages' and overall energy intensities were quantified in form of the total energy required to produce a k*l* of treated water.

The minimum energy required to abstract and convey the water was estimated using basic hydraulic principles. The energy usage at treatment plant levels was computed using the installed electrical capacities at the two existing water treatments for the Centralised Approach while the Decentralised Approach's demand was estimated by determining the treatment processes required to produce non-potable water, which is fit for usage. Energy requirements at the desalination plant were estimated using the salinity levels of the brackish groundwater and target salinity concentration of the treated water. The energy intensities of the approaches were then used as a basis to calculate the current and future electricity costs and their associated carbon footprints using the CSIR (2016) least cost scenario and the IRP (2016) base case future electricity mixes, as the higher and lower threshold for electricity generation costs and carbon emissions.

The study found that the electricity intensities of all three alternatives depended significantly on the spatial layout of their respective systems, that is, the topography, distance

and extent of their transmission networks. However, the embodied energy intensity of the Centralised alternative was found to be comparable to its electricity intensity, since more chemicals were to purify the water to potable levels. The Decentralised Approach's extensive pumped transmission networks contributed the most to its electricity intensity during the treatment process. The Desalination option was found to be the most energy intensive alternative, with energy intensities ranging from 7.41 to 9.62 MJ/k*l*, of all three options (1.16 to 1.57 MJ/k*l* for the Centralised Approach and 3.57 to 7.31 MJ/k*l* for the Decentralised Approach) and had the highest costs and emissions intensities, mostly caused by the country's coal intensive electricity mix.

The Centralised option was found to be the least energy and carbon intensive of the three options and the most viable approach investigated. Desalination, nonetheless, can still considered as an alternative, given the issue of water scarcity, to increase water supplies. Despite its high energy demands, its carbon footprint could potentially decrease with a larger uptake of renewable energy technologies as sources of electricity. The importance of holistic planning across sectors was brought out quantitatively by using current and future water and energy mixes, providing valuable insights on the water-energy nexus, in this study.

Table of Contents

List of figures

List of tables

Abbreviations and Acronyms

CoCT	City of Cape Town
CCS	Carbon Capture and Storage
CFA	Cape Flats Aquifer
CSIR	Council for Scientific and Industrial Research
CSP	Concentrated Solar Power
DEM	Digital Elevation Map
DWTP	Decentralised Water Treatment Plant
EC	Electrical Conductivity
ED	Electro-dialysis
EI	Energy Intensity
ERD	Energy Recovery Devices
GaBi	Ganzheitliche Bilanz (LCA Software)
GHG	Greenhouse gases
IRP	Integrated Resources Plan
KWh	Kilowatt hour
LCA	Life Cycle Assessment
MED	Multi effect distillation
MSF	Multi Stage Flash
mamsl	metres above mean sea level
m^3/$MM	metre cube per million dollars
MWh/$MM	Megawatt hours per million dollars
PV	Photovoltaic
PSP	Pumped Storage Plant
PPD	Peak Plateau Decline
RE	Renewable Energy
REIPPPP	Renewable Energy Independent Power Procurement Programme
RO	Reverse Osmosis
TDS	Total Dissolved Solids
TDH	Total dynamic head

WCWSS	Western Cape Water Supply System
WTP	Water Treatment Plant
WWTP	Wastewater Treatment Plant
VSD	Variable Speed Drive
UV	Ultra-Violet

1. Introduction

1.1 Background to study

Over the past few decades, water and energy resources have been exploited unsustainably, straining existing resources and negatively impacting the environment (IEA, 2016). The energy and water sectors have been historically considered separately across institutions, with little deliberation given to the linkages between them (Hussey and Pittock, 2012). With a growing population, global economic growth and resulting increases in demands for water and energy, both sectors have been facing numerous challenges (IEA, 2016). These have been exacerbated by the effects of global warming (Mabhaudhi *et al.*, 2016). Countries worldwide have ratified the UNFCCC's Paris Agreement in order to curb global greenhouse gas emissions and promote resilience through sustainable and holistic development (UNFCCC, 2017). In recent years, the relationship between water and energy has been investigated to provide information on its complexity and to include this during decision making while accounting for its impacts on the environment.

South Africa is one of the top twenty absolute greenhouse gas (GHG) emitters due to its energy intensive economy (WRI, 2017). Its energy sector contributes nearly 88% of the national carbon emissions caused by its large installed capacity of ageing coal power plants (DEA, 2013). It has committed itself to reduce its national GHG emissions by 34% by 2025 following the Peak Plateau Decline (PPD) trajectory and has developed future energy plans accordingly (RSA, 2015). This involves a significant cut in emissions from its energy sector and more particularly, its coal intensive electricity generation plants. Over the past decade, however, the country has been facing challenges in its supply of electricity, which have resulted in extensive periods of load shedding. South Africa has to sustainably plan its future electricity mixes to match demand and decrease its dependence on fossil fuels while mitigating emissions from its energy sector.

The current electricity mix in South Africa, which gave rise to the emission of some 223.4 Mt of CO_2 in 2015, is highly water intensive due to the reliance on coal (Eskom, 2015a). Wet cooling units are still extensively used in the coal power plants while the water and wastewater supply system sector creates the third largest demand for energy in the country (17%) (DWA, 2013; Eskom, 2015b; SEA, 2014). Deeper knowledge on the relationship between the water and energy sectors is crucial to provide for sustainable and reliable infrastructure planning and for ensuring security of supply. However, while there has been research on the water intensity of the energy sector, research on the local energy and carbon intensities of water infrastructure and the urban water cycle has been limited.

As a water-scarce country, where most of the available surface water has already been allocated, the viability of alternative water sources is being explored (WWF, 2016). The City of Cape Town (CoCT) has been considering seawater desalination, groundwater and recycled water as potential water sources to supplement their dwindling supplies (CoCT, 2017b). The water sector is a large user of energy, both in the form of liquid fuels, such as diesel generators, and electricity. An evaluation of the potential increases in energy demands from future water plans is, therefore, important. Furthermore, the carbon emissions cap set by the country will limit the emissions allowed from both sectors.

1.2 Aim and objectives

Given the CoCT's plans for future water mixes, the viability of using stormwater for artificial recharge of the Cape Flat Aquifer (CFA) as an alternative water supply in the Zeekoe catchment is being investigated in parallel by Okedi (2017). This study proposes a daily yield of 85 M*l*, from March to November, to offset the current demands generated by the catchment. The occurrence of large agricultural and residential areas creates significant demand for non-potable end-uses of up to 33.5 G*l*/annum and that can potentially be supplied by the CFA (Okedi, 2017).

This dissertation evaluates and compares the energy implications of abstracting water from the Cape Flat Aquifer (CFA) through a Centralised Approach for potable water, a Decentralised Approach for non-potable water and a groundwater Desalination Approach for potable water. The Centralised option considers the abstraction of the groundwater from Philippi with the water being sent to Blackheath and Faure Water Treatment Plants (WTP) for treatment to potable water levels. The Decentralised option, on the other hand, allows abstraction from 170 boreholes scattered across the catchment, feeding water to four proposed decentralised WTPs. The groundwater would then be treated for various non-potable end-uses identified in the Zeekoe catchment. A third alternative, in the form of a brackish water desalination plant, is also examined, based on the CoCT's plans for future water mixes, to provide potable water to the catchment. The following outputs were derived from the study:

- The direct energy intensities of the three approaches including electricity and liquid fuel usage,
- Embodied energy intensities of the chemicals used in all three approaches over the operational phase,
- Current electricity costing of all three approaches,
- Future electricity mixes, using the Integrated Resources Plant (IRP) 2016 and Council for Scientific and Industrial Research (CSIR) 2016 Re-Optimised scenarios, and resulting associated costs and,
- The carbon foot-print of the operational phase of the alternatives using the base case and future electricity mixes.

The purpose of the study is to provide more information on the energy implications and carbon emissions associated with the different water approaches proposed.

1.3 Scope and limitations of research

Due to the limited data available, the study uses theoretical values of possible head losses based on topographical properties of the catchment and hydraulic principles to calculate ranges of energy and carbon intensities possible for the three options considered.

The determination of embodied energy of new facilities and machineries requires more detailed designs of the systems and their resulting costs and has not been included in the energy intensity per unit treated water due to limited resources. Since the aim of the dissertation is to provide a comparison between the Decentralised, Centralised and Desalination options, the energy and carbon intensities computation was limited to the abstraction, transmission, and treatment stages of the water supply system. Wastewater collection, treatment and management have, therefore, not been considered in the study due to the similar paths followed by used water across all three options investigated.

1.4 Structure of the dissertation

The following outlines the Chapters of the dissertation.

Chapter 1 introduces the dissertation as well as provides the purposes, aims and limitations of this study.

Chapter 2 examines the available literature on the water energy nexus, considers existing international and local studies carried out on the energy intensity of water supply systems and explores the future electricity mixes of South Africa.

Chapter 3 presents the catchment area used for the study and the approaches explored, in a parallel study (WRC Project K5/2526), which were used as alternatives in this dissertation.

Chapter 4 outlines the data collected for the study using relevant literature and information gathered from the existing water treatment plants.

Chapter 5 explains the research methods followed throughout the modelling process including the preliminary design of the water systems, identification of the energy intensive units of the three approaches, quantifying the minimum and maximum energy consumption of the three approaches and computing current and future electricity costs and carbon foot-printing of the alternatives.

Chapter 6 presents the results obtained from the modelling process and the future scenarios and provides a discussion on the relevance of the results in the context of previous studies.

Chapter 7 summarises the findings and provides recommendations for future research.

2. Literature Review

This chapter provides background information on the relevant aspects of the study. A brief discussion and review of existing literature on the water-energy nexus in international and South African contexts is presented, followed by an analysis on the energy implications and associated carbon emissions of conventional water treatment processes and alternative water technologies. The different potential future electricity mixes and current and future greenhouse gas (GHG) emissions of South Africa are also reviewed.

2.1 The water energy nexus in an international context

Water and energy sectors, considered as being vital to economies, are both facing urgent challenges in countries worldwide (Hussey and Pittock, 2012). Despite the considerable progress made in the past decades to improve access to water and energy, nearly 16% of the world's population still lack access to modern electricity while 9% lack access to safe water and more than 40% are affected by water scarcity (World Bank, 2017; IEA, 2016). Access to water and energy are listed as two of the Sustainable Development Goals by the United Nations (UNDP, 2017). Demand for clean water services and energy, not only in the form of electricity but also liquid fuels, are projected to increase with growing global population, improved accessibility to services and further economic growth (IEA, 2016). Such increases translate to subsequent growths in the production and supply of water and energy, as well as to deepen the link between the water and energy sectors. The future water mix and energy mix may include energy intensive alternative water sources such as desalination and waste water re-use and water intensive energy conversion mechanisms including nuclear power and biofuel production (IEA, 2016).

There is a complex relationship between water and energy often referred to as the water-energy nexus. The latter has been recognised as being crucial in holistic planning for sustainable development and associated frameworks (Siddiqi and Anadon, 2011). Planning for both sectors has historically been carried out in parallel with minimal interaction (Hussey and Pittock, 2012). While there are rising concerns of resources depletion and climate change globally, the implications of the water-energy nexus are being studied mostly in developed countries and are focussed on the role of water in the energy sector. Wilkinson (2000), Stokes & Horvath (2011) and Bakhshi *et al.* (2012) have extensively investigated the effects of energy on the water sector in the U.S and Canada while the nexus in developing regions such as the Middle East and Africa have been explored to a certain extent by Siddiqi & Anadon (2011), Bazilian *et al.* (2011), Friedrich (2009), Madhlopa *et al.* (2016) and Sparks *et al.* (2014).

Shortages in one sector will inevitably affect the other and the inter-dependence of the two sectors is thought to have increasing influence on current and future policy issues of the 21st century (WEF, 2014). The relationship between water and energy has significant impacts across industries and both energy utilities and fossil fuel extraction are found to have high water and energy intensities as shown in Figure 2-1 (WRI, 2016).

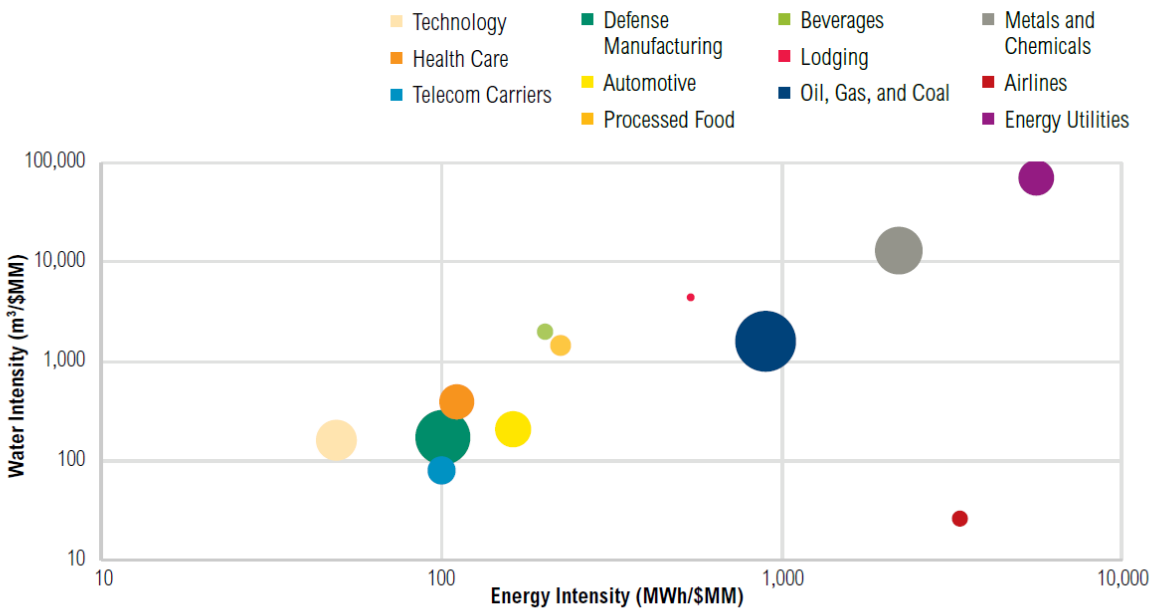


Figure 2-1: Global energy and water intensity per sector (WRI, 2016)

Industries are affected directly and indirectly by changes in energy and water availability and prices, and the energy utilities sector-having both the highest energy and water intensities is the most vulnerable one (WRI, 2016). The International Energy Agency (2016) has estimated the energy sector's share of water usage as being almost 10% of global water withdrawals. Similarly, the water sector is a significant user of energy through water extraction, purification, distribution and wastewater treatment processes. Electricity is the main form of energy used in the water sector and the latter is estimated to draw 4% of the total electricity production (IEA, 2016).

2.1.1 Water for energy

Energy production in various forms is highly water intensive, water being used extensively from primary energy production to power generation. The extraction of fossil fuel resources, such as oil, gas and coal, have water intensive processes including drilling, hydraulic fracturing for shale gas and oil, refining and washing. As new mechanisms are developed to extract more primary energy resources, water demands in the energy sector are constantly changing. For instance, the water requirements of hydraulic fracking for the extraction of locked natural gas have exceeded those of conventional methods (Glassman and Wucker, 2011). Similarly, the recent development of the Canadian oil sands produces synthetic crude with a water footprint up to twenty times that of the petroleum produced in the Middle East (Glassman and Wucker, 2011).

Although water is considered as a renewable resource, its availability and accessibility depend on the location of use. Water usage for energy is sub categorised into withdrawal and consumption where withdrawal is the volume of water extracted from its source and consumption if the volume of the withdrawn water that is not returned to its source (IEA, 2012). Figure 2-2 summarises the ranges of water intensity of the different energy sources used.

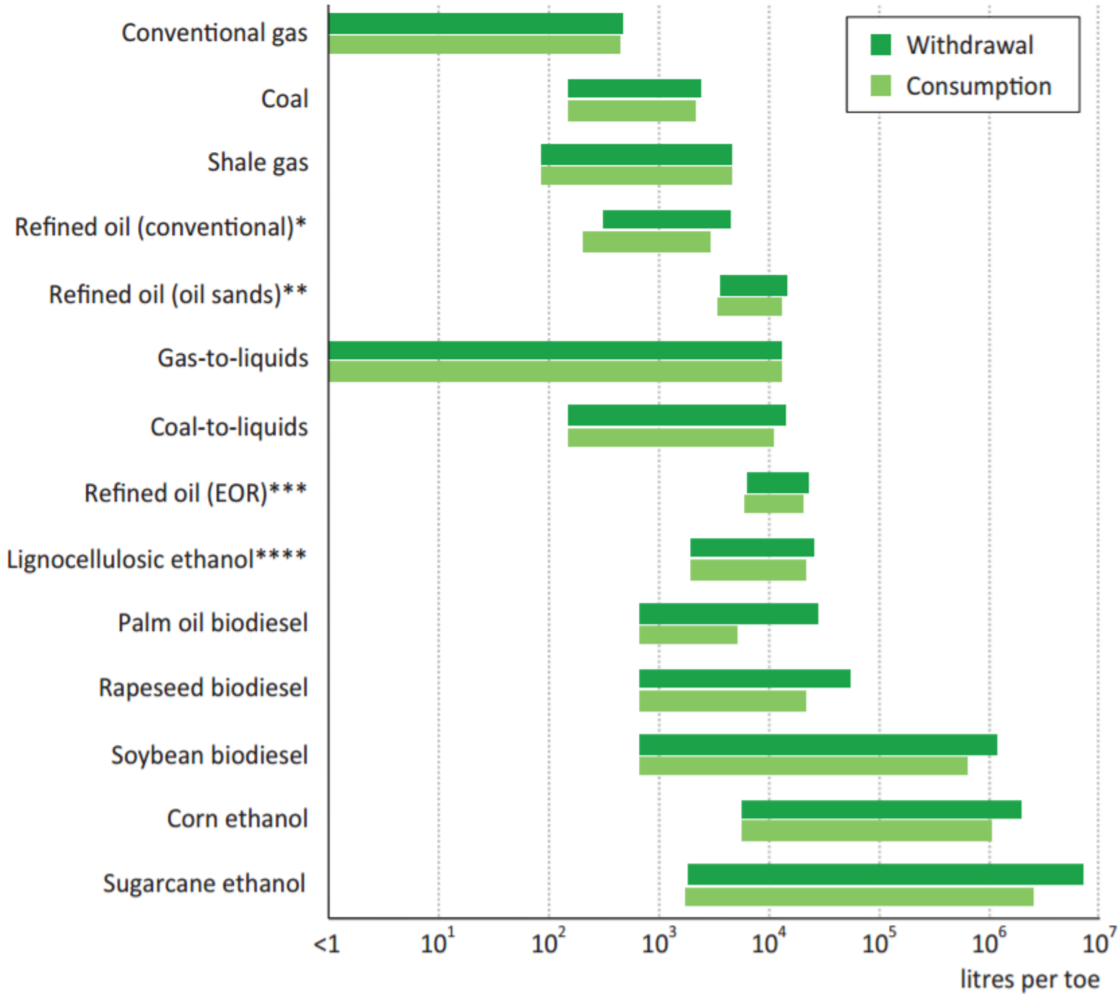


Figure 2-2: Primary energy water consumption v/s withdrawal (IEA, 2012)

Biofuels, despite being classified as renewable sources of energy, are the greatest water users amongst renewable energy sources due to the water required to grow and convert the plants into fuel sources (IEA, 2012). However, the sustainability of biofuels is constantly being improved on and alternative biofuel sources requiring low or no irrigation are being steadily developed (Elbehri *et al.*, 2013).

There have been several studies conducted to estimate the water consumption of the different electricity generating facilities. Both hydroelectric and thermoelectric electricity generation facilities, contribute more to the water demand of the energy sector than fossil fuel extractions do (Younos *et al.*, 2009). Hydroelectric power plants are relatively more water efficient as used water is returned to natural flows or dams while thermoelectric plants use considerable volumes of vapour to drive turbines (Younos *et al.*, 2009). Fossil fuel based, nuclear and renewable energy sources have water footprints, which are dependent on the types of mechanism used (Meldrum *et al.*, 2013). Water consumption varies mainly according to the geographical and climatic conditions of their locations.

Meldrum *et al.* (2013) compiled the estimated water intensities of both renewable and non- renewable power stations through studies carried out in the U.S and the data are represented in Figure 2-3.

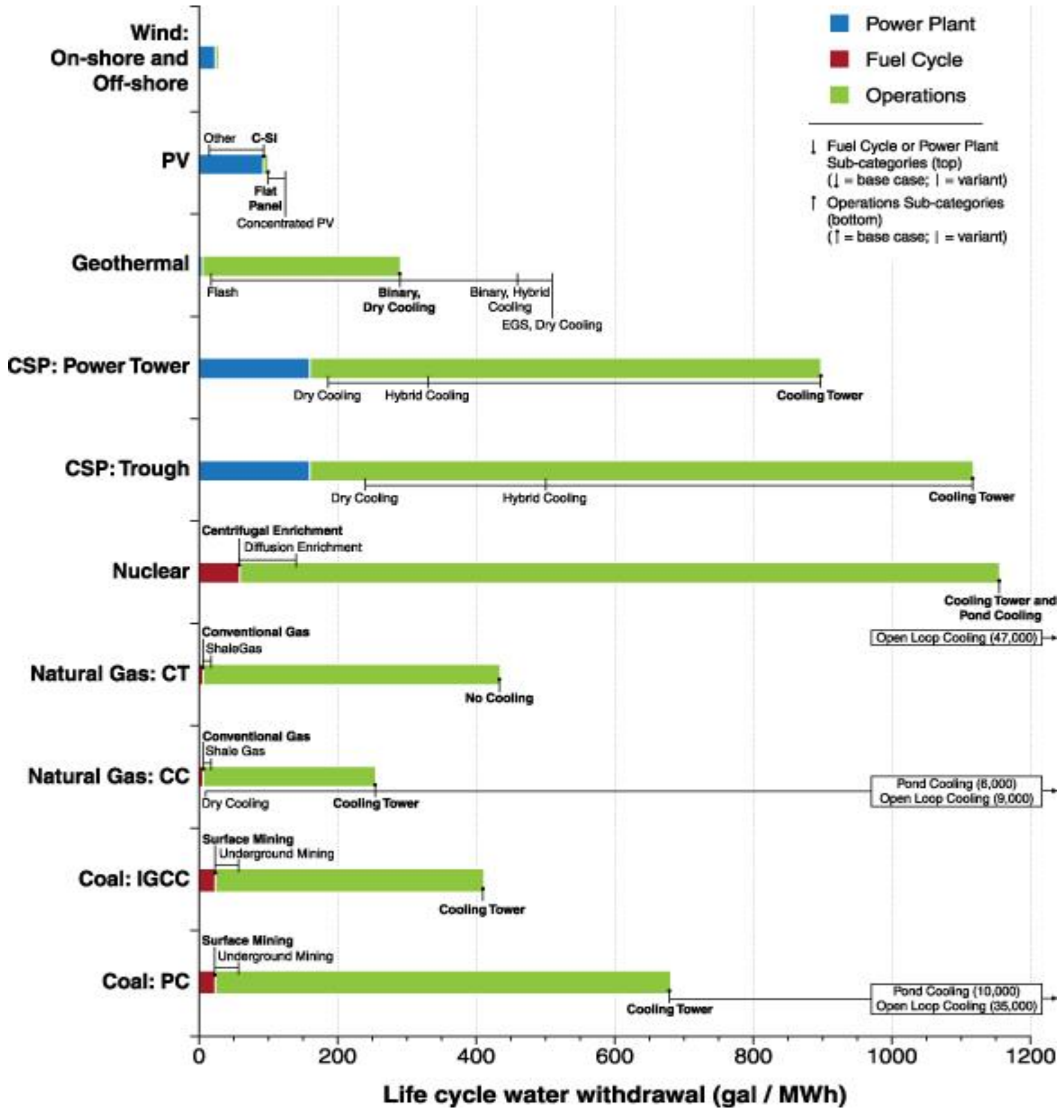


Figure 2-3: Water consumption of energy technologies (Meldrum *et al.*, 2013)

Conventional natural gas power stations are one of the least water intensive forms of power production while concentrated solar power’s (CSP) water usage is shown to be larger than all forms compared. However, the water usage of each thermo-electric power station depends on the type of cooling system adopted. CSP plants have a larger potential to decrease their operations' water consumption through dry cooling systems than other plants (Meldrum *et al.*, 2013; Carter and Campbell, 2009). Coal and nuclear power stations require at least 189 to 1136 *l*/MWh and 303 to 1893 *l*/MWh of water respectively, while carbon capture technologies (CCS) can increase the water consumption of coal power stations by up to 100% due to decreased plant efficiency (Glassman and Wucker, 2011; WRC, 2015). Non- thermal renewables, photovoltaic (PV) and wind turbines have the lowest consumption since electricity is generated without the use of heat (Meldrum *et al.*, 2013).

Hydro-electric power supplies almost 16% of the total global electricity demands and its share has been increasing steadily (IEA, 2017). Energy can also be stored in the form of potential energy using pumped storage plants (PSP). Water is pumped to an upper reservoir during off peak, and converted to electrical energy when electrical demands exceed supply. PSPs are considered as net electricity consumers since they use a considerable amount of electricity to pump water back to upper reservoirs (IEA, 2012). However, PSPs provide electricity with a high efficiency of 70% to 85% and therefore are effective for storing energy. The water consumption from hydropower plants is insignificant when compared to the amount of water withdrawn since water is mainly lost through evaporation and water diversion (Younos *et al.*, 2009). Due to a lack of information on the water related damages caused through destruction of marine life and ecosystems, the water consumption of large hydro-electric power plants is challenging to estimate (Glassman and Wucker, 2011).

The IEA (2016) projects that global freshwater withdrawals and consumption will increase by almost 2% and 60% respectively by 2040 while the share of the power sector decreases as old and less efficient coal power plants are decommissioned and substituted by nuclear and bio-energy based plants. Developing countries are expected to contribute more to increases in water demands while developed ones decrease their overall energy related water demand by switching to cleaner and more water efficient energy sources and technologies (IEA, 2016).

2.1.2 Energy for water

On the other side of the nexus is the energy requirement of the water sector relating to the supply, distribution and treatment of water. Energy is needed not only for water extraction, conveyance, storage, treatment and distribution but also for onsite water pumping, thermal inputs and wastewater collection, treatment and discharge (Wilkinson and Kost, 2006). Almost 60% of the water sector's global energy consumption is in the form of electricity while the remainder is in the form of fossil fuels in pumps and as thermal inputs in desalination mechanisms (IEA, 2016).

The energy intensity of water supply systems depends mainly on the type and location of the source and the distance between sources, treatment plants and users. Globally, the extraction and transfer stages of the cycle are often the most energy intensive ones as shown in Figure 2-4.

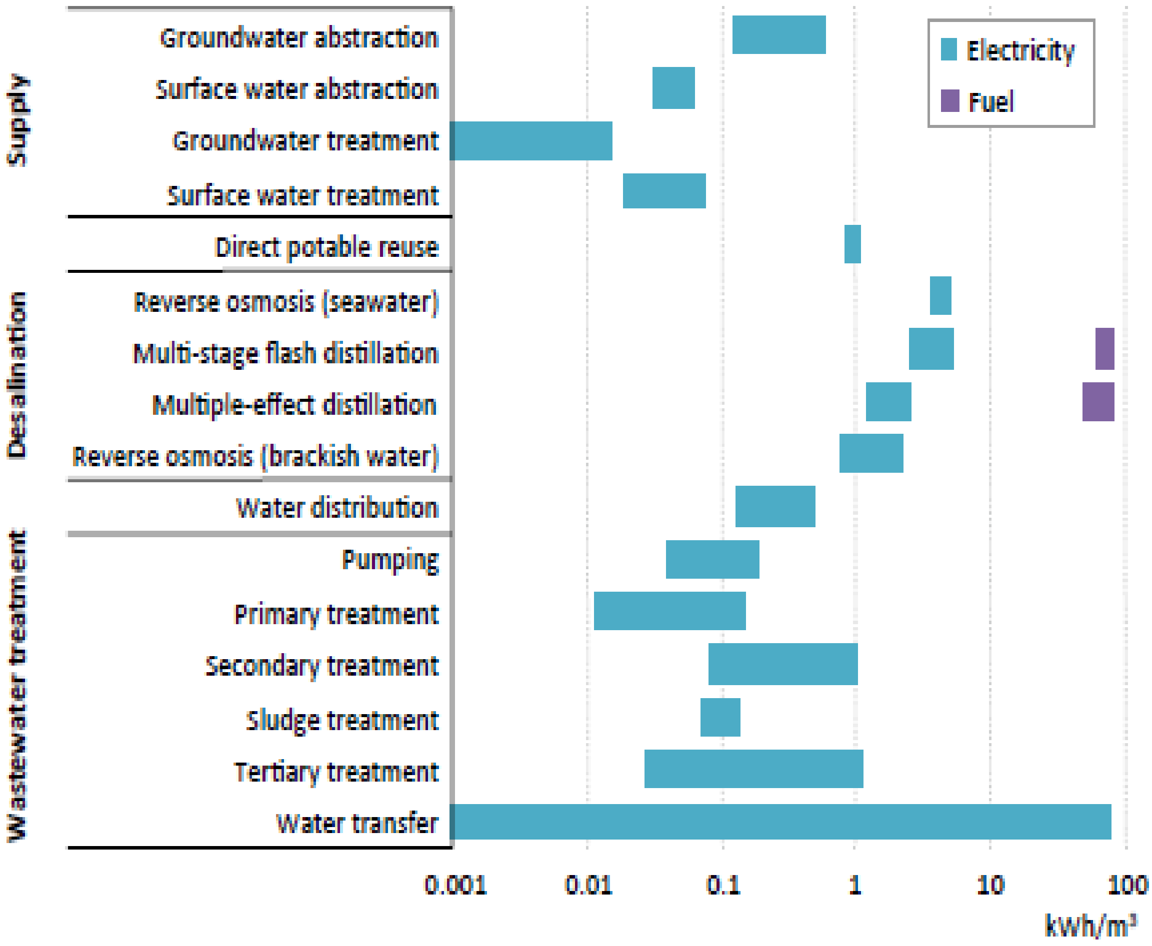


Figure 2-4: Energy intensity of water supply steps (IEA, 2016)

The degree of impurity of the source water and the targeted end-uses define the required treatment processes before distribution. The composition of different water sources vary from the existence of micro-organisms, dissolved chemicals and suspended solids to absorbed gases and high level of salinity (Plappally and Lienhard, 2012). Surface and groundwater usually require minimum treatment consisting of sedimentation and filtration as well as secondary treatment to neutralise any excess chemical and nutrients in the raw water. Brackish water and seawater have to undergo further treatment to remove their higher contaminant concentrations and therefore have higher energy footprints (Munoz and Fernandez-Alba, 2008; Karagiannis and Soldatos, 2008).

Various types of treatment processes are used to produce water for both potable and non-potable end-uses, depending on the latter's required water qualities. For instance, water for non-potable uses such as gardening and irrigation require minimal treatment and therefore have simpler treatment processes and lower energy requirements. On the other hand, water used in cooling towers has to reach a very high level of purity and accordingly, its treatment processes are highly energy intensive (EPA, 2012).

There are two types of energy components in determining the energy requirements of water systems, the embedded energy costs and the direct energy costs (including electricity) of the system. These will be discussed in more details in the subsequent sections.

2.2 The South African context

South Africa is a developing country with an energy intensive economy due to its electricity, mining and minerals sectors. Its cities are home to more than 60% of its population of 55.9 million, and comprise both of formal and informal settlement (StatsSA, 2017). With rapid urbanisation, these numbers are expected to grow in the coming decades. However, the country is still overcoming the backlog in services provisions and inequalities left behind as a legacy of apartheid. There has been significant progress made within both energy and water infrastructure provisions over the last decade. South Africa has an electrification rate of 85% (which is the highest in Southern Africa), and in 2015, 89.4% of households were connected to piped water networks and 80% had access to sanitation services (DGIS, 2016).

With rapid urbanisation and with high population and economic growth rates, demand for water and energy in Africa is expanding while its water supplies are shrinking and water quality is deteriorating ((Jacobsen *et al*., 2012).

2.2.1 The energy sector

The country's energy sector is deeply reliant on fossil fuels such as locally abundant coal, its main source of electricity. Coal power stations produces 86% of electricity while hydropower, nuclear energy, oil and renewable energy sources contribute 14% of the total electricity mix (CSIR, 2015). 60% of the country's crude oil requirements are imported from the rest of Africa and the Middle East while the rest is produced by gas to liquid and Sasol's coal to liquid facilities (Burton and Winkler, 2014). The resulting impact of the South African energy mix on the environment is significant since the energy sector alone contributes for over 88% of the national GHG emissions ((Burton and Winkler, 2014). Due to its energy intensive economy and large old coal fleet, South Africa is found amongst the top 20 GHG emitters globally (WRI, 2016).

The national electricity demand has stagnated over the years due to slowed-down economic growth, the inability of Eskom to fully meet demands and energy efficiency and demand side management measures (Odhiambo, 2009; Eberhard, 2011). The recent changes in installed capacities and demands are shown in Figure 2-5. The decrease in supply has resulted from delayed investment decisions and poor performance of Eskom's old coal fleet due to poor maintenance (Eberhard, 2011). These have resulted in electricity prices changing from their historical low prices to more than quadrupling with new build plans and related externalities (Thopil and Pouris, 2010).

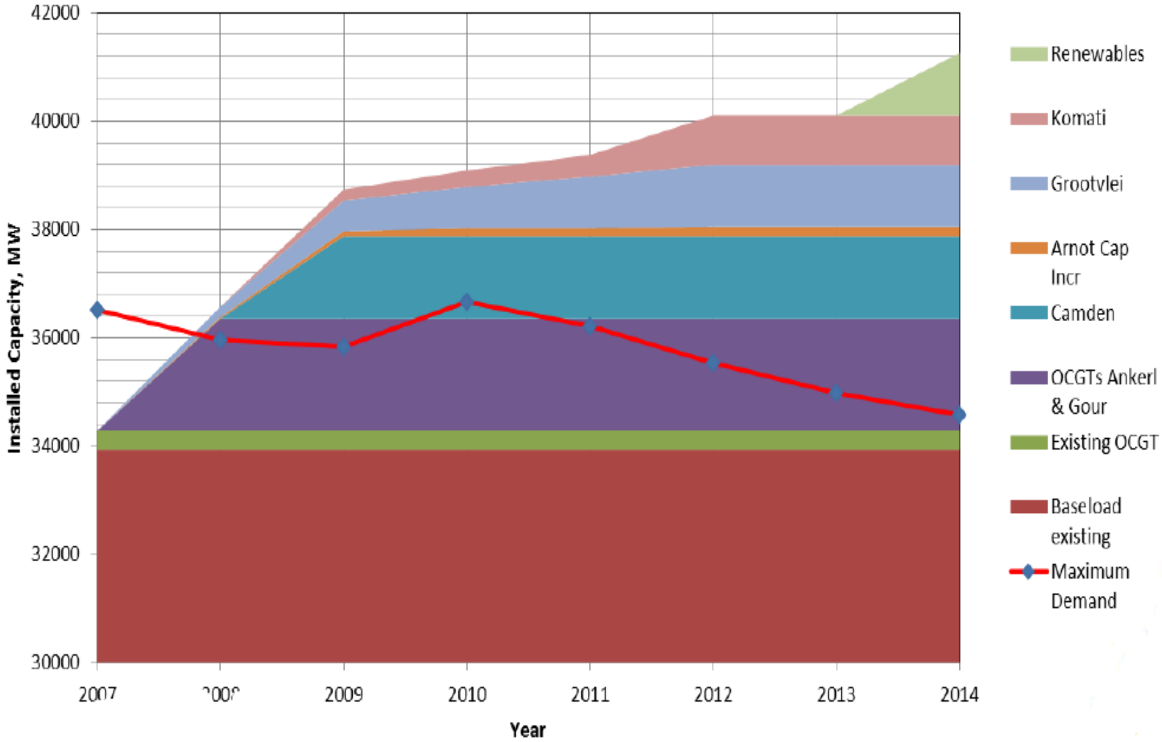


Figure 2-5: Installed electricity capacity v/s actual demand (NERSA, 2014)

The construction of two additional coal power plants, Medupi and Kusile, will add 9.8 GW of installed capacity once completed while almost 7 GW of renewable power had been procured by the end of 2016 through the Renewable Energy Independent Power Producers Procurement Programme (REIPPPP) (DoE, 2016a).

2.2.1.1 Future electricity mixes

After the ratification of the Paris Agreement, South Africa committed itself to decrease its GHG emissions by 34% by 2020 and 42% by 2025 (RSA, 2015). Future energy mixes are being considered by the government in an attempt to curb its emissions.

The Integrated Resources Plan (IRP) (2010) proposes a nuclear fleet of 9.6 GW and 6.3 GW of new coal power stations which allows for little flexibility in case of low electricity demand growths and changes in initial assumptions. The build plan locks the country into high electricity prices due to the large capital costs of a 9.6 GW nuclear fleet. The IRP 2010 document was revised in 2013 and 2016 but remain as draft documents awaiting the Cabinet’s approval. Alternatives to the IRP build plan have been investigated by numerous organisations. Such an alternative was investigated the ERC (2015) by comparing a committed scenario to a full nuclear fleet to a more flexible approach. The following parameters were used to investigate different possible outcomes: Low and high economic growths, lead times and construction costs as well as pessimistic and optimistic renewable energy process and natural gas prices were used as parameters to investigate possible outcomes.

