A COMPARATIVE LIFE CYCLE ASSESSMENT FOR THE PROVISION OF POTABLE WATER FROM ALTERNATIVE SOURCES IN SOUTH AFRICA

E Friedrich, T Goga and C Buckley

WATER RESEARCH COMMISSION

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A comparative life cycle assessment for the provision of potable water from alternative sources in South Africa

A Report
to the Water Research Commission

by

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EXECUTIVE SUMMARY

BACKGROUND

Water is becoming a scarce resource in many South African municipalities and, therefore, plans are being put in place to deal with increased urban demand for this resource. In the eThekwini Municipality, two methods are currently being considered, among other alternatives, namely the recycling of wastewater and the desalination of sea water. Advanced plans and designs are being developed and many factors are being considered in this decision-making process, including the environmental performance of these methods. In land-locked South African municipalities which do not have access to seawater, the use and treatment of polluted water is a possibility. In particular, water resulting from mining processes is an alternative source available in many of these municipalities and treating this water to potable water standards has been undertaken by several plants in the country. This study investigates the environmental burden resulting from three different membrane methods of providing potable water from alternative water sources (seawater, wastewater and mine water) available in local municipalities and identifies the main contributions to the overall burden of each method, focusing on areas for improvement.

AIMS

The overall objective of the research project is to generate information on the environmental impacts of treating alternative sources of potable water, namely wastewater from the sewer system, seawater from the Indian Ocean and mine water, by using membrane technologies. In particular, the study intends to calculate and compare the environmental burden of each of these water treatment processes by using a sustainability tool commonly referred to as a life cycle assessment (LCA). The aims of this study have been defined as follows:

1. To generate environmental information by investigating each of the water treatment technologies (desalination, recycling of wastewater and reclamation of mine water);
2. To improve the overall environmental performance of these processes;
3. To guide designers and owners as to the life cycle environmental consequences of the selected technologies;
4. To develop capacity in undertaking life cycle assessments.

METHODOLOGY

In order to gauge the environmental impact of the three membrane water treatment processes, an environmental LCA was undertaken for each of them. A LCA is an analytical tool that is used to determine the potential environmental impact of a product or process by characterising and quantifying the inputs and outputs of a specific system. In particular, the procedure provides an evaluation of the product's life cycle from "cradle-to-grave", i.e. from raw material acquisition through production, use, end-of-life treatment, recycling and concluding with final disposal. Thus, an LCA can be utilised to quantify the amount of energy used, the consumption of raw materials, emissions to the atmosphere, as well as the amount of waste generated during a product's life cycle. These inputs (energy and raw materials) and outputs (emissions to air, soil and water bodies) are scaled in relation to a functional unit, which in this case was defined as 1 kℓ (1 m^3) of treated water at potable water standards, for all three technologies. All inputs and outputs for the production of water by these three technologies were inventoried and quantified. For these quantifications, mass and energy balances were used. Based on the quantities of these inputs and outputs the potential impacts on the environment were calculated in different impact categories.

The three technologies investigated are based on existing or planned water treatment plants in South Africa, and three case studies were selected. These three case studies are in early stages of project development and, therefore, improving their environmental performance is possible. For desalination technology, the desalination plant planned for the south of the eThekwini Municipality was used. This project has moved from the feasibility stage into the pilot plant stage, and for this study the data and calculations contained in the feasibility report were used. Data from the operation and design of phase 1 of an existing mine water reclamation scheme situated in Mpumalanga was collected to model the environmental impacts of treating mine-affected water. The eThekwini Municipality is planning to implement membrane treatment of municipal wastewater using Remix technology, which combines wastewater with seawater. The technology was developed by the Hitachi Corporation. This project was selected as a third case study. This project is at pre-feasibility stage and obtaining detailed design data was a challenge.

The impact categories, on which the environmental performance of the three methods of producing potable water was compared, include global, regional and local impacts. They are as follows: global warming, stratospheric ozone depletion, photochemical ozone formation, acidification, nutrient enrichment, ecotoxicity, human toxicity and waste (hazardous and non-hazardous). The process of conducting a LCA is iterative in nature and requires the use of a software package capable of modelling large amounts of data. The SimaPro LCA software was utilised for the purposes of this study. It contains various inventory datasets for various processes and materials to aid in the creation of an accurate LCA model. These data sets are in the form of inventory tables which include all the inputs and outputs for a particular process (e.g. electricity generation) from the point of extracting raw materials used for that process (or product) to the point where this process (or product) is incorporated into another one and is sold on the market (also referred to as a “cradle-to-gate” approach). These data sets were used to construct a LCA model for each of the three membrane technologies investigated. Once the models were constructed it was possible to calculate environmental scores for each membrane technology for each of the impact categories considered, and an environmental profile for each technology was generated. In the next stage, the data was analysed to determine what caused the highest contributions to the environmental scores for each of the membrane technologies investigated and individual improvement analyses were conducted.

RESULTS AND DISCUSSION

Environmental scores were generated for the three case studies investigated (desalination of seawater, membrane treatment of mine-affected water and membrane treatment of municipal wastewater mixed with seawater). For desalination and treatment of mine-affected water, the operation stage of the life cycle assessment carried the highest environmental burden, with reverse osmosis processes making the highest contributions. For all three case studies, the energy required for the treatment of the different types of water was the predominant factor determining environmental scores. A direct comparison of these scores is not possible due to the large differences in the design and environmental modelling of the three technologies/case studies investigated. These results show that the main contributor in terms of the environmental impacts from these three technologies can be traced back to the generation of electricity as undertaken in South Africa.

Energy requirements differed with desalination needing about 3.73 kWh/kℓ of potable water, the membrane treatment of waste water and seawater (Remix system) needing 2.6 kWh/kℓ of potable water and the membrane treatment of mine-affected water needing, theoretically, about 2.16 kWh/kℓ of water treated. However, the mine-affected water treatment plant, which is the only plant where calculated theoretical data was compared with real, operational data, currently operates with a much lower demand for energy (about 1 kWh/kℓ of water intake). Comparison with the literature showed that the energy requirements for desalination are within the acceptable range (3.5–4.5 kWh/kℓ) for various desalination plants around the world. In South Africa, energy requirements for reverse osmosis desalination are in the range of 3.97 to 4.39 kWh/kℓ of potable water. These energy requirements have been lowered in Remix technology by mixing seawater with municipal wastewater, and in Japan this technology required between 2.9 kWh/kℓ (earlier versions) and 2.6 kWh/kℓ (most recent) of potable water produced.

Modelling of the eThekwini Municipality case study used the most recent figures. There is very little in the literature about energy requirements for mine-affected water, but requirements will vary depending on the quality of the water needing treatment and, in many cases, this is site specific, based on the local geology and the methods of mining. As energy inputs were considered quite significant for all three technologies, a series of additional modelling was undertaken in order to estimate whether renewable energy sources improve the environmental performance of desalination and the treatment of mine-affected water. The environmental burden of energy provided from alternative sources (solar and wind generated electricity) was modelled and showed that the overall environmental scores can be reduced, in particular, by employing solar electricity to run the desalination plant.

In the case of this improvement intervention, the desalination plant showed scores that were almost as low as conventional treatment of water as undertaken by Umgeni Water. For example, desalination using wind and solar power will produce greenhouse gas emissions in the range of 0.08–0.3 kg CO_2 e/Kℓ Water which is comparable with the current emissions from conventional processes – Wiggins Waterworks emits 0.11 kg CO_2 e/Kℓ water and Durban Heights emits 0.08 kg CO_2 e/Kℓ water. (These are the two main potable water treatment plants in the eThekwini Municipality).

Some of the chemicals which are used, or are planned to be used, in the three case studies also have a considerable environmental impact, namely the chemicals used for post-treatment (lime and carbon dioxide for desalination) and for pre-treatment (ferric chloride and biocide for the mine-affected water case study). In the case of Remix technology, sodium hydroxide had the highest environmental burden.

CONCLUSIONS AND RECOMMENDATIONS

Energy usage is the most important contributor to the overall environmental performance of the processes investigated. The reverse osmosis stage in the operation of the three membrane plants investigated makes the highest contribution in terms of environmental burden. Environmental improvement can be achieved by making this stage more energy efficient, improving system design, reducing membrane fouling, developing low-energy membranes and using alternative sources of power which have a lower environmental burden. It is envisaged that the energy efficiency of reverse osmosis will be improved by the development of novel membranes; however, this process needs time. There is also a chemical and technical limit to the improvements that can be achieved with regard to membrane development and the energy requirements of the process. Therefore, in South Africa, using energy efficiency measures (e.g. using variable frequency drives on energy intensive motors) and alternative energy sources for desalination that are based on existing technology should be encouraged as a possible short-term intervention which can achieve the best environmental improvements under current conditions. Recommendations for further research include the collection of more South African LCA data and the customisation of the LCA impact categories to suit local conditions. The number of case studies investigated by LCA studies should increase, particularly for mine-affected treatment technologies which are very sensitive to the quality of mine water and the processes employed.

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ACRONYMS & ABBREVIATIONS

AMD	Acid Mine Drainage
AP	Acidification Potential
BWRO	Brackish Water Reverse Osmosis
CEB	Chemically Enhanced Backwash
CIP	Cleaning in Place
DEA	Department of Environmental Affairs
DEAT	Department of Environmental Affairs and Tourism
DUP	Deep Bed Up-Flow
DWP	Drinking Water Production
DWAF	Department of Water Affairs and Forestry
DWA	Department of Water Affairs
DWS	Department of Water and Sanitation
EIA	Environmental Impact Assessment
EMS	Environmental Management System
EPA	Environmental Protection Agency (United States of America)
GHG	Greenhouse Gases
HDPE	High Density Polyethylene
IPP	Integrated Product Policy
IPR	Indirect Potable Reuse
ISO	International Organisation for Standardisation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCM	Life Cycle Management
MF	Microfiltration
MWRS	Mine Water Reclamation Scheme
NCPC-SA	National Cleaner Production Centre of South Africa
NF	Nanofiltration
NGO	Non-governmental Organisation
NMVOC	Non-methane volatile organic carbon
NREL	National Renewable Energy Laboratory
ODP	Ozone Depletion Potential
PES	Polyethersulphone
PMFP	Particulate Matter Forming Potentials
REDISA	Recycling and Economic Development Initiative of South Africa
REPA	Resource and Environmental Profile Analysis
RO	Reverse osmosis
RWQO	Receiving Water Quality Objective

SCA	South Coast Augmentation Pipeline
SEA	Strategic Environmental Assessment
SETAC	Society of Environmental Toxicology and Chemistry
SWRO	Sea Water Reverse Osmosis
TDS	Total Dissolved Solids
UF	Ultrafiltration
UKZN	University of KwaZulu-Natal
UNEP	United Nations Environment Programme
WC	Water Catchment
WDM	Water Demand Management
WMA	Water Management Area
WSSD	World Summit on Sustainable Development
WTP	Water Treatment Plant
WWT	Waste Water Treatment

GLOSSARY

Acid rain - Rainfall of abnormally high acidity which results from atmospheric pollution by emissions of sulphur dioxide, nitrogen oxide, and chloride.

Catchment - An area from which any rainfall will drain into the watercourse or watercourses or part of a watercourse, through surface flow to a common point or common points.

Desalination - The removal of unwanted salts (constituents) from seawater or brackish water to make it fit for use.

Effluent - The liquid discharged from a processing step, usually from an industry, from a water purification works or from a waste water treatment plant.

Emissions - Solid, liquid or gaseous substances, or energy in the form of heat, usually discharged into the environment, by people and other living organisms or by chemical or physical processes; usually refers to products of combustion emitted into the atmosphere.

Global warming - The increase in the average surface temperatures across the globe, usually measured over long periods of time; reported to have increased by 1ºC over the past hundred years.

Greenhouse gas - Gases such as water vapour, carbon dioxide and methane in the atmosphere that do not affect incoming sunlight but trap heat emitted from the earth, thus contributing to global warming; hence the greenhouse effect.

Groundwater - Rainfall that infiltrates into the soil surface and percolates downwards, seepage from water in streams, lakes and artificial impoundments, and irrigation water that percolates down into the ground and accumulates in aquifers comprising permeable underground layers of sand, gravel and rock.

Potable water - Water intended to be used for drinking or domestic purposes.

Rainwater harvesting - Interception, collection and storage of water during rain seasons for use in other times.

Reclamation - Treatment of wastewater for reuse, indirectly or directly, as potable water.

Reuse - Utilisation of treated or untreated wastewater for a process other than the one that generated it, i.e. it involves a change of user. For instance, the reuse of municipal wastewater for agricultural irrigation. Water reuse can be direct or indirect, intentional or unintentional, planned or unplanned, local, regional or national in terms of location, scale and significance. Water reuse may involve various kinds of treatment (or not) and the reclaimed water may be used for a variety of purposes.

Surface water - Runoff that occurs in streams and rivers, natural lakes and reservoirs; a major resource for water supplies.

Wastewater treatment - This includes any process which may be used to favourably modify the characteristics of wastewater.

Water resource strategy - A plan for dealing with uncertain future circumstances with respect to the availability of clean and sufficient water for domestic and commercial use. This is the set of rules by which the action to be taken depends on the circumstances, including natural events such as climate change and the actions of other people.

CHAPTER 1: **BACKGROUND**

1.1 INTRODUCTION

Lack of water is a growing concern in South African cities. In the near future, alternative sources of water will be necessary to satisfy demand. Currently, the eThekwini Municipality is in different stages of planning to obtain potable water from the recycling of wastewater as well as from desalination. Another alternative source of water, particularly in Gauteng, is the reclamation of mine water. This study investigates the environmental impacts of these three technologies by employing a life cycle assessment (LCA) approach. Such a study is useful and necessary in order to summarise and provide information regarding focus areas with the highest environmental burdens of these technologies in order to improve them environmentally and to assist in the future design of water treatment plants in the country. Previous studies have shown that LCA has the potential to deliver improvements to local water systems (Buckley et al., 2011). However, such studies have only been employed for conventional technologies. Water demand is increasing in all municipalities in South Africa (Department of Water Affairs, 2013); however, the supply is limited and the Department of Water and Sanitation (DWS) reports periodic droughts (DWS, 2015). Therefore, alternative sources and associated technologies for the production of potable water are necessary. Such technologies are currently relatively rarely used, and only on a small scale; however, in the future, with increasing demand they will become mainstream. Hence, it is imperative to shape the design process for these technologies by considering local environmental factors from the outset, so as to reach the best outcome locally that can be effectively utilised as a model for future projects of this nature.

As water is an essential ingredient and used for virtually any product manufactured in the country, the environmental burdens associated with the generation of potable water are a key component in a national LCA database. Such a database is planned under the umbrella of the United Nations Environment Programme (UNEP) and the National Cleaner Production Centre of South Africa (NCPC-SA). In the absence of South African information, importers of South African goods might use any international data available. Potentially, this has the tendency to reflect negatively on these goods which might lead to environmental scepticism towards South African exports. Previous studies (see Loubet et al., 2014, and Buckley et al., 2011, for international and local reviews) have demonstrated the versatility of LCA as a decision-making tool in the water industry for comparing technologies and scenarios, identifying improvement opportunities and prioritising interventions and their consequences in complex water systems. Therefore, in South Africa, it is important to promote the use of LCAs in the water sector in order to increase the efficiency of processes and systems, to promote life cycle-based water footprinting and to include differentiated water consumption data into life cycle inventories to efficiently utilise water as a resource (Buckley et al., 2011).

South African studies show that LCA is a valuable and versatile tool for the water sector (Buckley et al., 2011). It can not only be used as a “focusing” tool to increase the efficiency of existing water processes and/or systems but also as a “comparative” tool to direct decision making for future water-related developments and technologies. In particular, the quantitative and holistic approach of the LCA methodology makes this tool suited for scenario analysis which should lead to more informed decisions and better overall outcomes for the design in the water sector itself and also for other sectors in which water is a significant input stream" (Buckley et al., 2011). Most past investigations were focused on conventional water treatment processes in South Africa, and there is a lack of local LCA studies that investigate alternative sources of potable water. Thus, there is a real gap with regard to this type of research. Internationally, there is a strong body of literature with regard to desalination of sea water, but very little on the reclamation of mine water and the recycling of wastewater. Locally, there is only one study (Friedrich, 2002) which has investigated the use of membranes in the production of potable water from fresh water. However, there is no such investigation for the local desalination of sea water. Therefore, it is important to fill this gap in the local context and to use the LCA tool to its full potential in order to positively shape future developments of these alternative technologies.

1.2 PROJECT AIMS AND OBJECTIVES

The overall aim of the research project is to generate information on the environmental impacts of treating alternative sources of potable water, namely wastewater from the sewer system, seawater from the Indian Ocean and mine water. In particular, the study intends to calculate and compare the environmental burdens of each these water treatment processes by using a sustainability tool commonly referred to as a life cycle assessment (LCA). Therefore, the specific objectives of this study were:

1. To conduct life cycle assessments for each of the technologies/processes/cases;
2. To focus on areas of potential environmental improvements for each technology/process;
3. To compare the environmental impacts of all three technologies;
4. To compare the environmental burden of each of these proposed water treatment processes with specific environmental burdens of existing water treatment technologies.

1.3 SCOPE AND LIMITATIONS

The scope of this project is limited to the three case studies investigated. As different input as well as output water qualities are used in these processes a direct comparison of the three technologies is not possible. The LCA studies have been guided by the International Organisation for Standardisation (ISO) 14040 series of standards (ISO 14040, 2006) which specify the methodological steps to be followed. All three case studies investigated are at initial implementation, feasibility and planning stages in the development cycle; if, in the long-term implementation of these processes, there are changes in operational data, some of the conclusions of this study might be affected, in particular if energy demand figures change. There were confidentiality issues around the mine water treatment process data as well as the data for the membrane treatment of municipal wastewater (i.e. the Remix technology). These delayed the study considerably. In particular, problems were experienced with data collection for the membrane treatment of municipal waste water due to delays in the project by the eThekwini Municipality and their partners. Due to these delays, the feasibility study was not released and it was not possible to calculate precise environmental scores for the construction stage of the planned Remix plant, since data on infrastructure (tanks, pipes and pumps) was not available. Therefore, in this case study, only the operational stage was modelled and the environmental burdens of the construction stage were approximated by using the relevant literature. South African emission data was not available for some of the speciality chemicals specified to be in the three case studies investigated. Where such data was not available, international data was used from processes that were similar to the local ones. Since one of the aims of this study was to broaden the LCA knowledge of water professionals a lot of background information has been included in the literature review.

CHAPTER 2: **LITERATURE REVIEW**

2.1 INTRODUCTION

This section provides a background to the study. It firstly focuses on the water situation prevailing in South Africa, elaborating on current supply and demand, future forecasts and various strategies. Thereafter, a general discussion on the principles of a LCA follows. The chapter concludes with an insight into the applications of LCA for water systems and processes.

2.2 FRESH WATER IN SOUTH AFRICA

2.2.1 Water Resources

Water is widely seen as a valuable resource primarily for its ability to sustain both aquatic and terrestrial organisms. Across the world, water crises are erupting with water scarcity being listed as the third most significant global risk (World Economic Forum, 2014). South Africa is not unaffected by this phenomenon – on the contrary, it has been ranked as the 30th driest country worldwide based on the low and varied rainfall received together with high natural evaporation rates (Department of Water Affairs, 2013). According to the definition provided by the United Nations, South Africa is regarded as a “water stressed” country, receiving an average rainfall of 450 mm/annum which is less than half the global average of 860 mm/annum. This is equivalent to a water supply potential of approximately 1 100 m^3 of water that is available per person over a year. In addition, South Africa also uses more water per capita than the global average with South African citizens using 173 ℓ/day compared to 235 ℓ/day (Mckenzie, et al., 2012).Thus, careful management of the available resources needs to be undertaken to protect against the hazards of over-exploitation and pollution.

Water capacity is dependent on two aspects, namely availability and sustainability. The distribution of rainfall in South Africa varies greatly with the southern and eastern areas receiving the bulk of the water. The water situation is aggravated by the fact that rainfall received is highly seasonal with short, wet seasons and long, dry seasons being the norm nationally. Due to this disparity in rainfall, a substantial amount of water is transferred between the various Water Management Areas (WMAs) as illustrated in Figure 2.1. Large-scale inter-basin transfers also enable the water resource management programme to supplement water to metropolitan areas like Cape Town, Durban and Johannesburg. Within inland areas, rivers, lakes, dams and wetlands provide water. These resources, together with natural processes such as evaporation and rainfall, and human influences have a direct impact on the quality and quantity of water available in the inland districts.

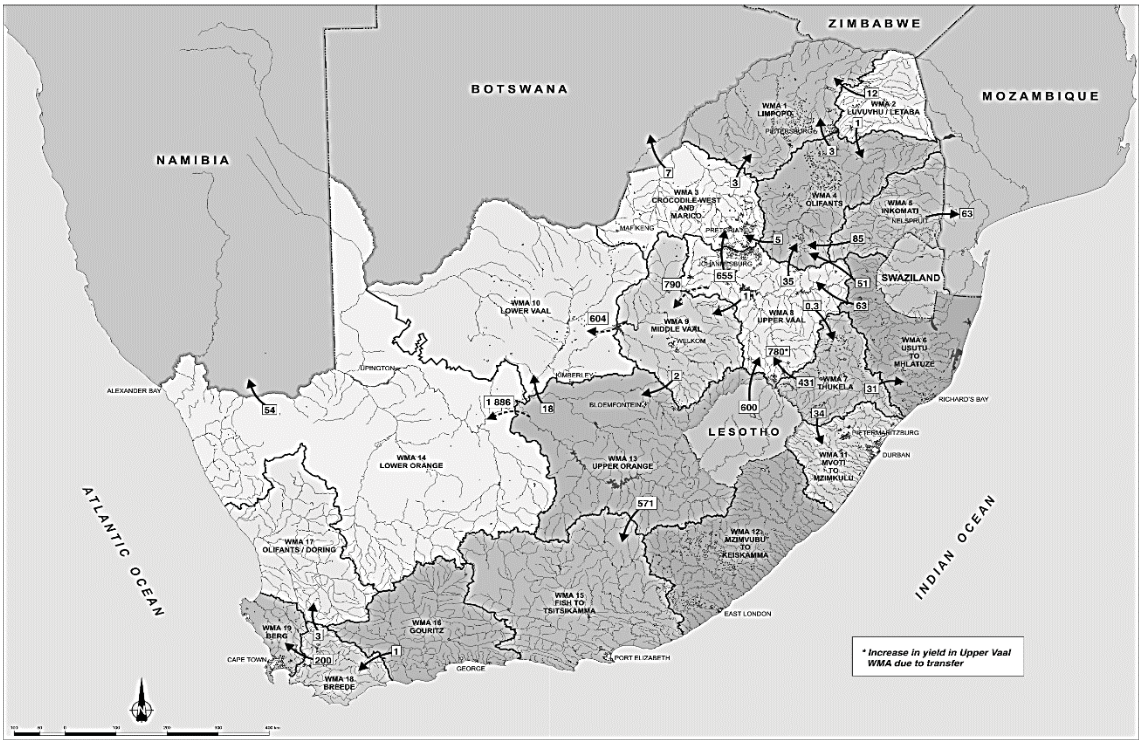

Figure 2:1: Location of WMAs and inter-WMA transfers (Department of Water Affairs and Forestry, 2004)

The majority of South Africa’s water is supplied by surface water features such as rivers and dams. A report commissioned by the Department of Environmental Affairs and Tourism states that the storage capacity of the 320 existing dams across the country is equivalent to more than two thirds of the country’s average annual runoff (Department of Environmental Affairs, 2012). This high percentage of total dam storage entails that the construction of additional large dams would be inefficient. Multiple dams can also have a detrimental effect on aquatic ecosystem integrity in inland waters. In the case of rivers, the potential yield is limited by water pollution originating from urban discharge and industrial, agricultural and mining activities. The above points to the fact that South Africa’s available water resources are already being intensively used and controlled.

In arid or rural areas where the supply of surface water is poor, groundwater is utilised to satisfy requirements. It is estimated that the total available groundwater resource in South Africa is 10 343 million m^3/annum or 5 000-7 500million m^3/annum under drought conditions (Department of Environmental Affairs, 2012). As in the case of surface water, groundwater availability varies across the country, with some WMAs possessing a greater amount of groundwater compared to others. This source of water is restrained by poor water quality as a result of excessive chlorides, nitrates and other salts which are costly to remove. Increasing utilisation of groundwater for human use could also have a detrimental effect on ecosystems which depend on groundwater to sustain life (wetlands, estuaries and springs).

2.2.2 Water Requirements

In order to ensure an equal distribution of water, current water demand needs to be carefully investigated. Complexities that arise upon such analysis include the large variation in water requirements as different areas utilise water based on specific water quality, quantity, and distribution factors. Other factors that contribute to the situation include affordability and priorities as well as various other social and economic considerations.

In order to facilitate economic growth and job creation, a reliable supply of water in sufficient quantities and at the required quality is crucial. The individual needs of the different water sectors are presented in Figure 2.2. From the pie graph, it is evident that irrigated agriculture is the largest single user of water in South Africa, using approximately 60% of available water resources in spite of its minimal 3% contribution to the GDP. Water is seen as a significant limiting factor in the growth of this area as poor water quality has a detrimental effect on agricultural exports and derived foreign income. Although the mining sector was found to use a relatively small portion of water available (5%), it is a major water user in areas where mining activities are predominant. Furthermore, the continuation of mining activities could adversely affect water quality. Another user of strategic importance is the energy sector. Power is generated in South Africa through a combination of coal-fired power stations, nuclear stations and solar-powered plants. The sector utilises approximately 2% of water and its contribution to the GDP and job creation is significant with the industry credited for providing an estimated 250 000 jobs.

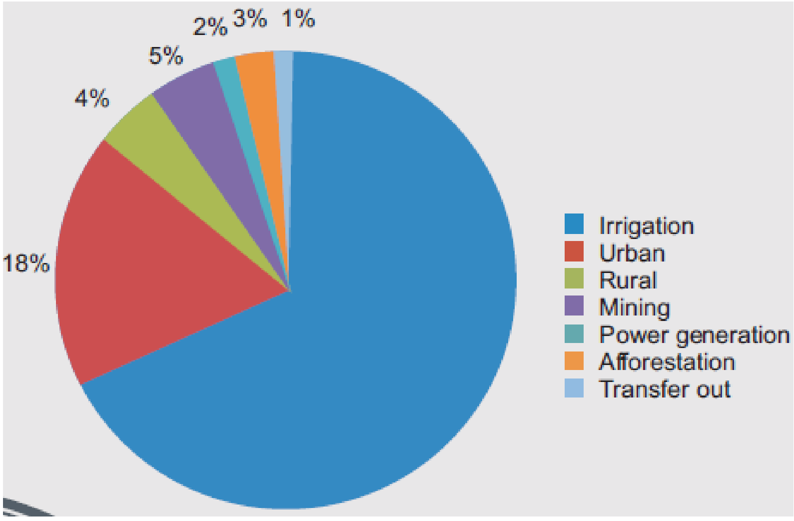

Figure 2:2: Contribution and current water needs to the major economic sectors (Department of Water Affairs, 2013)

2.2.3 Balancing Demand and Supply

The Department of Water Affairs and Forestry (currently the Department of Water and Sanitation) planned for water availability by making use of a 98% assurance of supply. Using this level of assurance, it is projected that there is about 10 000 million m^3/annum available for use (Department of Water Affairs, 2013). With surface water abstracted from rivers and dams providing the bulk of water available (9 500 million m^3/annum), a large percentage of the yield is moved via inter-basin transfers to locations where demand exceeds supply. The remainder of water is provided via groundwater flows, with the authors of the National Water Resource Strategy 2012 edition estimating that South Africa uses approximately 2 million m^3/annum out of a possible 7 million m^3/annum. Bearing the possibility of an underestimation in mind, this leaves around 3 500 million m^3/annum that is available for further development.

Due to the burgeoning economy and social development prevailing in South Africa, an increase in demand is inevitable. Future pressures on water resources are expected to arise from an increase in population and economic growth due to development of new mines and power stations. Many of these pressures are location-specific as shown in Figure 2.3 with future growth in water requirements largely concentrated in the large metropolitan areas.

In order to bridge the gap between demand and supply, various measures need to be implemented which are summarised in the following paragraphs. In practice, a combination of measures is necessary depending on geographical location and suitability to the particular WMA.

- **Demand Management**

This strategy is implemented in situations where demand exceeds supply. This can occur via resource development where the negatives include higher expenditure and increased environmental impacts. A more attractive alternative is water demand management which is generally unexplored in South Africa.

- **Water Resource Management**

The impending water scarcity situation has necessitated the development of reservoir management and inter-catchment transfer. In addition, advances in the management of smaller water resources and the revision of operating strategies for larger water resources will assist in the alleviation of the present condition.

- **Groundwater Resource Management**

There has been limited investigation into the utilisation and management of this resource due to it being deemed private water under previous legislation. Recent discoveries have pointed to potentially developing localised supplies of groundwater to aid in the reconciliation of the water balance. This source of freshwater is advantageous as a result of the relatively low investment required for exploitation.

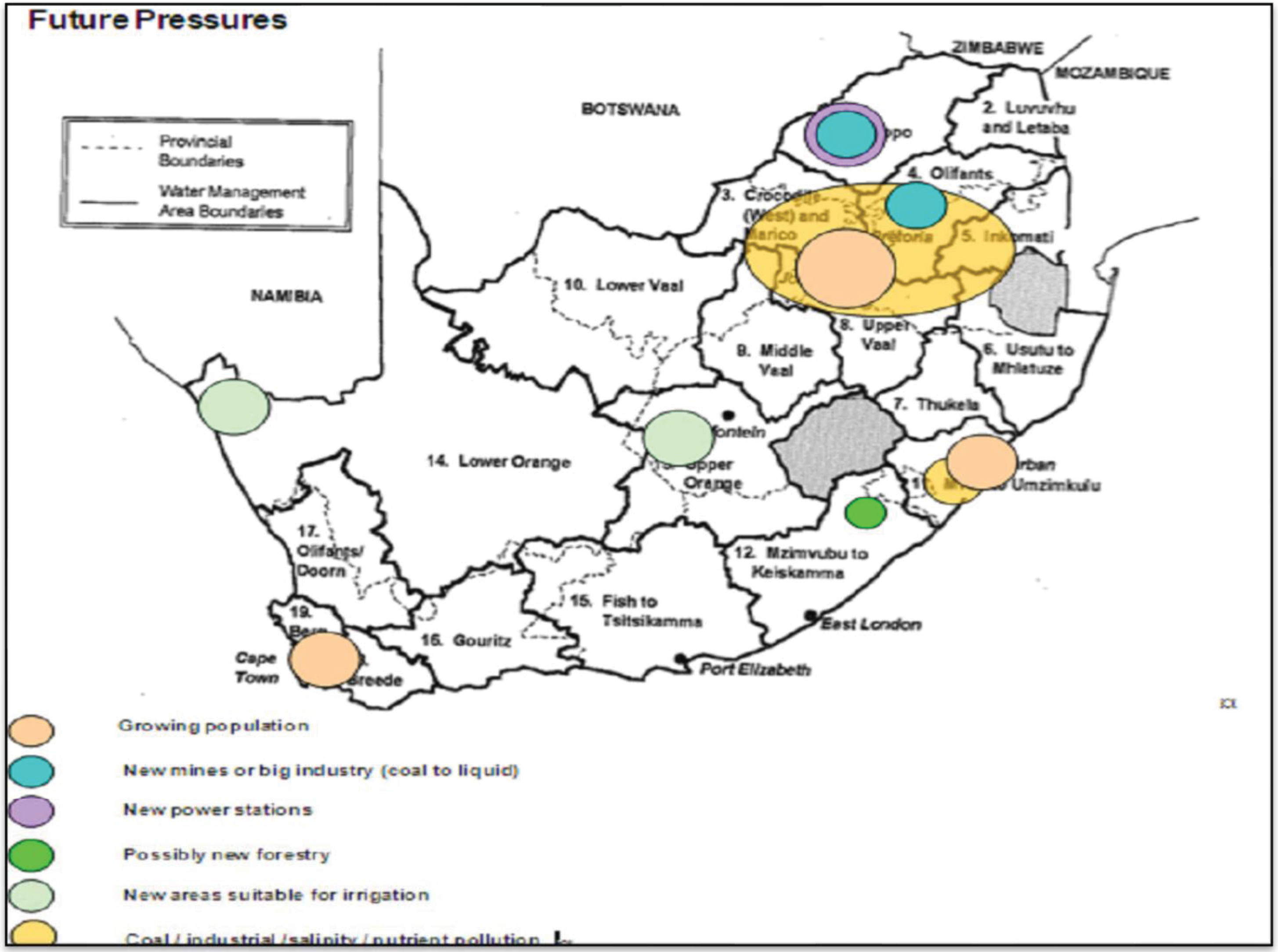

Figure 2:3: Future possible pressure on water resources due to potential development amongst various users (Department of Environmental Affairs, 2012)

- **Surface Water Resource Management and Inter-catchment Transfers**

There are currently existing opportunities to develop surface water resources further in certain parts of South Africa. The Department of Water Affairs reported in 2013 that it was supervising the implementation of over 150 water resource development projects, with several projects expected to reach completion by 2014 (Department of Water Affairs, 2013). However, it has been found that these projects require great capital investment with a long payback period which might diminish the economic viability of such ventures. An alternative is to induce changes in water-use patterns and to reallocate water.

The practice of inter-catchment transfer results from South Africa's geographical imbalance in water availability and unequal demand. The 2006 edition of an annual report documenting South Africa's environmental outlook states that more than 50% of WMAs rely on transfers to prevent water shortages, with approximately a third of the surface water yield in 2000 emanating from surface water sources.

- **Water Harvesting**

Collecting rainwater and fog has proved successful with eThekwini Municipality, which implemented a pilot project that was able to supplement the existing water supply to 500 underprivileged households thereby saving 10% on bulk water demand (Department of Water Affairs, 2013). Although the collected water is mainly utilised for irrigation of food gardens, it can also be used for domestic purposes in the event that communities do not possess a reliable source of potable water. Despite the fact that the full potential of this water resource has not been thoroughly investigated, it is an option that could be realised quickly due in part to the relatively low capital outlay.

- **Reuse of Water**

This form of water treatment is mainly employed in industrial areas such as Tshwane and Johannesburg where approximately 50% of industrial drainage is reused. Other metropolitan areas that lie on the coast, as in the case of Cape Town and Durban, reuse only 5-15% (Department of Environmental Affairs and Tourism, 2006). Thus, opportunities exist to increase reuse capacity taking into account the employment of suitable treatment technologies coupled with stringent quality control. At present, it is estimated that around 1 800 million m^3/annum of water flowing through rivers is return flow which represents approximately 14% of the total available water in South Africa. At the treatment facility level, South Africa has been found to possess more than 1 000 municipal water treatment plants which discharge an estimated 2 100 million m^3 per year of treated effluent back into the river network (Department of Water Affairs, 2013).

Reuse of water is becoming more common and feasible due to increasing demand, improvements in membrane technology and a decline in treatment costs. It is widely acknowledged that direct reuse of treated wastewater can pose a threat to public health and safety. Thus, stringent water quality management and control needs to be enforced. In addition, the DWA has acknowledged that the performance of current municipal water treatment plants needs to improve in order to rectify the negative public perception surrounding water treatment industries in general (Department of Water Affairs, 2013).

- **Desalination**

The term desalination describes a range of water treatment technologies which facilitate the separation of salts from water thereby rendering a useful water product. Available desalination technologies can be applied to various water and wastewater streams from brackish groundwater to sea water, thus providing an unlimited resource of fresh water. This is especially true for coastal cities which are located at the downstream end of catchments and may experience water shortages due to the upstream utilisation of available water (Department of Water Affairs, 2013).