The study concluded that in case of high economic growth and demand coupled with low costs of nuclear technologies, commitment to nuclear power will not result in higher electricity prices than the flexible approach. However, with current economic growth rates, low electricity demands and relatively high nuclear costs, an overinvestment in generation capacity with large shares of nuclear will result in negative impacts on the economy and higher electricity prices (ERC, 2015).

Further studies are being conducted by the CSIR, examining least- cost electricity mixes for South Africa using the draft IRP (2016) document as its base case. Scenarios using the latest energy technology costs were developed. The restraints on new solar PV and wind capacity that were used in the IRP modelling were removed and the costs of solar PV and wind technologies decreased more steeply than the assumptions of the IRP. A Re-Optimised scenario was developed without any limits on the energy supply options and compared to the Business as Usual (BAU) scenario of the IRP (2016).

The Re-Optimised scenario resulted in a larger uptake of renewable energy and natural gas in the mix without the addition of more nuclear and coal capacity. The total installed capacity in 2040 was 47 GW more than that in the BAU scenario to account for the intermittency in the renewable energy sources availability (CSIR, 2016). Despite having a larger installed capacity for the Re-Optimised scenario, the resulting investment costs were still found to be lower than that of the BAU scenario.

2.2.1.2 Electricity prices

The electricity tariffs consist of different components as shown in Figure 2.6. The primary energy component of the operating costs is the largest one and depends on the primary energy sources used. Recently, due to the mismatch between supply and demand, diesel open cycle gas turbines (OCGTs) which were designed to be used for peak loads were used extensively resulting in higher operating expenses (CSIR, 2015). Depreciation and amortisation expenses of new build programmes are further built into the cost of electricity. Future electricity prices arising from the new build fleet proposed by the DoE (2011) are shown in Figure 2-7. These will change with the capital costs of building new power plants as existing ones are decommissioned at the end of their lives. Primary energy cost share represents more than half of the total electricity operating expenses and has been increasing for the past five years.

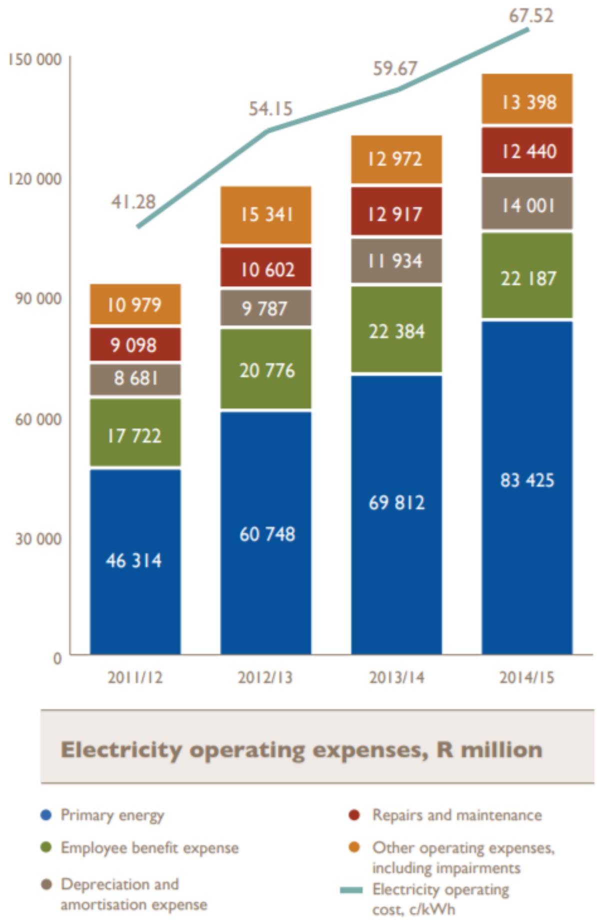


Figure 2-6: Electricity operating expenses (Eskom, 2015b)

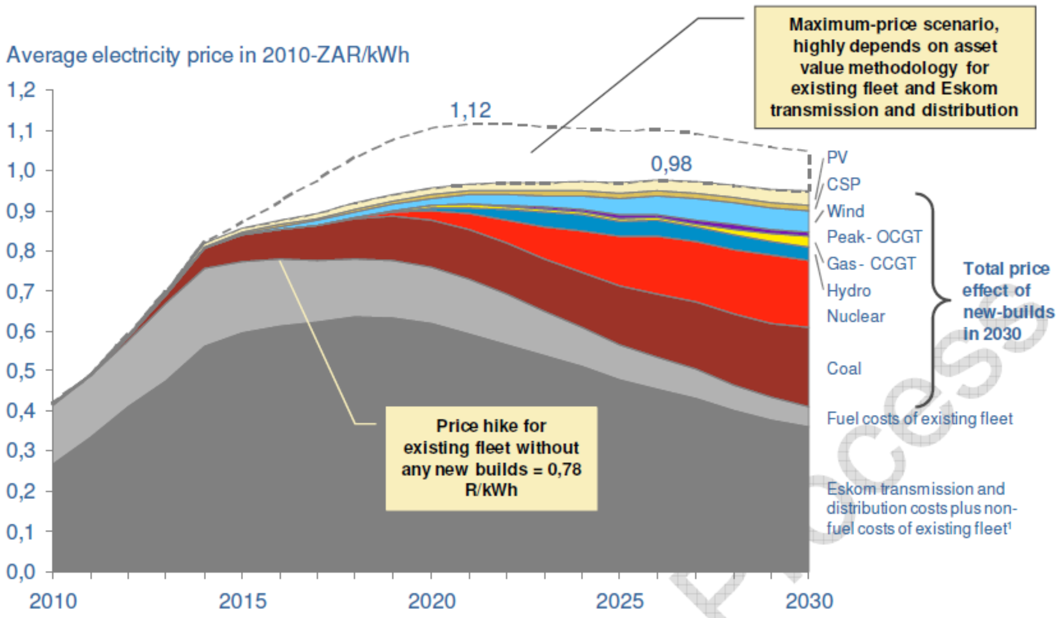


Figure 2-7: IRP 2010 electricity prices (DoE, 2011)

The operating costs also depends on the energy sources used to produce electricity. The historically low prices of electricity were due to an overinvestment in the 1970s and over the past decade, electricity prices have hiked as new power plants are being built to match demands (Steyn, 2006; Thopil and Pouris, 2013). The costs of primary energy such as coal, gas and diesel fluctuate due to external factors and changing market conditions and these affect the cost of production of electricity directly.

The introduction of renewable energy has diversified the electricity mix. While the primary energy sources used by renewable energy technologies are readily available, the intermittency of the availability of the resources contribute to the complexity of including these in the grid. However, the REIPPPP has proven to be highly successful and the costs of production of electricity from solar and wind have halved in the last five years thus competing with coal power generation costs (Eberhard *et al.*, 2014; CSIR, 2015).

Despite having a larger installed capacity of 47 GW in the CSIR's Re-Optimised scenario, its resulting investment costs were still found to be lower than that of the BAU scenario (CSIR, 2016). Consequently, the average cost of electricity production of the Re-Optimised scenario was found to be 19% less than that of the BAU scenario as shown in Figure 2-8.

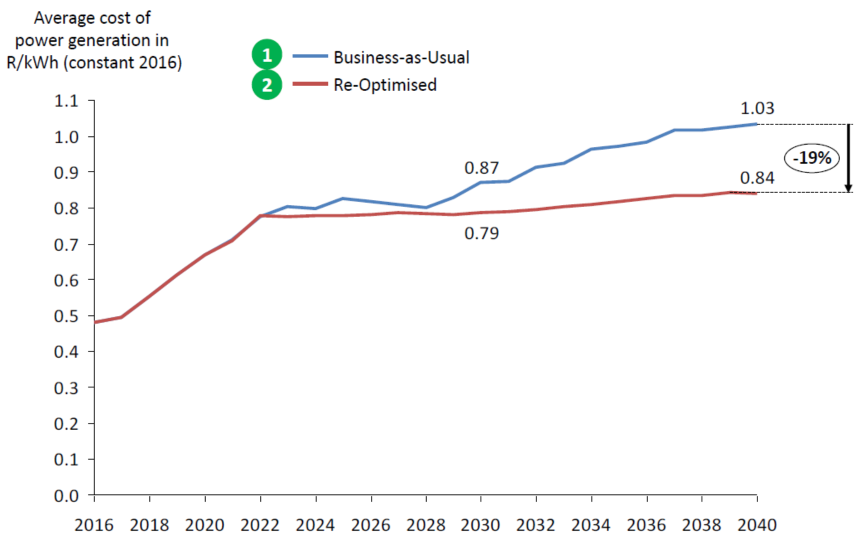


Figure 2-8: CSIR Re-Optimised electricity mix generation costs (CSIR, 2016)

2.2.2 The water sector

Water is considered as being a critical resource since South Africa is classified as a water scarce country, with an average rainfall of 498 mm per year and a per capita water availability of 1060m^3 per year (Kahinda *et al.*, 2010). The rainfall seasons and amount of precipitation vary across the country with the central and western parts of the country being considered as arid (Mukheibir and Sparks, 2003). South Africa's existing water resources comprise 77% surface water, 9%

groundwater and 14% return flows (DEA, 2012). Most of its available water resources are already being extensively exploited as most surface water has been allocated and current water usage is already exceeding supply during dry seasons. Water availability is not the only challenge faced by most cities, since effluent management, water quality and the protection of ecosystems against over-exploitation also have to be considered (SACN, 2015).

Most cities have provided access to potable water services to more than 90% of their households. The Cities of Johannesburg and Cape Town have been experiencing population growth rates of over 2.5% per annum since 2000 and with urbanisation (StatsSA, 2017). The cities' population is expected to grow further over the coming decades, consequently increasing their water demand (StatsSA, 2017). Future water requirements arising from urbanisation, development of mine and power stations, irrigation and poor water management can increase pressure on local water resources as shown in Figure 2-9 (CSIR, 2015).

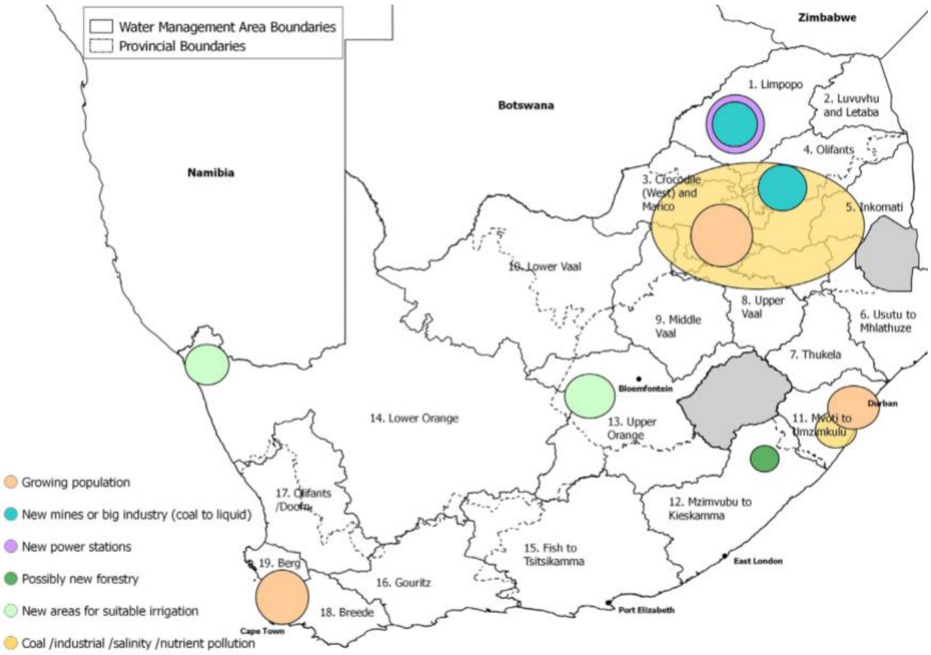


Figure 2-9: Future water requirements (CSIR, 2015)

There is significant variation of weather patterns and climatic conditions across the country and dams and transfer schemes are used to ensure a continuous supply of water to parts of the country with low surface and groundwater levels (SACN, 2015). It is therefore crucial in a country with such water disparities to have a better understanding of the location and availability of water sources and its possible end-users to allow for effective allocation of water.

Currently, the existing water supply capacity is approximately 15 billion m^3 and almost all the available surface water is being exploited. On the other hand, groundwater resources can be sustainably exploited up to 6 billion m^3 per annum but this is only being done at less than 20%

of its capacity (Knuppe, 2010). The country is already struggling to maintain a sustainable balance between water abstraction and usage and it will be further exacerbated with growing impacts from urbanisation, climate change and development. Africa has already been identified as being particularly susceptible to climate change due to its low adaptive capacity and vulnerability to changes (AfDB, 2007).

The possibilities of alternative sources of water such as rainwater harvesting (RWH), storm water harvesting (SWH), recycling of wastewater and desalination are being investigated and to some extent implemented. The eThekwini Water Services is already supplying 7% of Durban's water demands by recycling wastewater to supply its industrial sector, thus reducing strains on freshwater supplies and reducing effluent discharges by almost 10% (Jacobsen *et al.*, 2012).

The Western Cape has been facing a significant drought period caused by low annual rainfall since 2015. Water saving measures and restrictions have been reinforced and water savings of up to 20% have been achieved (CoCT, 2017b). Water losses in distribution systems have also decreased from 25% to 15% in the past 8 years with increased responsiveness to leaks and bursts and the increasing use of automatic pressure management systems (CoCT, 2017b). Planned new water supply sources will be added to the water mix according to the Western Cape Water Supply System (WCWSS) Reconciliation Strategy as shown in Figure 2-10. However, due the current drought conditions of the area, the introduction of the different supply sources were moved earlier to increase supply in short to medium term while improving the system's resilience against climate change effects (CoCT, 2017b).

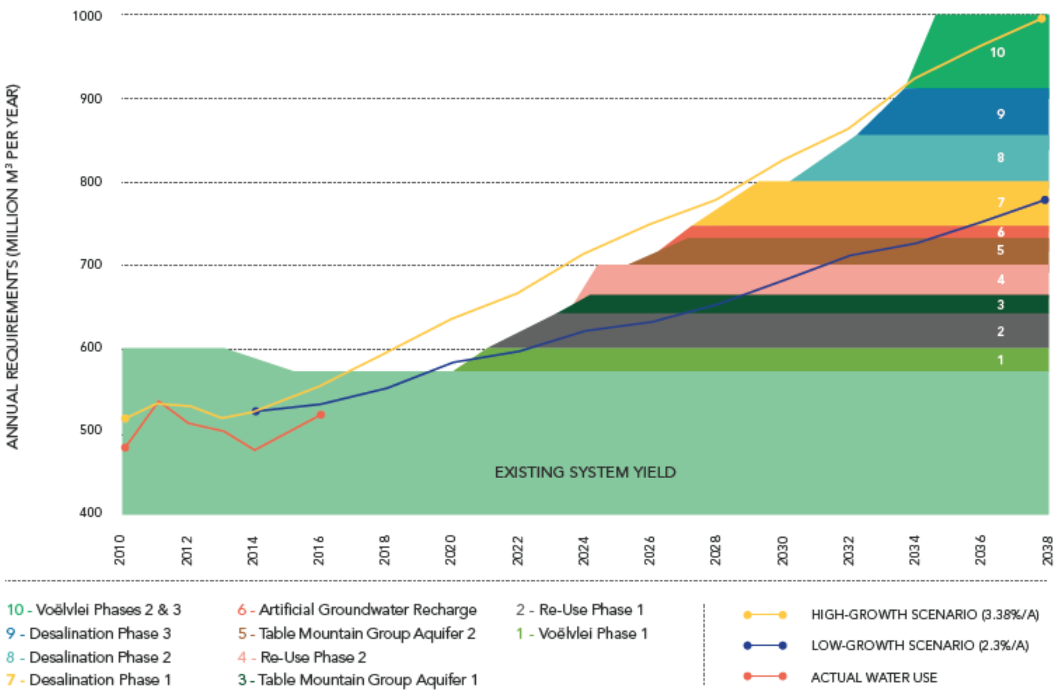


Figure 2-10: WCWSS future water supplies(GreenCape, 2017)

2.2.3 The water-energy nexus in South Africa

The energy and water sectors are intricately linked in South Africa. The highly coal dependent electricity sector requires substantial amounts of water from extraction to generation while energy is required throughout the conventional water cycle and wastewater treatment and management. The mining of minerals such as coal further represents approximately 12% of the costs related to the distribution of water (StatsSA, 2013). The energy sector is also considered as one of the main causes of degradation of water resource qualities due to the generation of highly polluted water and greenhouse gas emissions produced from the burning of fossil fuels (Madhlopa *et al.*, 2016).

Eskom is one of the largest consumers of freshwater in South Africa with up to 2% of the total national consumption delivered to its power stations for electricity generation (Eskom, 2017c). Currently, they are using 292 million m^3 per annum mainly for cooling purposes and three types of cooling mechanisms are employed, namely wet cooling, direct dry cooling and indirect dry cooling which have varying water intensities.

Most of the coal fleet is fitted with wet cooling, which is the conventional and most water intensive method although Matimba, Kendal, Majuba, Kusile and Medupi are fitted with dry cooling systems (Eskom, 2016). Blignaut & Inglesi (2012) carried out an estimation of the opportunity cost of water for Kusile and Medupi. Kusile is being constructed in Haartbeesfontein where water is sourced from the Vaal River while Medupi is found in Lephalale where 87% of the catchment's water is supplied for agricultural, industrial, mining and domestic purposes. Both have been designed with dry cooling systems using less water and with the possibility of CCS implementation (Inglesi-Lotz and Blignaut, 2012). The total water requirements from both stations will still amount to 52.3 million m^3 per annum, representing 14% of Eskom's total water consumption (Inglesi-Lotz and Blignaut, 2012). Figure 2-11 shows that the trends of the water footprint of electricity production and the peak in 2005 was a result of an increased use of wet cooled units (Eskom, 2017c).

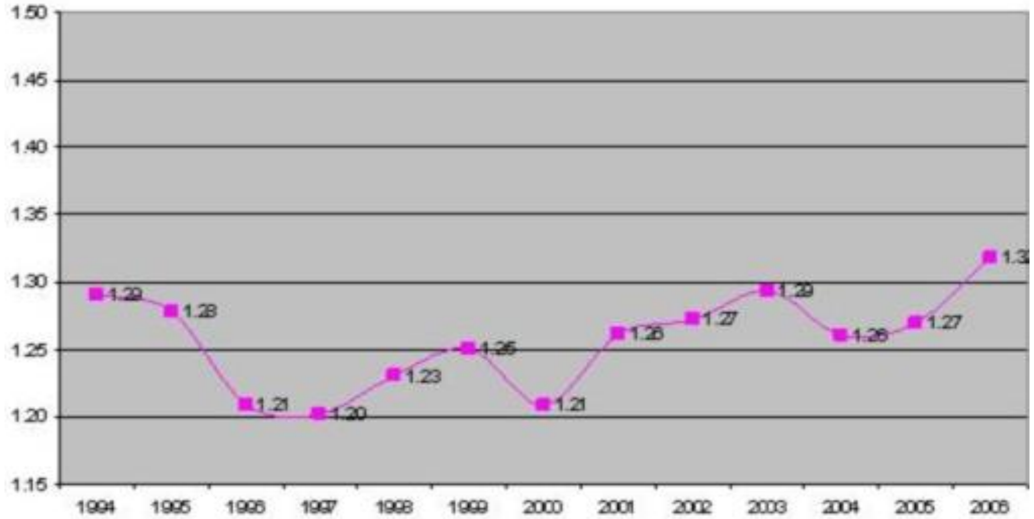


Figure 2-11: Water intensity of electricity sent out (*l*/kWh) (Eskom, 2017c)

The projected electricity mix given by the IRP (2013) proposes new build programmes centred on additional coal and nuclear power stations which will considerably increase Eskom's water demands. In an attempt to curb these, Eskom has, through its long-term water strategy, targeted to decrease the water intensity of its plants from 1.38 *l*/kWh to 1.29*l*/kWh with the use of dry-cooling systems in new power plants, retrofitting existing ones, desalination of effluents from mines, demand side management and technical improvements (Madhlopa *et al.*, 2016).

Eskom owns and operates two large hydropower stations, Gariep and Vanderkloof, and smaller stations, totalling an installed capacity of 660 MW. Its pumped storage power stations produce up to 3 GW including the new Ingula power station (DWA, 2013). The IRP (2013) document outlines further hydropower developments to increase the share of renewable energy in the mix by 2030.

On the other side of the nexus, the water and wastewater sector is also a large user of energy. Municipal energy consumption is divided into five main components; transport, buildings and facilities, water supply and wastewater treatment plants (WWTP), street lighting and traffic lighting as shown in Figure 2-12. On average, the transport sector is the largest energy end user, followed by buildings and facilities and water supply and the WWTPs (SACN, 2014). Electricity costs were found to range between 5% and 30% of the total operational costs of both water and waste water treatment plants (SACN, 2014).

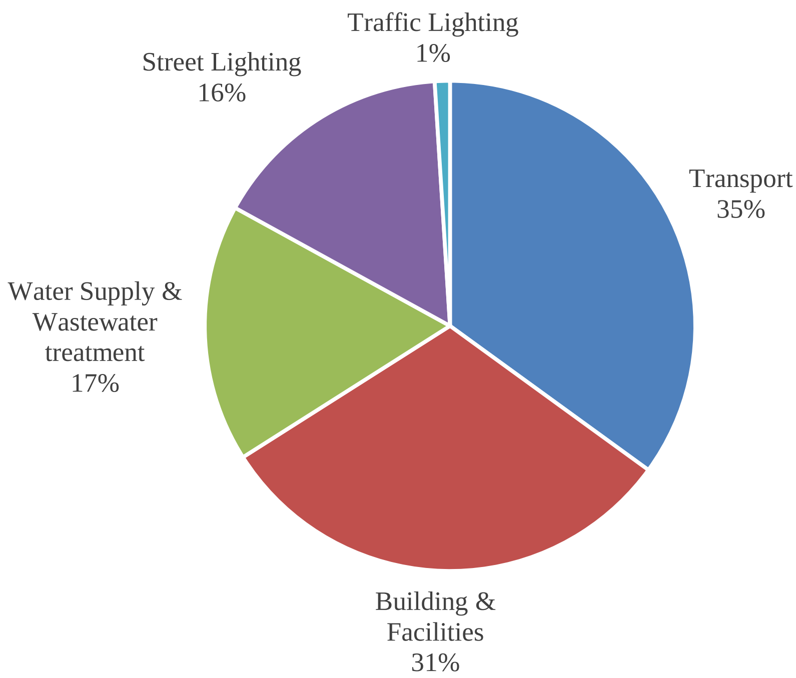


Figure 2-12: South Africa Energy usage per sector (SACN, 2014)

As water resources are being exploited to their limits, alternative water treatment mechanisms such as desalination plants are being set up around the country, increasing the sector's energy demands. Recently, the largest seawater desalination plant in South Africa was commissioned in Mossel Bay to provide water to the surrounding area and the largest single consumer of the treated water being PetroSA's gas to fuel refinery (Veolia, 2017). Even though desalination plants have the potential to supply additional potable water, such facilities increase electricity demands since desalination processes are highly energy intensive (Karagiannis and Soldatos, 2008).

2.3 Energy in water supply systems

The energy consumption of water supply systems is related to topography and spatial distribution of the network, climatic conditions, the location of available water resources and their demand sites and the quantity and quality of the water (Plappally and Lienhard, 2012; Pelli and Hitz, 2000). The water cycle typically starts with water extraction from source, conveyed through pipelines either for direct use by non-potable end-users or to treatment plants. Treated water is then distributed to end-users and the wastewater produced by the latter is then sent to wastewater treatment plants. Energy is required at each step of the cycle to drive the water around the networks and treat it to different levels

Pelli & Hitz (2000) use two energy indicators suitable for small to medium sized utilities, to evaluate the energy consumption and performance of water supply systems. The structural indicator used, considered the energy required to move water across the spatial distribution of the water supply system while a quality indicator was used to assess the efficiency of a water utility. Energy used for water transportation and operational pressure was estimated through the concept of minimal energy which is derived from the spatial and topographical layout of the system and based on potential energy of the water.

Globally, water supply systems make up 2% to 4% of the total electricity consumption, of which motor pumps absorb 80% to 90% (Vilanova and Balestieri, 2014; IEA, 2016). The movement of water in water supply systems requires energy to provide the necessary hydraulic heads using electrical energy or potential energy in the case of gravity flow. However, the efficiency of the system is greatly affected by losses of energy in pumping mechanisms and infrastructural flaws such as leakages (Plappally and Lienhard, 2012). The energy requirements of the systems also consist of the embodied energy of the materials used during the service lives of the WSSs. These are often comparable to direct energy consumption of water systems and is indispensable to the determination of the embodied energy of the treated water (Mo, 2012; Wilkinson, 2000).

Another approach for more sustainable water supply systems is the integration of energy production within the systems to promote hydraulic energy recovery in WSSs. Electricity is still mostly produced from fossil fuel sources despite a larger uptake of renewable energy technologies in the past decade. The electricity and water usage profiles have similar peak times

(Ramos *et al*., 2010).There are several measures that can be implemented in water systems. The systems can be fitted with turbines for electricity production in gravity pipes, pumping profiles can be shifted to off peak electricity usage periods and their energy requirements could be met by micro renewable energy sources. The City of Cape Town produces 5% of its internal electricity demands from micro-hydro generation using turbines fitted at its bulk water treatment works with a total installed capacity of 2.775 MW (CoCT, 2015).

The following subsections describes the main contributing factors of energy consumption at each stage of the water cycle and summarise the energy implications of the South African water sector with emphasis on the Western Cape.

2.3.1 Energy for water extraction

Water supply mixes worldwide consist of mainly surface water supplemented by groundwater and to some extent, brackish water and seawater supplies (UN, 2006). The energy associated with water extraction depends on the type of water resources exploited. Surface water and recycled water are more readily available than groundwater and seawater, requiring little to no energy to be used as supply. Surface water, the most widely utilised resource, is exploited through a network of feeder rivers, dams and raw water gravity pipelines. In contrast, groundwater, brackish and seawater must be abstracted through pumping mechanisms before being conveyed.). The energy components of groundwater abstraction will be discussed here while seawater supply will be further explored in Section 2.4.3.

The energy required for groundwater extraction depends on several factors including the water head, pressure head, the efficiencies of the pumps, average absorbed power, relative speed of the pump, friction factor of the pipe material and the useful life of the project (Plappally and Lienhard, 2012; Moreno *et al.*, 2009). While the electricity required to lift a unit volume of water out is directly proportional to the head, other factors such as friction loss and changing pressure heads increase the pump's energy demands. As water is pumped out of a well, the head fluctuates depending on the rate of recharge of the resource and its groundwater dynamics. The energy requirements of the pumps therefore changes accordingly, as their efficiency is also related to the rate and volume of withdrawal. As an example, the ranges of recorded energy intensities of groundwater abstraction in California are given in Figure 2-13 where the relationship between these and higher water depth levels is clearly apparent.

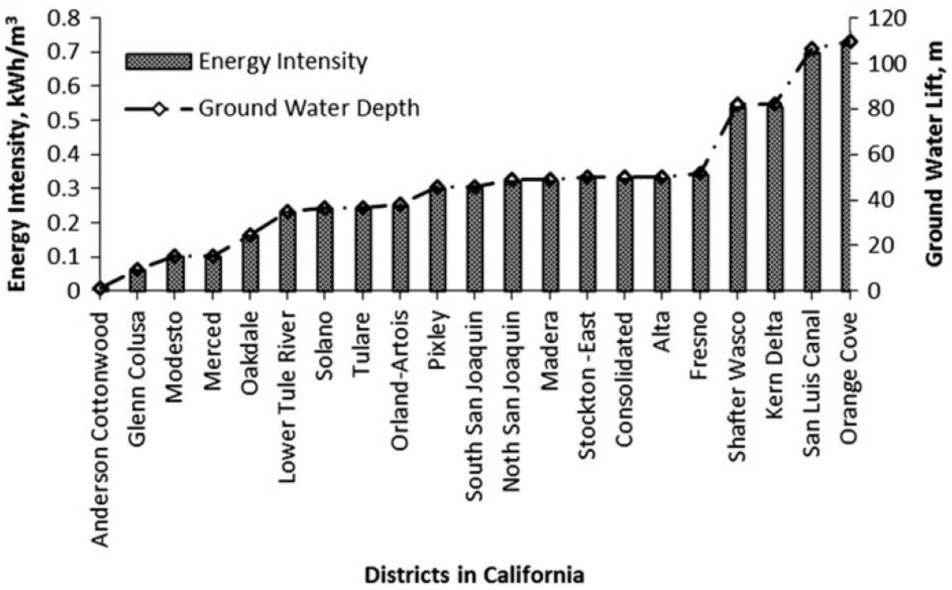


Figure 2-13: Abstraction energy intensity (Plappally and Lienhard, 2012)

Figure 2-14 shows the Western Cape's energy intensity for each process along its water supply system as well as international energy intensities for processes for groundwater supply systems. The abstraction and transmission intensities are lower than international ones. These differences can be explained by the WC's current water supplies. Its primary water source is surface water from six major dams across the province. These dams supply water through pipelines and tunnels using gravity flow due to natural head provided by their high elevations. In contrast, groundwater abstraction requires energy to pump water from aquifers and conveyance to water treatment plants since these are not always found on higher grounds.

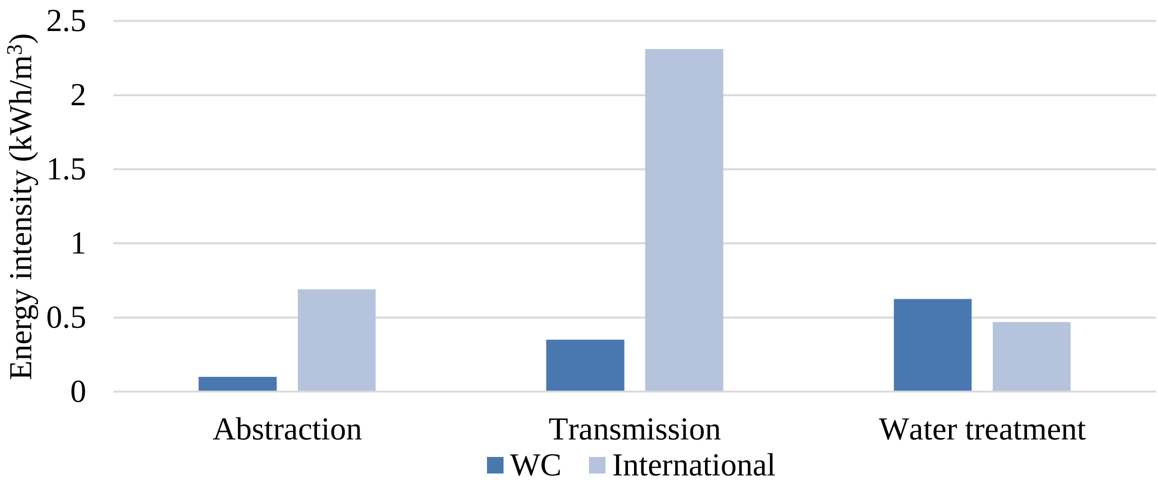


Figure 2-14: Western Cape and International groundwater energy intensity data (GreenCape, 2017; Plappally and Lienhard, 2012)

Energy costs related to pumping consist of more than half of the life cycle costs of groundwater extraction systems as shown in Figure 2-15. Optimally designed well systems and proper maintenance increase the well efficiency as the pumping is lowered and prevents pump failures due to sand and soil entering the well, increasing the lifespan of the well (Harter, 2003).

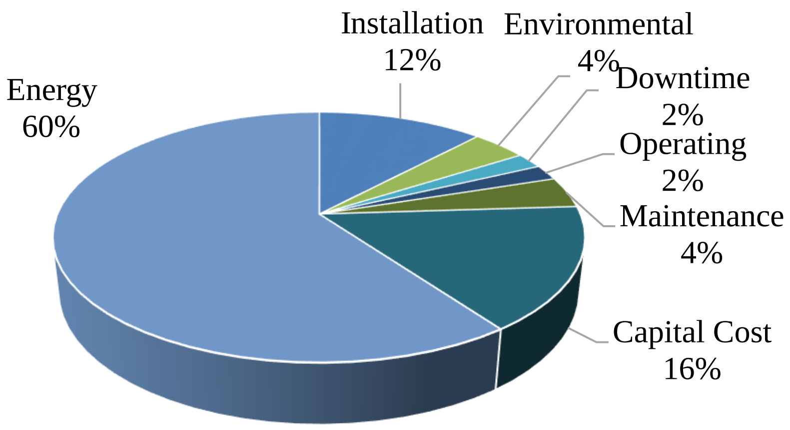


Figure 2-15: Groundwater pumping system costs (BWA, 2016)

2.3.2 Energy for water distribution

Water conveyance is the next stage in water supply systems. Water is often sourced away from where it is treated and used. Networks of tunnels, pipes and pumps are used to transfer large volumes of water and the energy intensity of this section of the system primarily depends on elevation differences, volume of water transported and the distances over which it is transferred (Water in the West, 2013). Urban planning influences the energy consumption of water systems because it determines the location of the consumers since the location of resources cannot be fixed. Therefore, the layout of water distribution systems, depending on the topography of the region, determines the majority of direct electricity costs related to the water supply systems (Pelli and Hitz, 2000).

South Africa is 77% dependent on surface water as input to its water supply systems followed by 9% groundwater and the rest is made up of water reuse (CSIR, 2015; DWA, 2013). Surface water is collected and stored in dams in areas with higher rainfall and transferred through raw water pipelines and tunnels to water treatment plants. The treated water is sent over long distances for distribution to users and for storage in reservoirs. The Western Cape Water Supply System (WCWSS) consists of six dams found in the higher lying areas of the province, providing for over 770 G*l* storage capacity (CoCT, 2017b). There is a network of raw water pipelines from the dams found in the Cape Fold Mountains into the twelve existing water treatment plants and an extensive distribution network to municipalities, direct end-users and storage facilities as shown in Figure 2-16. The bulk water pipelines extend over 600 km in length and range from

750 to 2400 mm in diameter (CoCT, 2017b). The system is further supported by 112 pump stations and smaller distribution networks (SEA, 2014).

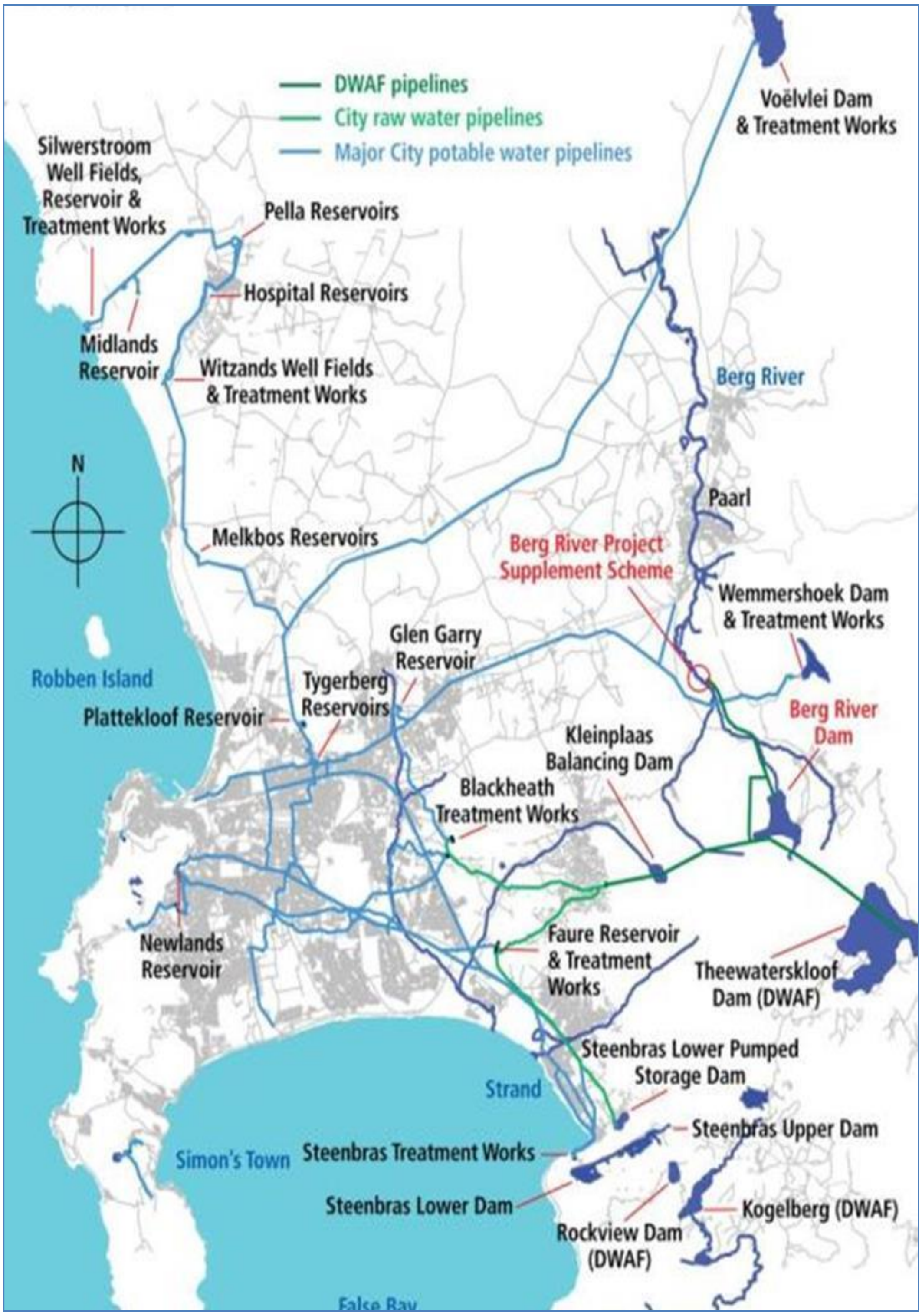


Figure 2-16: City of Cape Town Water sources (CoCT, 2017b)

Water conveyance systems' energy requirements consist of both embedded energy and direct electricity costs. The energy demands are mostly generated by pump stations which raise the hydraulic grade lines along the transmission pipes since these systems must maintain sufficient pressure to increase the velocities in the pipelines. The electricity demands from these pumps are dependent on the elevation between the nodes and physical properties of the pipes which influence the flow of the water (Mays, 2010). The design of the type of conduit used (open channels or pipelines), leakage, seepage and evaporation of water causing losses, are the other drivers of energy demand in conveyance systems (Bennett and Park, 2010).

The design of water pumps in water supply systems is a major determinant of the efficiency of the systems. It is estimated that most pumps are oversized by 20% to 30% of their respective design hydraulic heads to account for eventual wear and tear, excessive vibrations, overheating of engines and leakages in the systems, resulting in inefficiencies in energy management (Vilanova and Balestieri, 2014). There have been numerous studies to assess alternative technologies to improve energy efficiency of hydraulic systems including the use of renewable energy sources, pressure and leakage management, efficient pump sets and variable speed drive (VSD) motor pumps and recovery of hydro-power in pipelines (Vilanova and Balestieri, 2014; Ramos *et al.*, 2010; Brandt *et al*., 2011). Energy savings of up to 80% can be achieved with the use of VSDs while leakage and pressure management can contribute to energy savings varying from 25% to 50% (Vilanova and Balestieri, 2014; Marunga *et al.*, 2006).

The construction and maintenance of conveyance systems require considerable amounts of energy, in the form of direct fossil fuel use and as embodied energy in chemicals and material used during the life span of the system. Conveyance systems mostly comprise pipelines and pump stations made of concrete and steel which are highly energy intensive materials (Mo, 2012). Multiple studies have been carried out on the life cycle analysis of water supply systems, which also estimate their embedded energy. The embodied energy intensities can be derived from the energy intensities of the construction work and production and transportation of construction materials such as cement, sand, stone, steel and pipes (Mo, 2012; Stokes and Horvath, 2011).

2.3.3 Energy in water treatments

Water treatment is another contributor to energy consumption. The energy intensities of water treatment works depend on the water quality of the raw water received and the targeted water quality of the treated water. While most water treatment plants produce potable water, some end-users such as agricultural and industrial sectors do not require water treated to potable quality levels (Bennett and Park, 2010). The intended water quality standards of the treated water guide the treatment plant configurations and the types of water disinfection mechanisms and technologies used.

The energy intensities of removal of contaminants and impurities in different kind of feed water depend on their concentrations. The water quality of different water sources used in water mixes differs due to their salinity which is quantified as their total dissolved solids concentration

(TDS), electrical conductivity (EC) and the turbidity. These can be categorised as follows using their TDS concentration in milligrams per litre (mg/*l*) (Turner *et al.*, 2015):

- Potable water (<500 mg/*l* TDS)
- Surface water (500 –3000 mg/*l* TDS)
- Brackish water (1500 –15000 mg/*l* TDS)
- Seawater (15000-50000 mg/*l* TDS)

Conventional water treatment processes are often used to treat surface water using mechanical and chemical processes. These usually consists of screening, flash mixing, coagulation, sedimentation, filtration and disinfection (van Duuren, 1997). Chemicals such as aluminium sulphates, lime and carbon dioxide are used throughout the process to cause dissolved solids to precipitate and adjust the pH concentrations of the water while chlorine is added for disinfection (van Duuren, 1997).

Despite the fact that only 0.5% of the available water resources are classified as brackish water, it represents a relatively cheap and energy efficient source of water (Voutchkov, 2013). Groundwater is often classified as being brackish due to pollutant infiltrations in aquifers but is widely used for irrigation purposes without treatment (Winter *et al.*, 1998). Further treatment processes are required for brackish feed water due to the presence of increased concentrations of organic and inorganic pollutants to produce potable water (CSIRO, 2007). Treated effluents' TDS levels, produced from wastewater treatment plants, also fall within the brackish water salinity ranges. Advanced treatment in the form of ultra- filtration and desalination methods is often needed to remove the excess nutrients and chemicals from brackish feed water.

Seawater consists of the largest share of feed water for desalination technologies with almost 67% of the total global installed desalination capacity, followed by brackish water with 19%, wastewater with 6% and the rest made up to river water (Ullah *et al.*, 2013). Desalination processes are divided into three main categories (Turner *et al.*, 2015; Voutchkov, 2013):

- Thermal, using multi stage flash (MSF), multiple effect distillation (MED) and vapour compression (VC). Water is separated from impurities by evaporation through distillation processes with heat as input.
- Chemical, using electro-dialysis (ED) through ion exchanges and precipitation. Separation of contaminants and treated water occurs using a direct electric current to the feed water and using cation and anion exchange membranes.
- Physical, using ion exchange processes and membrane technologies. Freshwater is separated from the saline solution using pressure differences created using a membrane and creating a driving force greater than the osmotic pressure of the feed water.

Different desalination mechanisms are adapted for specific ranges of salinity and are given in Table 2-1. The salinity of the feed water determines the appropriate mechanisms for its purification and therefore, the energy required for contaminant removals.

Table 2-1: Desalination mechanisms with applicable TDS ranges (Voutchkov, 2013)

Desalination mechanisms	**Suitable TDS concentration (mg/*l*)**
Ion exchange	1-800
Electro dialysis	200–3000
Reverse osmosis	50-46,000
Distillation	20,000-100,000

The energy intensities of desalination processes are considerably higher than conventional water treatment plants. The largest energy demand within conventional water treatment plants are generally created by rapid mixing systems, internal pumping requirements and backwash systems (EPRI, 2013). Desalination processes are more energy intensive due to the high salinity concentration of the feed water and have high construction and material costs. The energy intensities, however, vary with each mechanism. Reverse osmosis is used in more than 60% of existing desalination plants and is the least energy intensive of the three mechanisms (Ghaffour *et al.*, 2013). ED's electricity consumption is comparable to reverse osmosis mechanisms but only applies for a lower range of salinity. Thermal processes create higher demand for energy than reverse osmosis since the water has to be heated up to a temperature of 100^{o}C and then cooled back over multiple stages (Voutchkov, 2013). Thermal desalination technologies can reach up to 20 kWh/m^3 (Goga *et al.*, 2015). The energy intensities of treated water from the different processes are tabulated in Table 2-2.

Table 2-2: Desalination technologies energy intensities (Voutchkov, 2013; Ghaffour *et al.*, 2015)

Process	**Thermal energy (kWh/m^3)**	**Electrical energy (kWh/m^3)**	**Total energy (kWh/m^3)**
MSF	2.5-12	2.5-4.0	5-16
MED	0.2-7	1.2-2	1.4-9
Seawater reverse osmosis (SWRO)		2.5-4.0	2.5-4.0
Brackish water reverse osmosis (BWRO)		0.3-2.5	0.3-2.5

Reverse osmosis units are usually preceded by pre- treatment processes including microfiltration and ultrafiltration to avoid fouling of the RO membrane by contaminants (Kucera, 2010).The driving force created by the difference in osmotic pressures between the feed water and the concentrate is produced by feed pumps. Centrifugal pumps are commonly used for internal pumping and backwash systems and are sized according to the design flow rate and the operating pressure required (ibid). The latter depends on several factors such as temperature, pressure and most predominantly by the salinity of the feed water and the recovery rate. Operating pressures for brackish water and seawater can reach up to 42 bars and 70 bars respectively (Kucera, 2010; Avlonitis *et al.*, 2003).

Over the years, the desalination costs have decreased because of an expansion of the market due to increased water demands and technological advances, resulting in improved technologies. Energy recovery devices (ERD) are often used to improve the energy efficiency of the mechanisms (Qiu and Davies, 2012).

2.3.4 Wastewater treatment

Water used by domestic, commercial and industrial end users is contaminated throughout its use and must be treated before being released back to the environment. There are three steps for the treatment of wastewater which have varying energy intensities. Primary treatment of wastewater consists of the removal of solids through screening, coagulation and sedimentation processes while secondary and tertiary treatment make use of aeration, clarification and stabilization processes using chemicals, bioreactors and membrane technologies to remove high concentrations of nitrogen and phosphorus (Spellman, 2013).

The energy intensities of secondary and tertiary treatment processes are generally greater than those of the primary treatment stage. Pumping requirements consist of the largest energy demands of primary treatment processes and energy intensities range from 0.01 to 0.37 kWh/k*l* (Plappally and Lienhard, 2012). Secondary treatment processes' energy intensities vary from 0.16 to 0.45 kWh/ k*l* and are mainly made of demands generated from aeration, digestion and pumping requirements for the biological treatment required to breakdown colloidal impurities in the wastewater (Plappally and Lienhard, 2012; Panepinto *et al.*, 2016). Mechanical aerators are the largest energy consumers in conventional wastewater treatment works (Daw and Hallett, 2012). Tertiary treatment processes depend on the final quality of the effluent necessary and remove remaining inorganic compounds left in the water. Microfiltration and reverse osmosis units can also be used to remove remaining contaminants. The energy consumption of third stage varies from 0.4 to 3.74 kWh/ k*l* depending on the volume of treated water and the treated effluents' targeted quality standards (Daw and Hallett, 2012; Plappally and Lienhard, 2012).

The energy efficiency of wastewater treatment works can be improved by adopting energy saving measures. These include better pressure and leakage management, installation of more efficient pumping systems, using variable speed drives, and more efficient aeration technologies and anaerobic digestion optimisation (EPA, 2013). The energy savings vary for each WWTW and ranges from 5% to 90% of savings with the use of energy recovery devices (Panepinto *et al.*, 2016).

2.3.5 Alternative water sources

Globally, fresh water resources around the world have been exploited in several forms and these have been changing according to human water needs. While surface water has been extensively developed, alternative water sources are being investigated and exploited to certain extents. Seawater desalination, rainwater harvesting (RWH), grey water recycling and wastewater reuse systems form part of such alternatives and have varying economic and environmental implications (Gleick, 2000). The energy intensities of water produced from these sources vary according to the design of the systems, the technology used and the water quality required for its targeted end-uses (Lazarova *et al.*, 2012). Desalination mechanisms are highly energy intensive (as explained in the previous sections) but are a viable alternative in water scarce countries. The energy intensities of the other existing alternatives have been tabulated below.

Table 2-3: Typical energy intensities of alternative water systems (Lazarova *et al.*, 2012)

Processes	**Typical energy intensities (kWh/m^3)**
Rainwater harvesting systems	0.32- 1.2
Greywater reuse	0.2- 2.5
Membrane bioreactors (MBR)	0.5- 2.5

2.3.6 Embodied energy

The energy intensities of the treatment stage of water supply systems also have to take into account the embodied energy during the construction, operation and maintenance phases (Mo, 2012). The construction of treatment plants is highly energy intensive since large treatment plants are built from concrete and steel for durability (Ibid). The embodied energy of machineries and parts such as RO membranes used and replaced throughout the design life service also must be quantified. Chemical usages such as chlorine, lime and carbon dioxide also must be accounted for.

Embodied energy can be quantified using estimations from actual material usage data but these do not take into account indirect energy intensities of products (Lundie and Peters, 2004; Mo, 2012). Another approach is to use a hybrid model using an economic input output model with process based LCA since the latter alone limits the scope of the assessment (Stokes and Horvath, 2011).

2.3.7 The energy intensity of the South African water industry

Water mixes in South Africa have been diversified due to increasing demands for potable quality water. Most of the treated effluent from wastewater treatment plants is released back into water bodies with the exception of cases such as Beaufort West where the treated water is sent directly to water treatment works for direct potable uses (Goga *et al.*, 2015). Desalination of both brackish and seawater have also been added to the mix. Most of the desalination plants are found in the Western Cape. Feasibility studies are being undertaken for the construction of a 450 M*l*/day desalination plant in the eThekwini area.

The electricity intensities of national water treatment plants are mainly attributed to pumping requirements for raw water pumps, booster pumps and backwash pumps. They vary from 0.057 kWh/ k*l* for the Wiggins Water Treatment Works to 1.154 kWh/k*l* for Sedibeng Water (Winter, 2011). The differences are mainly due to the type of feed used into the treatment work due to the location of the water sources. Sedibeng Water has pumped feeds where water is conveyed to significant height elevations while the others make use of gravitational feeds (Ibid).

Desalination plants have significantly higher energy usage than conventional water treatment plants. While all the desalination plants in South Africa make use of reverse osmosis mechanisms, their electricity consumptions vary from 2.4 kWh/m^3 to 4.2 kWh/m^3 (Plessis, Swartz and Musee, 2005). These depend on the blending ratios of seawater and brackish water used as feed to the plants. Energy recovery devices (ERD) installed in existing desalination plants have shown that energy savings of up to 50% can be achieved by using pressure exchangers and hydraulic turbines to increase the energy efficiency of the systems (Ibid).

There are also over 950 wastewater treatment works across the country treating almost 7600 M*l* per day providing preliminary, primary, secondary and tertiary treatments. The energy consumptions of the plants vary from 0.22 kWh/k*l* to up to 1.45 kWh/k*l* depending on the source and structure of the WWTWs (Winter, 2011). The energy requirements of the plants depend on the process units used in each WWTW and are again largely influenced by pumps, aeration and sludge management. The consumptions ranges from 0.15 kWh/k*l* to 0.59 kWh/k*l*, which again varies with the capacity of the WWTWs (Scheepers and Merwe-botha, 2011). However, it is estimated that up to 10 GWh per year can be recovered from wastewater using technologies such as anaerobic digestion for the production of biofuels (Burton *et al.*, 2009).

2.4 GHG emissions

There have been significant increases in the use of natural resources over the past few decades to meet the demand generated by growing populations, increased service delivery levels and improvement of lifestyles (DEA, 2012). The growing exploitation of resources, specifically fossil fuel resources, has in turn resulted in rising global greenhouse gas emissions. The share of the energy sector in the total GHG emissions has been increasing more steadily than the other sectors and currently represents almost 72% of the shares as shown in Figure 2-17 (WRI, 2017).

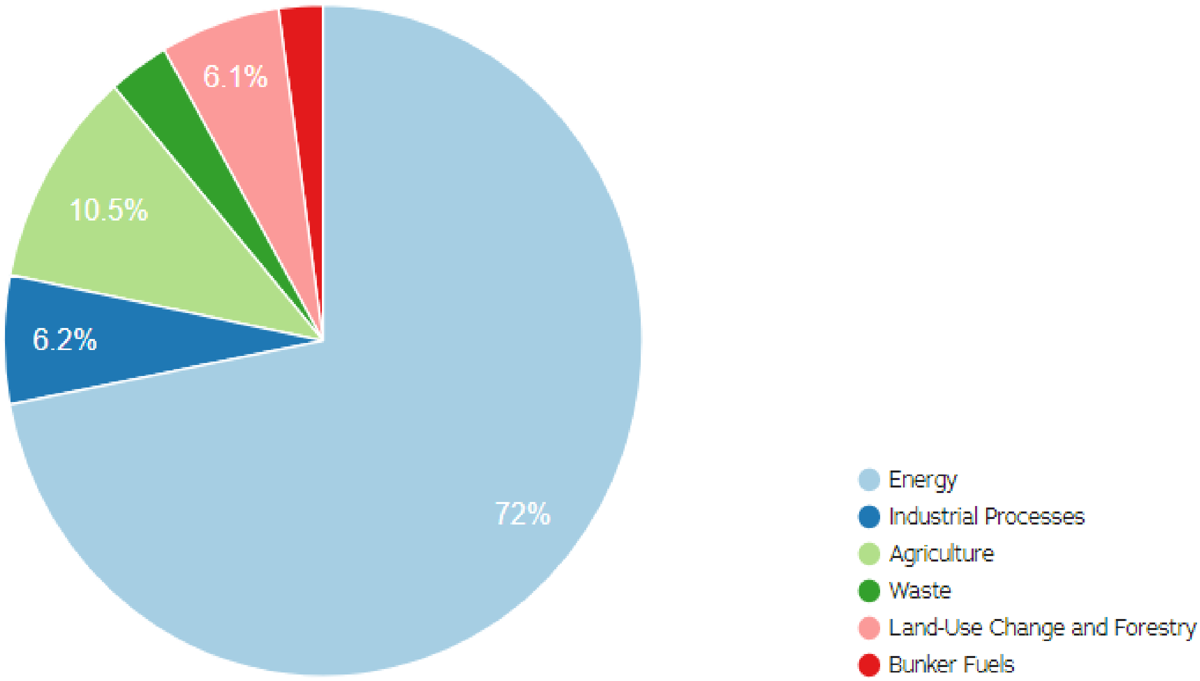


Figure 2-17:2013 GHG emissions sector share (WRI, 2017)

The energy consumption of the water sector causes the sector to indirectly contribute to an extent to the global GHG emissions. For instance, water related energy consumptions contribute 5% to the US emissions due to its electricity mix (Rothausen and Conway, 2011). The energy intensity consists of both direct energy and embodied energy, that is, direct electricity, material and chemical usages during the construction and operational phases of the system (Karney *et al.*, 2014). Direct energy in the form of electricity and fuel usage is used throughout the construction and operational phases of the water supply system. The carbon footprint of the latter can be obtained by using the energy sources and technologies used in the electricity mix of a country (Karney *et al.*, 2014). As shown in Figure 2-18, the global electricity mix is still largely dominated by coal power plants which are the most polluting form of energy source currently used (EIA, 2016; EPRI, 2015).

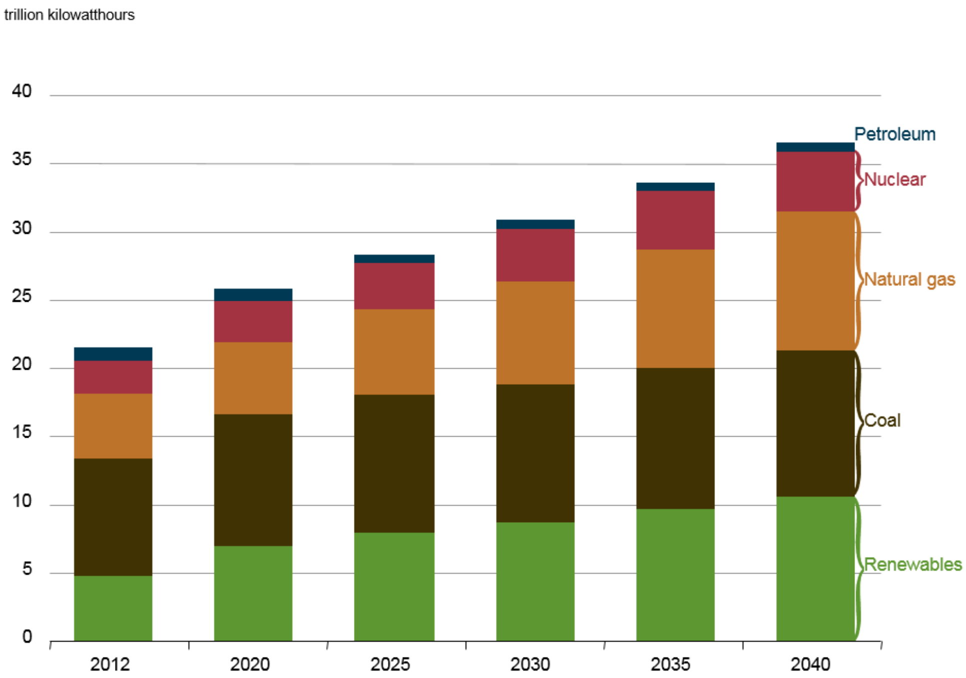


Figure 2-18: Global electricity mix (EIA, 2016)

The South African electricity sector's fossil fuel dependence is even larger than the world's average since coal plants consist of almost 85% of the installed capacity and emits 225 Mt of CO_2 eq. per year (40% of total national GHG emissions) (Eberhard, 2011). The energy sector contributes nearly 495 Mt of CO_2 eq. per year which represents 88% of total national emissions per year (Ibid). Figure 2-12 gives the share of energy consumption for each sector in South Africa and Figure 2-19 shows the share of emissions associated with the energy sector as compared to others in 2010.

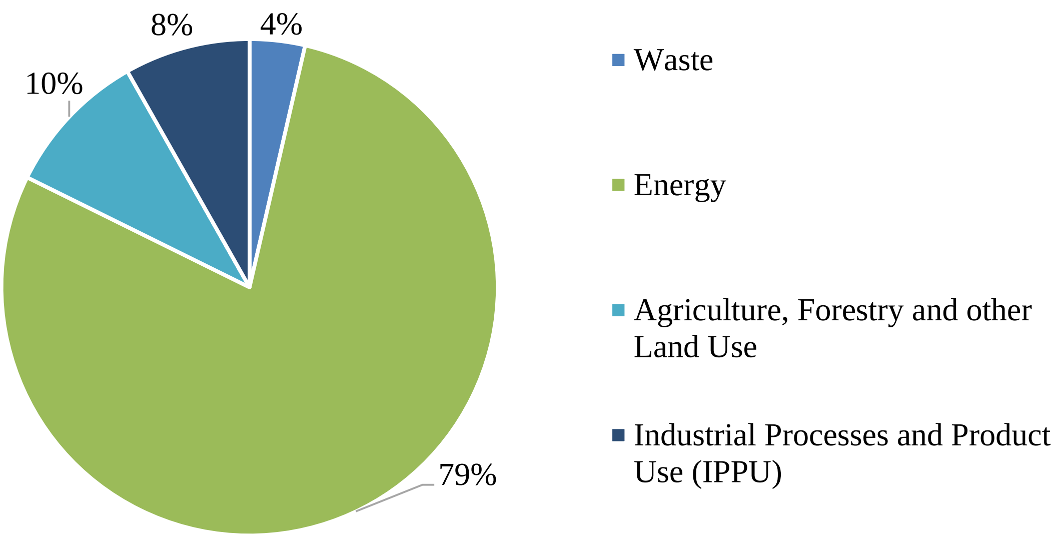


Figure 2-19: SA's emissions shares per sector (DEA, 2013)

The transport sector uses the most energy in the form of liquid fuels while the majority of the rest of the sectors uses electricity as the main energy source (SACN, 2014). The water supply and wastewater treatment sector uses 17% of the total energy demand. Energy saving potentials of up to 41% have been estimated as being possible in the water supply and wastewater treatment sector by retrofitting the system with energy efficient devices such as VSDs (Ibid). The resulting decreases in carbon emissions from the sector could be amount as much as 29%, that is, 0.136 Mt CO_2 eq. pa (SACN, 2014).

Life cycle assessment (LCA) studies of the water industry have been carried out in several countries. Most of them quantify the energy intensity of the supply system along with the carbon footprint of the systems. The type of treatment chain adopted in each treatment plant differs along with the quantity of chemicals and materials used. Bonton *et al.* (2011) compared the LCA of a conventional water treatment plant with a nano-filtration system in Canada. The system's global warming potentials (GWP) change with the electricity sources and the nano-filtration system's GWP was found to be higher than the conventional water treatment plant. The environmental impacts of chemicals usages in conventional water treatment plants, however, were found to be greater due to higher concentrations used throughout the treatment.

Stokes & Horvath (2009) obtained similar results as Bonton *et al*. (2011) and have highlighted that GHG emissions varied with the share of fossil fuels in electricity mixes and proposed a higher use of renewable energy as alternative energy supplies to water technologies. Their study also showed that energy production during the operational phases was the most significant contributing factor to GWP while material production and delivery represented a smaller percentage. The GWP of material production and delivery contributed more to the total GWP of the treatment plants considered in Bonton *et al.* (2011). These discrepancies can be explained due to the higher share of hydropower in the electricity mix of Canada when compared to that of California.

Friedrich *et al.* (2007) provide estimated values for the GHG intensities of the different stages of the South African water supply industry by conducting LCAs of the water industry. Electricity was found to be the largest contributor to environmental impacts of the industry and the operation stage of production of water was the largest contributor to GWP (Pillay *et al*., 2001). However, the production of chemicals used in the water systems were not accounted for due to limited data availability (Friedrich and Buckley, 2007). Treatment of wastewater was found to have the largest GWP since it is the most energy intensive stage of the water cycle. Measures such as leakage management and the use of recycled water as input to water treatment plants to decrease the environmental footprint of the treated water were also investigated. Reductions of up to 20% of GHG emissions can be achieved by reducing losses in distribution systems while adopting alternative water sources could potentially decrease the carbon footprint of the system by up to 79% (Friedrich and Pillay, 2009).

2.5 Existing Models

Studies of the energy consumption and carbon foot-printing of water supply systems have generally been carried out using two approaches, namely the process based life cycle assessment (LCA) and a top to bottom approach, using energy consumption per sector and the economic input output models of individual countries. LCAs have been used to put together an inventory of all the material and chemicals used for the construction, operation and decommissioning phases of water supply systems by adopting a cradle to grave method. LCA is a widely used and consistent method to identify and estimate the energy and environmental implications of water systems (Karney *et al.*, 2014).

Most estimations of the energy intensities of water supply systems in South Africa have been done using LCA approaches using GaBi. GaBi provides LCA modelling using an extensive database of materials, chemicals and processes from different sectors. Its outputs consider the primary energy used and carbon and water footprints of materials used throughout. However, indirect energy implications in the computation of energy and carbon intensities cannot always be accounted for in LCAs. Hybrid economic input output models using process based LCAs and energy and emissions intensities across sectors have been developed to provide a more holistic approach. The Water Energy Sustainability Tool (WEST) combines elements from both the economic input output matrix of the US and a process based LCA to account for linkages between sectors to follow products supply chains and their respective energy and carbon intensities (Stokes and Horvath, 2011).

2.6 Summary of literature review

The literature review has demonstrated that a greater understanding of the linkages between water and energy in the water energy nexus is considered as being key for holistic and sustainable planning. Historically, these have been carried out in parallel with little consideration given to their influence on one another despite their heavy interdependence. The importance of these relationships is further emphasized due to the escalating impacts of climate change.

South Africa, in particular, has been facing an energy crisis for the past decade and more recently, extensive drought periods. As it has committed itself to the Paris Agreement to curb its GHG emissions, the country’s future electricity build plans are being shaped accordingly with smaller shares of fossil fuels as energy sources and increasing shares of renewable and nuclear energy technologies. Its water sector is also adopting non-conventional water sources and treatment processes to supplement its dwindling existing supplies to cater for current and future demands. The energy footprint of water supply systems depends on the type of feed water used, quantity of chemicals, the distance between the source, plants and end-users and the type of mechanisms used for treatment and wastewater treatment. Non-conventional technologies such as desalination, using thermal, ED or RO mechanisms, create significantly higher energy demands than conventional water treatment methods. The water sector’s resulting share of GHG emissions therefore strongly depends on the energy sources used for electricity production of the country.

3. The Zeekoe Catchment

The Chapter describes location and characteristics of the study area which guided the determination of the approaches to be used for further investigations. The Zeekoe catchment is located in the Cape Flats area in the south east of Cape Town, Western Cape- east of the Southern Suburbs (Figure 3-1).

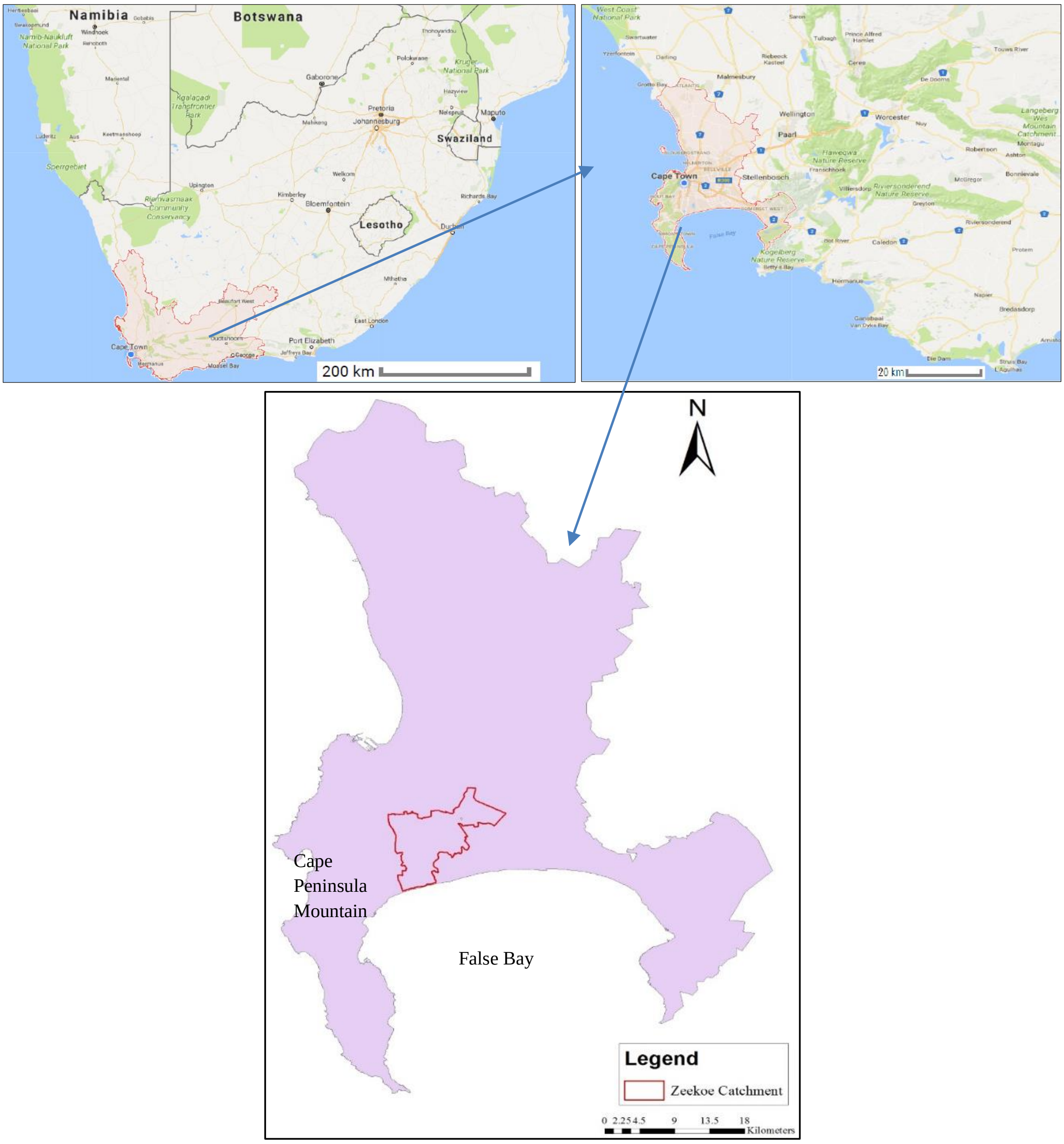


Figure 3-1: CoCT boundary and Zeekoe catchment location (CoCT, 2013; Google Maps, 2017)

The Zeekoe catchment is an extensive, relatively flat and low lying area bordered by the Cape Peninsula mountain range and False Bay. The Zeekoe catchment's land uses are outlined in Figure 3-2. It is densely populated with both formal residential areas and informal townships, but also industrial zones and important agricultural expanses such as the Philippi Horticultural Area. The catchment also features the Cape Flats Waste Water Treatment Works (WWTW) and the Athlone WWTW with a combined capacity of 305 M*l*/day.

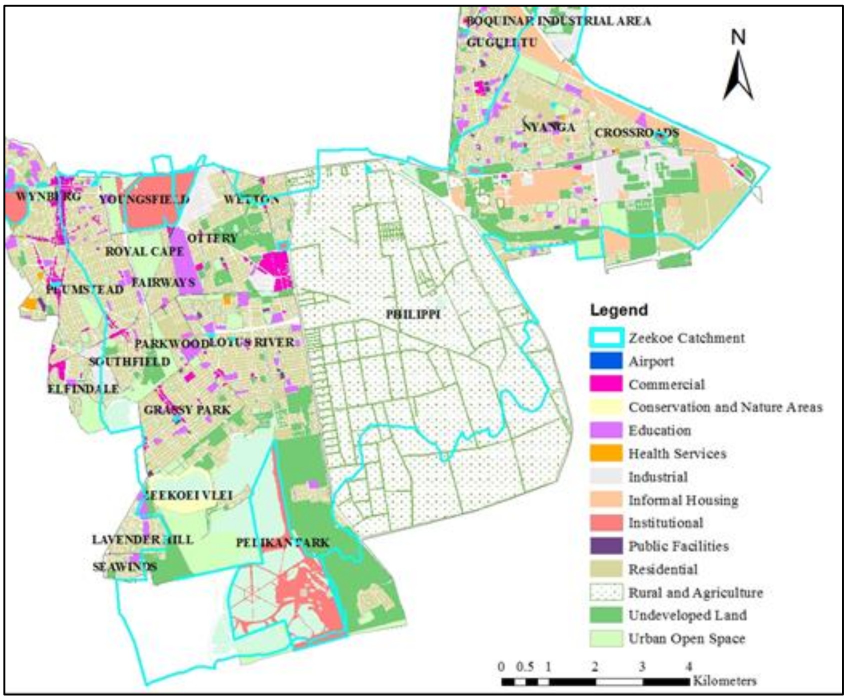


Figure 3-2: Zeekoe Catchment, suburbs and land use type (CoCT, 2013)

Several stormwater ponds have been constructed in the area to temporarily store flood water whilst an extensive water canal system has been developed to convey stormwater across the catchment to False Bay. The area also has high groundwater productivity as it lies above part of the Cape Flat Aquifer (CFA), which has an expanse of over 400 km^2 (Hay *et al.*, 2016). With the recent water restrictions enforced in the City, various alternative water resources are being investigated for potential use. The CFA represents a significant resource of approximately 20 Mm^3 per annum which could be further augmented through artificial infiltration with stormwater or treated wastewater (Winter, 2017).

3.1 Strategies

The feasibility and sustainability of groundwater abstraction from the CFA, yielding up to 85 M*l*/day with stormwater infiltration, is being studied through three different approaches in a parallel study (Okedi, 2017). The options considered are based on several factors including the water demand profiles in the area and the water quality of the resource. Abstraction points, to pump groundwater out of the CFA, are envisaged being placed around the existing stormwater ponds in the catchment. The stormwater ponds then could be used for artificial recharge points for the CFA using stormwater (Okedi, 2017). The first two approaches, the decentralised and centralised approaches, are considered to compare the viability of introducing small decentralised water treatment works and dual reticulation networks as opposed to conventional water treatment and distribution systems. Brackish water desalination was chosen as the third alternative to match the plans for future water mixes proposed by the City of Cape Town. Figure 3-3 provides an outline of the three approaches considered.