- **Acid Mine Drainage Management**

Mining in South Africa has always been of great importance and is widely seen as one of the key drivers of the country's economy. However, since the 1970s when large-scale closure of mining operations occurred, serious environmental contamination has been noted such as the onset of acid mine drainage (AMD) (Inter-ministerial committee on acid mine drainage, 2010). AMD is highly acidic water, usually containing large concentrations of metals, sulphides and salts. Major sources of AMD include drainage from underground mine shafts, runoff from open pits and mine waste dumps as well as tailings and stockpiles which contributes 88% of the total waste produced in South Africa (CSIR-(Natural Resources and the Environment, 2009).

The possibility of post-closure decantation of AMD is a major hazard and can be exacerbated if remedial activities are delayed. An example of this is when acid mine water started to discharge from an abandoned underground mine close to Krugersdorp in 2002 which led to polluted surface water. The DWA is in the process of investigating and identifying opportunities to treat AMD emanating from various sources in the Vaal River catchment, as well as drainage from coal mines in the Witbank area.

Many of the strategies summarised in the preceding paragraphs are based on technological processes which purify water that was polluted or is naturally saline and which would not be suitable for human or industrial use. Water purification technologies have been classified as conventional (e.g. filtration, coagulation, settling, activated sludge treatment) and membrane-based (e.g. reverse osmosis, ultrafiltration, nanofiltration and microfiltration). The use of membrane-based applications in the desalination of sea water and the treatment of wastewater and mine water has been increasing internationally and locally (Turner et al., 2015; Lee et al., 2016, and others). The use of membranes in the purification of water allows not only for the use of sea water, but also for the reuse of alternative sources of water in an urban environment such as mine water and sewage, which posed considerable challenges for treatment and disposal. In fact, these membrane processes transform polluted water which was previously a liability for urban water managers into a resource that can be used.

2.3 THE USE OF MEMBRANES IN THE TREATMENT AND RECYCLING OF WATER

Membrane technologies have the potential to increase fresh water supplies beyond what is available from the hydrological cycle, by seawater desalination and the recycling of various wastewaters (Elimelech and Philip, 2011). Some of these technologies have been used in the treatment of water for many decades; however, their importance is increasing and some countries like Qatar and Kuwait rely 100% on these technologies for the production of potable water (Ghaffour et al., 2103). However, the use of membranes has recognised challenges, most notably fouling (which decreases efficiency and increases costs), high energy requirements and associated costs (also linked with increased greenhouse gas emissions) and environmental impacts (due to water intake and the release of high-salinity brines (Elimelech and Philip, 2011 and Lee et al., 2016).

With recent innovations, the efficiency of processes employing membranes has increased and desalination, in particular, has become competitive with conventional water supply and treatment (Ghaffour et al., 2103) and is employed in many locations around the world. Therefore, installed desalination capacity is increasing from year to year, particularly membrane desalination capacity (as opposed to thermal desalination), as shown by Global Water Intelligence (GWI) in their yearbooks (GWI, 2016). Geographically, the Middle East has the largest number of such plants, however, other regions like the USA, Spain, Australia and others are also investing in such technologies (Ghaffour et al., 2103). South Africa is following this trend, albeit with a delay, and currently there are six existing plants which employ membrane desalination (Turner et al., 2015). These are situated in Mossel Bay (one potable and one industrial), Sedgefield, Albany Coast, Beaufort West and George. Many other costal local municipalities are in the process of investigating and planning other such plants (e.g. eThekwini Municipality).

Membranes are defined as "a thin physical interface that moderate certain species to pass through depending on their physical and/or chemical properties" (Lee et al., 2016). Most membrane processes employ a sieving process through membrane pores and the types of membrane currently used for water applications are classified based on their pore size and composition. Isotropic membranes have a chemically homogenous composition, and anisotropic membranes have a heterogeneous composition chemically and structurally (Lee et al., 2016) as summarised in Figure 2.4. There are inorganic membranes (e.g. ceramic membranes and zeolites) and organic membranes (e.g. polymeric materials). The majority of membranes currently used are polymeric membranes (Lee et al., 2016). Membranes can be prepared all from the same material (preparation methods may vary in order to produce different pore sizes) or from many materials combined (Lee et al., 2016).

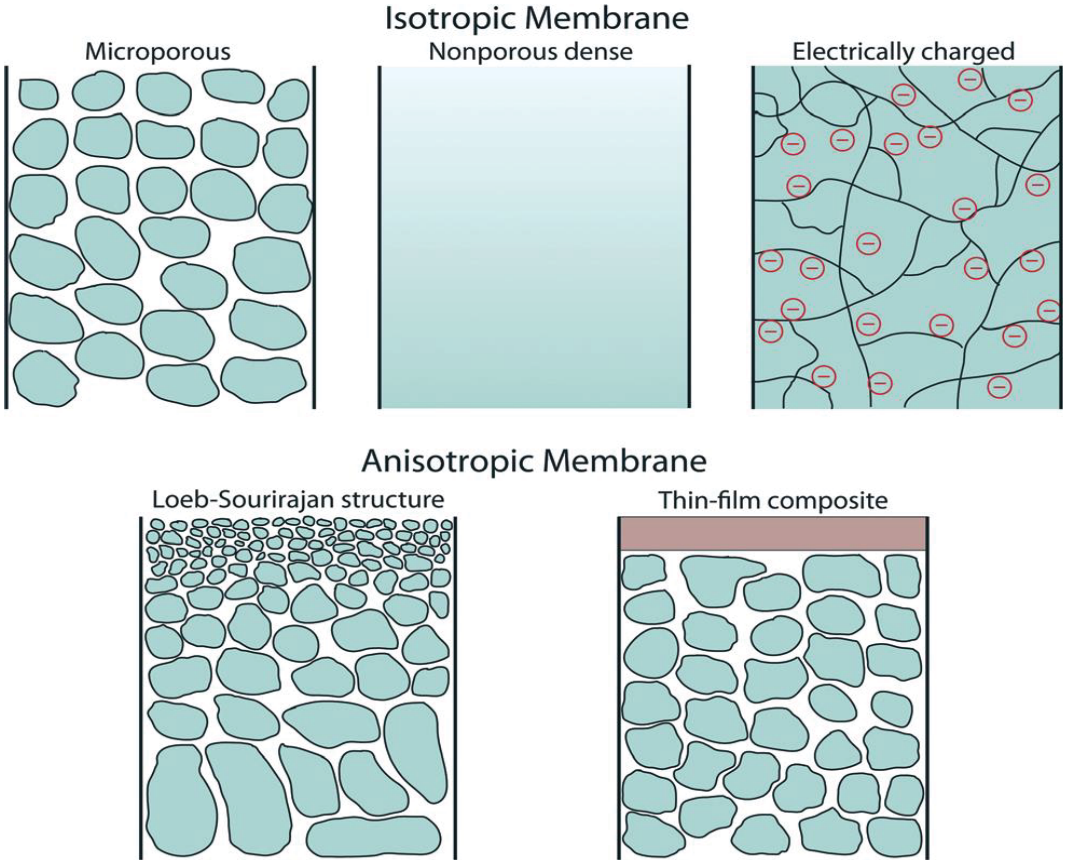

Figure 2:4: The different types of membrane (Source: Lee et al., 2015)

Membranes can be classified based on their pore size into reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), microfiltration (MF) and particle filtration membranes. Figure 2.5 summarises these processes. It is evident from this figure that membranes can be employed at different levels, which also explains their increased number of applications for water treatment. RO membranes, because of the small size (from approx. 0.0001 to 0.001 µm) of the pores involved, are considered non-porous and can filter low molecular weight species including salt and metal ions which makes them appropriate for desalination and the production of potable water from brackish water or sea water (Lee et al., 2016). Filtration at this level occurs because "solutes pass through the membrane by dissolving in the membrane material and diffusing down a concentration gradient under applied pressure exerted in excess of osmotic pressure. Separation occurs because of the difference in solubilities and mobilities of different solutes within the membrane" (Lee et al., 2016). Therefore, RO processes have relatively high energy requirements in order to achieve the pressure needed. These energy requirements translate into high costs and corresponding increases in greenhouse gas (GHG) emissions (Subramani et al., 2015).

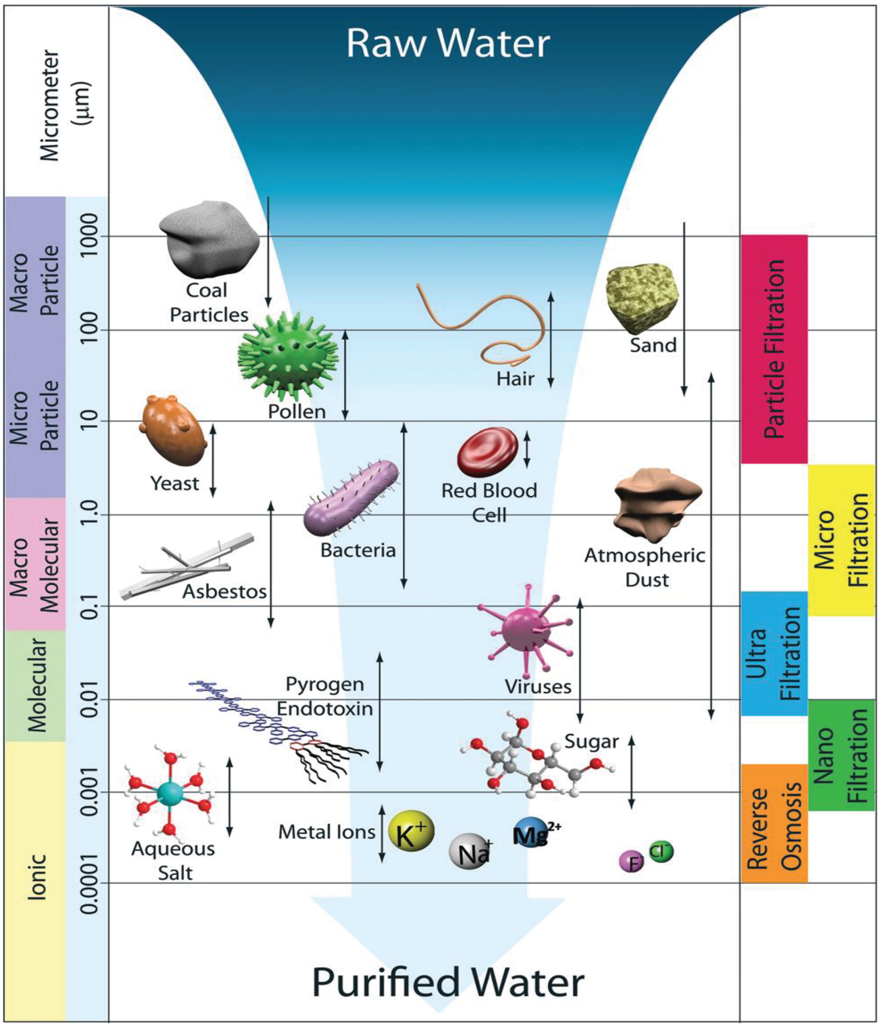

Figure 2:5: The membrane filtration spectrum (Source: Lee et al., 2016)

There is a multitude of current literature sources which present different aspects with regards to the use of membrane technologies for water treatment, be it economical (Ghaffour et al., 2013), technical (Turner et al., 2015 and Lee et al, 2016) or emerging processes (Subramani and Jacangelo, 2015). In particular, RO and the desalination of water have been studied extensively (for review articles, see Van der Bruggen and Vandecasteele, 2002; Cath et al., 2006; Greenlee et al., 2009 and Elimelech and Philip, 2011). In the South African context, Turner et al. (2015) present a detailed review with regard to all of these aspects and present best local practices with regard to the use of RO processes for desalination and the recycling of wastewater. From these studies, it is evident that in the last three decades major innovations have contributed to a decrease in energy requirements and associated costs. This has been achieved through the development of new low-pressure membranes, the use of recovery of energy devices and optimisation of the pre- and post-treatment stages (Subramani and Jacangelo, 2015). With regard to the energy needed by the different membrane technologies (including RO), Table 2.1 summarises these figures.

Table 2:1: Range of Electricity Consumption Values for Different Technologies (Source: Vince et al., 2008)

Potable water production plant life cycle steps	Electricity consumption in kWh/m^3 of potable water	
	Min	Max
Intake pumping	0.05	1
Water treatment process		
Conventional fresh water treatment process	0.05	0.15
UF/MF membrane fresh water treatment process	0.1	0.2
Advanced fresh water membrane treatment process	0.4	0.7
Brackish water desalination (NF, BWRO)	0.6	1.7
Seawater membrane desalination with ERI (SWRO)	3.5	4.5
Seawater membrane desalination without ERI (SWRO)	5.5	7
Thermal desalination (distillation)[a]	6.5	20
Reuse	0.25	1.2
Chemicals production	0.1	0.4
Potable water distribution	0.2	0.8

[a]Electricity + electrical equivalent of heat.

As seen from Table 2.1, the energy required by different technologies varies, with thermal desalination consuming the most amount of energy (6.5-20 kWh/m^3 of potable water). This technology, however, does not use membranes. Seawater membrane desalination utilising reverse osmosis without energy recovery devices is slightly less energy intensive (5.5 – 7 kWh/m^3 of potable water). In between the treatment of fresh water and desalination of seawater lies the electricity consumption of brackish water desalination. This variance is expected if these or similar technologies are applied in the proposed developments discussed in the case studies. Subramani and Jacangelo (2015) report that the total energy requirements for sea water desalination using RO (including pre- and post-treatment) is in the range of 3–6 kWh/m^3, with the lowest energy consumption required by an RO system being 1.58 kWh/m^3 at a feed water recovery of 42.5% and a flux of 10.2 $\ell\ m^{-2}\ h^{-1}$ (Seacord et al., 2006).

Turner et al. (2015) show that at the South African RO plants used in desalination and the production of potable water, the energy requirements are varying between 4.52 kWh/m^3 (Albany Coast Plant), and 4.39 kWh/m^3 (Mossel Bay Plant) and 3.97 kWh/m^3 (Sedgefield Plant). For all three plants, the energy costs were the main contributor to operation and maintenance cost representing 50.2%, 64.5% and 55.4% respectively. Four major reviews on desalination technologies and the reduction of energy used have been found in the literature (Charcosset, 2009; Elimelech and Philip, 2011; Subramani et al., 2011 and Peñata and Garcia-Rodriguez). Strategies to decrease energy requirements by membrane processes include energy efficient design, high-efficiency pumping, energy recovery, innovative technologies (i.e. forward osmosis, ion concentration polarisation and capacitive deionisation), advanced membrane materials and the use of renewable energy resources (wind, solar and geothermal). Subramani and Jacangelo (2015) evaluate several emerging desalination technologies and their expected energy requirements. The membrane-based emerging technologies include nanocomposite membranes, aquaporin membranes, nanotube membranes, graphene-based membranes, semibatch RO and forward osmosis. In addition, microbial desalination and hybrid configurations (i.e. a combination of two or more technologies) have been investigated (Subramani and

Jacangelo, 2015). Several of these technologies show potential for further reduction in energy consumption and it is expected that with more research and innovation, increased efficiencies for desalination are to be achieved. Therefore, it is anticipated that membrane technologies will maintain an important role in water purification and treatment (Lee et al., 2016). Municipal wastewater reuse and recycling is another promising solution to increase the amounts of water needed by a city and membrane filtration processes have been used for the treatment and purification of different types of municipal effluents. Wintgens et al. (2005) present a review of the categories of municipal wastewater reuses (i.e. agricultural and landscape irrigation, industrial recycling and reuse, groundwater recharge, environmental recharge, non-potable urban uses as well as potable uses) and relate them to the different types of membrane processes (RO, NF, UF and MF) used. They also summarise different case studies from around different countries.

Pellegrine et al. (2015a and b) conducted a very detailed review of the use of membranes for municipal wastewater treatment and summarised a large number of studies including pre-treatment, membrane bioreactors, industrial treatment, fixed film and anaerobic membrane systems, reuse, microconstituents removal, membrane technology advances, membrane fouling, and modelling. It is evident from these reviews that there is multitude of ways in which membranes have been integrated into wastewater treatment processes around the globe. In particular, membrane bioreactors have emerged as an application growing in importance (Wintgens et al., 2005). The plants employing these processes usually have lower energy consumption compared to a desalination plant. For example, in the southern African context the figures reported are 0.23 kWh/m^3 for the UF plant in George, 0.57 kWh/m^3 for the UF plant in Windhoek, 0.73 kWh/m^3 for the UF/RO plant in Mossel Bay and 2.07 kWh/m^3 for the UF/RO plant in Beaufort West. This lower energy consumption is due to the fact that less pressure is needed for these processes; however, they rely extensively on a range of pre-treatment methods prior to the use of membranes (Turner et al., 2015).

Another way to reduce the energy consumption is to decrease the salinity of the feed water. It is considered that the energy required by membrane plants is a “function of the feed water recovery, permeability of the membrane, operational flux, feed water salinity and temperature fluctuations, product water requirements and system configuration” (Subramani and Jacangelo, 2015). Therefore, higher concentrations of salt will need more energy for removal and the opposite is also valid – if seawater can be diluted with other water sources (i.e. municipal wastewater) the energy required for membrane treatment will decrease. Such processes have been employed in Japan at the Kitakyushu Water Plaza and a reduction of 30% in energy used was recorded (Takabatake, 2013). This combined method which employs membranes can help with decreasing the energy consumption associated with desalination, and municipal wastewater is recycled. The Remix technology planned to be implemented in the eThekwini Municipality employs this kind of approach.

In summary, the increased applications of membranes in the treatment of water are explained not only by the versatility, decreased costs and energy requirements of membranes (Subramani and Jacangelo, 2015) but also due to their technical advantages. These include high water quality with easy maintenance, stationary parts with compact modular construction, low chemical sludge effluent, and excellent separation efficiency (Lee et al., 2016). In particular, due to their modular design membrane water treatment plants can be erected faster than conventional infrastructure (e.g. dams) and can be fitted into a medium- and long-term planning cycle of municipalities (Turner et al., 2015). Currently, when municipal managers and water board managers decide which membrane technologies and designs should be used in a particular water plant, technical and cost-benefit information is used and environmental concerns are only included, by means of environmental impact assessments (EIAs), because they are legally mandatory. These assessments have considerable limitations. In particular, when environmental impacts are not immediately visible, as in the generation of electricity, these indirect impacts occurring away from the location of the project tend to be left out. Also, EIAs seldom include all the life cycle stages of a water plant and, therefore, a more comprehensive assessment tool such as an environmental LCA is useful in order to gauge all possible impacts.

2.4 LIFE CYCLE ASSESSMENT (LCA)

2.4.1 Background

Industrial processes play a significant role in the degradation of the environment. The more developed a country's industrial capacity, the greater its potential for economic development and growth. In order to preserve the fragile nature of the surrounding environment, industrial activities need to be carried out in a sustainable manner. The concept of sustainability dates back more than 30 years to the new mandate adopted by the International Union for the Conservation of Nature (IUCN) in 1963. This idea, which was a central theme of the United Nations Conference on the Human Environment in Stockholm in 1972, was coined to introduce the possibility of economic growth without environmental damage (Adams, 2006). From this point onwards, mainstream sustainable development thinking progressed through the World Conservation Strategy (1980), the Brundtland Report (WCED, 1987) and United Nations Conference on Environment and Development in Rio (1992). Over these decades, the definition of sustainable development has evolved, with the most commonly quoted definition emerging from the Brundtland Report, which states the following:

"*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*"

The main features that this and other definitions have, are the need for a desirable human condition, an enduring ecosystem and a balance between present and future generations. The core principles of sustainable development focus on three aspects, namely environmental, social and economic sustainability. These were named as the three pillars of sustainable development at the World Summit on Sustainable Development (WSSD) in Johannesburg in 2002 (Fien, 2010).

Figure 2.6 shows a well-known model illustrating three interlocking circles with the triangle of environmental (conservation), economic (growth) and social (equity). Thus, sustainable development requires the simultaneous and balanced progress of each dimension as one area inevitably affects the others. Governments, communities and businesses alike have all responded to the challenge of sustainability to a certain degree. Almost every national government present in the United Nations has a dedicated minster and department tasked with policies concerning the conservation of the environment. Since 1992, the volume and quality of environmental legislature both internationally and nationally has expanded tremendously with agreements such as the Kyoto Protocol driving global policy changes (Adams, 2006). This has led to development in public awareness of significant environmental and social issues.

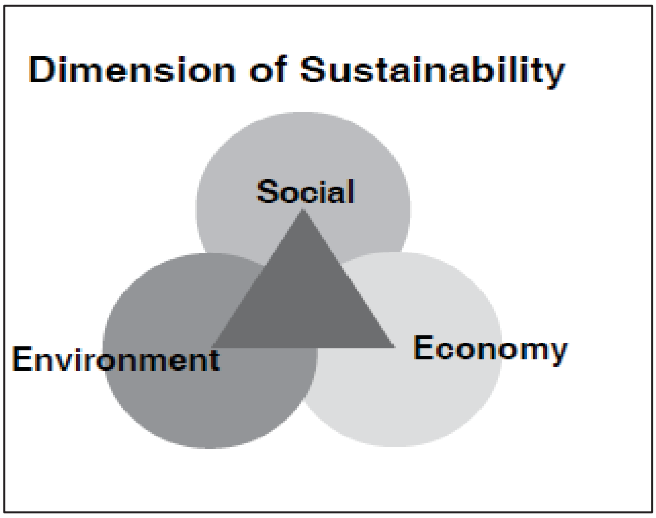

Figure 2:6: Visual representation of sustainable development (Anon., 2007)

One of the main themes of the Rio 2002 conference was the development of a green economy as a key strategy to improve compatibility between the increasing needs of the population for resources and the earth's dwindling capacity to replenish them. UNEP defines a green economy as one that "*results in improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities*". A simplified expression of a green economy is one where public and private investments are able to reduce carbon emissions and pollution, enhance energy and resource efficiency and prevent the loss of biodiversity while creating growth in income and employment (United Nations Environment Programme, 2012). To achieve this vision, society together with government needs to formulate and implement strategies and supporting programmes.

The publication of the Key Outcomes and Commitments of the WSSD held in South Africa cemented the role of environmental assessment tools to drive the policy of sustainable development. Numerous tools have been described in literature that can be utilised by all sectors of society (governments, private sector and civil society) to guide decision making. The most commonly used tools are listed in Table 2.2 together with a brief description of each management technique and its reference in South African official documentation.

Table 2:2: Common Environmental Tools (Department of Environmental Affairs and Tourism (DEAT), 2004)

Environmental Tool	Brief Description	Reference in South African Documentation
Environmental Management Systems (EMS)	Provides guidance on how to manage the environmental impacts of activities, products and services. They detail the organisational structure, responsibilities, practices, procedures and resources for implementing and maintaining environmental management.	DEAT (2004), Environmental Management Plans, Information Series 12.
Environmental Impact Assessment (EIA)	Aims to predict both the positive and negative environmental impacts of a proposed project and find ways to reduce adverse impacts, shape projects to suit the local environment and present the predictions and options to decision makers. This tool is designed to be project specific and site specific, and not to be focused on strategic issues.	DEAT (2004), Review in EIA, Information Series 13.
Life Cycle Assessment (LCA)	A tool for the systematic analysis and evaluation of the environmental aspects of a product or service through all stages of its life cycle by considering all inputs and all outputs.	DEAT (2004), Life Cycle Assessment, Information Series 9.
Environmental Auditing	This is a process whereby an organisation's environmental performance is tested against numerous requirements, for example, clearly defined policies, legislated requirements and key performance indicators.	DEAT (2004), Environmental Auditing, Information Series 14.
Strategic Environmental Assessment (SEA)	SEA is becoming an accepted and widely used tool for determining the environmental implications of decisions made at a policy, plan or program level. By focusing on higher-level processes, SEA complements and provides a framework for project-level EIA.	DEAT (2004), Strategic Environmental Assessment, Information Series 10.
Risk Assessment	Seeks to quantify the probability and severity of an undesired effect, expressed in the context of associated uncertainties. The risk assessment procedure can be integrated with the generic EIA procedure, as well as be applied at a policy level.	DEAT (2002), Ecological Risk Assessment, Information Series 6.

The diversification and expansion of manufacturing activities has led to an increased awareness of sustainability. This sub-section starts with the emergence of the concept of sustainable development over a period of time. Common environmental management techniques are thereafter listed with a special emphasis on LCA as a comprehensive tool. The history of LCA as well as the general methodology are elaborated upon, along with the strengths and limitations of this specific approach. The applications of LCA are also presented followed by a synopsis of the position of LCA in South Africa and the use of this tool in the water industry.

2.4.2 LCA as an Integrated Environmental Management Tool

Heightened awareness surrounding the issues of environmental protection and the potential impacts associated with the manufacture and consumption of products has prompted the need to develop methods to better comprehend and reduce such impacts. One such technique that is being commonly utilised to achieve this purpose is the LCA. A LCA is an analytical tool that is used to determine the potential environmental impact of a product or process by characterising and quantifying the inputs and outputs of a specific system. In particular, the procedure provides an evaluation of the product's life cycle from 'cradle-to-grave', i.e. from raw material acquisition through production, use, end-of-life treatment, recycling and concluding with final disposal (ISO 14040, 2006). Thus, a LCA is utilised to quantify the amount of energy used, the consumption of raw materials, emissions to the atmosphere as well as the amount of waste generated during a product's life cycle (Curran, 2006).

According to the latest version of the ISO 14040 document published in 2006, undertaking a LCA could assist in improving the environmental performance of products at various phases. Other advantages include the identification of relevant indicators of environmental performance. From a marketing perspective, a LCA could provide the substantiation required to make an environmental claim or produce an environmental product declaration.

LCA as an environmental management tool has its roots in the 1960s when concerns were raised regarding limitations of raw materials and energy resources. At the World Energy Conference in 1963, Harold Smith reported his calculation of cumulative energy requirements for the production of chemical intermediaries and products (Curran, 2006). This publication was followed by the initiation of global modelling studies detailing calculations surrounding energy use and output in industrial processes. During this period, approximately a dozen studies were performed to estimate the costs and environmental implications of alternative sources of energy.

In a landmark study in 1969, The Coca-Cola Company funded a study to compare different beverage containers on the basis of resource consumption and environmental releases (Jensen, et al., 1997). A similar approached that was being developed in the USA became known as a Resource and Environmental Profile Analysis (REPA) or Ecobalance as it was termed in Europe. Due to the oil shortages in the early 1970s as well as the formation of civil society groups encouraging industry to ensure accuracy of information, approximately 15 REPAs were performed between 1970 and 1975.

From 1975 through to the early 1980s, interest in comprehensive environmental studies waned as a result of the fading influence of the oil crisis. It was not until the mid-eighties to early nineties that interest in LCAs was revitalised over a much broader range of industries, design establishments and retailers. In 1984, the Swiss Federal Laboratories for Materials Testing and Research (EMPA) published a report that presented a comprehensive list of data required for LCA studies that also contributed to the broader application of LCAs (Guine´e , et al., 2011).

In 1991, concerns over the inappropriate use of LCAs for marketing purposes led to the issuing of a statement by 11 State Attorney Generals in the USA denouncing the use of LCA results to promote products unless uniform methods for conducting such assessments were developed (Curran, 2006). It was this action, together with pressure from other environmental organisations to standardise LCA methodology, that led to the development of LCA standards in the International Standards Organisation (ISO) 14000 series which dates from 1997. Another organisation of note is the Society of Environmental Toxicology and Chemistry (SETAC) which, through its European and North American branches, started playing a leading role in the collaboration of LCA practitioners, users and scientists in the continuous improvement and harmonisation of LCA framework and terminology (Jensen, et al., 1997). The period 1990–2000 can thus be characterised as a period of convergence through SETAC's coordination and ISO's standardisation methods which led to the 1990s becoming known as the decade of standardisation.

The year 2002 saw the launch of the Life Cycle Initiative which was an international partnership between SETAC and UNEP. Three programs that formed part of the Initiative aimed to improve the supporting tools for LCA through better data and indicators (Curran, 2006). The Life Cycle Management (LCM) program created awareness and improved skills among decision makers by producing informative material, establishing forums for sharing best practice and conducting training programs globally. The second program, namely the Life Cycle Inventory (LCI) program, strived to improve access to transparent, high quality data by hosting and facilitating expert groups. The Life Cycle Impact Assessment (LCIA) program aimed to increase the quality and reach of life cycle indicators by promoting an exchange of views among renowned experts whose work resulted in a set of widely accepted recommendations. The importance of LCA and its application was also highlighted in the European Commission's 2003 Communication on Integrated Product Policy (IPP). This led to the establishment of the European Platform on Life Cycle Assessment in 2005 which was mandated to promote the availability and use of life cycle data, methods and studies for reliable decision support (Jensen, et al., 1997). It was during this period that environmental policy became increasingly life cycle oriented with the US Environmental Protection Agency promoting the use of LCA. Various other national LCA networks were also established such as the Australian LCA network as well as the smaller Thai network. It was during this era that environmental policy became increasingly life cycle based worldwide.

2.4.3 Overview of the Methodology of LCA

Over time, LCA has been used in varying forms to evaluate the environmental impacts of a product or service throughout its life cycle. From a standards perspective, the ISO 14000 series is seen as pivotal by many LCA practitioners with the main documents listed as follows:

- ISO 14040 - Life Cycle Assessment - Principles and Framework (1997)
- ISO 14041 - Life Cycle Inventory Analysis (1998)
- ISO 14042 - Life Cycle Impact Assessment (2000)
- ISO 14043 – Life Cycle Interpretation (2000)

According to ISO 14040 (2006), LCA is a systematic approach which consists of four major components as illustrated in Figure 2.7. A brief description of each of the phases follows noting that a LCA is generally an iterative process as stages are often repeated as more information is gathered.

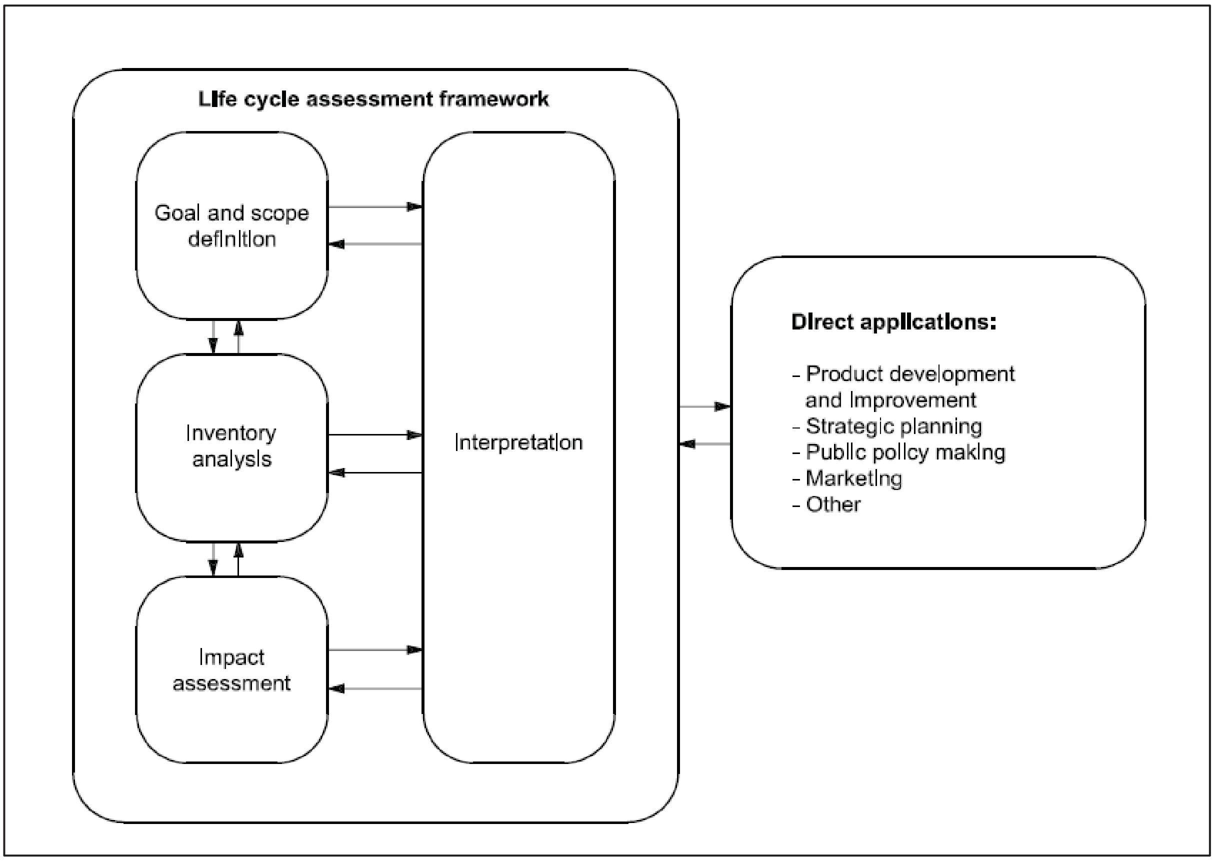

Figure 2:7: Life cycle assessment framework - Stages of a LCA (ISO 14040, 2006)

2.4.3.1 Goal Definition and Scoping

Goal and scope definition is the initial phase of a LCA study and forms the basis of the assessment. In determining the goal, the purpose and intended application of the assessment should be clearly specified. The initiator of the study and the intended audience should also be stated (Heijungs, 1992). Jensen et al. (1997) commented that the goal definition is susceptible to change as a result of the findings throughout the study, e.g. as a part of interpretation. Scope definition relates to the provision of sufficient detail to satisfy the stated objectives and should cover aspects such as the functional unit, the system boundaries that define the product system as well as assumptions and limitations that could potentially affect the assessment. Heijungs (1992) suggests that particular attention should be paid to determination of the functional unit as it represents the core criterion utilised in the comparison of LCA results. The selected functional unit should be defined and measurable so as to provide a suitable reference that links the particular inputs and outputs of the system (ISO 14040, 2006). The functional unit is of fundamental importance when comparing products as it forms the basis for the comparison (Jensen, et al., 1997). When setting the system boundary, several life cycle stages, unit processes and flows need to be taken into account, as depicted in Figure 2.8. As in the case of the goal definition, the system boundary that was initially defined may need to be refined as the study progresses.