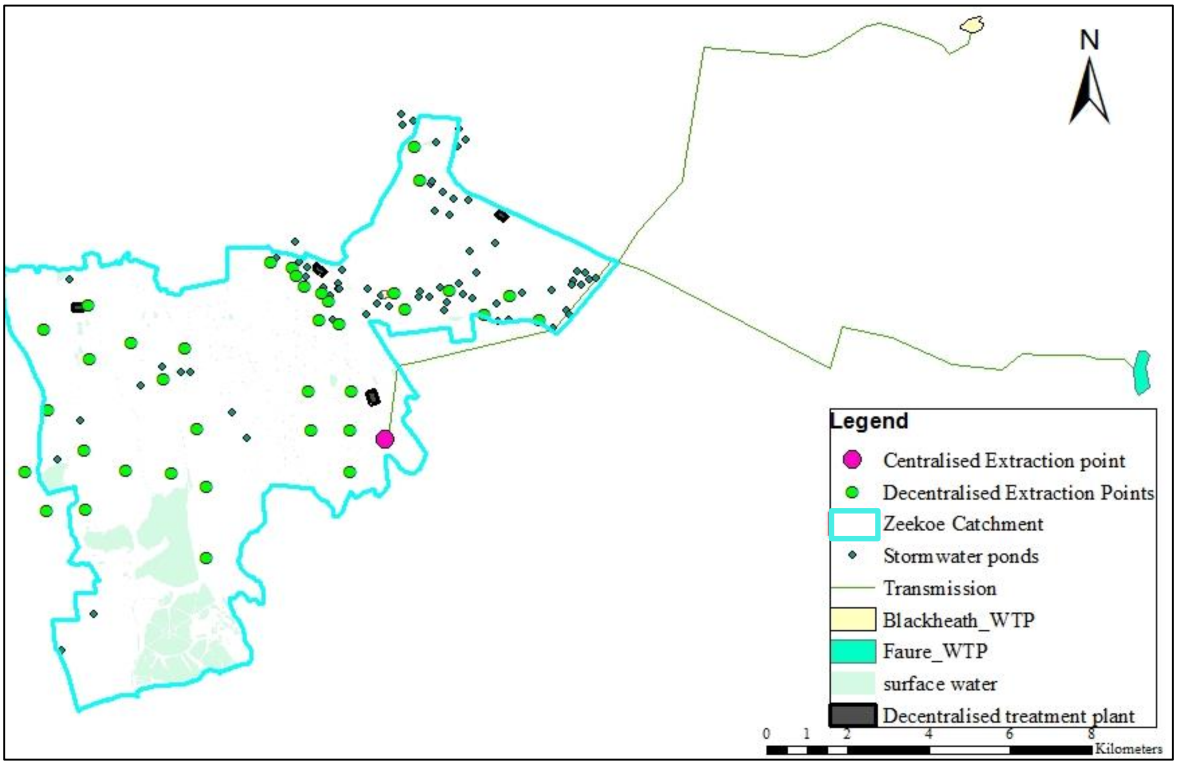


Figure 3-3: Map of the alternatives

3.1.1 The Decentralised Approach

A decentralised approach, involving minimum treatment of the groundwater, is considered to provide for non-potable end users. There have been increasing concerns of aquifer contamination through pollutants seepage from industrial zones, agricultural lands and also from the WWTWs found in the catchment (Adelana and Xu, 2006). The treated water would be used for non-potable uses, such as irrigation, gardening and non-potable domestic uses, and delivered through a dual reticulation system. Groundwater is already being abstracted, on small scale, in the Philippi horticultural area.

The study area was further divided into four extents according to the average aquifer depths in each extent, given that the aquifer thickness ranges from 20 to 55 m across the area (Adelana *et al.*, 2010). The preliminary results of groundwater abstraction modelling propose 170 boreholes spread notionally across the catchment. However, at the time of the study only 30 potential boreholes had been proposed as shown in Figure 3-4 (Okedi, 2017). The locations of the decentralized water treatment works were chosen to be at the highest elevation in each catchment to allow gravity flow in the dual reticulation systems to supply non-potable water to end-users.

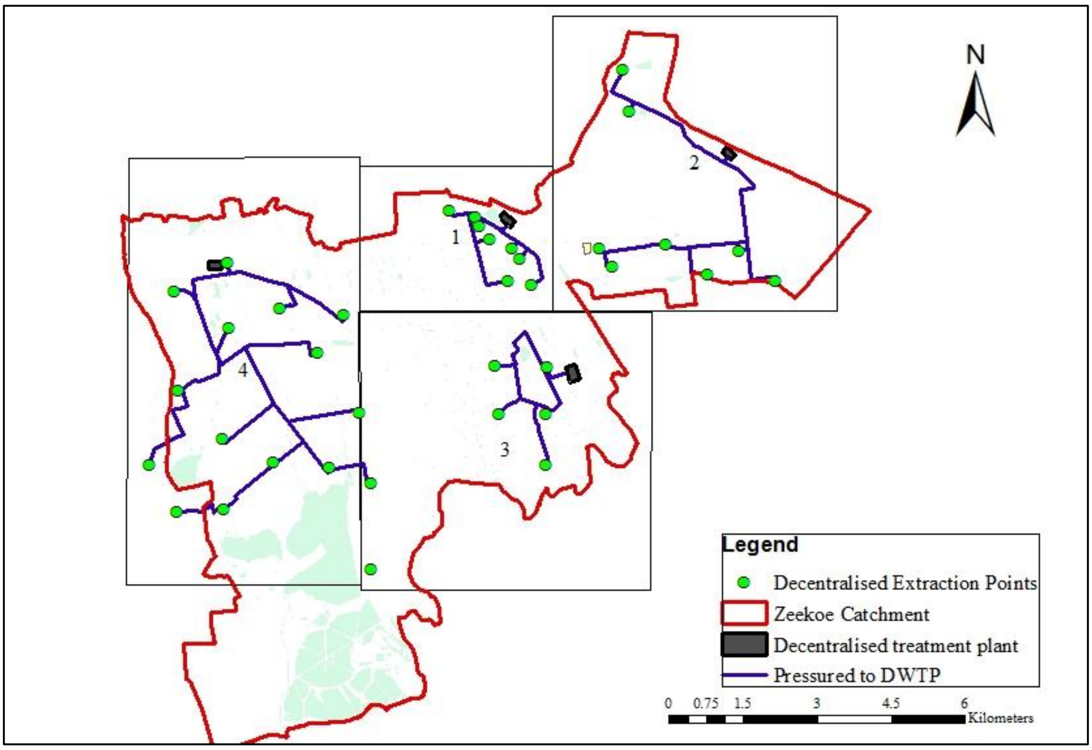


Figure 3-4: Aquifer Extents

3.1.2 The Centralised Approach

The second approach envisages water abstraction through eight boreholes situated in the Philippi area. The groundwater would then be sent for treatment to potable water quality at the Faure and Blackheath Water Treatment Plants. The treated water would then be distributed across the city through the existing reticulation system. The extraction points for the Centralised option is located in Philippi where the aquifer is estimated to be at its thickest as shown in Figure 3-5 (Hay *et al.*, 2016; Mauck, 2015).

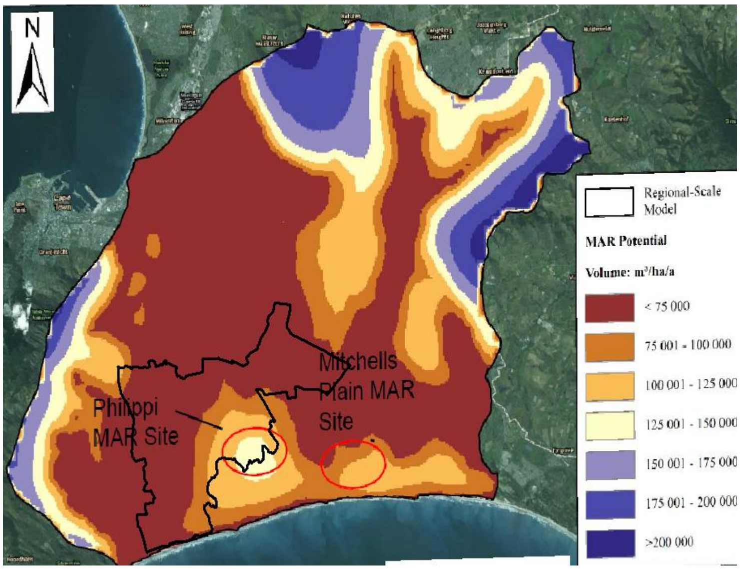


Figure 3-5: Aquifer Depth across the CFA (Mauck, 2015)

The groundwater would be pumped to the Blackheath and Faure Water Treatment Plants (WTP) through pressured transmission lines and three different possible routes were explored considering account various topographical and working pressure constraints.

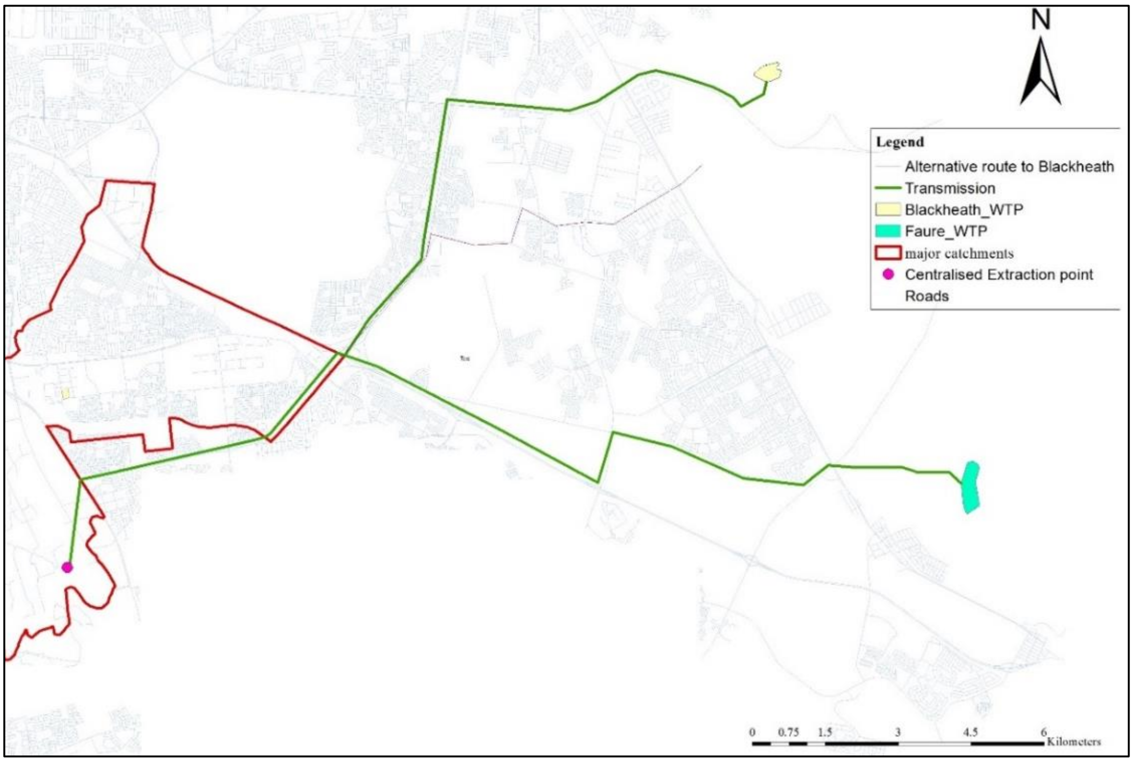


Figure 3-6: Centralised boreholes and transmission lines

3.1.3 The Desalination Approach

Most desalination plants in South Africa are equipped with reverse osmosis (RO) technology, using brackish water as feed water while a smaller proportion use seawater. Local brackish water desalination plants mostly use industrial and wastewater effluent diluted with borehole water as inputs and employ direct potable reuse mechanisms (Turner *et al.*, 2015).The treated water is then mixed and distributed with other treated supplies. Blending decreases the TDS of the feed water that in turn reduces the cost of production of water. The City of Cape Town has initiated upgrades on existing WWTWs to treat effluent while assessing the viability of large seawater desalination plants to increase its potable water supplies (Turner *et al.*, 2015).

Upgrades of Potsdam and Zandvliet WWTWs to 30 M*l*/day and 18 M*l*/day respectively are under consideration to introduce high quality effluent re-use using Membrane Bio Reactors (MBR) (Turner *et al.*, 2015). Further studies are being conducted to evaluate the feasibility of a seawater RO plant with a capacity of up to 150 M*l*/day along the western coast of Cape Town (Turner *et al.*, 2015). Considering the City's plans for a larger share for desalination in future water mixes (CoCT, 2017b), brackish water desalination was therefore chosen as the third possible alternative. The desalination plant site was selected to be in Pelican Park next to the existing Cape Flats Wastewater Treatment Work. The latter has a design capacity of 200 M*l*/day and has been previously assessed as a source for a possible Zandvliet reclamation works which would in turn feed Blackheath and Faure WTPs (DWA, 2007).

Literature has shown that existing brackish water desalination plants in South Africa have yielded purity levels satisfying potable water use guidelines (Turner *et al.*, 2015). There are, however, still several barriers preventing direct potable use of reclaimed water revolving around misinformation and social perceptions despite the success of the Atlantis Water Management Scheme and that of Beaufort West (Ormerod, 2016). The third alternative investigates the energy implications of treating groundwater abstracted from the CFA for direct use through RO membranes. The parameters of the Desalination Approach will be restricted to the design for groundwater abstraction and conveyance from the CFA and preliminary design of the treatment units.

3.2 Overview of the chosen approaches

This chapter has presented background information on the Zeekoe Catchment and the criteria by which the three Approaches were chosen. An abstraction rate of 85 M*l*/day will be used as the yield of the CFA augmented through artificial recharge using stormwater. The key points of each alternative are summarised below:

- The Centralised approach consists of abstraction of groundwater from the deepest section of the CFA and the water will be conveyed through two main transmission lines to Blackheath and Faure WTPs for treatment to potable water quality levels. The treated water will be distributed using the existing reticulation systems

- The Decentralised approach was chosen due to the significant demand for non-potable water uses in the catchment. Four theoretical decentralised WTPs would provide minimum treatment to remove fouling contaminants and sterilise the water. The treated water will be pumped through dual reticulation networks to the suburbs.
- The Desalination approach will use a desalination plant placed near the Cape Flats WWTW to treat the groundwater to potable water quality levels through reverse osmosis technologies.

The Approaches are used for further analysis to determine their major energy components and their intensities.

4. Data Collection

This Chapter describes the data collection processes, necessary for this study. There were seven main categories of data required to evaluate the energy demands of the three systems; topographical data, hydrogeological data, water quality data, water tariffs, electricity tariffs, electricity usage, and material and chemical usage records.

4.1 Topographical data

Pump stations generate almost 70% of the energy consumption of the City of Town's fresh water supply system due to elevation differences, leakages and friction losses in the networks (SEA, 2014). Topographical data is key to calculating the hydraulic heads required to pump extracted groundwater across transmission lines and dual reticulation system for all three approaches (Plappally and Lienhard, 2012). Elevation across the study area was extracted using a 10-m resolution digital elevation model (DEM) file obtained from the University of Cape Town Geographical Information System (UCT GIS) lab. The 10-m resolution was considered as being adequate since the new transmission lines were designed to follow existing road networks.

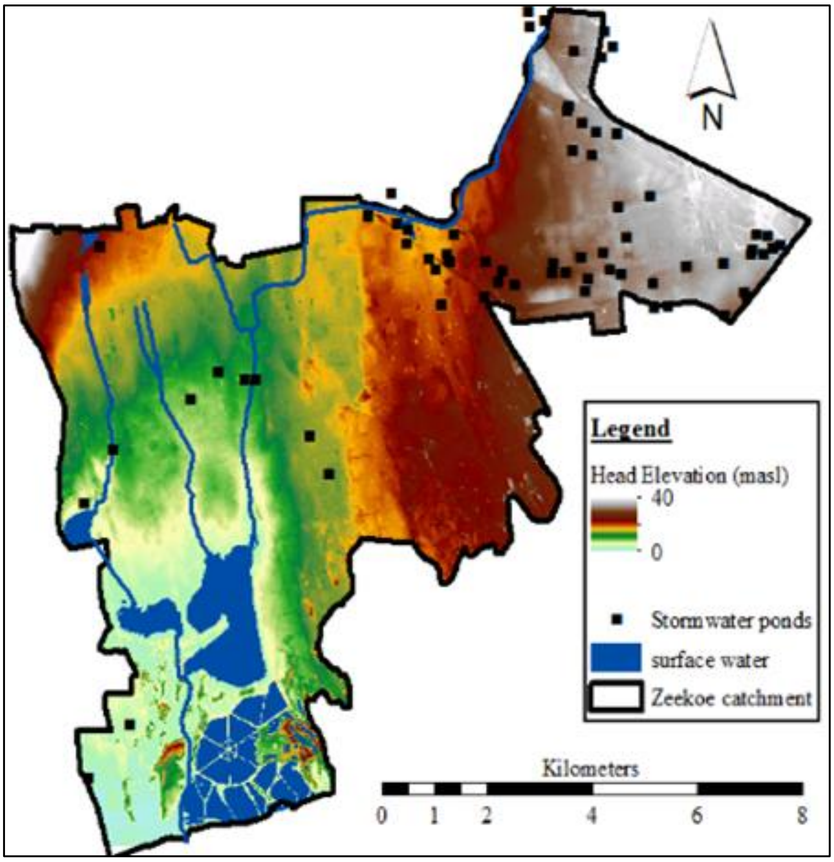


Figure 4-1: Elevation across CFA (Okedi, 2017)

4.2 Hydrogeological data

Groundwater infiltrations varies accordingly with the geology in each region along with possible water abstraction yields and methods. Sub-Saharan Africa (SSA) is divided into four main hydrogeological zones; Precambrian basement rocks, consolidated (post Precambrian) rocks, volcanic rocks and unconsolidated sediments (mainly Quaternary) (MacDonald *et al.*, 2002). Basement rocks consist of roughly 40% of the SSA's surface area and is followed by consolidated sedimentary, unconsolidated sediments and volcanic land types.

The Cape Flats Aquifer is regionally unconfined and is not linked to any other surrounding aquifers. It consists of sediments of the Sandveld Group such as sand, clay and peat of up to a thickness of 50 m, settled on top of an impervious layer of Malmesbury Shale (Adelana and Xu, 2006). While the rest of South Africa consists primarily of consolidated rocks, Cape Town's geology is based on Precambrian and Quaternary rocks as shown in Figure 4-2.

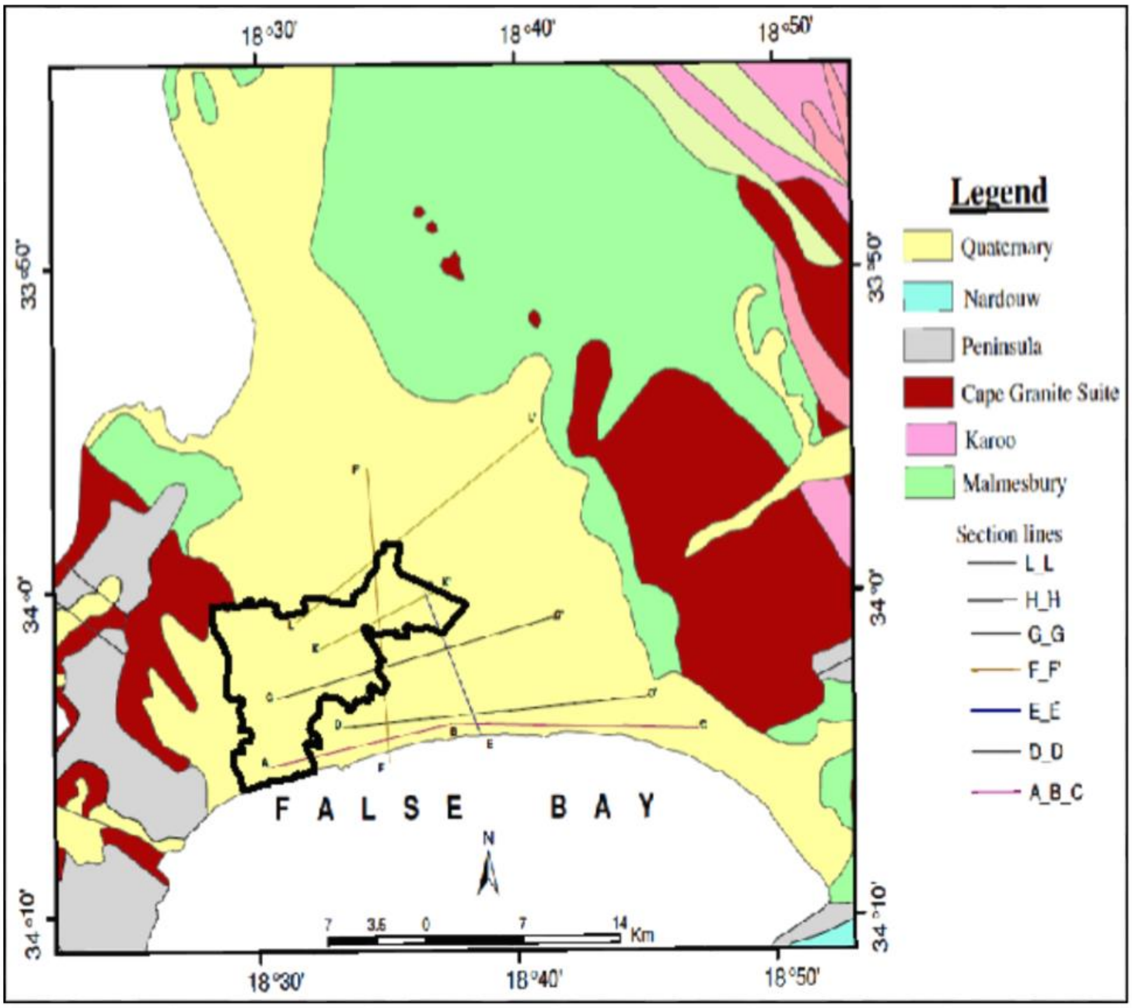


Figure 4-2: Cape Town geological formation (Adelana and Xu, 2006)

The Cape Flats Aquifer is found on a sandy unit of the Cenozoic Age deposited on impermeable Malmesbury shale and Cape granites (Adelana and Xu, 2006; MacDonald *et al.*, 2002). MacDonald *et al.* (2002) further describes yields from the unconsolidated sediments group as being moderate to high, with the possibility of using wells and shallow boreholes for high groundwater levels.

The annual precipitation of the Cape Flats area fluctuates between 400 and 800 mm and the aquifer is naturally recharged mainly at its western boundaries during winter months (Adelana *et al*., 2010; Seyler and Bollaert, 2016). Groundwater levels were extrapolated from the available data obtained from the Department of Water Affairs' National Groundwater Archives and from previous studies on the CFA and were found to vary from 2 to 7 m below the surface (Adelana *et al*., 2010; Jones *et al.*, 2014).

4.3 Water quality

Groundwater quality in the CFA had previously met the guidelines for potable water levels but has been deteriorating over the past years with the level of development in the area and the changing land-uses (Seyler and Bollaert, 2016). Pollutants originating from the residential, horticultural and industrial areas in the catchment are infiltrating the groundwater. Several sources of pollution have been identified, the largest being wastewater and solid waste (inadequate sanitation) mainly coming from the settlements in the catchment and the gravity sewer blockages (Adelana and Xu, 2006; Obree, 2004).

Groundwater analyses in the aquifer have shown higher fluctuating levels of chemicals including nitrates, lead, chlorides and phosphates from the use of pesticides in the agricultural area (Adelana, Xu and Vrbka, 2010). More recent analysis of stormwater collected around the catchment has shown low concentrations of arsenic and mercury but with higher total coliform counts and conductivity. The reports did not mention total dissolved solids (TDS) levels and turbidity, however- high TDS concentrations were noted in groundwater samples taken from the northern part of the Philippi horticultural area with concentrations reaching up to 4170 mg/*l* in studies done in and around the catchment (Adelana and Xu, 2006). Further studies conducted on the salinity of the ponds and borehole water in the Philippi area have also indicated relatively high concentrations of contaminants, increasing mostly during winter months (Aza-gnandji *et al.*, 2013).

Table 4-1 summarises the Cape Flats Aquifer's water quality tests done over the past few years and most of the components in the water exceeded the respective targets for irrigation and potable uses. For this study, remediation at the identified pollution points was considered to prevent further ingress of heavy metals and other contaminants in the stormwater and the aquifer before abstraction. Tredoux (1984), Adelana & Xu (2006) and Stewart (2009) have conducted studies on the vulnerability of the CFA due to the impacts of a range of pollutants and proposed remediation solutions. The pumped groundwater is assumed to have a lower concentration of heavy metals (after infiltrating the CFA) and would be treated up to the purity level required for each approach corresponding to the intended end-uses.

Table 4-1: CFA groundwater quality (Adelana and Xu, 2006; Aza-gnandji *et al.*, 2013)

Parameters	min	max	Target range for irrigation	Target range for potable uses
pH	6.6	7.7	6.5-8.4	6-9
EC (mS/m)	85	284	0-40	0-70
TDS (mg/*l*)	552.5	4170	-	0-450
Ca^{2+} (mg/*l*)	4.2	19.5	0-20	0-32
Na^{+} (mg/*l*)	38.8	279.4	0-70	0-100
Cl^{-} (mg/*l*)	96.9	643.3	0-100	0-100
K^{+} (mg/*l*)	3.8	68.4	0-2	0-50
$SO4^{2-}$ (mg/*l*)	1.3	14.9	0-20	0-200
NO^{3-} (mg/*l*)	0	10	0-5	0-6
Mn^{2+} (mg/*l*)	0	0.09	0-0.02	0-0.02
Fe^{2+} (mg/*l*)	0.01	6.99	0-5	0-0.1

4.4 Water tariffs

Retail water tariffs in South Africa are set by water services authorities (WSA), largely represented by municipalities while water resource development and bulk water and wastewater tariffs are jointly planned by the Department of Water Affairs (DWA) and WSA (Eberhard, 2003). Pricing of retail water is based on several factors including social equity- providing access to free basic water services through subsidies for the first 6 k*l* - ecological and financial sustainability and economic efficiency (ibid). However, there are no guidelines for price setting for retail water and sanitation prices and normally WSAs (including the City of Cape Town) adopt a cost plus formula and these are applied in increasing blocks. Price increases are normally adjusted from time to time to follow inflation rates while the actual cost of producing water could be increasing at a higher rate than inflation rates.

Tariffs have been increasing at a much higher rate during the past year due to the current drought condition as a form of water demand management measure. Figure 4-3 shows the recent water prices and as the City faces a Level 5 restriction, the -Domestic (full) category have started paying for water as from Step 1 which represents the lifeline block. Increasing block tariffs imposes higher pricing with higher levels of water consumption which are represented by Step 2 to Step 6 where electricity tariffs per k*l* increase with higher usage per month reaching 302 R/k*l*.

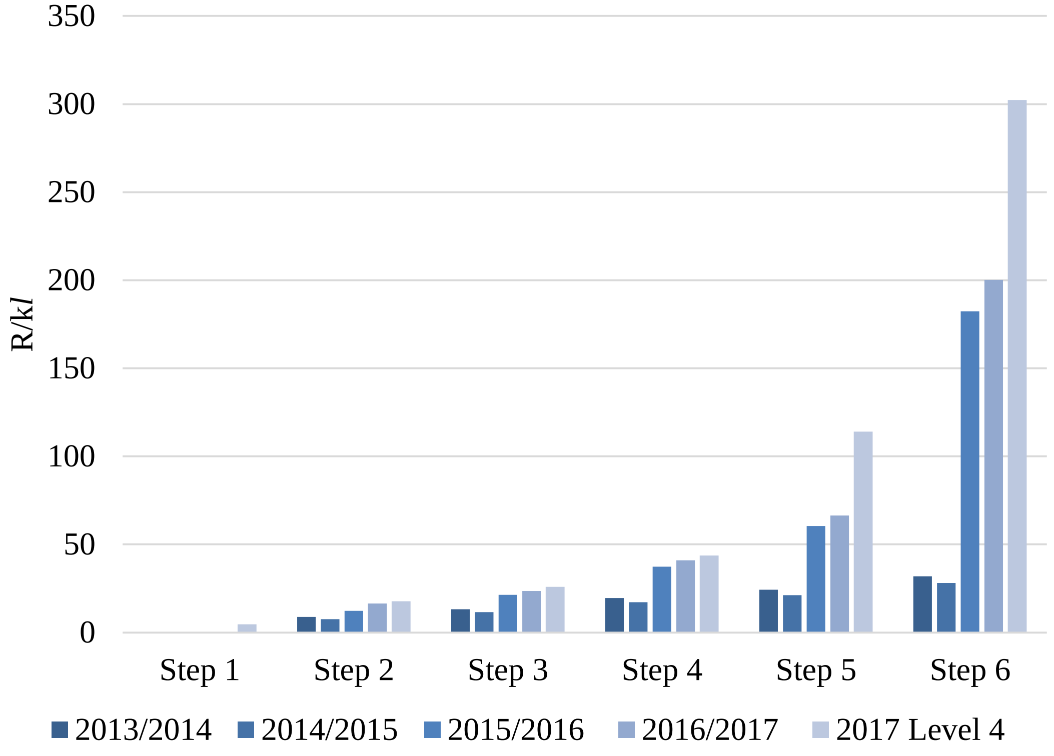


Figure 4-3: Water tariffs 2013-2017 (incl VAT)

4.5 Electricity tariffs

Historically, South African electricity prices have been one of the lowest globally due to an originally abundant generation capacity. However, electricity prices have been increasing significantly over the last decade and have now more than quadrupled since 2007 (Eskom, 2017b). Electricity prices for sectors such as residential, agricultural, local authorities, mining and commercial differ from one another. There are also different tariffs set for the time of use of electricity as shown in Figure 4-4 where electricity prices are lower when used during off peak periods of time.

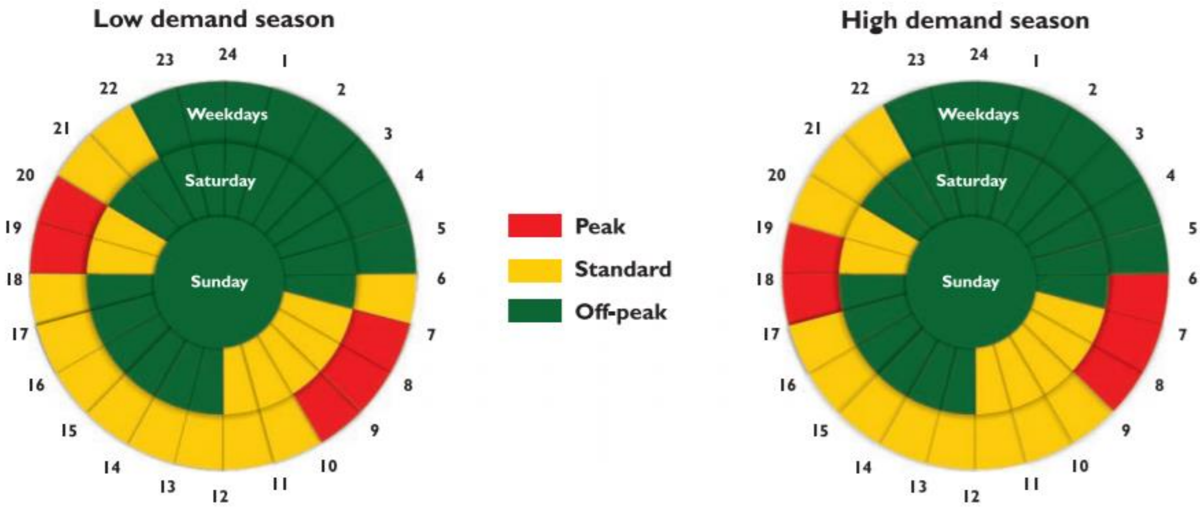


Figure 4-4: Electricity Time of Use (Eskom, 2017b)

The categories within which each electrical component of the approaches fall, depend on the total installed capacity of each component. Blackheath and Faure WTPs have an overall installed capacity of 400 kVa and 200 kVa respectively and can be categorised in the Small Power Users 1 group. The other categories and their respective installed capacity and tariffs for 2017 are tabulated below in Table 4-2.

Table 4-2: Electricity Tariffs 2017 (CoCT, 2017a)

Large Power User	**Time of use**	**Units**	**Low voltage (500-1000 kVA)**	**Medium voltage (>1MVA)**
Service		R/day	98.84	96.9
Energy	High Peak	c/kWh	391.53	381.03
	High Standard	c/kWh	138.03	134.55
	High- off peak	c/kWh	87.69	85.63
	Low- Peak	c/kWh	146.49	142.79
	Low- Standard	c/kWh	109.51	106.84
	Low- Off Peak	c/kWh	79.66	77.81
Demand		R/kVA	207.8	98.94
Small Power User (<500 kVA)		**Units**	**Small Power User 1 (>1000 kWh/ month)**	**Small Power User 2 (<1000 kWh/ month)**
Service		R/day	52.01	4.1
Energy		c/kWh	148.27	260.8

4.6 Electricity Usage

The information on the total installed demand for the City of Cape Town's water supply system was provided by Sustainable Energy Africa and the City of Cape Town. In 2014, 187 GWh of energy was used by the City's water services. As shown in Figure 4-5, CoCT's WWTWs' installed electrical capacity consisted of 66% of the total capacity of CoCT's water services, followed by pump stations with 23.8% and the rest was made up of bulk water services. The bulk water services category is further broken down into water treatment plants, dams and administration building demands subcategories (SEA, 2014).

The water treatment plants are currently being used at 45% usage capacity and consist of nearly 30% of the installed electrical capacity of the bulk water services (CoCT, 2017). Pump stations' energy requirements account for 44.42 GWh/ annum, while waste water treatment works (WWTW) in the Western Cape Town account for 123.43 GWh/annum of electricity in 2014, together accounting for 42% of the City's total electricity demands (SEA, 2014).

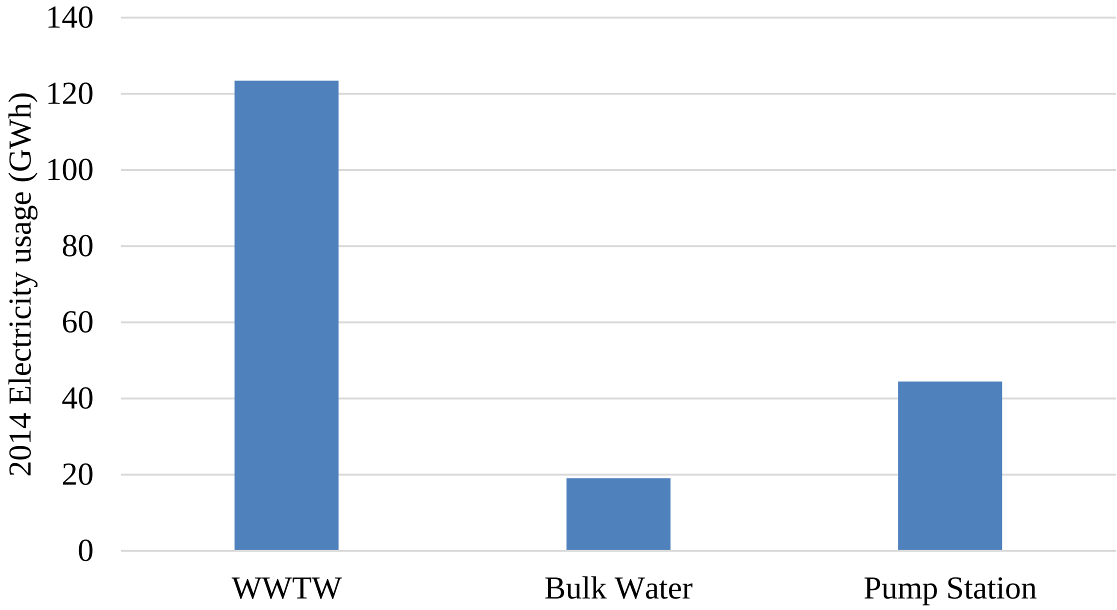


Figure 4-5: CoCT's water share of energy usage (SEA, 2014)

As shown in Figure 4-5, WWTWs make up the largest share of electricity demand and the main users of electricity within these facilities are aerators and pumps in all three categories (SEA, 2014). However, there is a lack of more disaggregated data on the actual power ratings of each component in each category and more particularly, the energy intensities of groundwater abstraction and transmission. This study, therefore, provides theoretical energy usage of each component of each supply system proposed by using design guidelines, topographical parameters and available data.

4.7 Material and chemical usage

The study also provides energy intensities of the products used during the construction and operation stages of the approaches. The quantity of chemicals used during the treatment processes was calculated using actual data (given in Table 4-3) obtained from Blackheath Water Treatment Plant. Since both Blackheath and Faure process a similar quality of raw water, the same chemical dosage and treatment levels have been assumed for the latter.

Table 4-3: Actual Blackheath chemical dosages (CoCT, 2017)

Chemicals	**Actual usage (kg/k*l*)**	**Chemical prices (R/k*l*)**
Chlorine	0.00174	27.6
Lime	0.02521	45.1
Aluminium sulphate	0.04917	120
Carbon Dioxide	0.00971	49
PAC	0.00384	95.8

In the absence of studies done on the production of chemicals used for water treatment in South Africa, the energy and environmental implications of the chemicals were obtained by the life cycle assessment tool GaBi (Ganzheitliche Bilanz) which provided the total energy input and resulting pollutants produced from the manufacturing processes per unit mass of each chemical in the European Union (EU). This was assumed to be similar to the local context as the manufacturing processes for these chemicals are fairly universal. The energy intensity given for each chemical was measured in MJ/kg. The energy demand for the production of powdered activated carbon using organic feed and the production of potassium permanganate and aluminium sulphate was derived from literature on the life cycle analysis of the chemicals (Spalding-fecher, 2011; Arena *et al*., 2016).The data extracted from GaBi and other sources are given in Table 4-4.

Table 4-4: Embodied energy and emissions of chemicals (GaBi, 2017; Randall *et al.*, 2016; Arena *et al.*, 2016)

Chemicals (per kg)	Chlorine	Lime	Aluminium Sulphate	Carbon Dioxide	PAC	Sand	$KMnO_4$
Total primary energy used (MJ)	21.04	4.018	1.224	8.544	2.16	0.633	21.35
Water Consumption (kg)	2452.3	2252		251.8		171.6	
Carbon dioxide (kg)	1.34	1.213	0.01-0.5	0.4342	6.46	0.0371	1.16
Carbon Monoxide (kg)	1.75E-03	1.07E-04		1.25E-04	0.00244	3.16E-05	
Halon (kg)	1.87E-17	1.47E-18		1.94E-18		1.16E-19	
Hydrogen Fluoride (kg)	2.42E-06	2.73E-07		2.52E-07		1.47E-08	
Hydrogen Chloride (kg)	4.35E-05	4.48E-06		4.46E-06		2.67E-07	
Methane (kg)	2.54E-03	3.70E-04		1.33E-03		9.91E-05	
Nitrous oxide (kg)	2.52E-03	4.89E-06		9.91E-05	0.00183	9.36E-07	0.00234
Sulfur hexafluoride (kg)	1.02E-14	4.12E-16		2.74E-16		2.40E-17	0.0032

5. Research Methods

This chapter describes the research methods used throughout the modelling process to determine the direct electricity demand generated by all three approaches from their respective abstraction, conveyance and treatment stages. The calculation of the embodied energy of the materials used throughout the service life of the approaches were also included in the total energy intensities of the treated water. The energy intensities were further used to compute the electricity and chemicals costs per kl of treated water to obtain their individual production costs. Future possible electricity mixes were used as inputs to estimate increases in electricity costs, therefore in water production costs, and their associated carbon footprint over the operational phase of the approaches up until 2040.

The energy intensive components were identified using available electricity usage data and preliminary designs of these components was carried out to estimate their energy demands. The calculated energy intensities of the approaches were then used as inputs to two electricity mix scenarios and the ranges of possible electricity costs and greenhouse gas emissions were projected.

As identified in the literature review (Section 2.3), pump stations are the largest electricity users of the Western Cape Water Supply System. The use of pumps, at all stages in the design, was considered as constituting the most significant direct energy demand. Therefore, the energy requirements of the pumping systems at the abstraction, conveyance and treatment stages of the approaches were calculated. Ranges of electricity usage for each option using theoretical values and electricity data from existing WTPs were calculated along with the chemicals consumption during the operational stage. Figure 5-1 summarises the main energy intensive components of each stage of the approaches that were considered in the study.

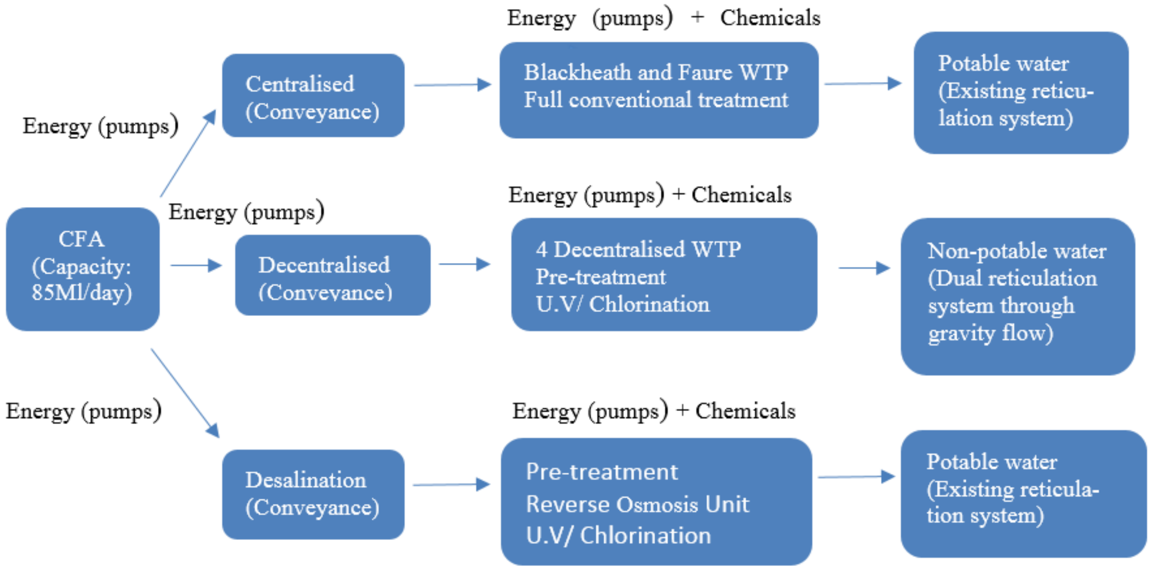


Figure 5-1: Overview of the three strategies

The energy intensity of each process in each approach mainly differs from the others due to differences in conveyance mechanisms and treatment processes adopted.

The scope of the study is therefore limited to the treatment and distribution stages of the water supply system and wastewater management was not included. Potable and non-potable waste water generated by the end-users of all three approaches were assumed to follow the same path of going through the sewer system to wastewater treatment works. Energy losses, mainly in form of heat, across distribution lines were also not accounted for in the study.

5.1 Water Supply Systems preliminary design

There are several available models e.g. WEST and GaBi, which analyse the energy intensity of water supply systems. However, these models have been created using country specific data and resources and are not directly applicable to the South African context. Microsoft Excel was therefore used to input local information and relevant data retrieved from WEST and GaBi for the modelling process of the study. EPAnet and ArcGIS were also used for the preliminary design of the water systems. The following sections will describe the abstraction, conveyance and treatment stages' design processes.

5.1.1 Abstraction

Groundwater abstraction through boreholes was kept at a constant rate of 85 M*l* per day in all three approaches investigated. However, the number of boreholes used in each alternative differed according to its specific conveyance system and the end-use it supplied.

The abstraction rates are also influenced by drawdown caused by the pumping of water and seasonally fluctuating groundwater levels. These are being examined in WRC Project K5/2526 (Okedi, 2017). The resulting decreases in groundwater levels were limited to a maximum of 1 m throughout these months to account for these fluctuations. The three approaches were also accordingly modelled for abstraction between March and November, which are considered as being the wet months (rainy months from May to August) to limit large variations in groundwater levels.

The decentralised approach consists of 170 abstraction points, each yielding 500 m^3/day and are spread across the catchment. At the time of the study, only 30 points' location had been proposed and are shown in the Figure 5-2.

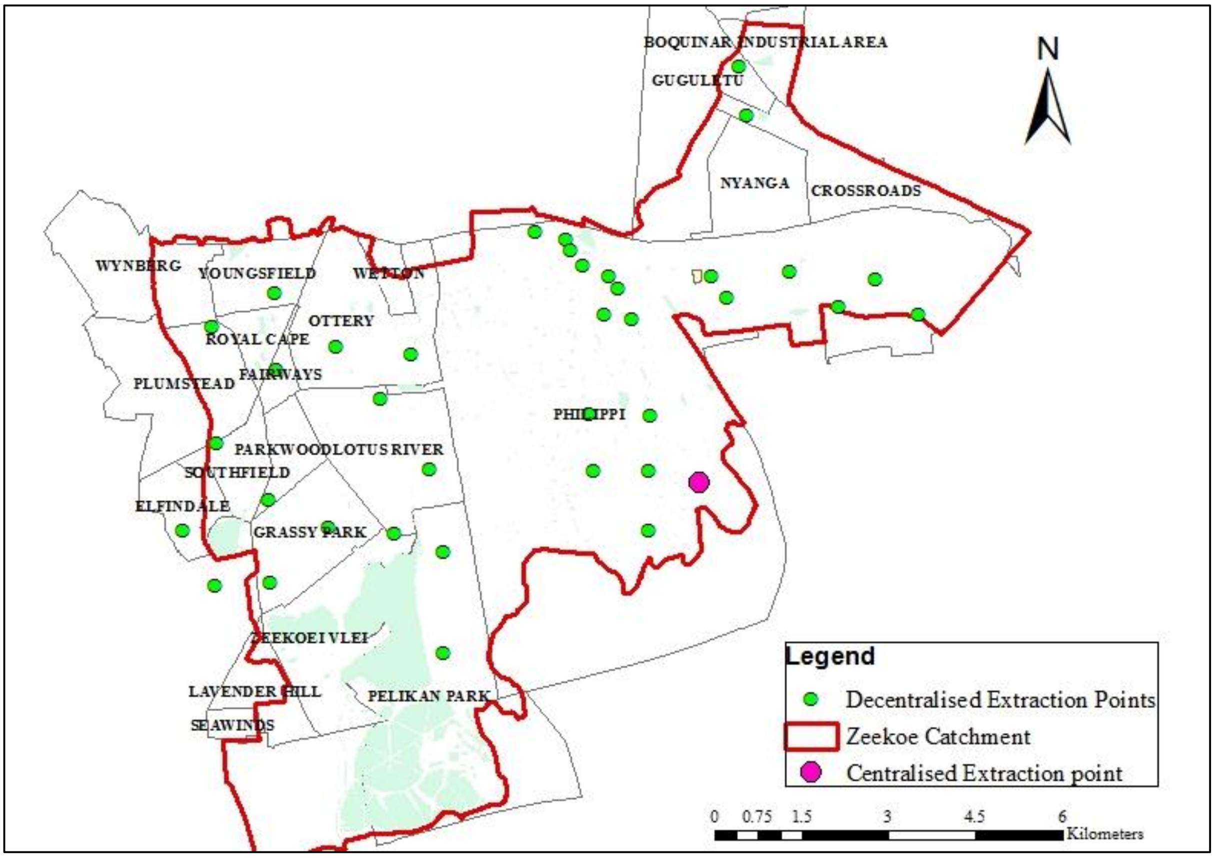


Figure 5-2: Proposed location of decentralised boreholes

Both the Centralised and Desalination options involve the use of major water transmission lines to their respective water treatment plants and therefore the groundwater is pumped from the Philippi area through 8 major boreholes.

The proposed well-points were placed on ArcGIS and categorised in each extent. The aquifer depth in each extent is given in the Table below.

Table 5-1: Aquifer Extent Depths (Okedi, 2017)

Aquifer Extent	Aquifer thickness (m)	Number of wells
1	30	20
2	20	30
3	30	50
4	50	70

Well depth for each abstraction point was assumed to be the same in each extent due to lack of more detailed groundwater level data. For the purposes of the study, the pumping rate was kept constant throughout the operational months and was assumed not to be affected by drawdown effects since stormwater infiltration will be carried out during winter months. A preliminary sizing of the boreholes was carried out using hydraulic principles and well design guidelines (Ahmed *et al.*, 2014). uPVC was used as the borehole pipe material and a friction factor of 0.02 was determined using the corresponding Reynolds Number for the flow in Equation 3.

The theoretical direct energy required to pump the groundwater depends on the flow rate and the total hydraulic head. Ahmed *et al.*(2014) define the direct output power of the well pump as functions of the total dynamic head of the well, h, (m), the rate of extraction of water, Q, (m^3/s), the density of the water ρ (kg/m3) and gravitational acceleration, g (m/s^2) and is given by Equation 1 in kW.

$$P_{out} = \frac{\rho g Q h}{1000} \qquad \text{Equation 1}$$

The total dynamic head was computed using the total drawdown in the well, gravitational lift of the water, head losses due to suction and friction forces in the pipes and the exit velocity head.

$$h = h_d + h_g + h_f + h_e \qquad \text{Equation 2}$$

Where h_d is the total drawdown (assumed to be 1 m),

h_g is the gravitational lift,

h_f is the head loss due to friction and

h_e is the exit velocity head.

Pipe friction head loss, h_f, along circular pipes for both laminar and turbulent flows were obtained using Equation 3 (the Darcy-Weisbach equation) while the exit velocity head is provided by Equation 4.

$$h_f = f \frac{L}{D} \frac{v^2}{2g} \qquad \text{Equation 3}$$

$$h_e = \frac{v^2}{2g} \qquad \text{Equation 4}$$

The resulting minimum theoretical power required to propel the water above ground at a given flow rate and head is given in Equation 1. The input power required at the motor level was therefore calculated using the brake power and efficiency of the motor (Equation 5). These depend on the flow rates, heads and individual power-capacity (P-Q) and efficiency-capacity (E-Q) curves of each system, generally ranging from 44% to 85%. A system efficiency of 70% was used to calculate the lower limit of the abstraction electricity demand for the transmission pumps and 50% was used for submersible borehole pumps due to changes in static and dynamic heads across each stage. An overall efficiency of 85% was further used to account for losses.

$$P_{in} = \frac{P_{out}}{n} \qquad \text{Equation 5}$$

The flow rates and total dynamic head at each borehole were matched to corresponding available borehole pumps in South Africa.

5.1.2 Conveyance

This section describes the modelling approach used for raw water transmission to the water treatment plants and the distribution of treated water.

The same hydraulic principles as abstraction were used to calculate the head required to pump the water across pipelines. Head losses due to pipe fittings used for changes in diameter and bends, are calculated using the flow velocity and the loss coefficient K of each fitting. However, due to the extensive pipe network of the approaches, the resulting total dynamic head was factored by 1.1 to allow for additional losses due to fittings. The direct minimum power required to convey water across the systems was calculated using Equation 1.

The choice of pipe materials used in each alternative depended on the working pressures and durability of the materials available. Ductile iron, steel, concrete and cement, variations of PVC, high density polyethylene (HDPE) and glass reinforced plastic (GRP) are amongst the commonly used pipe material in South Africa (van Zyl, 2014). uPVC and mPVC were assumed for small reticulation systems and the Decentralised pressured pipes, while GRP pipes were used for the Centralised and Desalination approaches due to the large expected working pressures.

Table 5-2: Pipe Material and Costs (Aurecon, 2013; Rhotech, 2017; Flowpipe, 2017)

Material	Available diameters (mm)	Operating pressures (m)	Safety Factors	2017 Prices excl VAT (R/6m)
U PVC	16- 500	40-250	2	96.84-12487
M PVC	50- 500	60-250	1.4	79- 11164
O PVC	110- 250	90-160	1.4	499- 5204
HDPE	50-1200	60-200	1.3	77- 74278
GRP (flowtite)	300-1400	1-320	1.8	15000- 55200

5.1.2.1 Decentralised Approach

Due to the water quality of the pumped groundwater, minimal treatment is still required before the water can be used for non-potable uses. The water quality of the groundwater across the extents has been tabulated in Table 4-1, along with the minimum water quality requirements for potable and non-potable uses. The pumped water from each extent was assumed to be sent to four small scale water treatment plants, one in each extent, through pressured pipes. The locations of the water treatment plants were chosen to allow gravity flow of the treated water through a dual reticulation systems to the suburbs.

A preliminary design of both raw water transmission lines and dual reticulation systems was done on ArcGIS using existing roads and catchment contours. Elevation profiles and distances of these systems were then exported to Excel. Excel was preferred to EPANET software, since less than 20% of the boreholes for the Decentralised approach had been proposed and addition of more boreholes at a later stage would result in changing pipe diameters, pressures and velocities. EPANET is a software that models water distribution systems and includes water flows, pressures and water quality tracking features. Theoretical minimum and maximum head loss calculations were preferred to allow for variations caused by the inclusion of more boreholes, thereby providing a range of designs for pipe diameters and the resulting TDH.

The pressured transmission pipes were modelled on Excel for a better evaluation of head loss across the pipes, with friction and elevation differences using a similar approach to the total dynamic head determination. Minimum and maximum head losses were estimated, using minimum and maximum allowable pipe velocities of 0.6 m/s and 1.2 m/s in the system as limits (van Zyl, 2014; CSIR, 2000).

The Decentralised Approach also includes the construction of a dual reticulation system supplying the treated water from each decentralised water treatment plant as shown in Figure 5-3. The dual reticulation system layers were exported from ArcGIS to EPANET for sizing of their components.

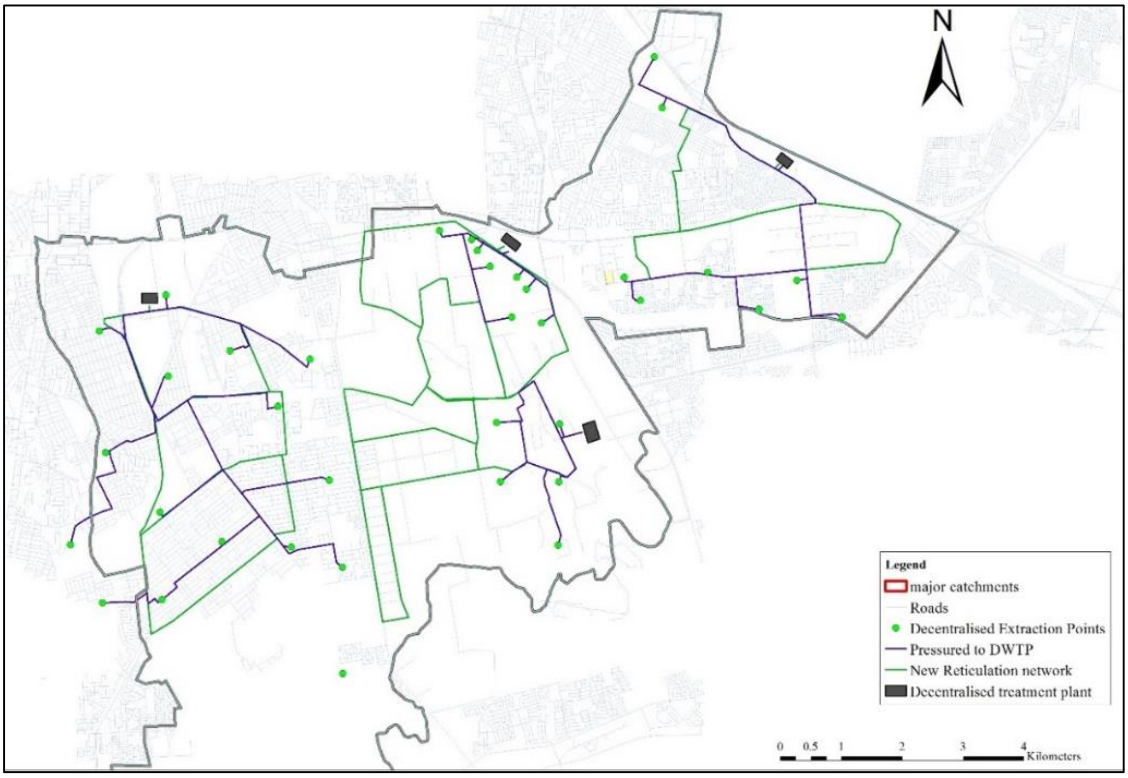


Figure 5-3: Proposed pressured transmission lines and dual reticulation systems

The CSIR (2000) guidelines for water supply systems were again followed to determine the pipe diameters and appropriate pressure needed across the networks. However, the systems were not tested for all conditions (e.g. minimum residual pressure) since the envisaged design did not supply non-potable water to each end-user but rather to each suburb. Additional reticulation design will be required for each erf in the catchment to obtain a better approximation of the network.

5.1.2.2 Centralised Approach

The Centralised approach consists of water being pumped from the Philippi area to the Faure and Blackheath Water Treatment Plants. Three potential transmission lines were proposed to the Blackheath WTP and a further one to Faure WTP, determined by the topography of the terrain between the boreholes and WTPs. While the area between these is relatively flat, both WTPs are found at higher altitudes than the boreholes, with elevation differences of up to 60m.

The first route considered the pumping of water from the boreholes directly to the Blackheath WTP which has an elevation of 187 m above mean sea level (mamsl). The proposed Routes 2 and 3 pumped groundwater to the lower ponds of Blackheath WTP at 68 mamsl. Routes 2 and 3 were considered since Blackheath WTP recycles sludge produced from its reclamation tanks on site by sending it to ponds found downhill of the WTP for secondary treatment.

Reclaimed water is then pumped back the treatment plant and mixed with the raw water from the surface reservoirs to the east of the city. Only one route was identified for transmission to Faure WTP which has an elevation of 96 mamsl.

Table 5-3: Transmission lines start and end elevation

Pipelines	Elevation $_{Start}$ (mamsl)	Elevation $_{Finish}$ (mamsl)	delta h	Length (m)
Common	27.02	39.32	12.3	8163
Blackheath				
Route 1	39.32	186.6	147.28	13110
Route 2	39.32	68.39	29.07	11610
Route 3	39.32	68.39	29.07	9940
Faure				
Route 4	39.32	95.53	56.21	14530

Due to the large elevation differences, the minimum and maximum head losses possible were calculated based on the flowrates in each transmission line and their chosen diameters.

5.1.2.3 Desalination Approach

The location of the Desalination plant is at a lower elevation than the abstraction point and a similar pipeline design process to the Centralised approach was followed. The proposed transmission line used is 8.06 km long and follows existing road networks.

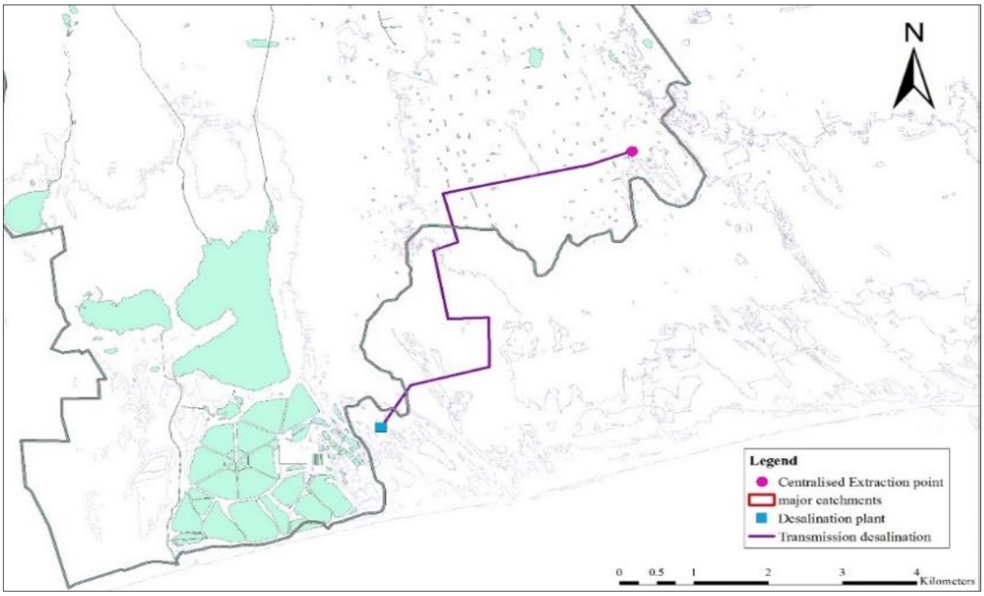


Figure 5-4: Proposed desalinated water transmission line

Even though the Desalination plant was located at a lower elevation than its abstraction points, the conveyance stage still required additional energy to transfer the groundwater to the Desalination plant. This is due to head loss caused by friction in the pipe over a distance of 8.06 km. The same abstraction point as the Centralised Approach was used as shown in Figure 5-4, instead of a location closer to the Desalination plant, to avoid to possible seawater and wastewater intrusion due to the plant's proximity to the sea and the WWTW.

5.1.3 Treatment

The treatment level of each approach was based on the water quality required for each end-use, that is, potable water levels for the Centralised and Desalination Approaches and non-potable for the Decentralised Approach. The scope of the design was limited to calculating the amount of chemicals used and the electricity consumption of the plants. Approximate sizing of the networks and construction costs were estimated using local standards.

5.1.3.1 Treatment units

A preliminary design of the most energy intensive processes (as identified in the literature review) in the water treatment plants required for Decentralised and Desalination Approaches was carried out. Blackheath and Faure WTP have treatment capacities of 420 M*l*/day and 500 M*l*/day respectively. The two WTPs operate at a capacity factor of 90% under non-drought conditions, that is, with dams at full capacities. However, with recent changes in rainfall patterns and dam levels, the capacity factor of the plants had fallen to 45% at the time of the study (CoCT, 2017b). Both treatments plants' capacities are therefore estimated as being sufficient to accommodate an additional 42.5 M*l*/day respectively in both drought and non-drought conditions.

Table 5-4: Blackheath and Faure WTP capacities (CoCT, 2017)

	Blackheath WTP	**Faure WTP**
Current Capacity (M*l*/day)	420	500
Current CF (45%)	45%	45%
Maximum CF (90%)	90%	90%
Flowrate (M*l*/day)	42.5	42.5
Overall installed capacity (kW)	400	200

The Decentralised water works design depends on projected volume of raw water for each of the four extents of the alternative.

Table 5-5: Capacity per extent and alternative

Extent	No of Boreholes	Capacity (Ml/day)
1	30	10
2	20	15
3	50	25
4	70	35
Desalination plant	8	85

The design of the treatment units also depends on the raw water quality factors such as the turbidity, suspended solids concentrations, dissolved solids concentrations and pH values. Studies done on the CFA groundwater indicated TDS levels varying between 300 to 4170 mg/*l* while traces of arsenic and mercury were found in stormwater samples in the catchment (Adelana *et al.*, 2010). Remediation at pollution sources identified in the catchment would be used to prevent the ingress of these contaminants in stormwater and subsequently, the aquifer. Filtration through the sand at the stormwater infiltration ponds would ensure removal of the remaining traces of heavy metals, if any.

The Decentralised water treatment plants would need to provide water quality suitable for non-potable uses such as irrigation (as given in Table 4-1 in Chapter 4). The surrounding suburbs in the catchment were previously identified as being residential, industrial and mainly agricultural areas where there are existing demands for non-potable water. Pre-treatment is required in the Decentralised and Desalination approaches due to high iron and manganese concentrations in the groundwater samples. Soluble forms of iron and manganese are naturally found in groundwater, however, both oxidise due to contact with oxygen in the air forming precipitates (Grigg, 2010). These precipitates contribute to fouling of pipes and membranes in desalination units and therefore have to be removed before passing through the RO unit (Voutchkov, 2013).

Removal of iron and manganese from raw water can be done using iron filters. Potassium permanganate may be used as the oxidising agent for both cations and the precipitate filtered using manganese greensand. Filtration using manganese greensand, UV treatment and chlorination processes was thus considered for removal of particles and impurities in the Decentralised option.

The pre-treatment stage with potassium permanganate and filtration may also be used in the Desalination approach to prevent fouling of the RO membrane before being sent to the RO unit. The desalinated water should then be disinfected through UV units and stabilised using chemicals such as lime, carbon dioxide and chlorine, as post treatment to add back necessary chemicals, prevent corrosion of the pipe materials and to prevent contamination of the treated water during distribution.

5.1.3.2 Chemical Usage

The concentrations of chemicals used throughout the treatment process for the Decentralised treatment plants and Blackheath and Faure WTPs were estimated using chemical usage data from the CoCT. The concentrations were compared to their respective billing data obtained from Blackheath WTP. Since Faure WTP also receives raw water quality like that of Blackheath, the chemical uses in the former was assumed to be comparable.

The desalination plant, however, will require different levels of treatment including the use of manganese greensand which requires regeneration using potassium permanganate to remove potential fouling chemicals before the RO unit (Kucera, 2010). The desalinated water also requires additional chemical treatment for disinfection and stabilisation using chlorine, lime, carbon dioxide and fluoride as post treatment. The necessary concentrations of these chemicals were estimated using their respective allowable concentrations as set out in Table 4-1.

5.1.3.3 Electricity demands

Treatment of raw water to different purity levels requires a significant amount of electricity. A major proportion of this demand is created by pumps and aerators in conventional water treatment works. The electricity demands at the treatment level were calculated using the installed capacities available for the existing WTPs for the Centralised Approach. The main processes which required electricity inputs in the Decentralised and Desalination Approaches were identified as being backwash mechanisms for membranes and filters and the feed water pressure for the RO membrane. Pump design steps at the treatment level are similar to those in Sections 5.1.1 and 5.1.2.

The electricity usage at Blackheath and Faure WTP can be estimated using their total installed capacity and the capacity factor at which they are operated throughout the year. Blackheath WTP is also equipped for primary treatment of sludge produced from the sedimentation process and its installed capacity includes the machineries and equipment power needed for the sludge treatment. The pumped groundwater will allow lower intakes of raw water from dams while it substitutes for the decrease in intake of dam water during drought conditions. Electricity consumption caused by the pumped groundwater can theoretically be calculated using the installed capacity and the total volume of water treated over a fixed period. In the case of higher water demands, the WTPs could be run at higher capacity factors of up to 100%.

The effluent produced from the sludge primary treatment is already being sent to ponds found downhill from Blackheath WTP at an elevation of 68 mamsl and the reclaimed water from secondary treatment is then pumped back to the treatment plant and mixed with raw water. A similar concept proposed for the groundwater, due to its high contaminant concentration and to prevent further degradation of the current water quality. Two of the possible transmission lines of the Centralised Approach consist of pumping the groundwater to these ponds for preliminary treatment. The energy required to do so in these two alternatives are therefore calculated using the current volume pumped back to the plant and their respective Eskom billing data.

The Decentralised Approach proposes minimal treatment of the groundwater through oxidation using potassium permanganate, rapid sand filters (gravity), UV disinfection and chlorination. The major consumer of energy was determined as being the backwash pumps for the cleaning of sand beds and UV filters. Backwashing can be carried out using three different mechanisms; water only, water and air consecutively and water and air simultaneously (EPA, 1995). The use of consecutive and simultaneous water and air mechanisms are more commonly used in South Africa (van Duuren, 1997). The sand beds must be fluidised to free accumulated particles and backwash mechanisms normally last 10 to 15 minutes. Again, the total capacity of both backwash pumps and UV filters depend on the volume of water treated in each extent.

Due to the lack of availability of more disaggregated electricity usage data in water treatment plants in South Africa, estimations using international energy intensities of water supply processes for backwash mechanisms of water treatment plants in the US have been compiled in Table 5-6. The values are given in kWh/day for the given capacities which can be interpolated for the decentralised water treatment plants.

Table 5-6: Typical backwash energy intensity (EPRI, 2013)

Plant production (MLD)	3.785	18.93	37.85	75.71	189.3	378.5	946.4
Backwash water pumps (kWh/day)	15	60	125	250	660	1290	3220
Residual pumping (kWh/day)	4	20	40	80	200	400	1000
Thickened solids pumping (kWh/day)	0	0	0	125	310	620	1540

Similarly, the direct energy demand in the brackish water desalination option is also mostly generated by backwash mechanisms and input feed water pressure in the RO unit. Pre-treatment consisted of oxidation of iron and manganese and filtration through manganese greensand through gravity flow. Centrifugal pumps are proposed to provide the head required to overcome the pressure difference between the feed water and permeate.

The minimum applied feed pressure F_p has to be greater than the osmotic pressure on the permeate side of the RO membrane, the permeate pressure P_p and the pressure drop across both sides, P_d, to create the net driving pressure (NDP) (Voutchkov, 2013; Kucera, 2012).

$$NDP = F_p - (O_p + P_p + 0.5\ P_d) \qquad \text{Equation 6}$$

The pressure gradient is further influenced by other variables such as temperature of feed water, TDS concentration and the rejection rate of the system.

5.2 Energy usage computation

The energy requirements of each approach were calculated using both direct energy and embodied energy used. These were quantified as the energy intensity of treated water. While the dual reticulation system construction was included in the scope of the study, wastewater treatment and management was not investigated.

5.2.1 Direct energy

Direct energy consists of both electricity and secondary fuel consumptions (e.g. diesel) throughout the life cycle of the- options.

5.2.1.1 Electricity demands

Energy is required at all levels to drive water across the supply system. Most of the energy demands of the system arise from pumps as well as the machineries used in pump stations and within treatment plants.

The minimum power required to abstract and pump water uphill to the water treatment plants were based on the total dynamic head calculated in Section 5.2.1 and is given by Equation 2. The energy, E, (kWh) required to pump the given flow rate of the water, Q, during operational hours, T, was then calculated using the following equation in kWh.

$$E_{min} = P_{in}\ T \qquad \text{Equation 7}$$

The energy intensity of the treated water in kWh/k*l* was therefore obtained by using the total treated water over time, T, and the energy required over the same time period.

$$\text{Energy intensity}_{min} = \frac{E_{min}\ \text{(kWh)}}{\text{Total Volume of water treated (kl)}} \qquad \text{Equation 8}$$

Pumps matching the required characteristics were then chosen and their efficiencies were factored in their power ratings, P_{pump}. The upper limit for energy intensity for abstraction and conveyance were calculated using the chosen pump power rating.

$$\text{Energy intensity}_{max} = \frac{P_{pump}\ T\ \text{(kWh)}}{\text{Total Volume of water treated (kl)}} \qquad \text{Equation 9}$$

The energy intensity calculations for the treatment stages were carried out using the above steps and while the flow in the treatment processes was assumed to be driven by gravity, backwash energy intensities, UV filters ratings and feed water pumps were also assumed for the estimate of the electricity demands generated using the flow of water through the various units.

5.2.1.2 Fuel Consumption

While most pumps used in the design of the systems were electric ones, the energy intensity calculated for each stage of the approaches could be converted to an equivalent fuel, such as diesel, needed to produce the required power. Blackheath WTP has diesel generators as backup in case its micro-hydro systems are not operational due to low water flows and Eskom electricity power failures. Generators were used in 2015 and 2016 during power failures (Southgate, 2017).

5.2.2 Embodied Energy

A considerable amount of energy is required to produce materials and products and to transport these to their final consumers. Embodied energy can often be compared to direct energy usage of water supply systems (Mo, 2012). The direct electricity demands of the three approaches were calculated using a bottom up approach. The embodied energy of the construction and decommissioning phases of the approaches is an important part in the calculation of the total energy and carbon footprints and the production costs of the treated water. Due to time and resources constraints, these will be discussed below but have not been included in the scope of the study.

5.2.2.1 Construction

The embodied energy of the construction of the new infrastructure required for each alternative can be estimated using the construction costs and the energy intensity of the construction industry (Mo, 2012). The 2014 energy balance published by the DoE, the latest available one, and the supply and use tables for the corresponding year can be used to estimate the direct energy intensity of the construction sector. However, indirect energy linkages between sectors can be further extracted using a similar methodology as adopted by Arndt *et al.* (2011) to estimate the carbon intensity of the South African economy.

Comparisons between the three approaches must include the costing of new infrastructure required in each case since these differ enormously as shown in Table 5-7.

Table 5-7: Infrastructure requirement of the approaches

Approach	Abstraction	Conveyance	Treatment	Distribution
Centralised	Borehole Construction Pump & Electrical/ mechanical works Pump house construction	Pipeline Pump & Electrical/ mechanical works Pump house construction	Existing infrastructure	Existing infrastructure
Decentralised	Borehole Construction Pump & Electrical/ mechanical works Pump house construction	Pipeline Pump & Electrical/ mechanical works Pump house construction	Storage Filtration Unit Internal Pumps UV Units Admin lab and maintenance	PVC reticulation system
Desalination	Borehole Construction Pump & Electrical/ mechanical works Pump house construction	Pipeline Pump + Electrical/ mechanical works Pump house construction	Storage Filtration Unit RO unit Internal Pumps UV Units Admin lab and maintenance	Existing infrastructure

5.2.2.2 Consumables

Actual chemical usage data obtained from Blackheath WTP were used in all three approaches due to the similar raw water qualities fed to the treatment plants. The total primary energy used for the manufacturing of unit mass of each chemical used during the processes has been tabulated in Table 4-4 in MJ/kg in Chapter 4.

The consumables considered for the study were also extended to the service life of the filter material (both silica and manganese greensand) and the RO membrane. Regeneration of manganese greensand can be carried out continuously using potassium permanganate as an oxidising agent for the removal of iron and manganese ions from the raw water at concentration ratio of approximately of 1:1 for iron and 1:2 for manganese (Kucera, 2010). The main materials consumed during the operational phase the three approaches were identified and are summarised in Table 5-8.

Table 5-8: Consumables used throughout water supply system

Consumables	Centralised	Decentralised	Desalination
Chlorine	✓	✓	✓
Lime	✓		✓
Aluminium Sulphate	✓		
Carbon Dioxide	✓		✓
PAC	✓		
Sand	✓		
Manganese greensand		✓	✓
Potassium Permanganate		✓	✓
Fluoride			✓

The energy intensity of each chemical used per k*l* (W_e) was calculated using the manufacturing energy intensity, the dosage and the flow rate through each process.

$$W_e \left(\frac{MJ}{Kl}\right) = \text{primary energy intensity} \left(\frac{MJ}{Kg}\right) * \text{dosage} \left(\frac{Kg}{Kl}\right) \qquad \text{Equation 10}$$

5.3 Electricity mixes

Most processes and mechanisms used in water supply systems have been optimised to deliver treated water in the most efficient manner and to decrease their energy dependence and their environmental footprints. While water technologies, in some instances, have matured, the largest potential to improve the sustainability of the sector, is to examine the energy sources. All three alternatives' electricity consumptions are matched to the current South African electricity mix and compared to the future electricity mixes as described in the updated IRP reports and CSIR (2016)'s least cost electricity mix scenario.

5.3.1 Current electricity mix

Historically, the South African electricity sector has been heavily dependent on coal as an energy source due to the large availability of the resource in the country. Eighty-five percent of its 44 GW installed capacity is from coal, followed by nuclear, hydro, gas and diesel and in the past five years, solar and wind sources as well. The share of each energy source in the total installed capacity is shown in Figure 5-5.