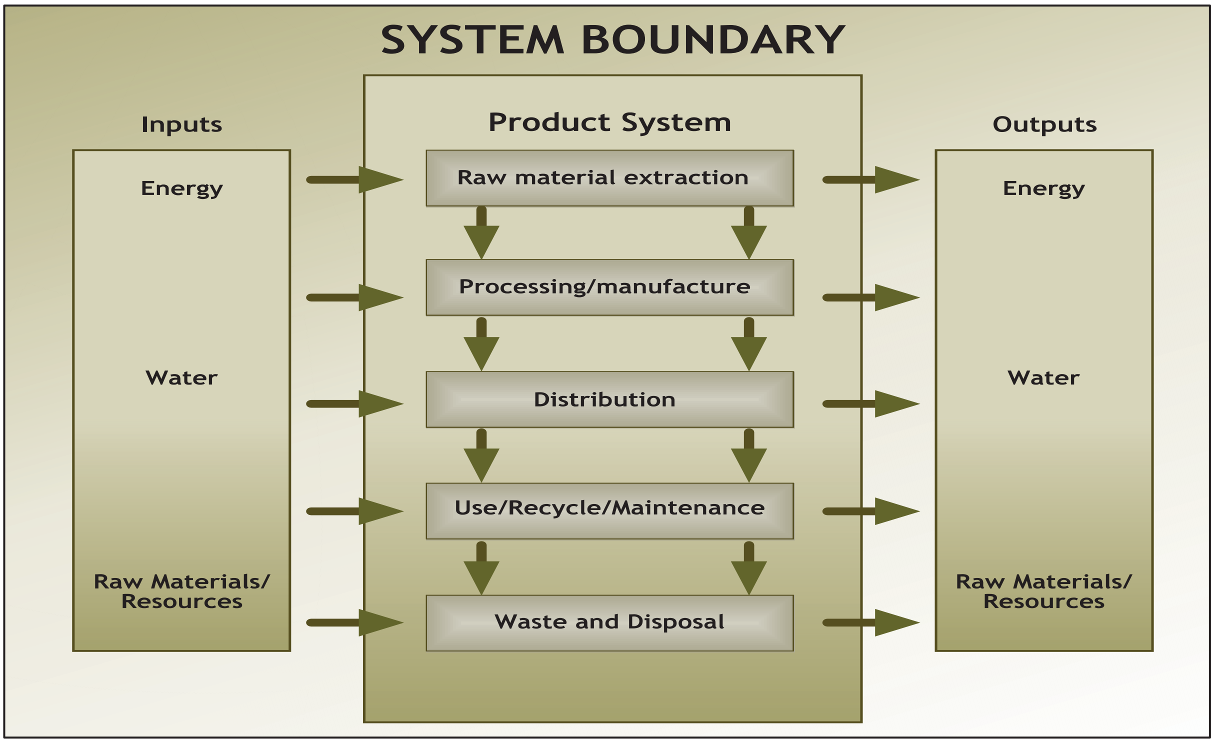

Figure 2:8: Components within a system boundary (Department of Environmental Affairs and Tourism (DEAT), 2004)

2.4.3.2 Life Cycle Inventory Analysis

The second step of the study involves compiling an inventory of all input and output data for the product system that is necessary to meet the defined goals. Such information includes the collection of environmentally relevant data as well as formulation of calculation procedures to quantify inputs and outputs such as raw material usage, energy usage and environmental emissions (ISO 14040, 2006).

In the Life Cycle Inventory Analysis (LCI), the economic processes that form part of the life cycle are evaluated. These processes are linked to each other as each input emanates from another process or is withdrawn directly from the environment. Likewise, each output flows to another process or is discharged into the surroundings. Such processes could relate to the extraction of resources, manufacture and use of the product as well as process flows for waste treatment and recycling. Figure 2.9 provides a framework to follow when conducting a LCI. The ISO 14044 (2006) document advises that certain measures should be taken in order to achieve consistent results. These include the construction of process flow diagrams that outline all the relevant unit processes, together with a list of flows and relevant data for operating conditions associated with each process. Curran (2006) mentions that a number of sources should be utilised when collecting data with the best results being well-characterised industry data for production processes. In the event that such data is unavailable, calculations need to be performed with all assumptions clearly stated and explained. Consideration should also be given to the need for allocation procedures when dealing with systems that involve multiple products and recycling systems.

Location of data is generally a labour-intensive process as both qualitative and quantitative data needs to be collected for each unit operation that occurs within the system boundaries. As new information is gathered, changes in the data collection procedure may be necessary in order to satisfy the objectives of the study (ISO 14040, 2006). The process of conducting an inventory analysis is iterative in nature and thus requires the use of a software package capable of modelling data. SimaPro will be utilised for the purposes of this study due to its accessibility at the University of KwaZulu-Natal (UKZN). The inventory analysis results in a list of environmental interventions associated with the product and can be presented in a tabular or graphic format. This forms the basis for the next stage of the LCA where environmental releases identified in the inventory phase will be evaluated.

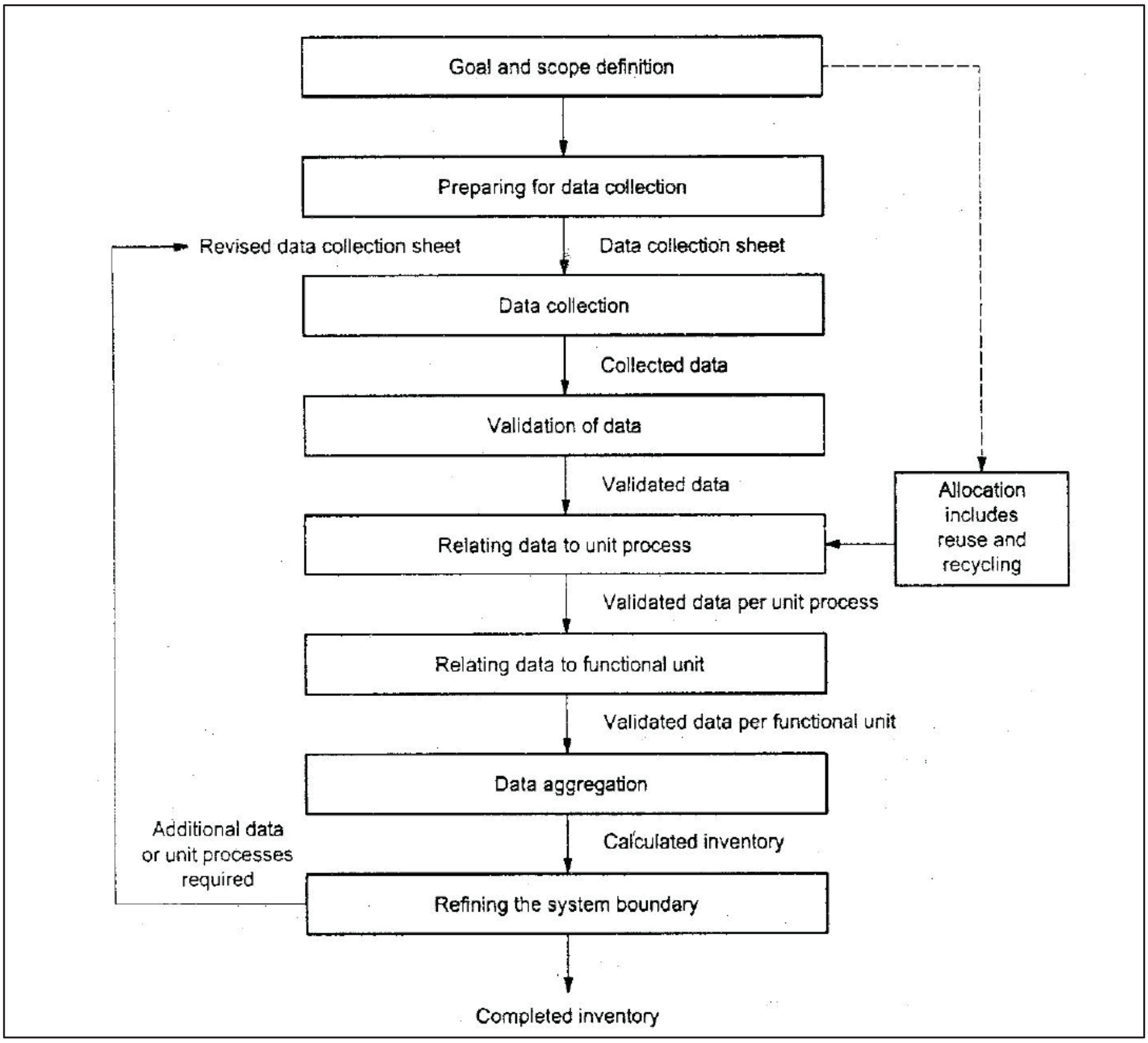

Figure 2:9: Basic procedure for LCI (ISO 14044, 2006)

2.4.3.3 *Life Cycle Impact Assessment*

The third phase of a LCA is termed the life cycle impact assessment or LCIA. The objective of this stage is to establish a link between the particular product or process and its potential environmental impact. This is achieved by assessing the data from the previous stage, fitting them to selected environmental issues which are termed impact categories and then using category indicators to condense and explain the LCI results. The collection of indictor results, which forms the LCIA profile, provides information regarding environmental issues associated with the inputs and outputs of the product system. According to the ISO 14042 (2000) document that deals specifically with LCIA, there are three steps that are mandatory for conducting an impact assessment, namely impact category selection, classification and characterisation. In addition, there are optional elements such as normalisation, grouping or weighting of the indicator results and data quality analysis techniques. Figure 2.10 provides a graphical representation of the various elements.

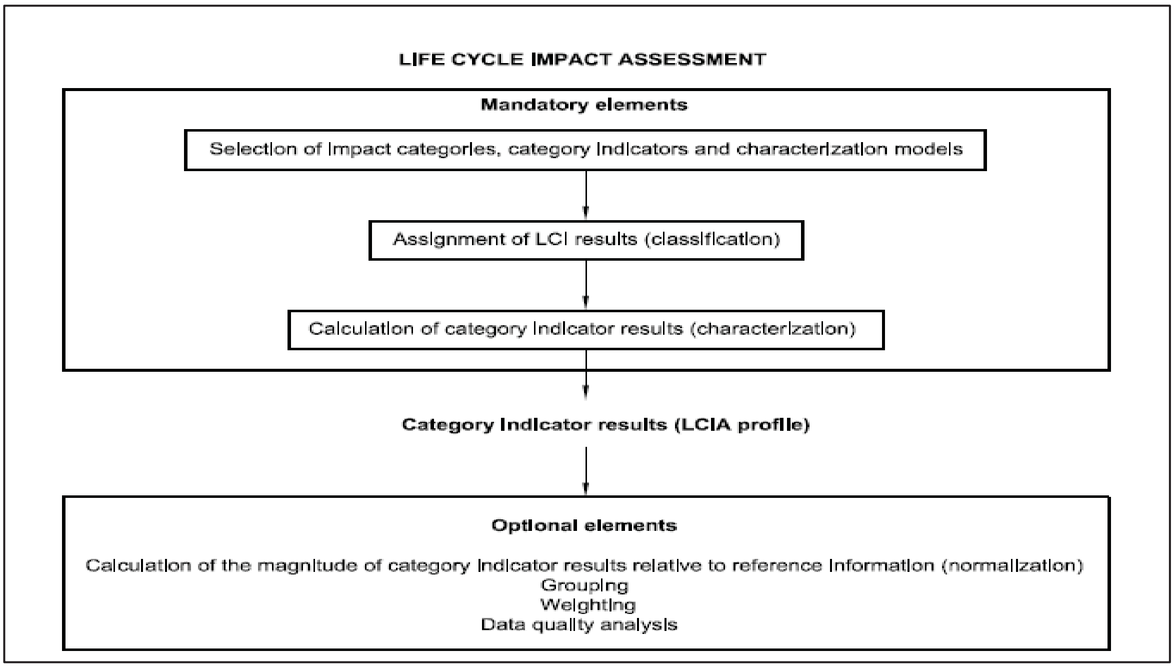

Figure 2:10:

Elements of a LCIA (ISO 14042, 2000)

Separation of the LCIA phase into individual sections is necessary as each element can be clearly examined for the purposes of goal definition and scoping.

i. **Selection of Impact Categories, Category Indicators and Characterisation Models**

The first step in an LCIA involves the selection of impact categories that will be considered as part of the total LCA study. For this particular stage, an impact is defined as the consequence on human health, plants, animals or the future availability of natural resources (Curran, 2006). Generally, LCIAs focus on the potential impact to three major categories: human health, ecological health and resource depletion. In the majority of cases, existing impact categories, category indicators or characterisation models will be selected.

In the event that the existing models are insufficient to fulfil the defined goal and scope, new ones will have to be determined. ISO 14042 (2000) lists a few requirements and recommendations to aid in the selection process. These include, but are not limited to the following:

- The selection of categories, indicators and models should be justified and consistent with the goal and scope of the study
- The sources should be referenced and internationally accepted

- Double counting should be avoided except in the case where deemed necessary by the goal and scope
- The category indicators should be environmentally relevant.

There is a range of software on the market to complete this step. SimaPro contains a large number of standard impact assessment methods where each method contains a number of impact categories (usually 10–20).

ii. **Assignment of LCI Results (Classification)**

Classification is a qualitative step based on an analysis of relevant environmental processes. The purpose of this phase is to assign the inventory input and output data to environmental impact categories (Jensen, et al., 1997). This is a relatively straighforward procedure for LCI items that contribute to only one impact category. However, for elements that contribute to more than one category, the procedure is dictated by ISO 14042 (2000) guidelines which state that there are two ways of allocating LCI results to multiple impact categories:

- Distinction between parallel mechanisms, i.e. partition a representative portion of the results to the various impact categories to which they contribute. This is generally allowed in instances where the effects are dependent on each other. An example is SO_2 which is allocated between the impact categories of human health and acidification.
- Allocation among serial mechanisms, i.e. assign all results to all impact categories to which they contribute. This is typically allowed when the effects are independent of each other. An example is NO_x which may be assigned to both ground-level ozone formation and acidification.

The impact categories can be divided into three spatial groups, namely global (continental), regional and local impacts. To date, there has not been any consensus reached regarding a single, standard list of impact categories. Table A1.2 in Appendix A1 provides a number of suggestions for lists of impact categories with reference to the scale at which they are valid.

iii. **Calculation of Category Indicator Results (Characterisation)**

Characterisation utilises science-based conversion factors, called characterisation factors, to convert and combine LCI results into representative indicators of impacts on both human and ecological health. Such a calculation involves the conversion of LCI results to common units and the collection of the converted results within the impact category to produce a numerical indicator result (ISO 14042, 2000). Curran (2006) summarises the process of characterisation as providing an avenue to translate different inventory inputs into directly comparable impact indicators.

The calculation process involves two steps:

- Selection and use of characterisation factors to convert the assigned LCI results to impact indicators. This is typically calculated using the following equation:

$$\text{Impact Indicators} = \text{Inventory Data } \times \text{Characterisation Factor}$$

- Aggregation of all the impact indicators into a single indicator result.

For example, all GHGs can be expressed in terms of CO_2 equivalents by multiplying the relevant LCI data by a CO_2 characterisation factor and then combining the resulting impact indicators to provide an overall indicator of global warming potential. Characterisation can also place different quantities of chemicals on an equal scale to determine the size of the impact each one has on global warming. Calculations carried out by Curran (2006) show, for example, that 10 pounds of methane has a larger impact on global warming than 20 pounds of chloroform.

The value of characterisation depends upon, amongst other aspects, the utilisation of an appropriate characterisation factor. For certain impact categories such as global warming and ozone depletion, a consensus exists on acceptable characterisation factors. However, for other categories such as resource depletion, opinions vary and a consensus is still being developed. For an accurate LCIA, the source of each characterisation factor will be documented to ensure that they are aligned to the goal and scope of the study. An example of where caution must be exercised is the utilisation of European characterisation factors to American data.

iv. **Calculation of the Magnitude of Category Indicator Results Relative to Reference Information (Normalisation)**

Normalisation is an optional tool that can be utilised to express impact indicator data in a manner that can facilitate comparison between impact categories. This procedure transforms an indicator result by dividing it by a selected reference value. There are various methods to select a reference value including the total emissions or resource use for a given area which may be global, regional or local, the total emissions for a given area on a per capita basis or the ratio of one alternative to another. Curran (2006) states that the choice of an appropriate reference value is dependent on the goal and scope of the LCA.

v. **Grouping**

Grouping assigns impact categories into one or more sets to further categorise the results into specific areas of concern by involving sorting or rank indicators. The ISO 14042 (2000) document states that there two possible ways to group data – either by characteristics such as emissions or location, or by a ranking system such as high, medium and low priority. It is possible that different individuals, organisations and societies will reach differing ranking results based on the same indicator results due to a disparity in preferences and opinions.

vi. **Weighting**

The weighting step assigns weights or relative values to the different impact categories based on perceived level of importance or relevance. This step is significant as impact categories should reflect the study goals and stakeholder values. Due to the fact that weighting is based on value choices and is not a scientific process, weighting methodology must be clearly explained and documented. In a LCA study, it may be desirable to use different weighting factors and methods followed by a sensitivity analysis to assess the impact on the LCIA results of the various choices.

2.4.3.4 Life Cycle Interpretation

As the final phase of the LCA process, the aim of life cycle interpretation is to reduce the amount of quantified data from the LCI and LCIA to a set of key results that will be utilised together with other inputs to facilitate a decision-making process. As such, the interpretation phase consists of three elements, namely identification of the significant issues based on the results of the LCI and LCIA phases of LCA, evaluation of the selected data by enforcing various checks (completeness, sensitivity and consistency) to assess the reliability and consistency of the results and reporting of conclusions and presentation of recommendations in an effective and transparent manner (ISO 14043, 2000).

Interpretation is performed in interaction with the preceding phases of a LCA. In the event that the results of the inventory analysis of impact assessment have not satisfied the initial goal and scope, the inventory analysis will have to be repeated by adjusting the system boundaries, improving data collection, etc. This iterative process must continue until the requirements in the goal and scoping phase are fulfilled (Jensen, et al., 1997). As a word of caution, Curran (2006) advises that it is imperative to draw conclusions and provide recommendations based only on the facts. She adds that communication of uncertainties and limitations should be viewed as significant to the final report, as such inclusions will enable the compilation of a comprehensive report containing all the necessary elements.

2.4.4 Strengths and Weaknesses of LCA

The process of undertaking a LCA is unique as the analysis encompasses all processes and environmental releases from the extraction of raw materials and the production of energy through to the use and final disposal of the product. The discussion below describes the strengths of LCA compared to other environmental assessment tools. It goes on to highlight the limitations of LCA.

2.4.4.1 Strengths

LCA was developed in light of increased awareness of environmental protection as well as the interest surrounding potential impacts associated with products. Among the many strengths of LCA is the unique '*cradle-to-grave*' approach which enables a systematic evaluation of the overall environmental implications of all the life stages associated with a particular product. This characteristic differentiates a LCA from other assessment methods and means that a LCA goes beyond the scope of an EIA. Curran (2014) comments that without life cycle thinking, practitioners run the risk of focusing on immediate environmental problems while ignoring or devaluing issues that occur in another place or form.