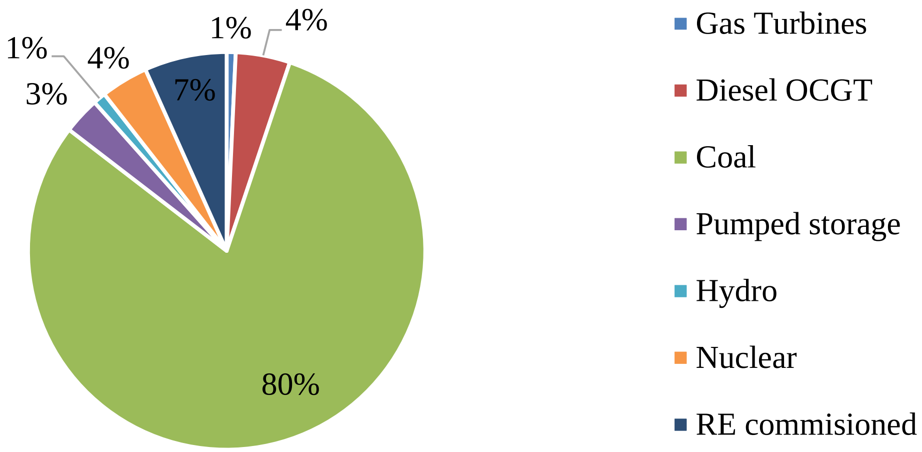


Figure 5-5: SA electricity mix (Eskom, 2017a; GreenCape, 2016)

5.3.2 Future Electricity mixes

The future electricity mix of South Africa is laid out by the Integrated Resource Plan (IRP) developed by the Department of Energy in 2010. The IRP 2010 proposes new build programmes for South Africa from 2010 and 2030 but the plan was later revised in 2013 and 2016. The later versions have not yet been adopted by the Cabinet.

The new build plan was developed using the country's aim of limiting GHG emissions from the electricity sector to 275 million tons per annum by 2025. However, the constraints of the model used by the DoE do not cater for decreasing costs for renewable energy, externalities associated to the various sources used and assumes a high economic growth rate and high electricity demands (DoE, 2011; ERC, 2015). There have been several studies carried out to examine alternative mixes without different parameters and allowing for more flexibility in planning. Table 5-9 shows the shares of energy sources in the future electricity mixes according to the IRP (2011).

Table 5-9: IRP 2011 future electricity mixes (DoE, 2011)

Energy Source	2010 Share	2030 Share	New Capacity added (GW)
Coal	90 %	65%	6.3
Nuclear	5%	20%	9.6
Hydro	5%	5%	2.6
Gas OCGT	0	1%	2.4
Peak OCGT	0.1 %	0.1 %	3.9
Renewables	0	9%	17.8

The IRP 2016's electricity mix has a higher share of coal and nuclear. There have been other studies carried out using the base case of the IRP with different parameters. The CSIR's study on the least cost electricity mix assumes a lower demand forecasts and have no constraints on the uptake of renewable energy technologies. The resulting electricity mix proposes no new coal and nuclear capacity added but higher renewable energy and gas capacity over the next 25 years. Figure 5-6 shows the differences in the electricity mixes.

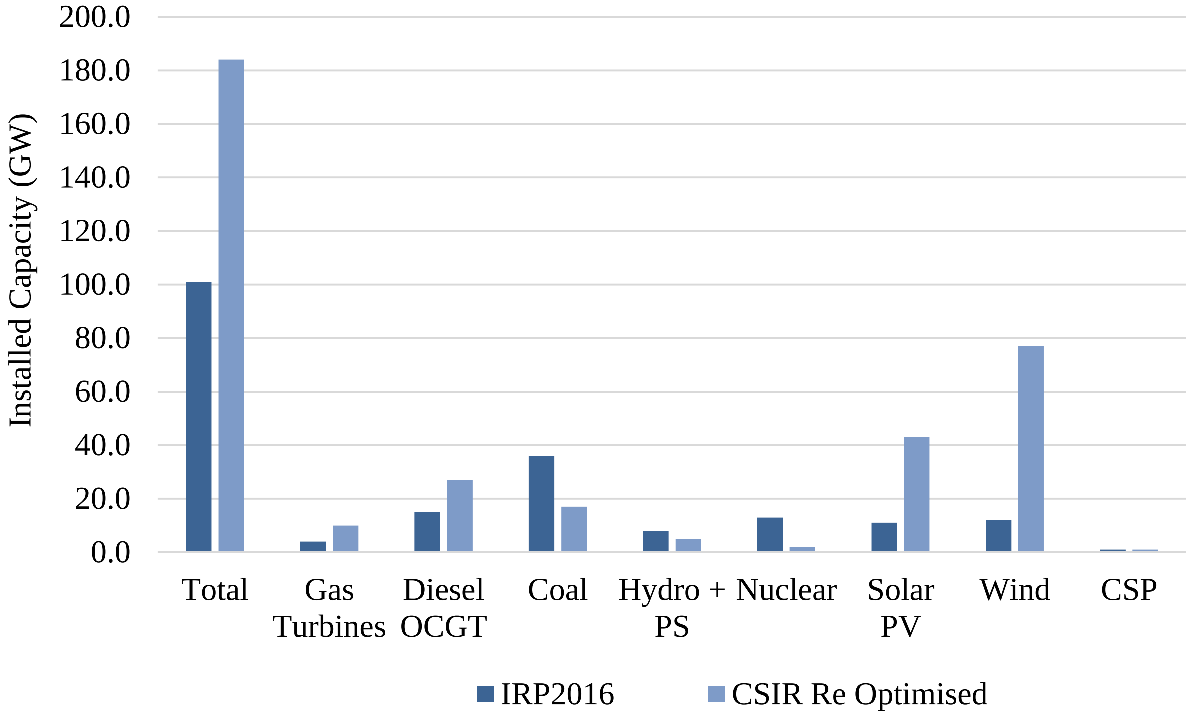


Figure 5-6: IRP 2016 & CSIR 2016 electricity mixes (CSIR, 2016; DoE, 2016b)

5.3.3 Electricity costs scenarios

Direct electricity costs of the three approaches change with two main variables, viz., the time of use of their electrical components and the future electricity tariffs.

5.3.3.1 Time of Use

The electricity costs resulting from varying the time of use of the electrical components of the systems depend on the tariff structure given in Table 4-2. However, changing the time of use from 24 hours to selected standard and off-peak times resulted in higher flow rates from boreholes and through the conveyance systems, since the total capacity abstracted per day was kept constant at 85 M*l*. The design of the transmission lines and associated pumps was modified to accommodate the new flows. Changes in electricity costs due to load shifting to standard and off-peak periods can therefore be calculated by increasing the abstraction rates and flows accordingly throughout the systems.

The operating hours of the Centralised and Desalination treatment plants were kept continuous, since these are designed to supply potable water into the existing reticulation systems. However, the abstraction and conveyance systems load can be shifted to off peak periods with the use of storage capacities for the 24-hour demand period (van Duuren, 1997) as shown in Table 5-10.

Table 5-10: Time of Use scenario

Approach	Stages		
	Abstraction	Conveyance	Treatment
Decentralised	Standard/ Off peak	Standard/ Off peak	Peak/ Standard/ Off Peak
Centralised	Standard/ Off peak	Standard/ Off peak	Peak/ Standard/ Off Peak
Desalination	Standard/ Off peak	Standard/ Off peak	Peak/ Standard/ Off Peak

5.3.3.2 Future electricity costs

Based on the latest draft IRP document released in 2016 and the studies carried out on the future electricity costs of possible electricity mixes for up to 2040, the share of energy costs of the three approaches was projected through the three alternatives (DoE, 2016b). The IRP(2016) and CSIR(2016) generation costs represent the upper and lower limits of generation costs possible for the proposed electricity mixes described below.

The two futures represent the IRP 2016 base case and CSIR's Re-Optimised scenario and the future electricity costs are listed in Table 5-11 in 2016 Rands.

Table 5-11: Future Electricity prices (kWh/k*l*) (DoE, 2016b; CSIR, 2016)

	IRP (2016R)	CSIR Least Cost (2016R)
2015	0.48	0.48
2020	0.68	0.68
2025	0.83	0.79
2030	0.87	0.79
2035	0.95	0.8
2040	1.03	0.84

5.4 GHG emissions

The carbon footprint of the electricity and materials usage of the options were also computed using the different electricity futures of the country, since the electricity sector produces almost half of South Africa's GHG emissions (DEA, 2013).

The two scenarios, as explained in Section 5.3, used the IRP 2016 and CSIR Re-optimised electricity mixes until 2040. The IRP 2016's electricity mix was modelled to follow the Peak Plateau Decline (PPD) emissions trajectory, that is, emissions will peak at 275 Mt of CO_2eq/ year by 2025, stay constant until 2030 and decline to 250 MtCO_2eq/year thereafter as more renewable and nuclear energy sources are added. The CSIR scenario does not impose any limits on the integration of renewable energy to the grid and follows a least- cost scenario. Its emissions profile peaks in 2020 at 232 MtCO_2eq/year and declines to 114 MtCO_2eq/year (CSIR, 2016).

Table 5-12: Energy technology emissions (EPRI, 2015)

Pollutants	**Coal Pulverised with FGD**	**Nuclear**	**OCGT**	**CCGT**	**Wind**	**PV**	**CSP**
CO_2 (kg/MWh)	947.3	0	574	367	0	0	0
NO_x (kg/MWh)	1.94	0	0.3	0.2	0	0	0

The electricity mixes for the base case and the two scenarios were used to estimate the emissions from each component of the mixes and the footprint of the treated water throughout the scenarios were calculated. Emissions from each energy technology were obtained from EPRI (2015), which provides energy technology costs and associated emissions adapted to the South African context.

6. Results and Discussions

This Chapter describes and discusses the results obtained from the modelling process. The following sections present the individual intensities of each stage of the three alternatives (Centralised, Decentralised and Desalination), identifying the most energy and carbon intensive ones.

Each alternative was chosen to reflect possible alternatives through which the groundwater could be exploited given the current drought situation in Cape Town. The results are then discussed to assess the viability of the three approaches from an energy perspective using the contribution of each alternative to current electricity demands of the WCWSS, in terms of minimum installed electrical capacities.

The economic implications and GHG emissions of the three alternatives are also assessed using two future potential electricity mix scenarios, namely the draft IRP (2016) and CSIR (2016), which represent plausible upper and lower thresholds of future electricity generation costs and emissions. The two scenarios were chosen because they could be seen to represent the extremes of the possible electricity mixes during the study period. The energy and consumables cost components of the operational phase are discussed and possible ranges of water production costs using the two electricity mixes' generation costs are provided. A comparison between the direct energy and consumables' carbon footprints is further provided using the two energy mixes and the country's future emissions target.

6.1 Energy intensities of the approaches

The energy intensities of the treated water are quantified at each level as MJ/k*l* for consumables and kWh/k*l* for electricity demands. The total energy intensity of each approach formed the basis for investigating the effects of possible future electricity mixes on the water production costs and their resulting carbon footprints.

6.1.1 Direct energy

The direct electricity intensities of each stage of the approaches were calculated by computing the total energy demands from each stage and dividing them by the total volume of treated water per day.

Theoretical values using hydraulic principles and the physical characteristics of the catchment were used to estimate the minimum and maximum possible energy intensities required at each step of the approaches. The abstraction energy intensities consist of the energy consumption of submersible pumps propelling the water above ground. The power used for the upper range was calculated using the dynamic and static heads and the design flow rates. These were then matched to real life submersible pumps ratings.

The conveyance stage was also quantified by a range of possible energy intensities using pumps for transmission of water from the abstraction points to the water treatment plants. In the Centralised Approach, three transmission paths were modelled for conveying the water to Blackheath WTP and the path with the lowest energy intensity was chosen as part of the base case. Route 3 was chosen since it resulted in the lowest elevation difference between the start and end of the transmission line. Its transmission lines network spread across the residential areas between the abstractions points and water treatment works in contrast to the original route (Route 1), which was designed around the settlements.

The energy intensities of the treatment stage of the Centralised and Decentralised Approaches were calculated using existing installed capacity from Blackheath WTP and backwash systems' energy intensities from literature (EPRI, 2013). The Desalination option's energy intensive units were designed using the water quality of the feed water and the targeted treated water quality and the minimum and maximum possible energy intensities were modelled.

Figure 6-1 shows the ranges of values obtained for the electricity demands of each alternative and the values of each components are provided in Appendix B. The values for each stage fell within the ranges of those obtained in the literature review. The figure shows that the Desalination option generates higher electricity demands than the Centralised and Decentralised Approaches.

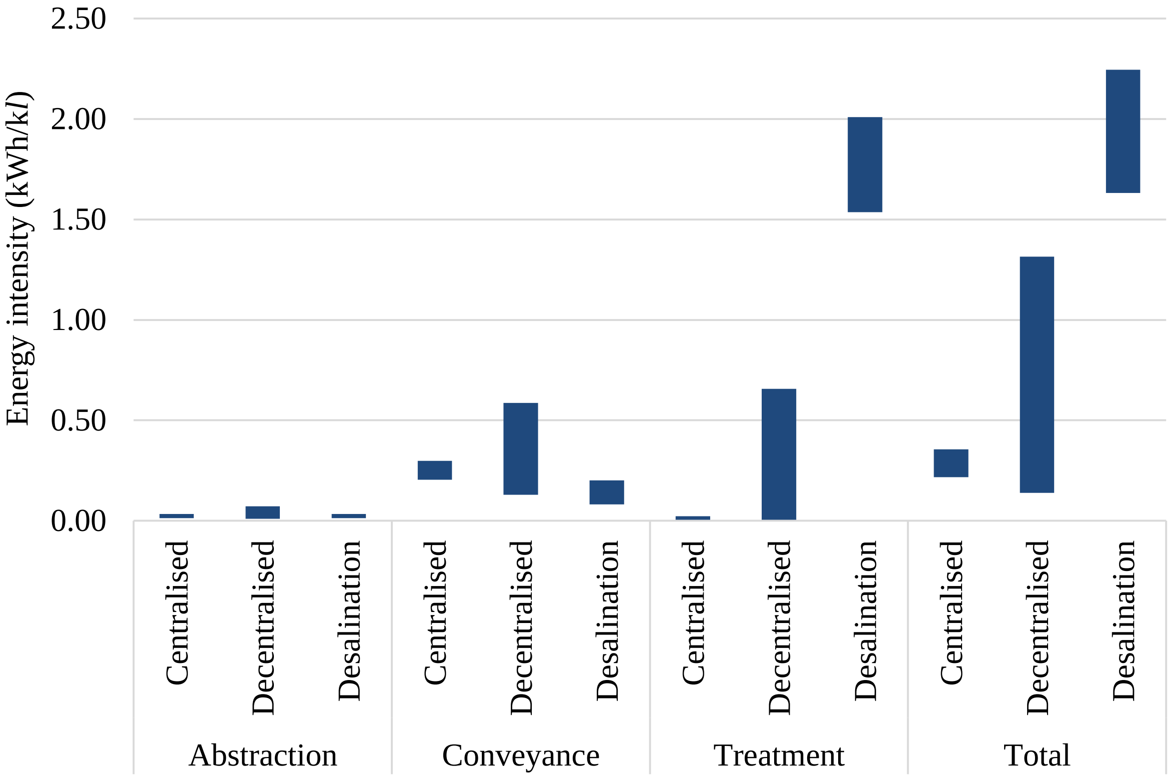


Figure 6-1: Electricity intensities of the three alternatives (kWh/*kl*)

The abstraction stage's electricity demands from submersible pumps were similar across the three approaches and are the least energy intensive part of the system. The occurrence of groundwater at an average depth of 2.6 m across the catchment and a constant drawdown depth of 1 m caused the total dynamic head of the abstraction stage to be smaller than that of the conveyance stage. However, drawdown due to abstraction of groundwater has seasonal variation depending on the rainfall and abstraction rate. It would be useful to incorporate these into the model in a follow up study to obtain a more accurate estimate of the power required for each well-point.

The electricity demands are generated by conveyance pumps during transmission which are dependent on the distance and elevation differences between the supply and the water treatment works used. Elevation differences in the Centralised Approach were significantly higher than the other two approaches. The energy required to transmit the water over these elevation differences was greater than the friction losses that occurred in the pipelines, despite having longer transmission pipe lengths. On the other hand, the Decentralised and Desalination Approaches' total dynamic heads largely consisted of friction losses generated in the pipes used in the transmission networks since the maximum elevation difference between the well-points and the Decentralised water treatment works was found to be 17 m. The Conveyance alternative has a larger range of values due to a more extensive network of pressured pipes required to convey water from 170 abstraction points to the DWTPs.

The energy intensities of the conveyance stage varied greatly with the share of static and dynamic heads of the systems, along with the working pressures used as parameters. The design of the transmission pipes was found to be crucial in determining the minimum power required to convey the water through the network. The selection of pipe diameters, in particular, was found to have a significant impact on the power required for all three alternatives and was limited to allow flow velocities of up to 1.2 m/s.

The largest demands for electricity in the treatment stage were generated by the use of UV units for water disinfection and the use of feed water pumps in the RO unit to create the required large pressure gradients. The choice of UV treatment coupled with chlorine addition, as opposed to only chlorination, in the Decentralised and Desalination approaches was preferred despite the lower total energy intensities associated with chlorination-only because UV/chlorine treatment disinfects the water more effectively.

The design pressure gradient required across the membrane depends greatly on the molar concentration of the dissolved solids (TDS) of the feed water. The resulting electricity demands were found to be within range of the energy intensities of local and international brackish water desalination plants identified in the literature. Despite a relatively low TDS concentration (4170 mg/*l*), these were still slightly higher than the lower limits obtained in the literature review. The differences could have been caused by the high rejection rates (97.7%) used for the system since only one RO unit was used in the treatment chain to produce potable water quality.

The desalination plant's location was also chosen to be in the proximity of the Cape Flats WWTW and the coast. Effluent from the WWTW and seawater (TDS > 15000 mg/*l*) could be used as feed water through blending. However, the relatively high TDS of the water will result in an electricity consumption twice or thrice that of the groundwater, due to higher pressure differences required to remove the salts.

A daily abstraction rate of 85 M*l*/day was used across all three approaches between March and November to offset the amount from the water drawn from the dams. However, electricity usage also increases during the winter period. The Centralised alternative would have an installed capacity of at least 1.3 MW while the Decentralised and Desalination alternatives would have machineries with installed capacities ranging from 2.7 to 2.9 MW and 5.8 to 6.3 MW respectively. The current installed capacity of the electrical components of the Western Cape Water Supply System is 47.6 MW including the wastewater treatment plants (SEA, 2014) and the proposed alternatives could increase the capacity by up to 13%. The electricity implications of the three alternatives vary considerably from each other and will add significantly to the total electricity demand for water services in Cape Town.

6.1.2 Embodied energy

The embodied energy of the treatment stage of the approaches was quantified as MJ/k*l* of treated water and is displayed in Figure 6-2. The amount of primary energy used for the production and transport of the raw materials to manufacture the chemicals was quantified using life cycle assessment data from international inventories.

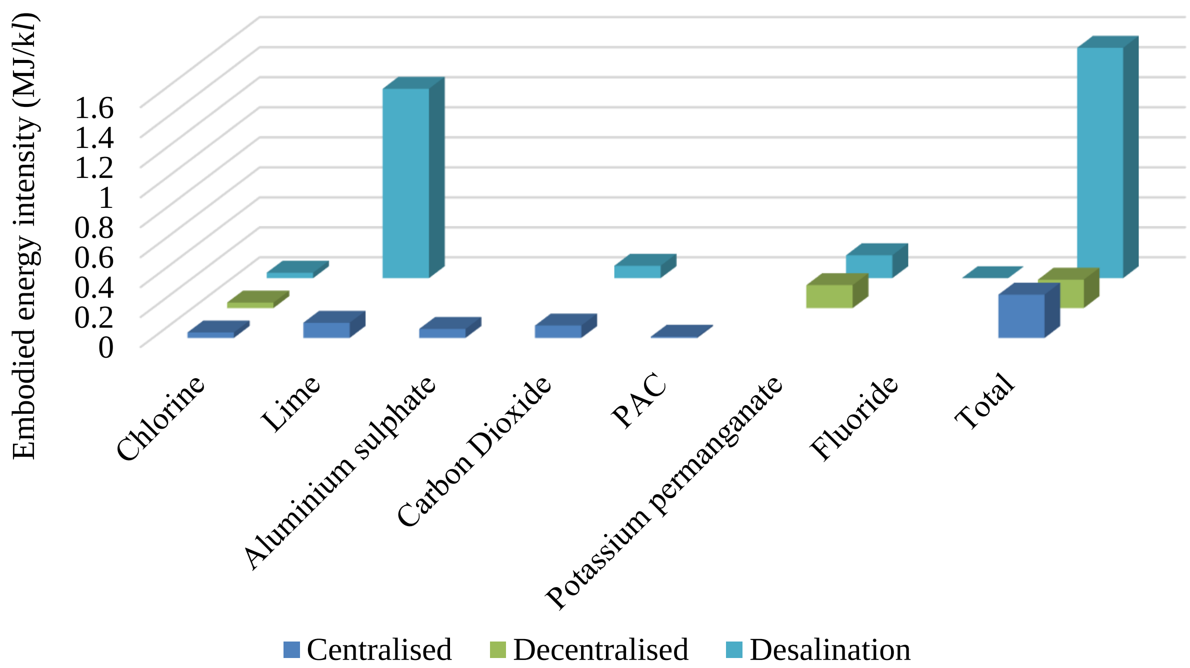


Figure 6-2: Embodied energy intensities of the treatment stage (MJ/k*l*)

The total embodied energy intensity of the Centralised Approach is 35% higher than the Decentralised alternative due to larger quantities of chemicals used to remove contaminants, through extensive chemical and physical processes to produce potable water. The use of lime, to remove hardness from the raw water, contributes the most to the total embodied energy intensity of the chemicals used in the Centralised Approach. However, with the use of membranes to purify the water, the Desalination Approach has the highest embodied energy intensity of all three options and the high intensity of this stage accounts for the Desalination alternative having the highest overall total energy intensity. This is due to the considerable number of inhibitors and stabilisers used as post-treatment to achieve potable water quality levels. The concentrations and related embodied energy intensities of each chemical used are given in Appendix B.

6.1.3 Comparison of the alternatives

Energy implications have significant weight in the feasibility of the exploitation of groundwater from the CFA due to the water quality and location of the source and treatment options. The direct electricity consumption and embodied energy of the chemicals used for the different treatment chains have been presented in the previous sections. This section further compares the two types of energy intensities quantified and discusses their viability from an energy perspective.

Figure 6-3 provides the embodied energy intensities of the treated water of each approach and the electricity intensity of the options during the operational phase, calculated as MJ/k*l* of treated water.

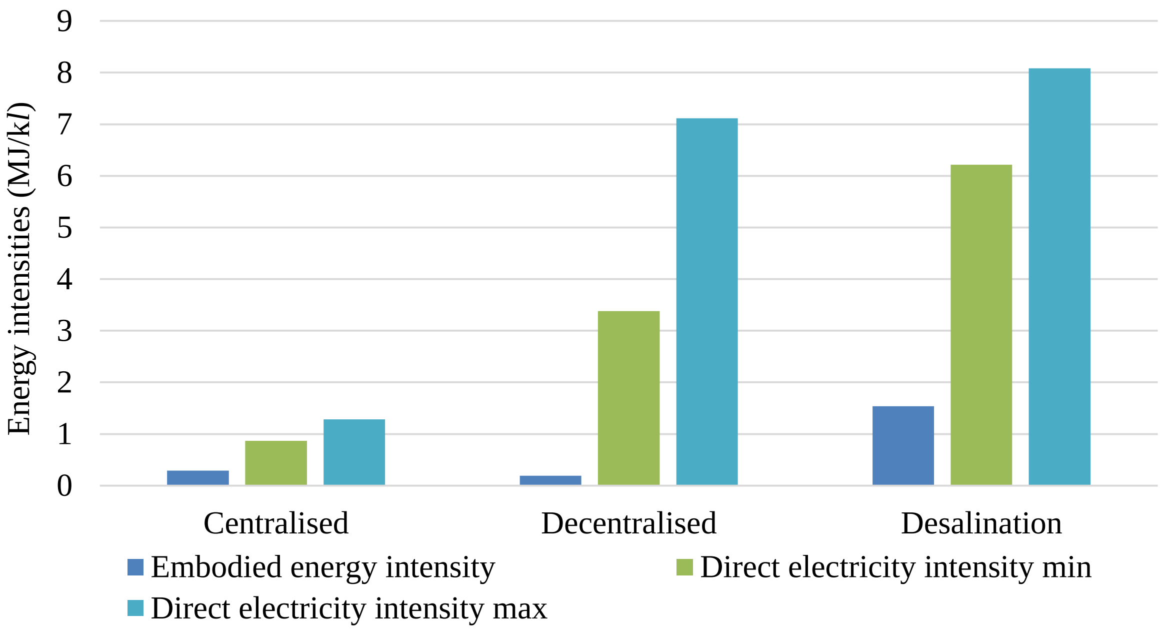


Figure 6-3: Comparison of the two types of EIs of the three approaches

The Desalination alternative is highly dependent on electricity for purification of the raw water due to the high osmotic pressure differences required in the RO unit and its embodied energy component (1.53 MJ/k*l*) is the highest of all due to the chemicals added during post treatment. Its maximum electricity demand of 7.23 MJ/k*l* was generated in its treatment stage despite having the lowest conveyance electricity intensity.

The Centralised Approach's embodied energy intensity is more comparable to its electricity demands since these are smaller than the other two options and more chemicals were needed to remove contaminants to produce potable water as shown in Figure 6-2. The embodied energy of the chemicals made up almost 25% of the total energy footprint of the treated water. At the treatment stage however, the chemicals energy intensity outweighs that of its direct electricity demands (0.08 MJ/k*l*) by 0.21 MJ/k*l* and its share is shown in Figure 6-4.

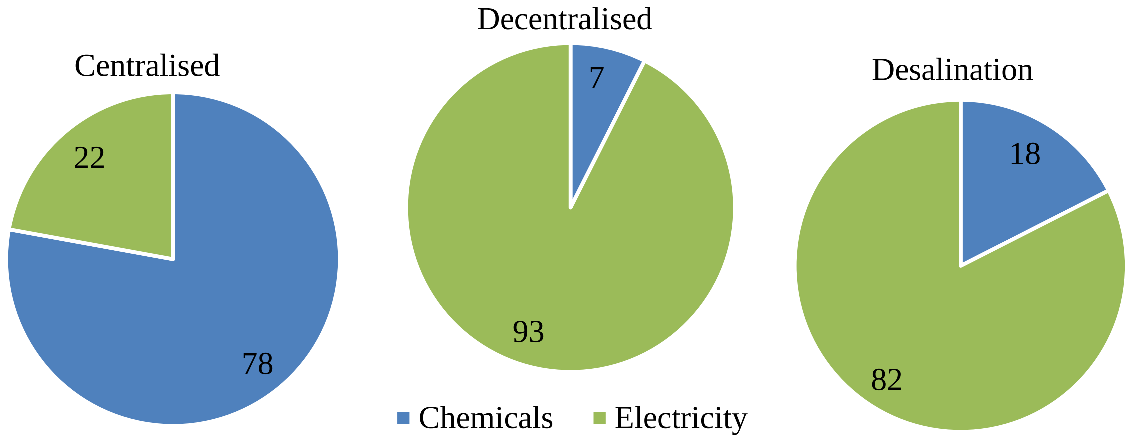


Figure 6-4: Centralised, Decentralised and Desalination alternatives' treatment stage EI breakdown

The Decentralised Approach makes use of only chlorine and $KMnO_4$ for chemical treatment. UV units are used for disinfection which significantly increase its direct electricity intensity component to produce non-potable water.

The resulting total energy intensities of the three alternatives are shown in Figure 6-5. The Centralised option was the most affected by the addition of its embodied energy component. It can be inferred that the treatment stage is the more energy intensive part of the alternative than the abstraction and transmission stages' where only direct electricity intensities were quantified. Desalination was still the most energy intensive one of the three approaches investigated. However, the energy intensity of each approach depended on both their chemicals and electricity consumption across the abstraction, conveyance and treatment stages. The Decentralised option has a larger conveyance component due to its extensive pressure pipelines linking the well-points to the decentralised water treatment plants.

The Desalination option's EI was mostly dependent on its treatment process as a result of the membrane technologies used. However, the implementation of energy recovery devices (ERDs) in South African desalination plants has shown that up to 50% of the energy could be recovered, which can significantly decrease the energy intensity of the Desalination Approach (Swartz *et al.*, 2015). However, the scope of the study was limited to finding the base case and the use of ERDs in this particular option was therefore not further investigated.

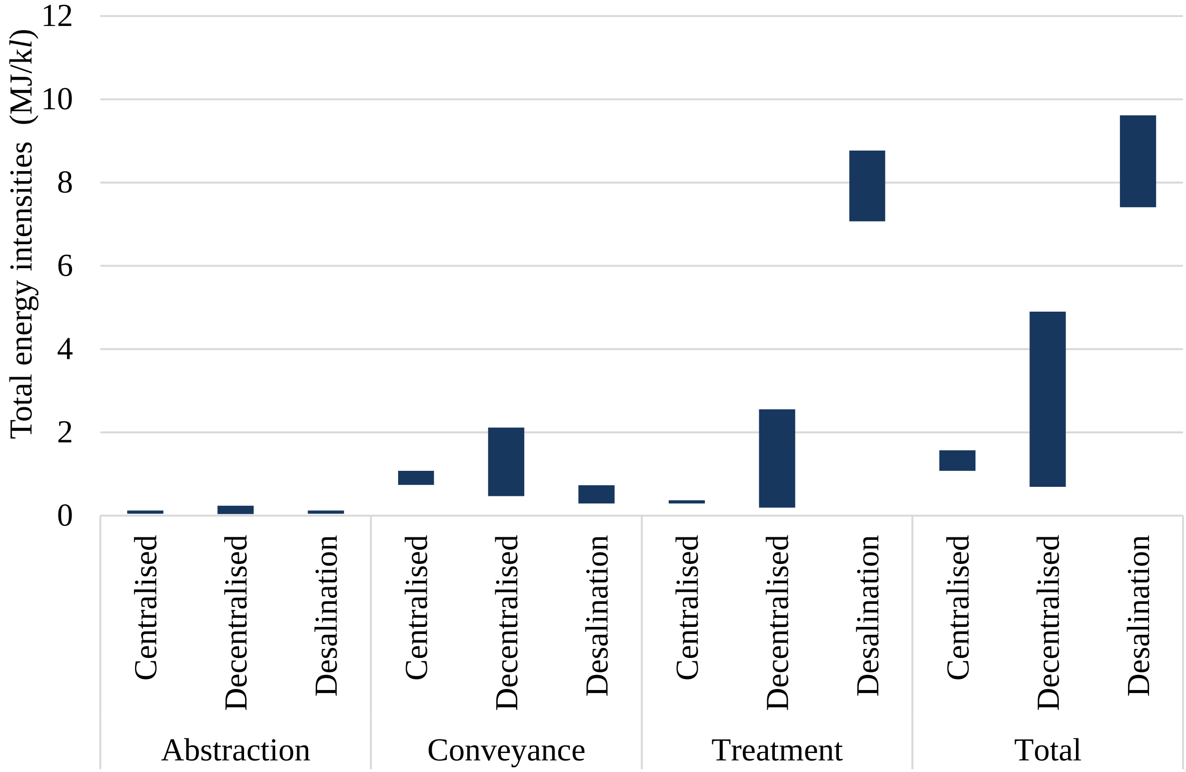


Figure 6-5: Total energy intensities of the three approaches (MJ/k*l*)

While studies on the actual determination of the energy intensities of different parts of the water treatment unit processes in South Africa have not been carried out, there have been several LCAs carried out on specific water treatment works. Friedrich *et al.* (2002), in particular, compared the LCA of an existing water treatment work in Durban to an alternative water work using membrane technologies. The operational stage was also found to be the most energy intensive part of the water treatment work's service life for both the conventional and membrane methods. The results obtained for the Centralised option, which makes use of existing conventional water treatment works, have been found to be lower than the energy intensities obtained by Friedrich *et al.* (2002). However, the differences in results obtained was partially due to the focus of the study being the comparison of the total electricity intensity of the approaches. The LCA approach, in contrast, takes into consideration all materials and chemicals used during construction, operation and decommissioning phases, including their transport, using a cradle to grave approach.

6.2 Water production costs

The costs of producing water using the three approaches were calculated by taking into account both the electricity tariffs and the prices of chemicals used during the operational phases. Possible future electricity tariffs were also used to model the electricity costs component for the three approaches over the next 25 years.

6.2.1 Current costs

The costs of production of potable water have several components including the electricity consumptions, chemicals used during the operational phase as well as the cost of construction, maintenance and decommissioning of the infrastructure. The results obtained in this study are focussed on the costs of chemicals and electricity demands of the operational phase of the three alternatives. Figure 6-6 shows the total costs of the three alternatives, which are again given as ranges of values between the best case and worse case scenarios and are dependent on the physical characteristics of the systems.

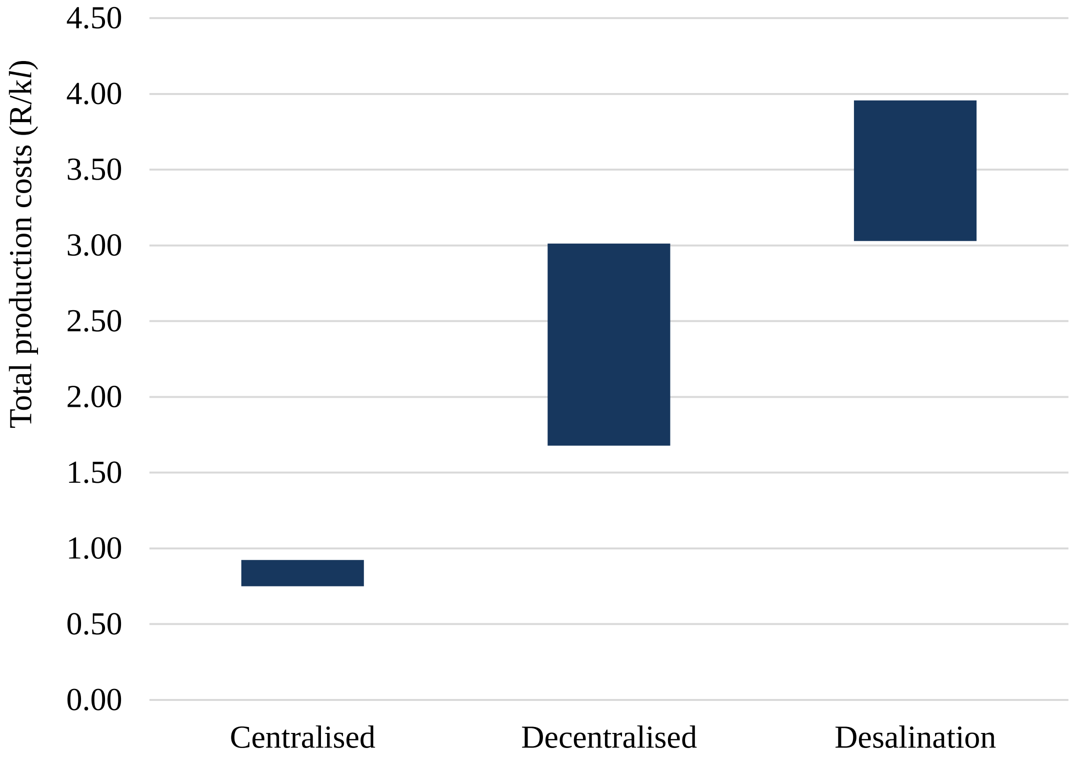


Figure 6-6: Total water production costs (R/k*l*) of the three alternatives

The Desalination option again has the highest costs of production due to its high electricity demands, followed by the Decentralised and Centralised Approaches. The individual costs components of the electricity and chemicals used are given in Table 6-1.

Table 6-1: Individual component costs (R/k*l*) of the alternatives

Approaches	Electricity costs		Chemicals costs	Total	
	min	max		min	max
Centralised	0.38	0.55	0.37	0.75	0.92
Decentralised	1.40	2.74	0.28	1.68	3.01
Desalination	2.47	3.40	0.55	3.03	3.96

The electricity costs were estimated from Eskom's 2017 tariff schedule, explained in Chapter 5, and the different components' total installed capacity required, were matched against the type of users listed in the schedule. However, there are several components related to the delivery of electricity to end-users such as network access and demand charges as well as active and reactive energy charges. Given that the aim of the study is to provide a comparison between the three approaches investigated, the generated electricity demands' production costs calculated only included the generation cost of electricity and did not take into account the other components of electricity tariffs.