The broad scope of LCA creates awareness amongst users when dealing with complex, interconnected systems that require a specific remedy for a certain situation. In this respect, LCA identifies the transfer of environmental impacts from one media to another (e.g. eliminating air emissions by creating wastewater effluent) or from one life stage to another (from use and reuse of the product to the raw material acquisition phase). By including all the impacts at each life cycle stage, LCA provides a true reflection of the potential environmental trade-offs in product and process selection. This could prove useful to decision makers for the purposes of strategic planning, product or process design.

A LCA is dependent on the use of scores, together with reliable sets of data and impact categories. The generation of such data enables a more effective comparison to be made as opposed to one that can be achieved in an EIA. ISO 14040 (2006) also states that LCA can assist with the selection of relevant indicators of environmental performance, including measurement techniques. Thus, entities such as government institutions will possess accurate, detailed and practical systems as a basis for legislative standards and requirements.

The use of a LCA provides structure to an investigation. The ISO series lays out the framework for conducting an assessment by dividing the study into four stages. By utilizing these and other standards, common comparison criteria are developed which enables effective analysis and comparison (Department of Environmental Affairs and Tourism (DEAT), 2004).

2.4.4.2 Weaknesses

LCA is one of several environmental management techniques that can be utilised to evaluate the environmental impacts of a system. It is indeed the only tool that provides a holistic approach which allows for the identification of major sources of environmental impact throughout all life stages (Fédération des Industries Electriques, Electroniques et de Communication (FIEEC), 2013). While recognising the benefits of LCA, there are some limitations to LCA that cannot be ignored. For one, LCA traditionally only focuses on environmental impacts with social and economic impacts not being addressed. The addition of another analysis, e.g. an economic analysis, would result in a more comprehensive application.

The amount of data, as well as the quality of data accumulated, can create obstacles in LCA studies. In particular, data shortages and limitations exist for a number of impact categories such as ecotoxicity and human toxicity, soil erosion and biodiversity change (Department of Environmental Affairs and Tourism (DEAT), 2004). To compound the issue, there is no consensus on these indicators between LCA experts as they are still open to exploratory studies. This lack of cohesiveness creates an impediment for LCA industry users and LCA tool providers alike.

Europe has been at the forefront of compiling LCI databases with Plastics Europe being one of the first organisations to gather data on energy usage for plastics manufacturing (Rebitzer, et al., 2004). As a result, much of the default data originates from Europe. This can create difficulties in the case of products manufactured in other parts of the world, especially developing countries with older utility infrastructures (Lloyd & Ries, 2007).

By and large, traditional databases for LCA are often government-based and publicly funded projects. The one problem associated with databases is a lack of a certification scheme to validate databases and a lack of reference databases (Fédération des Industries Electriques, Electroniques et de Communication (FIEEC), 2013). In addition, these databases have been criticised for being inaccurate. Researchers have attempted to address the accuracy issue with the database ecoinvent offering data on individual technological processes. SETAC is also collecting data on individual processes (electricity, transportation, raw materials) in an attempt to individualise LCA (Thorn, et al., 2011). The large aggregated databases have also been criticised for outdated data. An example is the National Renewable Energy Laboratory (NREL) database which was published in 1997 (Thorn, et al., 2011). Such gaps create issues of quality, reliability and comparability of results and could ultimately contribute to unreliable environmental scores.

The broad scale practice of LCA is limited by both cost and time constraints with small companies unlikely to be able to afford to specialise in LCA or to sponsor studies externally. The high costs are compounded by the added expense of fulfilling ISO requirements for review and the need to purchase data from commercial data bases. To be more cost effective, it is recommended that a LCA should be integrated into the existing environmental management system and information systems within a company (Keoleian, 1993).

2.4.5 Applications of LCA

The principle of life cycle thinking implies that everyone associated with a product's life cycle has a role to play in decreasing the environmental impact of the particular product. As such, LCA can be used in both the private and public sector. Jensen et al. (1997) state that there are essentially four primary types of users: industry and other types of commercial enterprises, government at all levels and other regulatory bodies, non-governmental organisations (NGOs) such as consumer organisations and environmental organisations, and consumers. The motivation for use may vary amongst the user groups with LCA being used for both internal and external applications. The wide variety of applications can be condensed into four major applications, namely (Jensen, et al., 1997):

- Internal industrial use for product development and improvement purposes
- Internal strategic planning and policy decision making in industrial settings
- External use by industry for marketing
- Governmental policy making in the fields of ecolabelling, green procurement and waste management opportunities.

A LCA should always be holistically based in the sense that all inputs and outputs must be examined. Varying levels of sophistication are required for different applications. Jensen et al. (1997) present the three main levels of sophistication on a scale of increased level of detail: conceptual LCA or Life Cycle Thinking, simplified LCA and detailed LCA. Although most of the effort and attention in the development and standardisation of LCA has been directed towards detailed LCA, very few have been published.

2.4.5.1 *Conceptual LCA – Life Cycle Thinking*

As the name suggests, conceptual LCA is the first and most basic level of LCA. It is at this level that the life cycle approach is used to assess environmental impacts based on a limited, and generally qualitative, inventory. Jensen et al. (1997) points out that this type of LCA cannot be used as a basis for marketing claims or any other public presentation of results. However, it can assist decision makers for the purposes of comparison between different products.

2.4.5.2 *Simplified LCA*

A simplified LCA is an attractive alternative to a full-scale LCA as it can be accomplished with a substantial reduction in time, cost and data. The primary aim of simplification is to identify aspects within the LCA which can be omitted or simplified without compromising the overall result. The process of simplification consists of three steps outlined by Jensen et al. (1997): screening, simplifying and assessing reliability. Screening involves identification of items within the life cycle that are significant, or gaps in data. Simplifying utilises the results from screening to focus on the important elements of the system, while assessing reliability ensures that simplification does not significantly reduce the reliability of the overall result. The major focus of a simplified LCA is on the main contributing incoming materials, water and energy use. A greater level of detail needs to be achieved, compared to a conceptual LCA, in order to increase the representativeness of the results (Gyetvai, 2012).

Communication of the results of a simplified LCA can be internal or external. For external communication purposes, the report needs to comply with the requirements set out in the ISO 14040 (2006) document and an independent review is needed prior to publication. Furthermore, additional precautionary measures need to be adhered to when conducting comparative assertions on the basis of a simplified LCA. These include the documentation of all parameters used and assumptions made for the comparison (Gyetvai, 2012). To avoid misinterpretation of the results, the user should be made aware of all the limitations of the study including all simplifying methods applied in the LCA (Jensen, et al., 1997).

2.4.5.3 *Detailed LCA*

A detailed LCA is one that meets the requirements set out in the ISO 14040 (2006) document. It involves an analysis of the entire product's life cycle, yielding a comprehensive view of the environmental performance of the product or process. This type of study assists in the identification of environmental hot spots and provides information regarding the contribution of the individual life cycle stages to the overall environmental impact. Thus, a detailed LCA can serve as a basis for comparative studies and other forms of external communication (Gyetvai, 2012).

For a detailed LCA, all LCI data needs to be taken into account. Cut-off rules should only apply with the aim of easing the process of conducting a LCA, e.g. neglecting minor components in a product. To ensure the accuracy of this form of study, the recommendations of the ILCD handbook (European Commission, 2010) should be followed. In practice, LCA practitioners experience difficulty in meeting these requirements as extensive documentation for each material is required (Gyetvai, 2012). Table 2.3 provides an indication of the level of detail required in a few applications of LCA.

Table 2:3: Level of Detail in Some Applications of LCA (Jensen, et al., 1997)

	Level of detail in LCA			
Application	**Conceptual**	**Simplified**	**Detailed**	**Comments**
Design for Environment	**x**	x		No formal links to LCA
Product development	x	**x**	x	Large variation in sophistication
Product improvement		x		Often based on already existing products
Environmental claims (ISO type II-labelling)	**x**			Seldom based on LCA
Ecolabelling (ISO type I-labelling)	x			Only criteria development requires an LCA
Environmental declaration (ISO type III-labelling)			x	Inventory and/or impact assessment
Organisation marketing		**x**	x	Inclusion of LCA in environmental reporting
Strategic planning	**x**	**x**		Gradual development of LCA knowledge
Green procurement	x	**x**		LCA not as detailed as in ecolabelling
Deposit/refund schemes		x		Reduced number of parameters in the LCA is often sufficient
Environmental ("green") taxes		x		Reduced number of parameters in the LCA is often sufficient
Choice between packaging systems	x		**x**	Detailed inventory, Scope disputed LCA results not the only information

x in Bold indicates the most frequently used level

2.4.6 Position of LCA in South Africa

The LCA approach provides a systematic method to anticipate environmental problems and their solution along the whole life cycle of a product. This approach is in line with South African environmental policy which advocates the adoption of a cautious approach to development. The policy position is informed by the Agenda 21 blueprint on sustainable development which compels government to put in place "*reasonable legislative and other measures*" to protect the environment for the benefit of current and future generations.

South Africa was one of the first developing countries to employ LCAs, with pioneering work being initiated in 1999 (Buckley, et al., 2011). Currently, there are no legal requirements in South Africa to conduct LCA studies and there is no specific mention of LCA in government policies and strategies. Despite this, several academic institutions (University of Cape Town and University of Natal) and companies (Sasol, Mondi and Eskom) have carried out LCAs (Department of Environmental Affairs and Tourism (DEAT), 2004). Examples of LCA applications in South African industry include a LCA commissioned for the Recycling and Economic Development Initiative of South Africa (REDISA) to provide options regarding recycling of waste tyres, and for the chain store, Woolworths, with the purpose of understanding food supply chains in South Africa (Notten, 2014).

Common problems that occur when conducting a LCA in South Africa centre around data collection. It was found that data was not available or accessible, considered to be confidential and lacking in the depth required for a LCA study (Sevitz, et al., 2011). Furthermore, the EIA methodologies that are generally used have all originated in Europe thus decreasing their accuracy at predicting conditions in South Africa. Another factor of note is the lack of regional and local characterisation factors developed for South African conditions (Brent, 2004). It was also discovered that environmental impacts due to water and land usage are critical in the South African context but are barely addressed by the European methods. Despite these limitations, LCA has the capacity to contribute substantially particularly against the backdrop of the government’s commitment to sustainable development.

An African LCA Network has been recently launched which is linked to the UNEP/SETAC LCA Initiative. It is apparent that the gap between developing and developed countries in terms of LCA needs to be bridged by emphasising the use of LCAs in decision-making processes at local, provincial and national levels.

2.5 APPLICATION OF LCA FOR WATER TREATMENT TECHNOLOGIES

The use of LCA to gauge the environmental impacts of water technologies has been increasing since the late 1990s. The earlier LCAs focused on parts of the urban water system, namely waste water treatment (WWT) and drinking water production (DWP). Since 2005, the number of case studies has increased rapidly with half of them originating in Europe and the rest located in North America, Australia, South Africa, China and southeast Asia (Loubet, et al., 2014). The following sub-section discusses LCA tools used in the water industry, provides information regarding significant results found in case studies and highlights common problems encountered during the course of studies.

2.5.1 LCA Tools Used for the Water Industry

A wide variety of tools and modelling packages are available to assist in conducting a LCA. However, most of these programs were developed to assess the environmental impact of industrial products. Very few of them have been utilised in the fields of municipal water and wastewater (He, et al., 2013). The programs that are most widely used for these purposes include SimaPro and GaBi.

2.5.1.1 SimaPro LCA Software

SimaPro is a commercial LCA software developed by PRé Consultants based in the Netherlands and adheres to the ISO standards. It contains various inventory datasets for the most common processes and materials to aid in the creation of an accurate LCA model (PRé Consultants, n.d.). The program comes standard with ten data libraries, including ecoinvent V3 and the European reference life cycle database (ELCD) (The Green House, 2015). Although the initial version was mainly process-based, the new version includes the economic input-output (EIO) LCA database. SimaPro has been successfully utilised to perform LCA for wastewater supply and treatment technologies, as in the studies of Ortiz et al. (2007) and Lassaux et al. (2007).

2.5.1.2 GaBi LCA Software

GaBi is another software package, also developed in Europe by PE International. With its first release in 1993, the program was designed to fulfil numerous objectives, such as the carrying out of LCAs, energy efficiency analysis and sustainability reporting. As with SimaPro, GaBi allows users to construct various scenarios to compare the different environmental impacts. The software has also been used by studies such as Vince et al. (2008) to perform LCAs with the aim of comparing different potable water supply systems. Table 2.4 summarises the databases and LCIA methods used in both packages.

Table 2:4: Database and LCIA Methods Used in SimaPro and GaBi

	Databases	LCIA Methods
SimaPro	Ecoinvent, US LCI, ELCD, US Input Output, EU and Danish Input Output, Dutch Input Output, LCA Food	ReCiPe, Eco-indicator 99, USEtox, IPCC 2007, EPD, Impact 2002+, CML-IA, Traci 2, BEES, Ecological Footprint EDIP 2003, Ecological scarcity 2006, EPS 2000, Greenhouse Gas Protocol and others
GaBi	GaBi Databases, Ecoinvent, U.S. LCI	CML 2011 – version Dec 2007, Nov 2009, Nov 2010, CML 1996, Eco-Indicator 95, Eco-Indicator 95 RF, Eco-Indicator 99, EDIP 1997, EDIP 2003, Impact 2002+, Method of Ecological Scarcity (UBP Method), ReCiPe, TRACI 2.0, USEtox

2.5.3 Review of International and Local LCA Case Studies for Water Systems

In order to compile a comprehensive inventory for a water treatment system, that contains all the major inputs and outputs, each flow in the system needs to be analysed. For a water treatment system, this would typically include the pumping of raw water, the construction material, consumables, energy and chemicals used for each process component during construction and operation as well the quantity of waste disposed (He, et al., 2013). Upon reviewing several case studies, there appear to be various factors that influence the end results. Chief amongst them is the selection of an appropriate functional unit for comparison purposes. Loubet et al. (2014), in their review, mentioned that half the studies defined the functional unit as “the provision and treatment of 1 m^3 of water at the user” whereas 17% of the studies defined it as “the provision and treatment of water per capita for one year”. It was noted that the problem with using the former is that only one type of user is defined, namely domestic and the rest (e.g. industry) are excluded.

Another critical factor is the demarcation of system boundaries. Amongst the papers, Loubet et al. found that three papers extended their boundaries to encompass both domestic and industrial users whereas Lemos et al. (2013) and Lundie et al. (2004) also included administration features, e.g. office buildings, vehicle fleets, etc. Upon conducting a contribution analysis, it was discovered that water users contributed a large share of the impacts while the impact of administration items was negligible.

In the assessment of components, three stages exist, *viz*. the construction, operation and, finally, the decommissioning stage. In their studies, Vince et al. (2008) and Mery et al. (2011) assumed that the impact of the decommissioning phase was negligible. This was based on the findings of Friedrich (2001) and Raluy et al. (2005) who evaluated the environmental impact of this phase. In their analysis of the construction phase, the Friedrich (2001) study showed a higher environmental impact of 15% compared to Raluy et al.’s finding of 5%. This was probably due to Raluy et al.’s study focusing only on desalination technology. Vince et al. (2008) utilised the bibliographic data from both studies in his establishment of an LCI for the construction phase. With respect to the operational phase, three studies in Loubet et al.’s review (2014) took the pipe infrastructure into account, with ten studies going one step further and including the entire system infrastructure. Results show that impacts due to infrastructure can be significant and are probably underestimated due to the fact that only the necessary components and materials are considered, with the exclusion of civil works associated with construction. This is supported by Ampofo-Anti’s (2008) report which is based on the findings of LCAs conducted on the most commonly used construction materials and finds that the production of construction materials is a very energy intensive process.

The issue of electricity is critical and can severely increase the operational costs of a plant. The main conclusion found from the literature is that electricity production and consumption are generally the main source of environmental impacts (Barjoveanu, et al., 2010) (Vince, et al., 2008). He et al. (2013), in their study, compared the energy consumed by running the plant (operational phase energy) to the energy involved in producing the chemicals (operational phase chemicals) and construction of the plant (capital phase materials and equipment). The results show that 70% of the energy is consumed in the production of chemicals and construction of the plant. This analysis indicates that including only the operational phase energy consumption will result in an underestimation of the carbon emissions associated with water treatment plants. In terms of the different treatment processes, it was found that the most energy intensive steps were thermal desalination followed by membrane treatment processes (Vince et al., 2008). Considering the importance of electricity consumption in the LCA of potable water production, Raluy et al. (2005) analysed the influence of different electricity supplies on the impacts of various desalination plants and showed that the impacts of the desalination plants could be significantly reduced with an energy supply from renewable sources or using waste heat. In general, there appears to be a lack of data quantifying electricity consumption for DWP processes utilising desalination, with only Munoz et al. (2010) providing a range of 1–4 kWh/m^3 of water produced (Loubet, et al., 2014). In Rothausen and Conway's (2011) review of energy use in the water sector, it was found that when water resources are inaccessible, this can greatly increase energy use, as it is needed for supply, conveyance, and, in the case of desalination, treatment of water. However, there can be serious drawbacks in comparing the results of various studies, as most results hinge on site specific assumptions (Barjoveanu, et al., 2010).

The flow of water into and out of the system is a major concern in view of the water scarcity situation globally. Loubet et al. (2014) note that an appropriate inventory should be provided with water flows within the technosphere, water withdrawn and released to the local environment and water released to the global environment all being considered. Another inter-related aspect is that of emissions into water, air and soil. In terms of water pollution, eutrophication, ecotoxicity and acidification were found to be the major impacts. The studies that utilised normalisation found that water pollution impacts also formed the greatest contribution to the overall toxicity scores.

One of the challenges of desalination is the disposal of the concentrated brine solution. Peters and Rouse (2005) aimed at assessing the impact of the brine discharges. However, due to LCIA restrictions for local impact assessment, the impact of brine discharge was only taken into account in the construction phase for the piping network from the plant to the sea. In their paper, three scenarios were compared: brackish water reverse osmosis (BWRO), sea water reverse osmosis (SWRO) and water transfer from a distant river. SWRO was shown to be the worst solution for all the considered impacts while BWRO and water transfer scenarios had comparable electricity consumption, thus generating similar impacts.