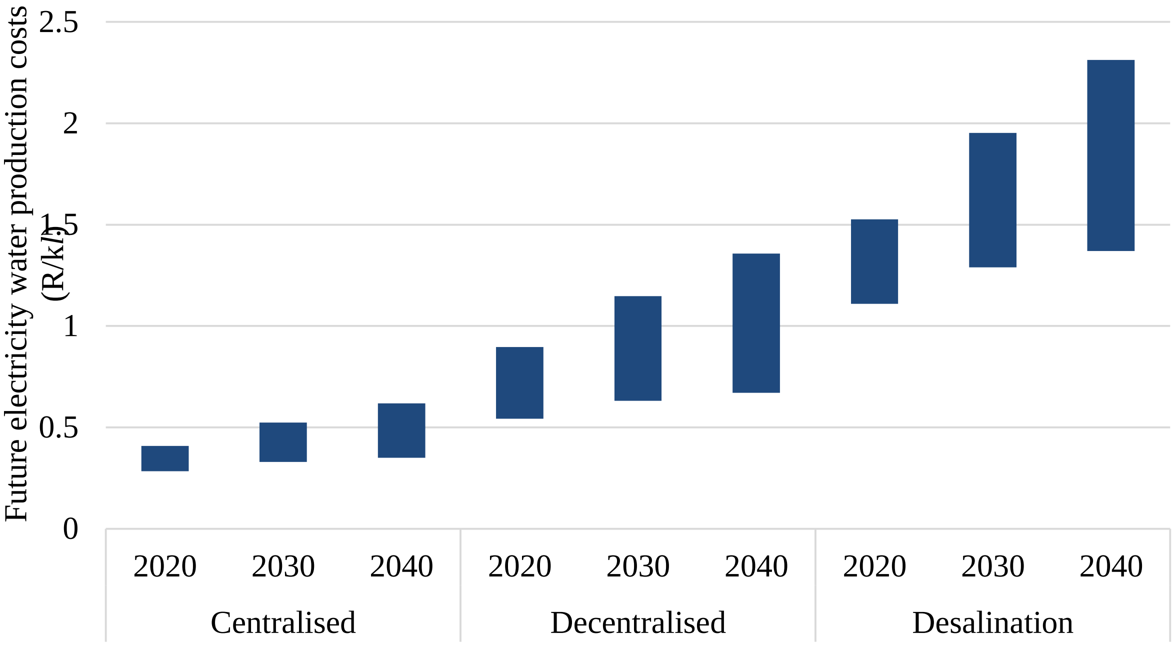
Two time-of-use scenarios were also investigated where the hours of operation of the abstraction and conveyance stages were changed to off peak and standard and off-peak periods as shown in Figure 4-5 (Chapter 4) and Table 5-10 (Chapter 5) while the treatment stage's operational hours were left unchanged. The changes in total costs depended on the alternatives. The highest savings per kl were achieved in the Centralised Approach where its largest electricity demand was created by its conveyance stage. Its electricity costs per kl decreased by 6.2% when standard and off-peak hours were used. The Decentralised and Desalination alternatives had reductions of 0.35% and 2% respectively since most of their electricity demands were created at the treatment stage. However, when the time of use of the abstraction and conveyance stages were limited to only off-peak hours, the energy intensities of the approaches increased, resulting in higher electricity costs. These changes were caused by increased flow rates in the transmission pipes and resulting changes in the network designs. These gave rise to higher friction losses and resulted in greater power required to pump the water across the systems during the off-peak periods.

The costs of the chemicals used during the treatment process were estimated using billing data from Blackheath WTP over a 6-month period. The chemical costs component of the Centralised option was comparable to its electricity uses. The Decentralised and Desalination alternatives electrical demands were larger than their chemical consumption due to their nature and level of treatment procedures adopted.

The costs of water production from desalination processes across South Africa have been documented by Swartz *et al.* (2013). The electrical components of the operating costs of the treatment processes consist of nearly 51% and the desalination option's water production costs fall within range of the reported values. However, the study takes into account a larger proportion of seawater desalination plants than groundwater (brackish) desalination plants, which increases the average energy intensities and production costs.

6.2.2 Future electricity prices

The IRP (2016) and CSIR (2016) future electricity mixes and their respective generation costs were used to map the possible changes in electricity components of the approaches investigated. The results follow the trends of the costs of two future electricity mixes used as shown in Figure 6-7.



Note: Lower end of ranges represent costs using CSIR (2016) and upper ends represent costs using the IRP(2016) electricity generation costs

Figure 6-7: Future electricity costs components in water production costs (R/k*l*)

The Centralised alternative's lower and upper limits are below those of the Decentralised and Desalination alternatives because of its lower electricity intensities. The trends and percentage differences between the approaches stay constant since the same energy intensities are used throughout their design life. However, the lower limits of the future electricity costs of each alternative in Figure 6-7 were made up of the CSIR (2016) electricity generation mix while the higher ends were due to the IRP (2016) mix.

The 2040 electricity costs component of the production costs increases by up to 42% in the case of the CSIR (2016) and 53% in the IRP (2016). The CSIR (2016) scenario's 2040 electricity generation costs are lower than the IRP 2016 future electricity generation costs. The CSIR (2016) study suggests that electricity generation costs can be lower than the 2040 IRP (2016) electricity mix using renewable energy technologies, due to the lower investment costs of the renewable energy technologies used in its mix. The Desalination option's electricity component's share increases by 16% (1.24 R/k*l*) while the Centralised and Decentralised alternatives' electricity costs increase by 0.33 c/k*l* and 0.67 c/k*l* respectively.

6.3 Carbon footprinting

With growing concerns on the impacts of global warming, the carbon footprint of the approaches is an important aspect to be taken into account during decision-making. The carbon footprint of the treated water considered the emissions related to the production of the chemicals and electricity used during the treatment stage.

Figures 6-8 and 6-9 compare the current emissions from each alternative using the current electricity mix of South Africa given in Section 5.3 and the associated emissions of chemicals. The emissions include carbon dioxide, methane and nitrous oxides and their respective global warming potential factors.

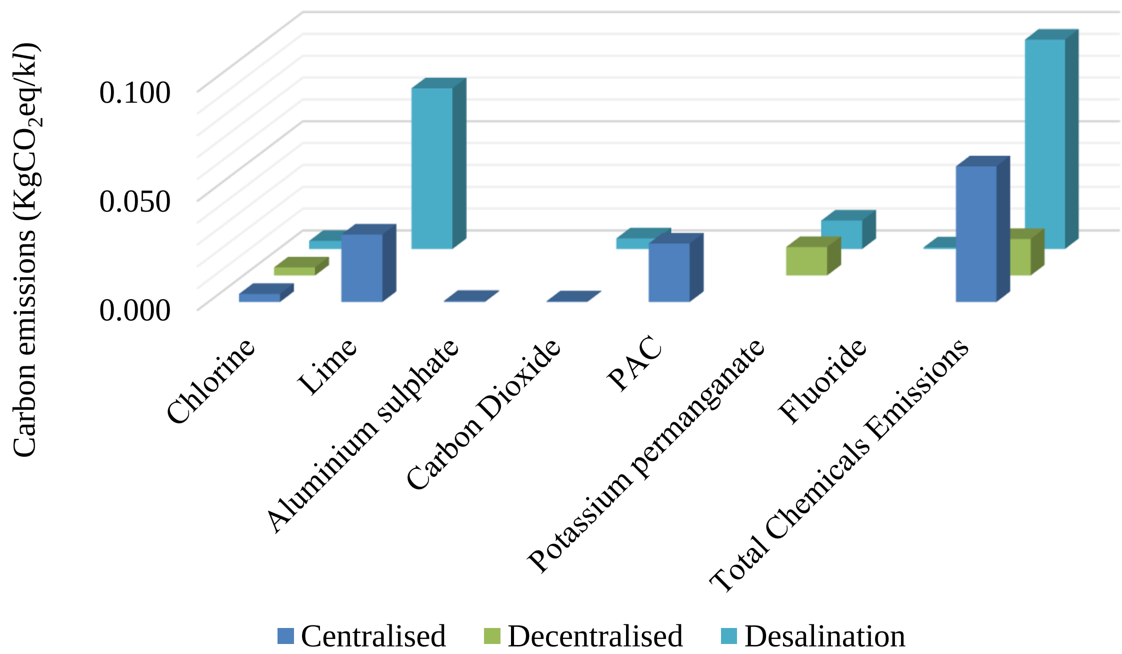


Figure 6-8: 2017 embodied emissions of consumables of the different alternatives

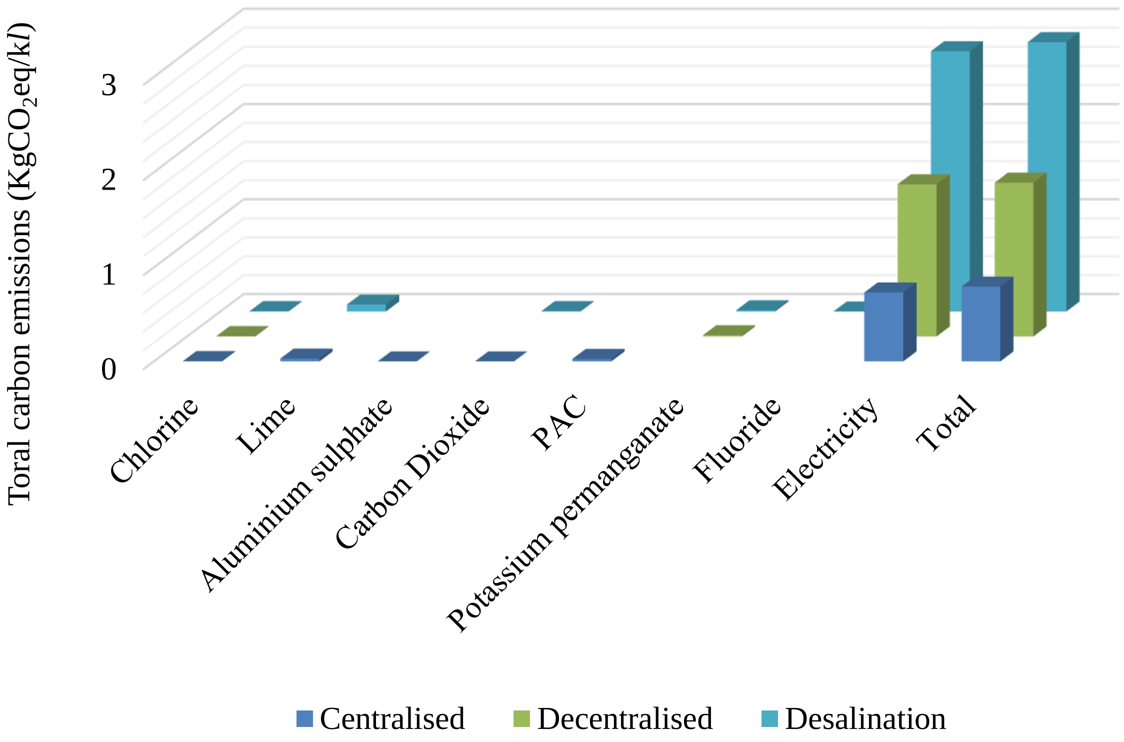


Figure 6-9: 2017 Total emissions intensity of the alternatives

Despite the fact that the Centralised option employs a higher concentration of chemicals (0.09 Kg/k*l*) during its treatment process, the Desalination option (0.079 Kg/k*l* of chemicals) emits 40 g CO_2eq per unit treated water more than the former. A higher usage of lime in the desalination option to stabilise the treated water resulted in emissions of approximately 74 g CO_2eq/k*l*, representing the highest footprint of the chemicals used in all three alternatives. The results also show that emissions from the electricity sector outweigh the associated emissions from the production of the chemicals.

There are several factors that affect the carbon footprint of the options. The electricity component is the largest one in all three approaches since the electricity component's emissions are mainly produced by coal-powered stations. The higher electricity consumption of the desalination option consequently results in a higher carbon footprint of the treated water. The abstraction stage's electricity demands were comparable while the conveyance stage's electricity stage electricity intensities affected their respective total electricity intensities.

Distance and the infrastructural layout between the source and the water treatment plants influence the power required to convey water and therefore, greatly impact on the resulting carbon footprint of the Centralised and Decentralised alternatives. The carbon intensity of the conveyance stage of the Desalination option is smaller than the other two due to the proximity of the abstraction points to the desalination plant. Despite the higher total energy and carbon intensities of the desalination option, the conveyance of fresh water over long distances for conventional treatment, could make desalination a viable alternative. A study conducted in the U.S. where seawater desalination was found to be the better option when compared to conventional treatment methods due to long conveyance distances (Shrestha *et al.*, 2011), confirms this.

The energy sector's contribution to the national GHG emissions in 2010 was almost 428.4 Mt and the water and wastewater sector's energy consumption contributes 72.8 Mt CO_2eq per annum (DEA, 2013). The City of Cape Town's energy related emissions amounted to 21.4 Mt in 2011 and its water services sector contributed 0.194 Mt through its energy usage (SEA, 2015). The total emissions for each approach per annum for the exploitation of the CFA using the current electricity mix are given in Table 6-2.

Table 6-2: Annual emissions (kt CO_2eq)

Centralised	Decentralised	Desalination
17.66	36.1	62.9

The Desalination Approach could potentially emit up to 62.9 kt of CO_2eq per annum during its service life. This represents a small percentage of the total national water sector emissions (0.09%) but represents a significant one for the City of Cape Town's water sector emissions (32%) if a brackish water desalination plant is implemented since the energy intensity of the alternative is mostly generated by the treatment stage. However, the Centralised option represents the least energy and carbon intensive approach with total emissions of up to 17.7 kt CO_2eq per annum. The changing electricity mixes of the country have a considerable impact on these emissions over the design life of the approaches.

The PPD emissions trajectory that South Africa has committed itself to, involves a significant cut in emissions from the energy sector and more particularly from its electricity generation plants. The two possible electricity mixes used for the study, the IRP (2016) and CSIR (2016), have lower shares of fossil fuel based generation plants than the current electricity mix. However, CSIR (2016) scenarios propose a more significant emissions than the IRP (2016) cut over the next 25 years at a lower electricity generation cost. Figure 6-10 shows the reduction in emissions intensities of the treated water with the two future electricity mixes. The emissions decreases over the years with both alternatives with emissions reductions of 47% and 79% using the IRP (2016) and CSIR (2016) electricity mixes respectively. The embodied emissions' share in the Centralised option increases to nearly 30% in 2040 as compared to 8% in 2017 since the electricity mixes are different to the primary energy sources, used for the manufacture of the chemicals to estimate the embodied energy intensity of the chemicals.

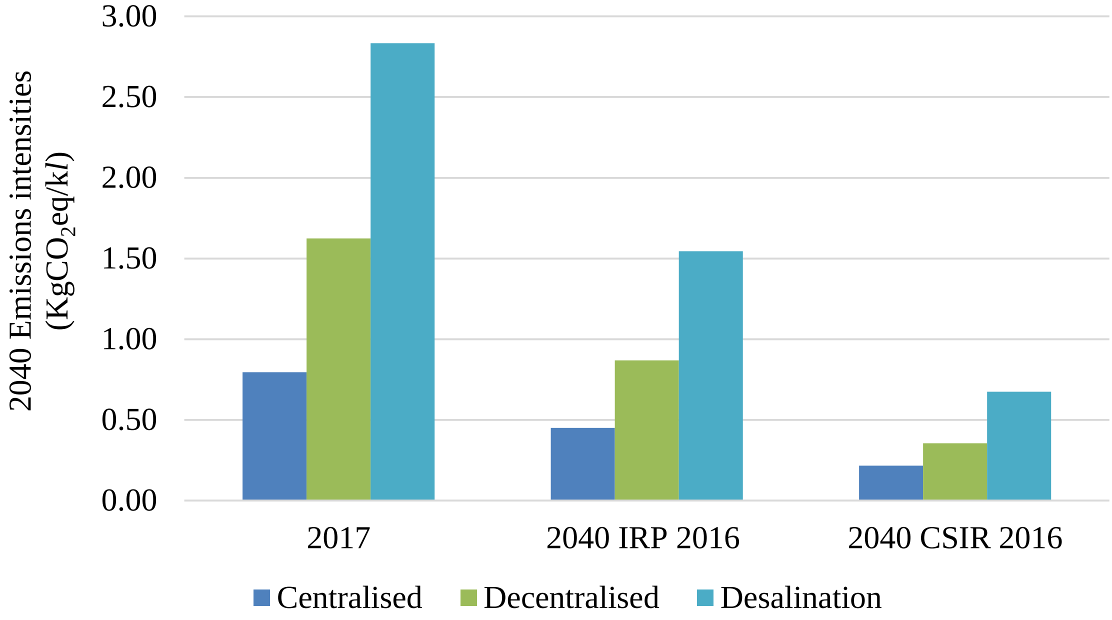


Figure 6-10: 2040 carbon emissions intensities

The costs of renewable energy technologies such as PV and wind turbines have been decreasing over the past few years and have become more cost effective compared to conventional energy technologies. The IRP 2016 scenario has a higher share of fossil fuel sources in its mix, which resulted in higher carbon emissions than the CSIR 2016 scenario. The carbon footprint of the desalination option is the highest one amongst the three approaches due to its electricity source. However, as shown in Figure 6-7, with renewable energy sources, desalination, despite being more energy intensive, could produce water with lower carbon footprints than with the current electricity mix and the IRP (2016) scenario.

The CSIR (2016) scenario also has a much smaller water usage than the IRP (2016) scenario since no new coal and nuclear technologies are added to its mix (CSIR, 2016). Renewable energy technologies, as explained in Chapter 2, have lower water footprints than fossil fuel based energy sources, with the exception of biofuels. With a larger share of wind, PV and gas, less water is required for the functioning of the systems.

6.4 Comparison of the implications of the approaches

The choice of future water supplies and treatment technologies results in direct implications on the energy demands of the water sector, which in turn determines the carbon footprint of the treated water. With the aim of promoting resilience in cities, future water mixes should be formulated by taking into account their current and future impacts on the energy sector, production costs and resulting carbon footprints. Table 6-3 summarises the energy intensities, costs and carbon footprints of each strategy.

Table 6-3: Comparison of the implications of the alternatives

Approaches		Centralised	Decentralised	Desalination
Energy intensities (MJ/k*l*)	min	1.15	3.57	7.75
	max	1.57	7.31	9.62
2017 Production costs using electricity generation costs ((R/k*l*)	min	0.20	0.38	0.78
	max	0.28	0.633	1.08
2040 Production costs using electricity generation costs (R/k*l*)	min	0.35	0.67	1.37
	max	0.62	1.36	2.31
2017 Carbon footprint ($KgCO_2eq$/k*l*)		0.80	1.62	2.83
2040 Carbon footprint ($KgCO_2eq$/k*l*)	CSIR (2016)	0.15	0.34	0.58
	IRP (2016)	0.39	0.85	1.45

The Centralised option has the lowest energy intensity (1.07 to 1.57 MJ/k*l*) which results in the lowest possible production costs and the lowest carbon footprint of the three options investigated, making it the most viable alternative from financial, energy and environmental perspectives. The carbon footprints of the approaches are dependent on their electricity intensities and the Desalination alternative results in the most polluting form of water production. Larger uptakes of renewable energy technologies in the electricity mixes decrease its carbon emissions but are still higher than those of the Decentralised and Centralised alternatives.

6.5 Summary of findings

The energy intensities of the approaches and their implications in terms of current and future costs and environmental impacts have been presented in this chapter. The total and embodied energy intensities were modelled as MJ/k*l* and the direct electricity intensities as kWh/k*l* of treated water. The viability of the options depends on two primary factors, the physical design and layout of the systems and the energy sources used, as highlighted in the previous sections.

The calculations to determine the energy intensities, of each stage of each alternative, depended on physical constraints such as the topographical layout of the catchment and the design of the pumped transmission networks. As was found in the case of the Decentralised option, despite having lower elevation differences and distances between the abstraction points and their WTPs than the Centralised option, the Decentralised Approach had a relatively higher electricity requirement for its transmission stage. This was due to the extensive network required to link 170 abstraction points while preserving the hydraulic integrity of the network. The effects of changing the time of use (on electricity costs) of the abstraction and conveyance stages to standard and off-peak hours resulted in varying results. The design of the networks changed as flows increased and therefore, the EI of the systems running during the whole day was used as the base case.

The Desalination option has been identified as being the most energy intensive option with the highest water production costs. The embodied energy intensity of the chemicals used for pre- and post-treatment were also found to be more than that of conventional water treatment works. Its resulting carbon footprint is mostly caused by South Africa’s coal intensive electricity sector. However, the energy demands of the plant can be significantly decreased with the use of ERDs. Its carbon footprint can further be decreased with cleaner electricity sources as shown in the CSIR 2016 scenario. The various alternatives can potentially increase the Western Cape Water Supply System’s installed capacity by up to 13%.

The composition of the electricity mix supplying the three alternatives shape their water production costs and carbon emissions, due to their electricity demands. The results obtained from the modelling process show that the energy intensities of the alternatives depend on the design of the network but that their costs and carbon footprints are heavily dependent on the electricity sources used. The viability of the Decentralised and Desalination approaches are more dependent on the electricity sources since they have higher electricity intensities than the Centralised Approach. Currently the use of coal as the main electricity source was found to be the highest contributor to the carbon footprint of all three options.

The Centralised approach has been found to have the lowest water production costs, energy intensities and makes use of existing infrastructure as compared to the other two options. Nonetheless, with increased concerns on the availability of water in the region, it is important to consider desalination as an option, due to its versatility in using different feed water types.

7. Conclusions and recommendations

Understanding the intricate water-energy nexus relationship is crucial to assess the impacts of decision-making between the two sectors and is indispensable for holistic planning and development. The growing global and South African energy sector has been moving away from fossil fuel energy sources to renewable energy ones to address the issue of climate change. Increasingly, renewable energy sources are providing electricity at more competitive prices and at lower environmental costs. Similarly, the water sector has been diversifying water supply mixes and adopting non-conventional water treatment mechanisms such as seawater desalination. These changing water supply mixes and treatment mechanisms create significant energy demands from both the fossil fuel and electricity industries while the energy mixes considerably affect the water industry's production costs and resulting carbon emissions. South Africa in particular has been facing energy supply crises and water shortages over the past few years.

The Western Cape is facing a significant period of drought and a number of solutions have been proposed to help alleviate the stress on surface water supplies. The City has been implementing increasing demand side management programmes, at the time of the study imposed a 500M*l*/day cap on water usage, and is considering water augmentation programmes such as seawater desalination and water recycling. The study of the feasibility of the use of stormwater for the artificial recharge of the Cape Flats Aquifer to produce a potential yield of 85 M*l*/day, from March to November, is carried by Okedi (2017) (WRC Project K5/2526). The preliminary results have been used in this dissertation to investigate the energy implications of the abstraction, conveyance and treatment of the water through three different and plausible approaches.

The alternatives were chosen according to the categories of end-users in the catchment and the quality of the groundwater. The presence of large agricultural, industrial and residential areas creates a large demand for non-potable water and the groundwater was classified as having high salinity concentrations at some points (Aza-gnandji *et al.*, 2013). The Centralised Approach makes use of Blackheath and Faure WTPs for treatment to potable water, the Decentralised alternative proposes four decentralised water treatment plants in the catchment to produce water for non-potable end-uses and the Desalination Approach looks at the production of potable water with the groundwater as feed. The dissertation has quantitatively presented the energy demands, water production costs and carbon footprints of the three alternatives investigated and how these will change with possible South African energy futures.

The energy demands created by the alternatives differed mainly due to the topography of the area of study, design of the networks connecting the abstraction points, their treatment plants and respective treatment mechanisms. These consisted of mostly electricity, for the functioning of pumps to abstract and pump the water across the networks, and diesel backup generators. The abstraction stage's energy intensities were found to be the lowest of the three stages examined ranging from 0.01 to 0.07 kWh/k*l* while the conveyance and treatment stages resulted in intensities ranging from 0.08 to 0.59 kWh/k*l* and 0.02 to 2.01 kWh/k*l* respectively. The Desalination Approach was found to have the lowest conveyance energy intensities due to the proximity of the location of the Desalination plant to its abstraction point. The high energy demands produced from its treatment stage were caused by feed-water pumps, used to create high osmotic pressure differences in the RO unit. However, the implementation of ERDs could potentially decrease its energy intensity by up to 50% (Swartz *et al.*, 2013). The EIs of the conveyance of the Decentralised Approach are the highest of the three and depend on the design of the pumped transmission networks to the DWTPs and vary from 0.13 to 0.59 kWh/k*l*.

The total installed electrical capacity required for each alternative varied significantly and could add notably to the WCWSS's energy demands. With the implementation of a brackish water desalination plant, the installed capacity of the WCWSS could potentially increase by 13% (6.3 MW), while the Centralised option only adds 1.3 MW. The location of the Desalination plant was chosen to be close to the existing Cape Flats WWTW to accommodate the possibility for blending of the groundwater with the effluent produced from the WWTW. While blending would significantly increase the volume of water produced from the plant, its electricity usage would also increase due to the higher salinity concentrations of blended feed water.

The embodied energy intensities, quantified in this study, were limited to the chemical usage of the plants during the treatment processes. While the Centralised Approach made use of extensive physical and chemical processes to purify its feed water to potable levels, the Desalination Approach also required a significant amount of chemicals for pre-treatment before the RO unit and post-treatment to stabilise the purified water despite the use of its membrane technology. The embodied energy intensity of the Desalination alternative was found to be the highest (1.54 MJ/k*l*) due to the high usage of chemicals during post treatment while the Centralised Approach's embodied EI was found to be 0.29 MJ/k*l*. However, the share of the chemicals' EI in the total treatment EI of the Centralised approach was 78% as only 0.08 MJ/k*l* of electricity was required at that stage. The Desalination plant's electricity demands were found to be as high as 7.23 MJ/k*l* and its chemicals' EI share is much lower. The Decentralised WTPs, with EIs varying between the Centralised and Decentralised ranges, made use of minimal chemical treatment and backwash pumps and UV units mainly generated its electricity demands.

The costs of water production using Eskom's 2017 tariff schedule and the costs of chemicals obtained from Blackheath WTP for the three approaches were estimated. The water production costs of the Desalination alternative were the highest due to its high electricity usage ranging from 3.03 R/k*l* to 3.96 R/k*l* while the Centralised and Decentralised approaches' production costs ranged from 0.75 to 0.92 R/k*l* and 1.68 to 3.01 R/k*l* respectively. The chemicals costs of the Centralised Approach were found to be comparable to its electricity costs while the Decentralised approach's chemicals costs contributed a small share of the total costs. The large range of possible costs of the Decentralised approach was caused by the design parameters of its pressured pipe networks.

Two time-of-use scenarios were also investigated by changing the abstraction and conveyance stages' operational times to standard and off peak and off-peak only hours according to Eskom's TOU schedule. Increases in flow rates resulting from fewer operating hours caused changes in the base case's EIs as the design of the abstraction and conveyance systems increased with larger flows. While a reduction in electricity costs were noted when the two stages was limited to operation during standard and off peak hours, the costs increased when they was limited to only off-peak periods. These changes were caused by large flows and resulting increases in energy required to pump the water throughout the network while keeping their hydraulic integrity. The Decentralised Approach was found to be the most sensitive to changes in time-of-use due to its vast pipe networks.

It is important that choices of water sources and treatment mechanisms in future water mixes take into account their impacts on the energy sector and their contributions to the water sector's share of GHG emissions. South Africa has committed itself to decrease its emissions following the PPD trajectory and the energy sector, its largest polluting one, must decrease its emissions by half. It is therefore crucial to consider the additional emissions which may arise, by the uptake of these choices. The study further determined the current carbon intensities of the three approaches using both the carbon footprint of electricity and chemical usage during their operational phases. Due to the large share of coal powered plants in the mix, the carbon intensities of the treated water were found to be significant. The Desalination Approach was found to be the most carbon intensive, potentially contributing at least 62.9 kt CO_2eq per annum due to its high dependence on electricity.

The future production costs and carbon intensities, up to 2040, were further estimated using the IRP (2016) future electricity mix and the CSIR (2016) Least-cost scenario as the upper and lower boundaries respectively. The water production costs increased in both cases, with a larger rise in the IRP (2016) 2040 scenario due to its larger share of coal and nuclear and high RE technology prices. The CSIR (2016) has a higher uptake of RE technologies and does not have any new coal and nuclear power plants coming online in the future years. Consequently, the carbon intensities of all three alternatives decreased by 47% in the 2040 IRP (2016) case and by 79% in the CSIR (2016) scenario.

There are also several limitations regarding the scope of the dissertation. Additional studies based on the results of this dissertation can potentially enhance its quality and relevance and may include the following possible recommendations:

- This study consisted of preliminary designs of pumped transmission and dual reticulation networks. More detailed design of the hydraulic components of the Decentralised Approach might yield more accurate energy demand estimations and further targeted end-uses could be investigated. These could be used to carry out a cost benefit analysis of the approaches which would be crucial to determine the overall viability of the alternatives;
- The embodied energy intensities of the construction and decommissioning phases of the three approaches could be further added to the study to provide more insight as to the viability of the approaches. These have different infrastructural developments as explained earlier in the thesis and only the Centralised approach makes use of existing treatment plants.

The energy and carbon intensities will differ with the addition of the construction and decommissioning stages since the Decentralised approach also proposes the construction of a dual reticulation system in addition to its pumped transmission networks;

- The inclusion of energy efficiency measures, technology maturation and energy recovery devices in all three approaches would also influence the energy demands created and further studies incorporating these would be helpful in assessing the potentials of the systems;
- The energy implications of wastewater management and its associated infrastructures would also significantly influence the viability of the approaches and would be a valuable addition to this study;
- The water-energy nexus in this study can be further investigated by evaluating the water consumption of producing electricity using different energy sources, which in turn is used by water supply systems.
- A more detailed assessment of the implications of these findings on water tariffs would be beneficial.
- A follow-up study considering the quality of water delivered would be further worthwhile addition.

Desalination proved to be an expensive, energy and carbon intensive option. It can considerably increase the supply of water but at the same time increase the energy demands generated from the sector. The alternatives were modelled during wet and winter months and these are also considered as peak periods for electricity usage. The Centralised option has lower energy and carbon intensities and produces water at the lowest cost as it makes use of existing facilities. However, potable water produced from the Desalination and Centralised treatment plants would still be supplied non-potable uses which represents a waste of resources. The Decentralised Approach proposes a different approach to introduce dual reticulation systems to avoid misallocation of potable water. However, these have higher costs and carbon footprints than the conventional option (Centralised). The design of the networks and their spatial layout influences their energy consumption and solutions have to be adapted and optimised for each specific area. Their resulting production costs and impact on the environment depend essentially on the electricity mixes of the country.

This study has provided the potential energy implications of the different possible means of exploiting groundwater from the CFA and the related carbon intensities of the treated water through several treatment mechanisms in line with the City's future water mixes. The links between the water and energy sectors have been highlighted and presented quantitatively. The consequences of future water and energy mixes, on each other have been investigated and their importance and role have been emphasised. The study therefore contributes to a growing knowledge on the water-energy nexus in South Africa and to addressing and overcoming the issue of water scarcity and energy related climate change commitments.

8. List of references

Adelana, M., & Xu, Y.(2006). Contamination and protection of the Cape Flats Aquifer , South Africa. Available at: http://www.academia.edu/8832479/Contamination_and_protection_of_the_Cape_Flats_Aquifer_South_Africa [Accessed: 04 January 2017]

Adelana, S., Xu, Y., & Vrbka, P. (2010). A conceptual model for the development and management. Available at : http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S181679502010000400011 [Accessed: 04 January 2017]

Ahmed, N., Taylor, S. & Sheng, Z.(2014). *Hydraulics of Wells: Design, Construction, Testing and Maintenance of Water Well Systems*. U.S: ASCE.

Arena, N., Lee, J., & Clift, R. (2016). Life Cycle Assessment of activated carbon production from coconut shells. *Journal of Cleaner Production*, 125, pp.68–77. doi:10.1016/j.jclepro.2016.03.073

Arndt, C., Davies, R., Makrelov, K., & Thurlow, J. (2011). Measuring the carbon intensity of the South African Economy. Working Paper No. 2011/45, UNU-WIDER.

Aurecon. (2013). *Factors affecting lifetime costs of water supply pipelines*. IMESA Conference 2013. Available at: https://www.aurecongroup.com/~/media/1F38AF9C2A1C492C9601A3740194ECFD.pdf [Accessed: 15 May 2017]

Avlonitis, S.A., Kouroumbas, K., & Vlachakis, N.(2003). Energy consumption and membrane replacement cost for seawater RO desalination plants. *Desalination*, 157, pp.151-158 doi:10.1016/S0011-9164(03)00395-3

Aza-gnandji, C.D.R., Xu, Y., Raitt, L., & Levy, J.(2013). Salinity of irrigation water in the Philippi farming area of the Cape Flats , Cape Town , South Africa. Available at: http://repository.uwc.ac.za/xmlui/handle/10566/709 [Accessed: 06 February 2017]

Bakhshi, A.A., & deMonsabert S.M. (2012). Estimating the carbon footprint of the municipal water cycle. *American Water Works Association*, 104(5), pp 337-347. Available at: http://dx.doi.org/10.5942/jawwa.2012.104.0064.

Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Steduto, P., Mueller, A., Komor,P., Tol, R.S.J., & Yumkella, K.K.(2011). Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy*, 39, pp 7896-7906. doi:10.1016/j.enpol.2011.09.039

Bennett, B. & Park, A.L.(2010). Embedded Energy in Water Studies Study 2 : Water Agency and Function Component Study and Embedded Energy- Water Load Profiles. Available at:http://www.energydataweb.com/cpucFiles/topics/34/Statewide%20Regional%20Water-Energy%20Relationship%20Main%20Report%20Draft%2005-20-10.pdf [Accessed: 15 April 2017]

Blignaut, J., & Inglesi-Lotz., R. (2012). Estimating the oppportunity cost of water for the Kusile and Medupi coal-fired electricity power plants in South Africa. *Journal of Energy in Southern Africa*, 23(4), pp 76-84.

Bonton, A., Bouchard, C., Barbeau, B., & Jedrzejak, S. (2011). Comparative life cycle assessment of water treatment plants. *Desalination*, 284, pp 42-54. doi:10.1016/j.desal.2011.08.035

Brandt, M., Middleton, R., Wheale, G. & Schulting, F.(2011). Energy efficiency in the water industry, a Global Research Project. *IWA.* Available at: http://wpt.iwaponline.com/content/6/2/wpt2011028 [Accessed: 10 March 2017]

Burton, J., & Winkler, H. (2014). South Africa's planned coal infrastructure expansion: drivers, dynamics and impacts on greenhouse gas emissions. University of Cape Town: ERC

Burton, S., Cohen, B., Harrison, S., & Pather-Elias, S.(2009). Energy from Wastewater: A feasibility study. Available at: http://www.wrc.org.za/Knowledge%20Hub%20Documents/Research%20Reports/1732-1-09.pdf [Accessed: 10 March 2017]

BWA, (2016). Making cents of a borehole installation, *Borehole Water Association of South Africa.* Available at: http://bwa.co.za/the-borehole-water-journal/2016/7/3/making-cents-of-a-borehole-installation [Accessed: 10 March 2017].

Carter, N.T., & Campbell, R.J. (2009). Water Issues of Concentrating Solar Power (CSP) Electricity in the U.S. Southwest. Available at: http://www.g-a-l.info/solar-water-use-issues-in-southwest.pdf [Accessed: 15 April 2017]

City of Cape Town (CoCT). (2015). Cape Town: State of Energy. Available at: http://samsetproject.net/wp-content/uploads/2016/02/SEA-Cape-Town-State-of-Energy-Report-2015.pdf [Accessed: 15 April 2017]

City of Cape Town (CoCT). (2017a). Annexure 4: Revised Consumption Tariffs, Rates and Basic charges for electricity services, water services and waste. Available at: https://resource.capetown.gov.za/documentcentre/Documents/Financial%20documents/Annexure%204%20-%20Consumptive%20Tariffs%20-%20Electricity_1516.pdf [Accessed: 10 May 2017]

CoCT. (2017b). Water crisis. 24th Energy Efficiency Forum 2017, Cape Town.

CSIR. (2015). Financial Costs and Benefits of Renewables in South Africa in 2014. Available at:http://www.csir.co.za/media_releases/docs/Financial_benefits_Wind_PV_2014_CSIR_10Feb2015_report.pdf [Accessed: 10 May 2017]

CSIR. (2000). *Guidelines for Human Settlement planning and design. CSIR Building and Construction Technology*. ISBN 0-7988-5498-7

CSIR. (2016). *Least-cost electricity mix for South Africa until 2040*. Green Drinks Panel Discussion, Sandton. Available at: http://climatereality.co.za/wp-content/uploads/2016/12/20161124_Least-cost_electricity_mix_SA_CSIR.pdf [Accessed: 10 May 2017]

CSIRO. (2007). Guidance for the use of recycled water by industry. Available at: https://www.vu.edu.au/sites/default/files/Guidance for the Use of Recycled Water by Industry.pdf [Accessed: 16 March 2017]

Daw, J., & Hallett, K. (2012). Energy Efficiency Strategies for Municipal Wastewater Treatment Facilities Energy Efficiency Strategies for Municipal Wastewater Treatment Facilities. U.S.:National Renewable Energy Laboratory.

DEA. (2012). South Africa Environment Outlook. Department of Environmental Affairs. Pretoria. ISNB 978-0-621-44217-5

DEA. (2013a). GHG Inventory South Africa 2000-2010. Department of Environmental Affairs, Pretoria.

DoE. (2011). Integrated Resource Plan for Electricity 2010-2030. Department of Energy, Pretoria.

DoE. (2013). Integrated Resource Plan for Electricity: Update Report 2013. Department of Energy, Pretoria.