One of the major impacts that generate great interest is the impact of the process on climate change. Loubet et al. (2014) note that the papers they studied made use of a variety of impact assessment methods with Lassaux et al. (2007) finding similar results when using two methods. Upon analysis, it was also found that climate change impacts were highly dependent on electricity consumption and the energy mix used in each country. Two of the studies listed relatively high impacts on climate change, in spite of their relatively low electricity consumption, due to their electricity mix emitting a large amount of GHGs (Loubet, et al., 2014).

2.5.4 Common Problems and Limitations

Many of the reviewed case studies are based on site specific assumptions with various choices made for the LCA system limits and for the LCIA method (CML, Eco-indicator 99 etc.). As a result, comparison of results on a common basis is not possible nor is the identification of local influences on calculated impacts (Vince, et al., 2008). In addition, each unit operation of a water treatment process is dependent on specific local conditions and technological choices, e.g. the process of reverse osmosis varies with feed water salinity while coagulation and decantation vary with the concentration of suspended solids. Vince et al. (2008) recommended that the analysis cannot remain at plant level but has to focus on each treatment step in turn.

Another common problem that is encountered when conducting a LCA for water treatment processes is the lack of detailed LCI data that is relevant to the particular study. Most of the published literature for the water and wastewater industry is at a strategic level with the aim of providing a framework for GHG and water footprint assessments. He et al. (2013) noted that it is quite rare for material and consumable data to be documented in detail. In particular, Landu (2005) found gaps in information about land usage and certain output flows. Such a characteristic is a limiting factor that restricts the depth of such studies.

Concerning the available software and databases, a challenge exists regarding the location of equipment, processes and chemicals that are commonly used in the water industry. He et al. (2013) notes that such components are excluded from existing databases thus creating a barrier to the utilisation of LCA in water applications. This also results in more time being allocated for steps such as raw data gathering, assembling and analysis.

The ecoinvent database is typically used in the literature to provide information on foreground and background flows. It includes several categories of equipment such as pumps and compressors, blowers and fans, etc. However, it is not a comprehensive list of all the equipment used in water treatment processes and excludes components such as mixers, scrapers and flocculators, amongst others.

In addition, the categories do not distinguish between types of pumps/compressors or motor sizes thus bringing the accuracy of data into question. With respect to chemicals, a gap also exists in locating a particular concentration of chemical, e.g. the database may contain properties for a 50% solution of caustic soda but may lack information for a 25% solution. A last resort would be to make assumptions based on the conclusions of previous case studies in order to proceed. However, care must be taken not to oversimplify as this might decrease the accuracy of LCA studies. It is recommended that additional research be undertaken to prioritise the collection of necessary data that can be used in a water treatment LCA.

2.6 SUMMARY

Due to the burgeoning economy and population growth, the water situation globally is at a critical stage. This condition is particularly relevant to South Africa bearing in mind national rainfall patterns and temperatures. Many strategies have been put in place by the various departments to alleviate the situation. Three of the main technological developments that are highlighted and which will be discussed in greater detail are desalination, waste water reclamation and acid mine drainage reclamation.

The concept of sustainable development has evolved from earlier years with the inherent message revolving around the need for economic progress without sacrificing the environment. There are many tools that can actively contribute to sustainable development. To provide a holistic perspective of the overall environmental impact of a particular product or process, an environmental assessment tool, namely LCA, has been introduced. LCA methodology enables the calculation of environmental burdens in a scientific and systematic manner by evaluating each life stage in what is commonly referred to as a "*cradle-to-grave*" approach. Such a tool allows for comparison of processes and highlights areas where environmental improvement can be achieved.

The concept of LCA can be utilised in various industries with varying degrees of success. This study reviews the application of this environmental management tool in the water industry, citing the results from different case studies both nationally and internationally. Finally, the common problems encountered when embarking on such a study are highlighted.

CHAPTER 3: DESCRIPTION OF CASE STUDIES AND APPROACH

3.1 INTRODUCTION

This chapter introduces three different membrane processes used in the production of potable water from seawater, mine water and municipal wastewater. The first process is based on a reverse osmosis (RO) desalination technology. Umgeni Water, in KwaZulu-Natal, is planning to implement this process. The second process is used in a mine water treatment plant in Mpumalanga Province, and eThekwini Municipality in KwaZulu-Natal is planning to implement the third process to treat municipal wastewater. For all three plants investigated, all three life stages of a water treatment plant were considered, namely the construction, the operation and the decommissioning of the plant. For each case study, a detailed account of the LCA approach is given, in separate sections, starting with the goal and scope definition, followed by the data collection and validation, the generation of a LCA model and inventory list and the generation and interpretation of results.

3.2 DESCRIPTION OF CASE STUDIES

3.2.1 Seawater Desalination - eThekwini Municipality

A graph presenting the water balance for the South Coast of the eThekwini Municipality in September 2015 is shown in Figure 3:1: (Department of Water and Sanitation, 2015). The existing water supply is shaded in light blue with the dark blue block illustrating the effect of the South Coast Augmentation Pipeline The red lines show the projected water requirements, both including and excluding the water catchment (WC)/water demand management (WDM) projects. In order to bridge the gap between the current supply and projected demand, implementation of either a seawater desalination plant or the Lower uMkhomazi Bulk Water Supply Scheme is necessary. To determine the feasibility of constructing a large-scale desalination plant, Umgeni Water undertook a desalination pre-feasibility study. The ultimate capacity of this plant was set at 450 Mℓ/d and the the intention was to service the eThekwini area (Meier, 2012). However, upon further examination, it emerged that there were few points that existed within the water supply network of the municipality that had the capacity to receive such a large quantity of potable water from a single desalination plant. In addition, space constraints dictated that implementation of the pipelines in phases would not be possible. With this in mind, a revised strategy was adopted where the detailed feasibility study would consider the option of a 150 Mℓ/d plant situated on both the North Coast and the South Coast (Meier, 2012). This volumetric flow rate was based on the capacity of existing and planned bulk water supply infrastructure which would be used to convey the final potable water from the desalination plant to several distribution plants.

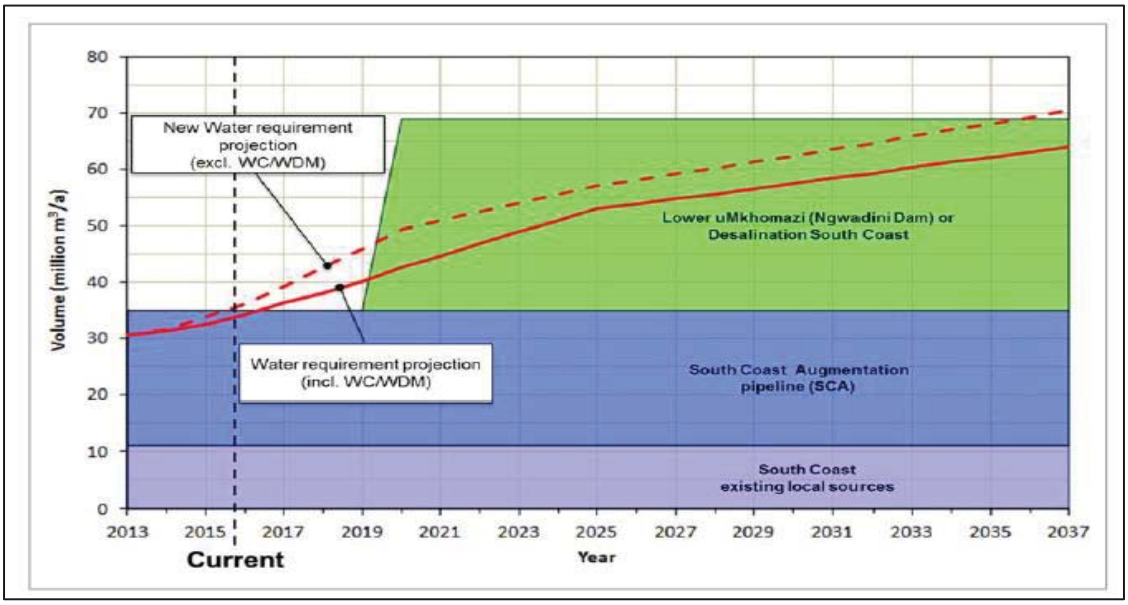

Figure 3:1: South Coast water balance (Department of Water and Sanitation, 2015)

Through a site selection study which was undertaken by Umgeni Water's Planning Department, two potential sites were identified. The location of these sites would enable the new plants to supplement the Mgeni and Hazelmere systems in the medium term with supply to locations in the various municipalities. In general, the desalination plants at the selected locations would include the following key components (Umgeni Water, 2015a):

- offshore open intake and discharge pipeline with diffusers
- pipeline and structures conveying intake water to the desalination plant
- pre-treatment facilities
- reverse osmosis systems equipped with energy recovery devices
- post-treatment systems for remineralisation and disinfection
- water storage tanks and pump stations
- electrical substations connected to power grid.

A diagram of the desalination process, highlighting the key components, is presented in Figure 3:2:. The feed water flows from an open ocean intake through an initial screening period before entering a two-stage Gravity Granular Media Filter. The permeate then gets pumped by high-pressure feed pumps through the RO system. Post-treatment of the product water for alkalinity and disinfection then occurs prior to storage for distribution. The subsidiary flow, which consists of concentrate from the RO membranes as well as backwash water from the filters, is discharged via the outfall pipeline, which is equipped with diffusers. The aim of the pre-treatment process is to provide pre-treated seawater of a specified quality and quantity, which is necessary for membrane desalination. .

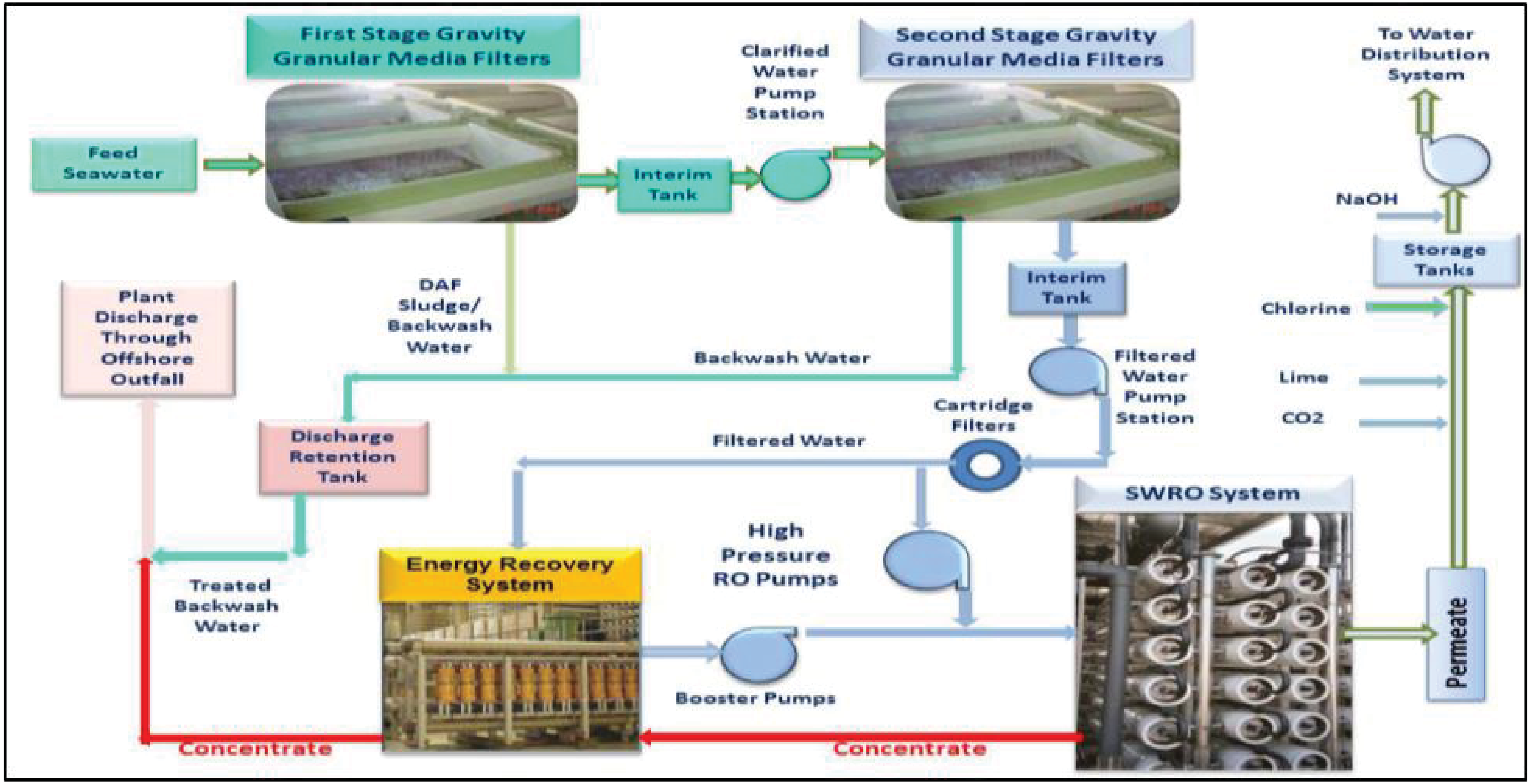

Figure 3:2: The proposed desalination process (Umgeni Water, 2015a)

In addition, the pre-treatment system would increase the useful life of the RO membrane elements and would satisfy the customary performance warranties (Umgeni Water, 2015a). It is recommended that the RO system consist of 16 SWRO trains with one high-pressure feed pump. The system must be designed to meet the specified product water quality and possess a certain degree of flexibility to accommodate a potential increase in production, or future changes in membrane technology (Umgeni Water, 2015a). Approximately 40–50% of the energy requirements for desalination are contained within the concentrate produced by the RO process. In order to optimise the energy consumption of the system, this energy can be recovered and reused by installing energy recovery devices. It is noted in the feasibility report that the payback period of equipment costs for installation of these devices through energy savings is usually less than five years. Thus, the consulting engineers have suggested the addition of 16 pressure exchange recovery systems - one per SWRO train (Umgeni Water, 2015a).

According to the design specifications, individual components are to be arranged in parallel, modular units (e.g. RO membrane trains) to enable independent operation if necessary (Umgeni Water, 2015a). The RO system would comprise of spiral-wound, polyamide, composite-type membrane elements with standard dimensions of 200 mm by 1 016 mm (Umgeni Water, 2015a). Due to design constraints, the average membrane flux of the elements per pressure vessel cannot exceed 15 litres per square metre per hour, when the plant is operated at an average production rate of 150 Mℓ/d (Umgeni Water, 2015a).

3.2.2 Mine Water Reclamation - Mpumalanga

Coal mines have been in existence in Gauteng and Mpumalanga for a substantial period of time. Among these are the underground mining operations located at the Goedgevonden, Tweefontein and iMpunzi Mines (Golder Associates Africa, 2012). In order to allow safe access to the coal reserves, water is pumped away from active areas and stored in previously mined underground cavities. The objective of the proposed mine water reclamation scheme (MWRS) was to abstract and treat the accumulated mine water in order to increase the potable water supply and allow mining to occur within areas that were previously flooded (Golder Associates Africa, 2012).

An EIA was undertaken prior to the commencement of the project to assess both positive and negative impacts and propose potential mitigation measures. It was proposed that the project involve the construction and operation of a MWRS which would consist of mine water abstraction points and delivery pipelines, a mine water storage dam, a water treatment plant (WTP), sludge and brine ponds for WTP waste, treated water supply pipelines and support infrastructure such as power lines and access roads (Golder Associates Africa, 2012). The WTP would comprise a raw water pond, pre-treatment and UF facilities and a two-stage RO system. It was envisaged that the project would be carried out in three phases with the aim of abstracting and treating a total of 45 Mℓ/d.

Figure 3:3: is a simplified depiction of the mine water reclamation process.