DoE. (2016a). Independent Power Producers Procurement Programe (IPPPP): An overview. Department of Energy, Pretoria.

DoE. (2016b). Integrated Resource Plan Update: Assumptions, Base case results and Observations. Department of Energy, Pretoria.

DWA. (2007). Western Cape Water Supply System: Reconciliation Strategy Study- Treatment of Effluent to potable standards for supply from the Faure Water Treatment Plant. Department of Water Affairs and Forestry, Pretoria.

DWA. (2013). National Water Resource Strategy: Water for an Equitable and Sustainable Future. Department of Water Affairs, Pretoria.

Eberhard, A., Leigland, J., & Kolker, J. (2014). South Africa's Renewable Energy IPP Procurement Program: Success Factors and Lessons. Available at: http://www.ee.co.za/article/south-africas-reippp-programme-success-factors-lessons.html [Accessed: 15 August 2016]

Eberhard, A. (2011). The future of South African coal: Market, investment, and policy challenges. *Program on Energy and Sustainable Development*, (January), p.20,21,30.

Eberhard, R. (2003). Administered prices: Water. National Treasury, Pretoria.

EIA. (2016). *International Energy Outlook 2016*. Available at: https://www.eia.gov/outlooks/ieo/electricity.php [Accessed: 27 March. 2017].

Elbehri, A., Segerstedt, A., & Liu, P.(2013). Biofuels and the sustainability challenge: A global assessment of sustainability issues, trends and policies for biofuels and related feedstocks. Food and Agriculture Organisation of the United Nations: Rome.

EPA. (2013). Energy Efficiency in Water and Wastewater Facilities: A guide to developing and implementing Greenhouse Gas Reduction Programs. Environmental Protection Agency, U.S.

EPA. (2012). Guidelines for water reuse. Washington D.C, U.S.

EPRI. (2013). Electricity Use and Management in the Municipal Water Supply and Wastewater Industries. EPRI, U.S.

EPRI. (2015). Power Generation Technology Data for Integrated Resource Plan of South Africa. EPRI. U.S.

ERC. (2015). South Africa ' s proposed nuclear build plan : An analysis of the potential socio-economic risks. Energy Research Centre, University of Cape Town, Cape Town.

Eskom. (2015a). Eskom fact sheets 2015. Available at:

http://www.eskom.co.za/IR2015/Documents/Eskom_fact_sheets_2015.pdf [Accessed: 15 May 2017]

Eskom. (2015b). Integrated report. Available at: http://www.eskom.co.za/IR2015/Documents/EskomIR2015single.pdf [Accessed: 15 May 2017]

Eskom. (2016). Cooling techniques at eskom power stations. Available at: http://www.eskom.co.za/AboutElectricity/FactsFigures/Documents/CO0005CoolingTechniquesRev12.pdf [Accessed: 15 May 2017]

Eskom. (2017a). Electricity Technologies. Available at: http://www.eskom.co.za/AboutElectricity/ElectricityTechnologies/Pages/Electricity_Technologies.aspx [Accessed: 10 June 2017]

Eskom.(2017b). Tariffs & Charges 2017/2018. Available at: http://www.eskom.co.za/CustomerCare/TariffsAndCharges/Pages/Tariffs_And_Charges.aspx [Accessed: 10 June 2017]

Eskom. (2017c). Water Management. Available at: http://www.eskom.co.za/OurCompany/SustainableDevelopment/Pages/Reduction_In_Water_Consumption.aspx [Accessed: 20 March 2017].

Friedrich, E., & Buckley, C.A. (2007). The use of LCA in water industry and the case for an environmental performance indicator an environmental performance indicator. ISSN 1816-7950. Available at: https://www.researchgate.net/publication/228627550 [Accessed: 14 March 2017]

Friedrich, E., & Pillay, S. (2009). Environmental life cycle assessments for water treatment processes – A South African case study of an urban water cycle. ISSN 1816-7950. Available at: https://www.ajol.info/index.php/wsa/article/view/76710 [Accessed: 14 March 2017]

Ghaffour, N., Missimer, T.M., & Amy, G.L. (2013). Technical review and evaluation of the economics of water desalination : Current and future challenges for better water supply sustainability. *Desalination*, 309, pp.197–207. Available at: http://dx.doi.org/10.1016/j.desal.2012.10.015

Glassman, D., & Wucker, M. (2011). The water-energy nexus: Adding Water to the Energy Agenda A World Policy Paper. World Policy Institute, U.S.

Gleick, P.H. (2000). A Look at Twenty-first Century Water Resources Development. Water International, 25(1), pp127-138. Doi: 10.1080/02508060008686804

Goga, T., Friedrich, E., & Buckley, C.A. (2015). A lca (life cycle assessment) comparison of wastewater reclamation and desalination for the ethekwini municipality – a theoretical study. Available at: http://prg.ukzn.ac.za/docs/default-source/projects/wisa_2016-paper_taahira.pdf?sfvrsn=2 [Accessed: 17 May 2017]

GreenCape. (2016). *Utility- scale renewable energy sector: Market Intelligence Report 2016*. Available at: https://www.green-cape.co.za/assets/MIRs%202016/GreenCape-Renewable-Energy-MIR-2016.pdf [Accessed: 10 March 2017]

GreenCape. (2017). *Market Intelligence Report: Water*. Available at: https://www.greencape.co.za/content/greencape-2016-market-intelligence-reports/

[Accessed: 10 March 2017]

Grigg, N. (2010). Secondary Impacts of Corrosion Control on Distribution System and Treatment Plant Equipment. U.S. Environmental Protection Agency, U.S.

Harter, T. (2003). Water Well Design and Construction. Available at: http://groundwater.ucdavis.edu/files/156563.pdf [Accessed: 10 March 2017]

Hay, R., Mcgibbon, D., Botha, F., & Riemann, K. (2016). Cape Flats Aquifer and False Bay – opportunities to change. Umvoto Africa, Cape Town

Hussey, K, & Pittock, J. (2012). The Energy–Water Nexus: Managing the Links between Energy and Water for a Sustainable Future. Doi:10.5751/ES-04641-170131

IEA. (2012). World Energy Outlook 2012. Organisation for Economic Co-operation and Development, Paris.

IEA. (2016). World Energy Outlook 2016. Organisation for Economic Co-operation and Development, Paris.

IEA. (2017). International Energy Agency: Hydropower. Available at: https://www.iea.org/topics/renewables/hydropower/ [Accessed: 20 April 2017]

Inglesi-Lotz, R., & Blignaut, J. (2012). Estimating the opportunity cost of water for the Kusile and Medupi coal-fired electricity power plants in South Africa. *Journal of Energy in Southern Africa*, 23(4), pp.76–84.

Jacobsen, M., Webster, M., & Vairavamoorthy, K. (2012). *The Future of Water in African Cities*. The World Bank. Available at: http://elibrary.worldbank.org/doi/book/10.1596/978-0-8213-9721-3 [Accessed: 20 April 2017]

Jones, S., Mason, S., & Conrad, J. (2014). Groundwater Specialist Study-Cape Town International Airport Runway Re-alignment and Associated Infrastructure Project. GEOSS, Stellenbosch.

Kahinda, M.J., Taigbenu, A.E., & Boroto, R.J. (2010). Domestic rainwater harvesting as an adaptation measure to climate change in South Africa. *Physics and Chemistry of the Earth*, 35(13-14), pp.742–751. Available at: http://linkinghub.elsevier.com/retrieve/pii/S1474706510001336 [Accessed 9 Jul. 2014].

Karagiannis, I.C., & Soldatos, P.G. (2008). Water desalination cost literature : review and assessment. *Desalination*, 223, pp.448–456. Doi: 10.1016/j.desal.2007.02.071

Karney, B.W., Racoviceanu, A.I., Karney, B.W., Kennedy, C.A., & Colombo, A.F. (2014). Life-Cycle Energy Use and Greenhouse Gas Emissions Inventory for Water Treatment Systems Life-Cycle Energy Use and Greenhouse Gas Emissions. Doi: 10.1061/(ASCE)1076-0342(2007)13:4(261)

Knuppe, K. (2010). The challenges facing sustainable and adaptive groundwater management in South Africa. Germany. ISSN 1816-7950

Kucera, J. (2010). Reverse Osmosis: Design, Processes and Applications for Engineers. Scrivener Publishing LLC, U.S.

Lazarova, V., Lefebvre, O., Conrad, S., Liu, Y., Cornel, P., & Choo, K. (2012). *Summary and concluding remarks – solving the water-energy nexus for tomorrow*. IWA Publishing, UK.

Lundie, S., & Peters, G.M. (2004). Life Cycle Assessment for Sustainable Metropolitan Water Systems Planning.Environmental Science and Technology, vol 38, pp.3465–3473. Doi: 10.1021/es034206m.

MacDonald, A., Davies, J., & Dochartaigh, B.E. (2002). Simple methods for assessing groundwater resources in low permeability areas of Africa. British Geological Survey, UK.

Mabhaudi, T., Mpandeli, S., Madhlopa, A., Modi, A.T, Blackeberg, G. & Nhamo, L. (2016). Southern Africa's Water-Energy Nexus: Towards Regional Integration and Development. *Water*. Doi: 10.3390/w8060235

Madhlopa, A., Pegram, G., Sauka, S., Sparks, D., Keen, S., & Moorlach, M. (2016). The Water-Energy Nexus in the Context of Climate Change: Investigating Trade-Offs between Water Use Efficiency and Renewable Energy Options for South Africa. Water Research Centre. ISBN: 978—4312-0753-4

Marunga, A., Hoko, Z., & Kaseke, E. (2006). Pressure management as a leakage reduction and water demand management tool: The case of the City of Mutare, Zimbabwe. *Physics and Chemistry of the Earth*, 31, pp.763–770. doi:10.1016/j.pce.2006.08.032

Mauck, B. (2015). Managed Aquifer Recharge (MAR) for Stormwater Management on the Cape Flats, Cape Town. University of Cape Town

Mays, L.(2010). *Water Resources Engineering*. Wiley, U.S. ISBN : 978-0-470-46064-1.

Meldrum, J., Nettles- Anderson, S., Heath, G., & Macknick, J. (2013). Life cycle water use for electricity generation: a review and harmonization of literature estimates. doi: 10.1088/1748-9326/8/1/015031

Mo, W. (2012). *Water's Dependence on Energy: Analysis of Embodied Energy in Water and Wastewater Systems*. University of South Florida.

Moreno, M., Planells, P., Corcoles, J., Tarjuelo, J., & Carrion, P. (2009). Development of a new methodology to obtain the characteristic pump curves that minimize the total cost at pumping stations. *Biosystems Engineering*, 102, pp.95–105. doi:10.1016/j.biosystemseng.2008.09.024

Mukheibir, P., & Sparks, D. (2003). Water resource management and climate change in South Africa:Visions, driving factors and sustainable development indicators. Energy Research Centre, University of Cape Town.

Munoz, I., & Fernandez-Alba, A.R. (2008). Reducing the environmental impacts of reverse osmosis desalination by using brackish groundwater resources. *Water Research*, 42, pp.801–811. doi:10.1016/j.watres.2007.08.021

NERSA, 2014. *Regulation of Electricity, Piped Gas and Petroleum Pipelines Industries.* (Presentation). Available at: http://pmg-assets.s3-website-eu-west-1.amazonaws.com/141111pcenergy_nersa.pdf

Obree, M. (2004). Catchment, Stormwater and River Management in Cape Town, South Africa. *Journal of Water Management Modeling*, 6062, pp.589–602. DOI: 10.14796/JWMM.R220-28

Odhiambo, N. (2009). Electricity consumption and economic growth in South Africa: A trivariate causality test. *Energy Economics*, 31(5), pp 635-640. Available at:

https://doi.org/10.1016/j.eneco.2009.01.005

Okedi, J. (2017). Viability of stormwater ponds in the Zeekoe catchment as water resources for Cape Town, South Africa. Draft document. WRC Project K5/2526.

Ormerod, K. (2016). Illuminating elimination: Public perception and the production of potable water reuse. *WIREs Water* 2016(3), pp 537-547. doi: 10.1002/wat2.1149

Panepinto, D., Fiore, S., Zappone, M., Giuseppe, G., & Meucci, L. (2016). Evaluation of the energy efficiency of a large wastewater treatment plant in Italy. *Applied Energy*, 161(January), pp.404–411. Available at: doi.org/10.1016/j.apenergy.2015.10.027

Pelli, T., & Hitz, H. (2000). Energy indicators and savings in water supply. *American Water Works Association Journal*, 92(6), pp 55-62.

Pillay, S., Friedrich, E., & Buckley, C. (2001). LCA Studies of Water Delivery Systems. University of Kwazulu-Natal

Plappally, A.K., & Lienhard, J.H.V. (2012). Energy requirements for water production, treatment, end use, reclamation, and disposal. *Renewable and Sustainable Energy Reviews*, 16(7), pp.4818–4848. Available at: http://dx.doi.org/10.1016/j.rser.2012.05.022.

Plessis, J.A., Swartz, C.D., & Musee, N. (2005). A Desalination Guide for South African Municipal Engineers. Water Research Commission. Available at: http://hdl.handle.net/10019.1/10816 [Accessed: 20 May 2017]

Qiu, T., & Davies, P.A.(2012). Comparison of Configurations for High-Recovery Inland Desalination Systems. *Water*, 2012(4), pp.690–706. doi:10.3390/w4030690

Randall, R., Meyer, D., Inwersen, W., Vineyard, D., Bergmann, M., Unger, S. & Gonzalez, M. (2016). *Life Cycle Inventory (LCI) Data-Treatment Chemicals, Construction Materials, Transportation, on-site equipment, and other processes for use in spreadsheets for Environmental Footprint Analysis (SEPA).* U.S Environmental Protection agency, U.S.

Ramos, H.M., Vieira, F., & Covas, D.I.C. (2010). Energy efficiency in a water supply system: Energy consumption and CO2 emission. *Water Science and Engineering*, 3(3), pp.331–340. Available at: http://dx.doi.org/10.3882/j.issn.1674-2370.2010.03.009.

Rothausen, S., & Conway, D. (2011). Greenhouse-gas emissions from energy use in the water sector. *Nature Climate Change*, pp 210-219. Doi: 10.1038/nclimate1147

RSA. (2015). South Africa's Intended Nationally Determined Contribution (INDC). Available at:http://www4.unfccc.int/ndcregistry/PublishedDocuments/South%20Africa%20First/South%20Africa.pdf [Accessed: 20 March 2017]

SACN. (2014). Modelling Energy Efficiency Potential in Municipal Operations in the Nine Member Cities of the SACN. Available at: http://sacitiesnetwork.co.za/wp-content/uploads/2014/07/Modelling-Energy-Efficiency-Potential-in-SACN-Cities-full-report.pdf [Accessed: 18 March 2017]

SACN. (2015). State of Water in Cities Analysis of water resource and its management in Cities. South Africa.

Scheepers, R., & Merwe-botha, M. (2011). Energy optimization considerations for wastewater treatment plants in South Africa–A realistic perspective. Available at: http://hdl.handle.net/10520/EJC136517.

SEA. (2015). *State Of Energy in South African Cities*. Available at: http://cityenergy.org.za/uploads/resource_322.pdf. [Available at: 18 March 2017]

Seyler, H., & Bollaert, M. (2016). Regional Water Sensitive Design Scenario Planning for Cape Town using an Urban (Geo)hydrology Model. WRC Report No: TT 708/16. ISBN: 978-4312-0878-4

Siddiqi, A., & Anadon, L.D. (2011). The water – energy nexus in Middle East and North Africa. *Energy Policy*, 39(8), pp.4529–4540. Available at: http://dx.doi.org/10.1016/j.enpol.2011.04.023.

Spalding-fecher, R. (2011). What is the carbon emission factor for the South African electricity grid? *Journal of Energy in Southern Africa*, 22(4), pp.8–12.

Sparks, D., Madhlopa, A., Keen, S., Moorlach, M., Dane, A., Krog, P., & Dlamini, T. (2014). Renewable energy choices and their water requirements in South Africa. Energy Research Centre, University of Cape Town.

Spellman, F.R. (2013). *Handbook of Water and Wastewater Treatment Plant*. Lewis Publishers. ISBN 1-56670-627-0

StatsSA. (2013). *National Accounts: Input-Output table for South Africa 2012*. Available at: http://www.statssa.gov.za/publications/Report-04-04-02/Report-04-04-022012.pdf [Accessed 25 Mar. 2017].

StatsSA. (2017). *Mid-year population estimates 2016*. Pretoria, South Africa.

Steyn, G. (2006). Investment and uncertainty: Historical experience with power sector investment in South Africa and its implications for current challenges. University of Cape Town. Available at: http://www.gsb.uct.ac.za/files/Eskom-InvestmentUncertainty.pdf

Stokes, J., & Horvath, A. (2011). Life-Cycle Assessment of Urban Water Provision: Tool and Case Study in California. Department of Civil and Environmental Engineering, University of California.

Swartz, C.D., van der Merwe-Botha, M., & Freese, S.D. (2013). Energy Efficiency in the South African Water Industry: A compendium of best practices and case studies. WRC Report: TT565/13. ISBN 978-1-4312-0430-4

Swartz, C., Genthe, B., Menge, J.G., Coomans, C.J., & Offringa, G. (2015). Direct Reclamation of Municipal Wastewater for Drinking Purposes: Volume 1. WRC Report No. TT 641/15. ISBN: 9781431207091

Thopil, G.A., & Pouris, A. (2010). An overview of the electricity externality analysis in South Africa within the international context. *South African Journal of Science*, 106(11-12), pp.1–6.

Thopil, G.A., & Pouris, A. (2013). Electricity pricing in South Africa International positioning of South African electricity prices and commodity differentiated pricing. *South African Journal of Science*, 109(7), pp.1–4.

Turner, K., Naidoo, K., Theron, J., & Broodryk, J. (2015). Investigation into the cost and operation of Southern African Desalination and Water Reuse Plants. WRC Report No. TT 638/15. ISBN: 9781431207008

Ullah, I., Rasul, M.G., & Khan, M.M.K. (2013). An overview of solar thermal desalination technologies. ISBN: 9781618041753. Available at: https://www.researchgate.net/publication/258568401_An_overview_of_solar_thermal_desalination_technologies [Accessed: 20 April 2017]

UN. (2006). Water: The United Nations World Water Development Report 2. United Nations Educational, Scientific and Cultural Organisation, U.S. ISBN: 92-3-104006-5

UNDP. (2017). *Sustainable Development Goals*. [online] Available at: http://www.undp.org/content/undp/en/home/sustainable-development-goals.html [Accessed 22 Feb. 2017].

UNFCCC. (2017). *Paris Agreement.* [online] Available at: http://unfccc.int/paris_agreement/items/9485.php [Accessed 27 May 2017].

Veolia. (2017). *South Africa's largest desalination plant*. [online] Available at: http://www.veoliawatertechnologies.co.za/vwst-southafrica/ressources/files/1/32048-Mossel-Bay-Desalination.pdf [Accessed 20 Mar. 2017]

Vilanova, N.M., & Balestieri, P.J. (2014). Energy and hydraulic efficiency in conventional water supply systems. *Renewable and Sustainable Energy Reviews*, 30, pp.701–714. Available at: http://dx.doi.org/10.1016/j.rser.2013.11.024.

Voutchkov, N. (2013). *Desalination Engineering Planning and Design*. McGraw-Hill Companies. ISBN: 9780071777155

Water in the West. (2013). Water and Energy Nexus: A Literature Review. Available at: http://waterinthewest.stanford.edu/sites/default/files/Water-Energy_Lit_Review_0.pdf [Accessed: 20 March 2017]

WEF. (2014). *The Water-Energy Nexus : Strategic Considerations for Energy Policy-Makers*. Available at: https://www.weforum.org/reports/water-energy-nexus-strategic-considerations-energy-policy-makers [Accessed: 24 April 2017]

Wilkinson, R., & Kost, W. (2006). *An Analysis of the Energy Intensity of Water in California : Providing a Basis for Quantification of Energy Savings from Water System Improvements Overview of Energy Inputs to Water Systems*. California, U.S.

Wilkinson, R. (2000). Methodology for Analysis of the Energy Intensity of California's Water Systems and An Assessment of Multiple Potential Benefits Through Integrated Water-Energy Efficiency Measures. Available at: http://large.stanford.edu/courses/2012/ph240/spearrin1/docs/wilkinson.pdf

Winter, D. (2011). Power Outages and their Impact on South Africa's Water and Wastewater Sectors. WRC Report KV 267/11. ISBN: 978-1-4312-0101-3.

Winter, K. (2017). *ACDI: Future water options from within the Cape Flats Aquifer: poorly understood risks*. [online] Available at: http://acdi.uct.ac.za/news/future-water-options-within-cape-flats-aquifer-poorly-understood-risks [Accessed 24 Apr. 2017].

Winter, T.C., Harvey, J.W., Franke, O.L., & Alley, W.M. (1998). *Groundwater and Surface water: A single resource*. [online] Available at: https://pubs.usgs.gov/circ/circ1139/pdf/circ1139.pdf.

World Bank. (2017). *Improved water source*. [online] Available at: http://data.worldbank.org/indicator/SH.H2O.SAFE.ZS [Accessed 22 Feb. 2017].

WRC. (2015). *Annual Report 2015/2016*. Pretoria, South Africa.

WRI. (2017). *CAIT: Climate Data Explorer*. [online] Available at: http://cait.wri.org/ [Accessed 23 Mar. 2017].

WRI. (2016). *Water-energy nexus: Business risks and rewards*. Available at: https://www.wri.org/publication/water-energy-nexus [Accessed: 22 February 2017]

WWF. (2016). *Water Facts and Futures: Rethinking South Africa's Water Future*. Available at:http://awsassets.wwf.org.za/downloads/wwf009_waterfactsandfutures_report_web__lowres_.pdf [Accessed: 22 February 2017]

Younos, T., Hill, R., & Poole, H. (2009). Water Dependency of Energy Production and Power Generation Systems. VWRRC Special Report No. SR46-2009. U.S.

Van Aalst, M., Hellmuth, M., & Ponzi, D. (2007). Come Rain or Shine: Integrating Climate Risk Management into African Development Bank Operations. *African Development Bank Working Paper*, 89.

Van Duuren, F.(1997). Water Purification Works Design. Republic of South Africa. Water Research Commision, Pretoria

Van Zyl, J. (2014). *Introduction to Operation and Maintenance of Water Distribution Systems*. WRC Project No: K5/2135. ISBN: 978-1-4312-0556-1.

Appendices

Appendix A: Pump ratings used

Table A-1: Sample abstraction calculations

Strategies	Decentralised				Centralised	Desalination
	Extent 1	Extent 2	Extent 3	Extent 4	C1	D1
Well Depth (m)	27.6	17.6	27.6	42.6	50	50
Effective Head (m)	3.78	3.73	3.78	3.86	4.83	4.83
Volume extracted (m3/s)	0.00579	0.00579	0.00579	0.00579	0.123	0.123
Efficiency	50%	50%	50%	50%	50%	50%
Output power (kW)	0.21	0.21	0.21	0.22	5.83	5.83
Input Power (kW)	0.505	0.498	0.505	0.516	11.7	11.7
Pump (kW)	1.5	1.5	1.5	1.5	15	15
Minimum Energy used (kWh/kl)	0.0242	0.0239	0.0242	0.0248	0.0263	0.0263
Energy used (kWh/kl)	0.0720	0.0720	0.0720	0.0720	0.0339	0.0339
Drilling depth (m)	27.6	17.6	27.6	42.6	50	50
Borehole diameter (m)	0.1	0.1	0.1	0.1	0.264	0.264
Pipe lengths (m)	27.6	17.6	27.6	42.6	50	50

Appendix B: Energy Intensities

Table B-1: Centralised electricity intensities

Abstraction		
No of boreholes	8	
	min	**max**
theoretical energy intensity (kWh/kl)	0.0132	0.0339
Conveyance		
Length of pipelines (km)	8.163	
	min	**max**
TDH (m)	17.0	32.9
Power (kW)	233.7	453.4
theoretical energy intensity (kWh/kl)	0.066	0.128
Faure		
Length of pipelines (km)	14.530	
	min	**max**
TDH (m)	70.4	110.6
Power (kW)	719.3	762.1
theoretical energy intensity (kWh/kl)	0.102	0.108
Blackheath Option 1		
Length of pipelines (km)	13.11	
	min	**max**
TDH (m)	169.8	206.0
Power (kW)	993.9	1419.9
theoretical energy intensity (kWh/kl)	0.140	0.200
Total (kWh/kl)	0.308	0.436
Blackheath Option 2		
Length of pipelines (km)	11.610	
	min	**max**
TDH (m)	38.9	70.9
Power (kW)	342.2	488.8
theoretical energy intensity (kWh/kl)	0.048	0.069
Total (kWh/kl)	0.216	0.305

Conveyance		
Blackheath Option 3		
Length of pipelines (km)	9.940	
	min	**max**
TDH (m)	37.9	65.3
Power (kW)	261.1	450.2
theoretical energy intensity (kWh/kl)	0.037	0.064
Total (kWh/kl)	0.204	0.299

Table B-2: Desalination electricity intensities

Abstraction		
No of boreholes	8	
	min	**max**
theoretical energy (kWh/kl)	0.0132	0.0339
Conveyance		
Length of pipelines (km)	8.06	
	min	**max**
TDH (m)	29.9	
Power (kW)	288	714
theoretical energy intensity (kWh/kl)	0.081	0.202
Treatment		
	min	**max**
Feed water Pump (kW)	3108	4781
UV(kW)	2324	
Backwash pump (kWh/kl)	0.00340	
theoretical energy intensity (kWh/kl)	1.537	2.009
Total	**1.632**	**2.245**

Table B-3: Decentralised electricity intensities

Abstraction		
No of boreholes	170	
	min	**max**
theoretical energy (kWh/kl)	0.0104	0.0720
Conveyance		
Total length of pipelines (km)	785.111	
	min	**max**
TDH(m)	1328.1557	994.252647
Power (kW)	80.635073	366.605107
theoretical energy intensity (kWh/kl)	0.129	0.587
Treatment		
	min	**max**
UV(kW)	2324	
Backwash pump (kWh/kl)	0.00340	
Energy intensity	0.656	0.656
Total	**0.799**	**1.318**

Table B-4: Centralised chemical usages and costs

Chemicals	Actual usage (kg/kl)	Chemical prices (R/kl)	Embodied energy (MJ/kl)	(kWh/kl)
Chlorine	0.0017	0.0296	0.0366	0.0102
Lime	0.0252	0.0901	0.1013	0.0281
Aluminium sulphate	0.0492	0.1037	0.0602	0.0167
Carbon Dioxide	0.0097	0.0503	0.0830	0.0230
PAC	0.0038	0.0958	0.0083	0.0023
Total	0.0897	0.369	0.289	0.0781

Table B-5: Decentralised chemical usages and costs

Extent	Total PE (MJ)	Chlorine (kg/kl)	Embodied energy (MJ/kl)	Costs (R/kl)
1	13300	0.0017	0.0366	0.0296
2	17024	0.0017	0.0366	0.0296
3	29791	0.0017	0.0366	0.0296
4	38303	0.0017	0.0366	0.0296

Table B-6: Desalination chemical usages and costs

Consumables	Dosage (Kg/Kl)	Energy intensity (MJ/kl)	Cost (R/kl)
KMnO4	0.007	0.153	0.246
Chlorine	0.002	0.037	0.030
CaCO3	0.060	1.262	0.214
Fluoride	0.001	0.000	0.014
CO2	0.010	0.083	0.050
Total	0.079	1.535	0.554

Table B-7: Comparisons of the shares of embodied and electricity intensities (MJ/kl)

Approach	Embodied energy intensity	Direct electricity intensity		Total	
		min	max	min	max
Centralised	0.289	0.866	1.281	0.212	0.251
Decentralised	0.190	3.378	7.116	0.035	0.053
Desalination	1.535	6.215	8.082	0.177	0.198

Appendix C: Map of possible dual reticulation networks

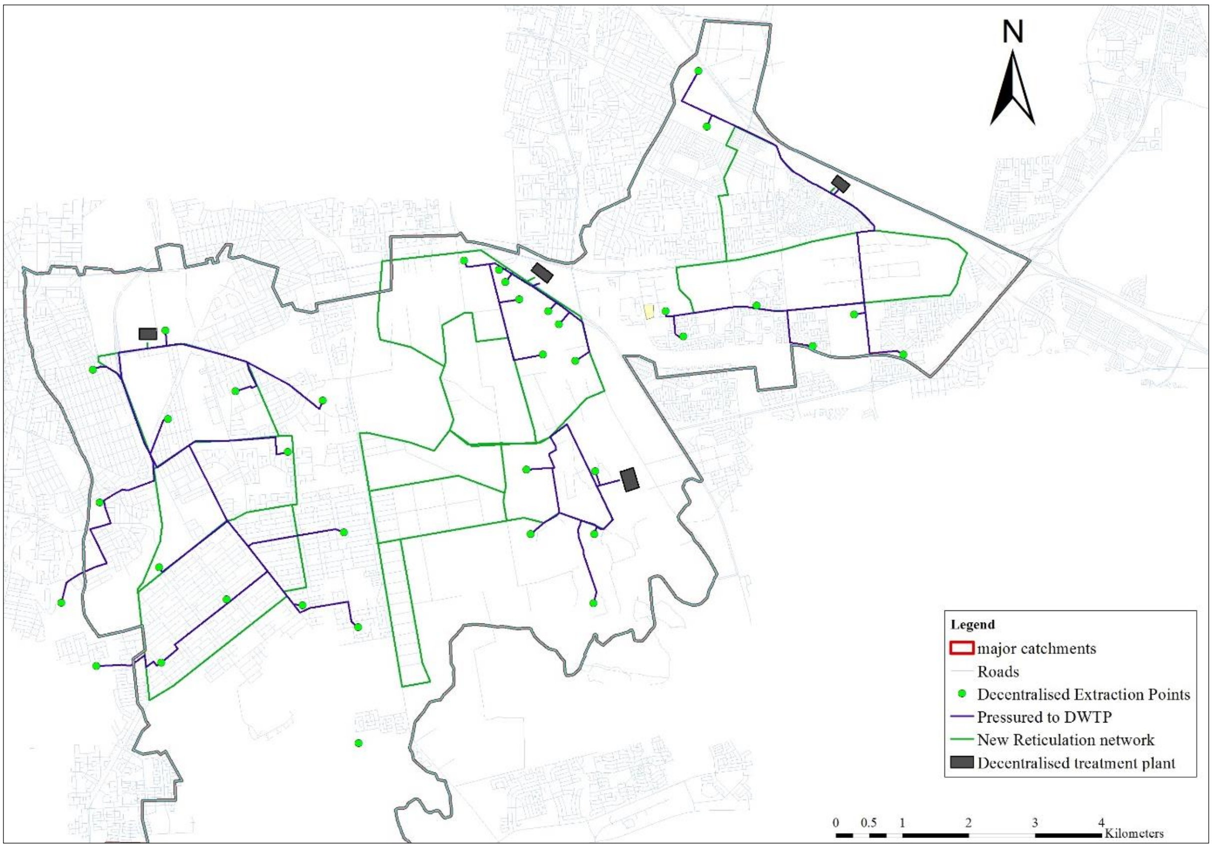


Figure C-1: Map of pumped transmission and dual reticulation networks

Appendix D: Future electricity mixes and production costs

Table D-1: Future electricity mixes technology shares (GW)

2040 Installed Capacity	IRP (2016)	CSIR (2016) Re Optimised
Total	101	184
Gas Turbines	4	10
Diesel OCGT	15	27
Coal	36	17
Hydro + PS	8	5
Nuclear	13	2
Solar PV	11	43
Wind	12	77
CSP	1	1

Table D-2: Future electricity costs (CSIR, 2016; DoE, 2016)

Years	Scenarios		Centralised		Decentralised		Desalination	
	IRP (2016R)	CSIR Least Cost (2016 R)	min	max	min	max	min	max
2020	0.68	0.68	0.284	0.409	0.543	0.896	1.110	1.527
2025	0.83	0.79	0.330	0.499	0.631	1.094	1.289	1.863
2030	0.87	0.79	0.330	0.523	0.631	1.147	1.289	1.953
2035	0.95	0.8	0.334	0.571	0.639	1.252	1.305	2.133
2040	1.03	0.84	0.351	0.619	0.671	1.358	1.371	2.312

Appendix E: Emissions per electricity technology

Table E-1: Emissions per technology (EPRI, 2016)

Pollutants	Coal Pulverised with FGD	Nuclear	OCGT	CCGT	Wind	PV	CSP
CO_2 (kg/MWh)	947.3	0	574	367	0	0	0
SO_x (kg/MWh)	0.46	0	0	0	0	0	0
NO_x (kg/MWh)	1.94	0	0.3	0.2	0	0	0

Table: E-2: Centralised Approach's current and future emissions (Kg/kl)

Pollutants (Kg/kl)		CO_2	SO_x	NO_x	CH_4
2017	**min**	0.326	1.54E-04	6.55E-04	
	max	0.469	2.22E-04	9.43E-04	
IRP 2016 (2040)	**min**	0.183	6.85E-05	3.11E-04	
	max	0.263	9.86E-05	4.47E-04	
CSIR (2040)	**min**	0.080	1.77E-05	9.78E-05	
	max	0.115	2.55E-05	1.41E-04	
Chemicals	**Chlorine**	0.002	1.78E-17	4.39E-06	4.42E-06
	Lime	0.031	1.04E-17	1.23E-07	9.33E-06
	Aluminium sulphate	4.92E-04			
	Carbon Dioxide	0.000	2.661 E-18	9.623 E-07	
	PAC	0.024788	0	7.02E-06	
	Total Chemicals Emissions	5.82E-02	3.08E-17	1.25E-05	1.37E-05

Table E-3: Decentralised Approach's current and future emissions (Kg/kl)

Pollutants (Kg/kl)		CO_2	SO_x	NO_x	CH_4
2017	**min**	0.624	2.95E-04	1.25E-03	
	max	1.029	4.87E-04	2.07E-03	
IRP 2016 (2040)	**min**	0.349	1.31E-04	5.94E-04	
	max	0.577	2.16E-04	9.81E-04	
CSIR (2040)	**min**	0.153	3.40E-05	1.87E-04	
	max	0.253	5.60E-05	3.09E-04	
Chemicals	**Chlorine**	0.002333	1.78E-17	4.39E-06	4.42E-06
	KMnO4	0.008317	2.29E-05	1.68E-05	
	Total	0.01065	2.29E-05	2.12E-05	

Table E-4: Desalination Approach's current and future emissions (Kg/kl)

Pollutants (Kg/kl)		CO_2	SO_x	NO_x	CH_4
2017	**min**	1.274	6.02E-04	2.56E-03	
	max	1.753	8.29E-04	3.52E-03	
IRP 2016 (2040)	**min**	0.714	2.68E-04	1.21E-03	
	max	0.982	3.68E-04	1.67E-03	
CSIR (2040)	**min**	0.313	6.93E-05	3.82E-04	
	max	0.430	9.54E-05	5.26E-04	
Chemicals	**Chlorine**	2.33E-03	1.78E-17	4.39E-06	4.42E-06
	KMnO4	8.32E-03	2.29E-05	1.68E-05	
	CaCO3	7.28E-02	2.47E-17	2.93E-07	2.22E-05
	Fluoride	7.28E-04			
	CO2	4.22E-03	2.66E-18	9.62E-07	1.29E-05
	Total	8.84E-02	2.29E-05	2.24E-05	3.95E-05

Appendix F: Ethics clearance

Application for Approval of Ethics in Research (EiR) Projects
Faculty of Engineering and the Built Environment, University of Cape Town

APPLICATION FORM

Please Note:
Any person planning to undertake research in the Faculty of Engineering and the Built Environment (EBE) at the University of Cape Town is required to complete this formbeforecollecting or analysing data.The objective of submitting this application *prior* to embarking on research is to ensure that the highest ethical standards in research, conducted under the auspices of the EBE Faculty, are met. Please ensure that you have read, and understood the EBE Ethics in Research Handbook(available from the UCT EBE, Research Ethics website) priorto completing this application form: http://www.ebe.uct.ac.za/usr/ebe/research/ethics.pdf

APPLICANT'S DETAILS		
Name of principalresearcher, student or external applicant		AUMASHVINI GOBIN
Department		ERC
Preferred email address of applicant:		Gbnaum001@myuct.ac.za
If a Student	Your Degree: e.g., MSc, PhD, etc.,	MSc Sustainable Energy Engineering
	Name of Supervisor (if supervised):	Debbie Sparks
If this is a researchcontract, indicate the source of funding/sponsorship		
Project Title		Energy impact of stormwater as a source of water in the Lotus River Catchment

I hereby undertake to carry out my research in such a way that:

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

SIGNED BY	Full name	Signature	Date
Principal Researcher/ Student/External applicant	AUMASHVINI GOBIN		15 Feb 2017

APPLICATION APPROVED BY	Full name	Signature	Date
Supervisor (where applicable)	DEBBIE SPARKS		20-02-17
HOD (or delegated nominee) Final authority for all applicants who have answered NO to all questions in Section1; and for all Undergraduateresearch (Including Honours).	HARALD KLINCK		28.2.2017
Chair : Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above questions.	Pp. SAMANTHA KEEN		11.5.2017