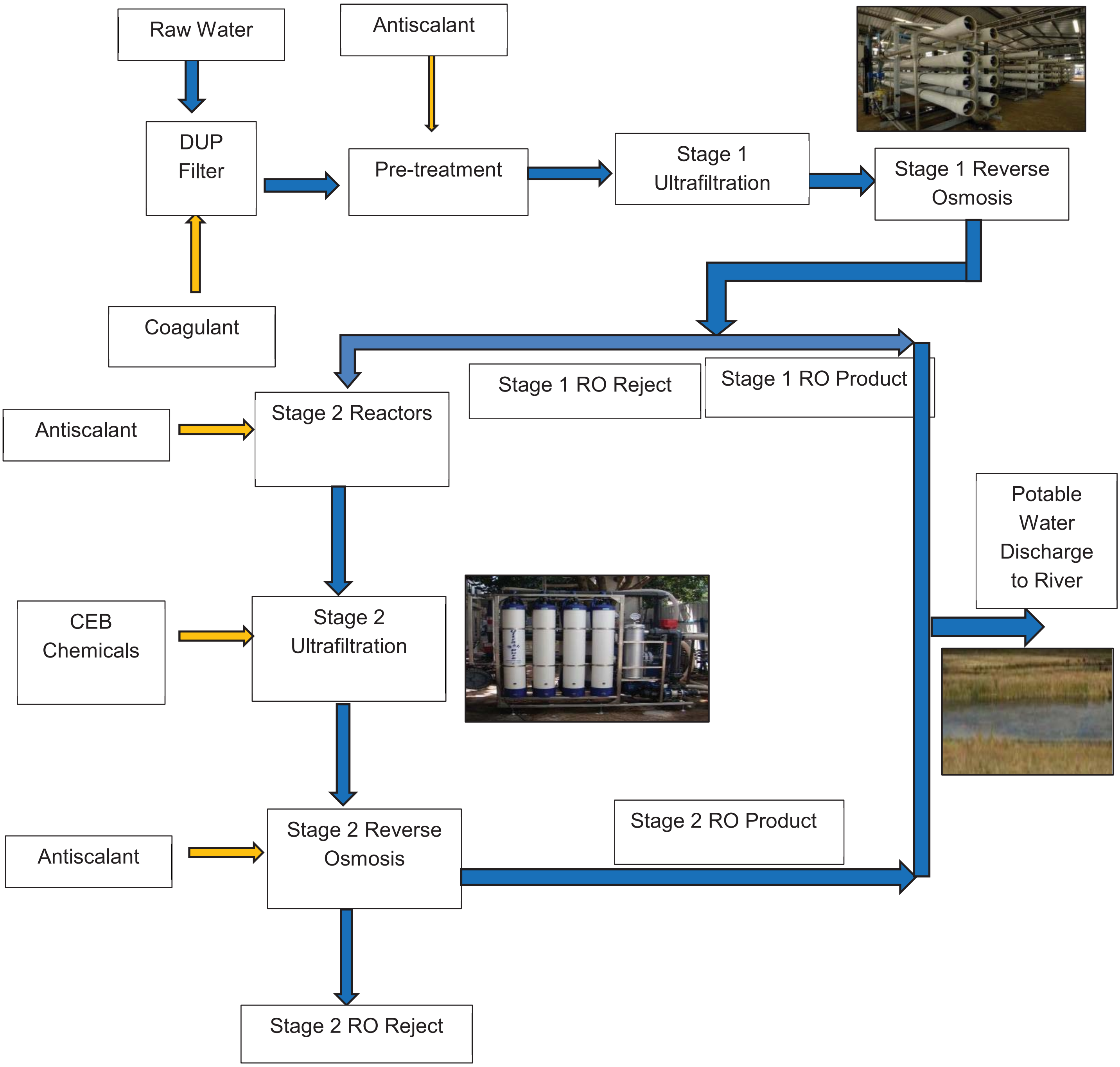

Figure 3:3: Process flow diagram depicting the mine water reclamation process

Currently, phase 1 of the plant has been successfully completed which processes 15 Mℓ/d of contaminated mine water (Golder Associates Africa, 2012). Provision will be made for future modular upgrades in the design phase for additional feed capacity. The mine-affected water is pumped through Deep Bed Up-Flow (DUP) filters and treated with the addition of several chemical compounds (Prentec, 2013).Special focus is reserved to achieve a balanced flux across all elements in the array, together with a regular permeate flush. The water then flows through the first stage of UF and RO. The reject flow from this first stage then flows through a secondary treatment phase. The product water from both stages is collected and then discharged into a river. All process units are housed in customised modules and integrated with process, mechanical electrical and control components for full functionality and ease of design (Prentec, 2013).

It is envisaged that future uses of this treated water would include the mine's internal use (4 Mℓ/d), the proposed power plant (1.2–1.7 Mℓ/d) and possible potable water supply to surrounding communities (Golder Associates Africa, 2012). It is for these reasons that the water treatment plant was designed to produce water suitable for environmental discharge as well as for potable water purposes. Thus, the treated water quality must comply with potable water standards together with the receiving water quality objectives (RWQO) of the surrounding catchment area (Golder Associates Africa, 2012).

The design for the mine water reuse plant makes extensive use of membranes, with two stages of UF and RO. The primary UF module consists of polyvinylidene fluoride (PVDF) membranes with 0.08 micron pore size (Hydranautics, 2016). Stage 1 of RO is configured into two banks of spiral-wound elements with polyamide thin-film composite membranes with a 75–80% recovery (Dow Filmtec, 2015). The secondary treatment stage is designed to effectively recover water from a saline solution. Stage 2 of UF utilises 1.5 mm membranes with an inside out configuration to reduce the potential for scaling (Prentec, 2013). The modified polyethersulphone (PES) membrane material is resistant to fouling while the large 1.5 mm size allows for a more effective cleaning process (Prentec, 2013). The second stage of RO comprises three banks of membrane elements with a higher feed pressure then the first stage (Prentec, 2013).

3.2.3 Remix Wastewater Recycling - eThekwini Municipality

The eThekwini Municipality, together with Hitachi, are planning to construct and commission a demonstration and commercial plant that uses treated wastewater as its primary input. To remove contaminants and treat the water to potable water quality, a three-stage system that treats effluent through RO and UF will be used together with disinfection by ultraviolet light and chlorine (Bosworth, 2013). The treated water would then be stored and tested before release into the water distribution network. Before commencement of the design work, the site location and plant capacity had to be confirmed. In the pre-feasibility study, Central Waste Water Treatment Works (Central WWTW) was chosen as the project site due to the availability of space through excavation of a hill (Hitachi, 2015).

However, this would substantially affect the cost of the project. According to an article published by the Inter Press Service News Agency, the municipality's senior planning manager states that the purified water will be mixed with conventional drinking water at a ratio of 30% reused water to 70% conventional water.

Reusing wastewater in this manner will effectively add 116 Mℓ/d of tap water to the municipality's supply (Bosworth, 2013). This will feed the northern regions, including areas such as Umhlanga, Durban North, Reservoir Hills and KwaMashu.

The demonstration plant for this project is modelled on a plant located in Japan called Water Plaza Kitakyushu, and the overall technology was developed by the Hitachi Corporation (Ltd), based on the Remix technology. The feed to the system is initially comprised of 1 500 m^3/d of wastewater and 500 m^3/d of seawater (Hitachi, 2013). Once the wastewater is pumped through membrane bioreactors and a "sewage RO" system (BWRO), the permeate is combined with seawater before entry into the "seawater RO" system (SWRO) (Hitachi, 2013). The Remix system produces 1 400 m^3/d of product water (Hitachi, 2013). A general diagram of the main processes involved is presented in Figure 3.4.

As per the demonstration plant, the Remix plant has two feed sources, namely wastewater and seawater. Treated wastewater enters the system and is filtered through a sand filter before flowing through a UF unit. Together with the addition of several chemicals, the water is further processed through a BWRO operation. The reject stream is combined with an incoming seawater stream which has been through an initial UF process. The combined stream is then processed via two RO units: an SWRO and a BWRO unit. The permeate from both the wastewater and seawater stream are then stored in a product water tank awaiting discharge. This water treatment process is designed to produce 100 000 m^3/d of product water (Hitachi, 2013 and Takabatake et al., 2013).

The Remix system, as applied in Kitakyushu, has been shown to have major benefits as compared to desalination without the use of wastewater, or a conventional treatment (i.e. activated sludge process) alone. These benefits are a reduction in energy needed, due to a reduction in the power needed for filtration and a reduction in aeration volume, and a reduction in costs (Hitachi, 2013; City of Kitakyushu, 2014). Lower environmental impacts, due to a 30% decrease in energy requirements, and the lower salinity of the resulting brine, and stable operation and product water quality have been also reported for the Remix system as employed in Kitakyushu (Takabatake et al., 2013).

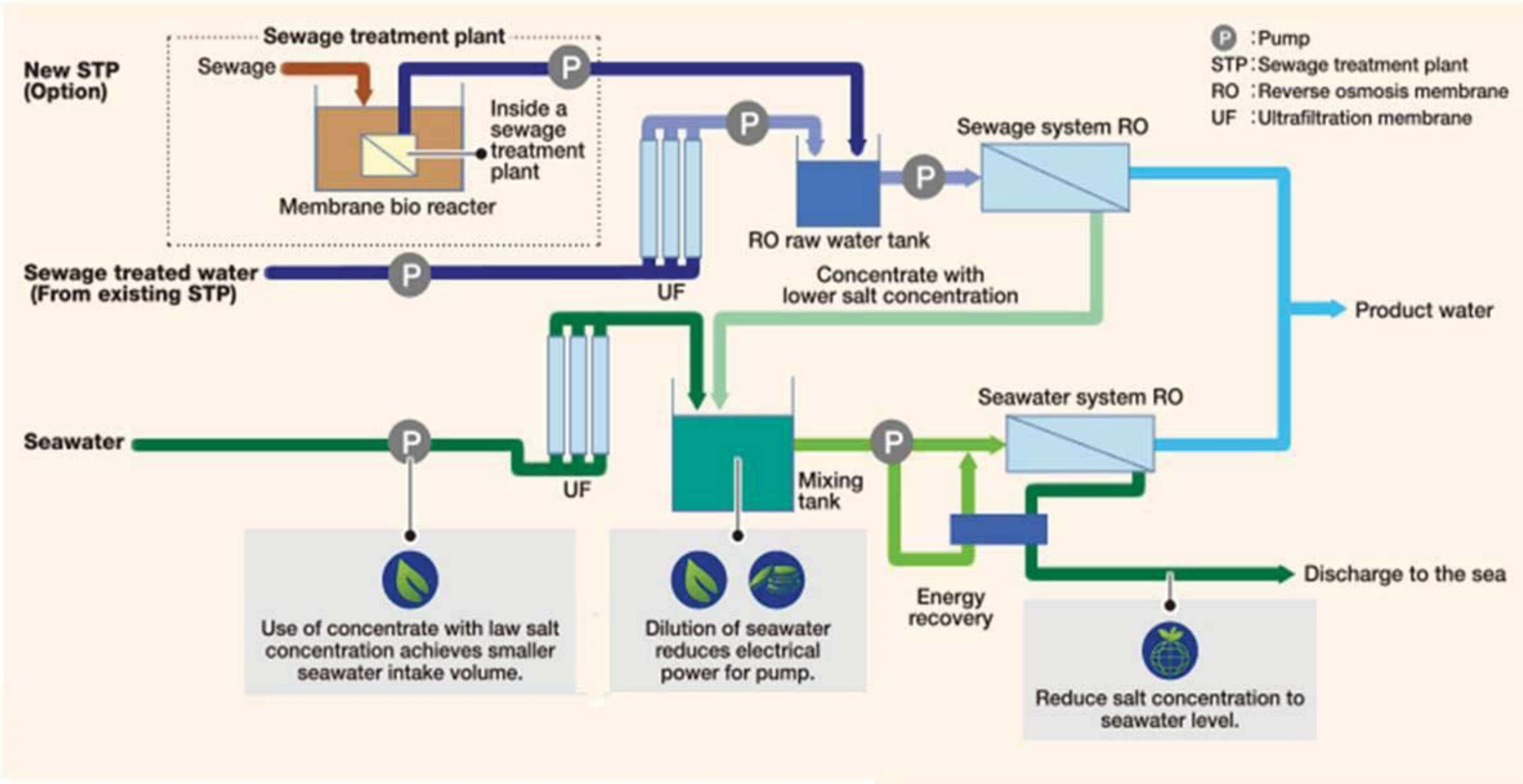

Figure 3.4: Processes planned for the eThekwini wastewater recycling and desalination plant (Source: Hitachi, 2013)

3.3 DESCRIPTION OF THE LCA APPROACH

3.3.1 Goal and Scope Definition

This phase provides details regarding the purpose and application of the study as well as the recipients of the final results (ISO, 2006). Additional information such as the fixing of system boundaries and selection of the functional unit is also given.

3.3.1.1 Defining the Goal

As presented in Chapter 1, the main objective of this study was to quantify the overall environmental impact of each of the water treatment processes, with the generation of local LCA data. Furthermore, the report aims to provide a comparison between the different treatment technologies. The intended audience for this study is broad and includes professionals in the water sector such as environmental and operational managers who undertake environmental assessments as part of their professional duties. It is envisaged that government authorities who are responsible for investigating environmental processes could also gain insight from the findings of such a research project. In addition, the results could also potentially benefit process engineers who are involved in designing new water treatment plants.

3.3.1.2 Defining the Scope

The purpose of defining the scope is to provide sufficient detail regarding the object of the LCA study. This should be completed in conjunction with the goal definition (European Commission, 2010). The items that need to be considered include the product system demarcated by the system boundaries, the selected function and functional unit, allocation procedures if necessary, data requirements, assumptions made during the course of the study, and limitations. The systems under consideration are the three processes for the production of potable water. The first process under review was the desalination of seawater while the second process focuses on the reclamation of mine-affected water. For both processes, only the construction and operation phase were considered as the decommissioning phase was considered negligible, based on the findings of Friedrich (2001) and Raluy et al. (2005).

Figure 3:4: depicts the stages in the LCA, with the black box depicting the system boundary. The function for all three water production systems is identical, i.e. to produce potable water of a certain quality. The functional unit for this study is 1 kℓ of water at the specified standard for potable water produced over the life span of each process unit. The selection of this particular functional unit enabled a reference to which all inputs and outputs are related and provided a basis for comparison between the two processes. Allocation continues to be a highly contentious issue in LCA circles. There is a general consensus that avoiding allocation is the most appealing option (Curran, 2013). For the systems under study, there is no allocation necessary due to the lack of by-products.

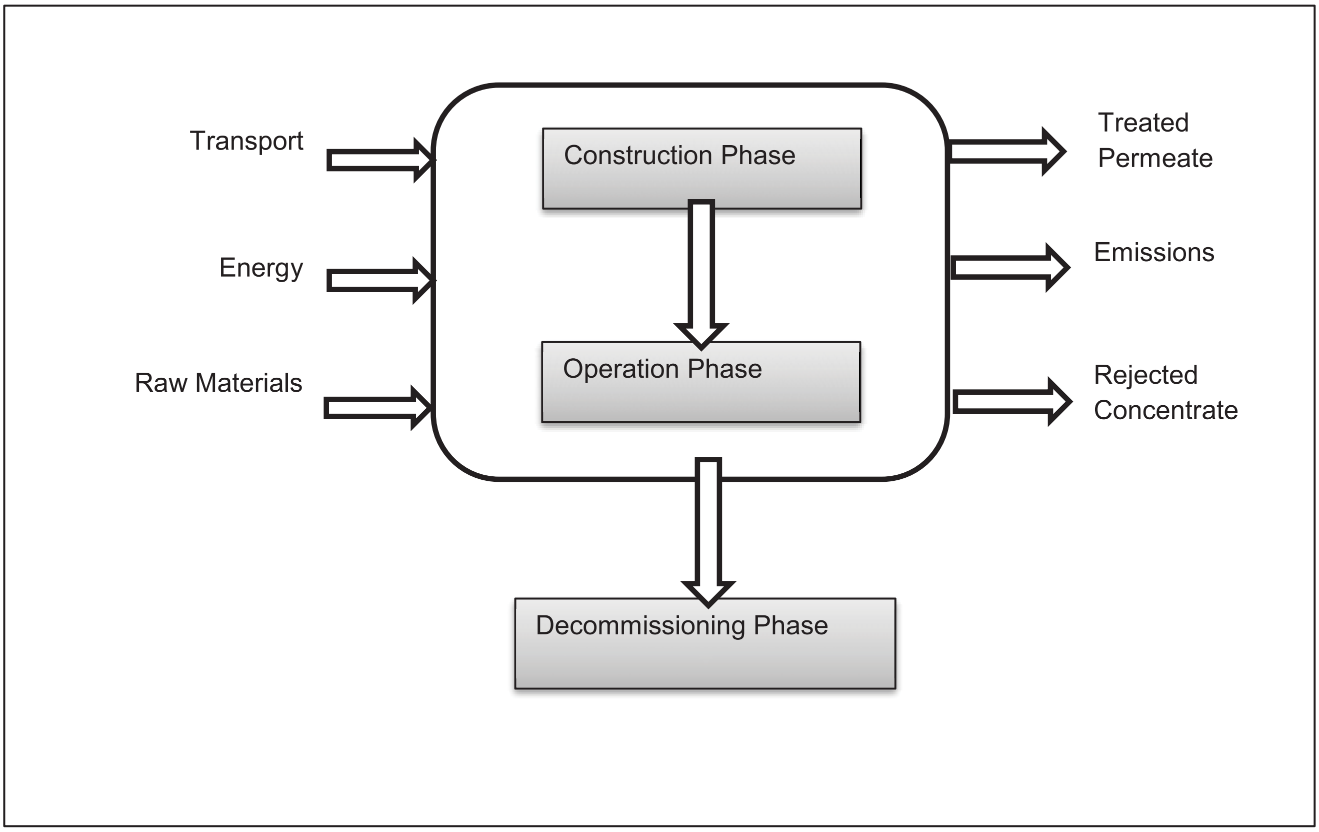

Figure 3:4: LCA stages for the three case studies

However, production for most of the inputs (e.g. production of sulphuric acid) requires allocation as by-products are produced in addition to the main product. It was decided that the total environmental burden be attributed to the core product even though this may add to the burden of the system. However, as quantities for these inputs, in terms of the functional unit, were relatively small, such burdens were considered to be minor.

Data quality requirements are a general indication of the characteristics of the data and thus affect the reliability of the results. For the study, data that was directly obtained from the feasibility and design reports was preferable. Such data included the consumption of electricity and chemicals. For process flows within the system that were not available, mass balances were employed. In the event that direct data was unavailable, as was the case for the construction of civil engineering structures, calculations based on technical literature were utilised. Several calculations were often undertaken and the highest values, representing a worst-case scenario, were used for the purposes of the study. Decisions regarding construction materials and equipment types were based on case studies of similar water treatment processes. The geographical area for data gathering was South Africa. Within the SimaPro databases, South African data was only available for national electricity and mined coal (i.e. anthracite) that was used as filter media. For the remainder of the inputs, European or global figures were utilised.

Limitations to a certain extent were to be expected, considering the great task of accounting for all inputs and outputs of the system. In general, data was found to be sparse and lacking which is often the case for LCAs, but even more so for industries based in South Africa. One problem was that data was considered to be confidential and thus was not easily accessible. This was the case for all three case studies and lengthy negotiations had to occur before any exchange of information happened. Agreements between Umgeni Water, Prentec and the consulting engineers had to be made in order to obtain certain process details. Another reason for the lack of data can be attributed to the fact that the desalination plant was still in the early design phases. Thus, some information, such as the weights of certain pumps, was unavailable. As a result, information from design specification sheets for similar pumps had to be used as input for the calculations. For the mine water reclamation plant, design data rather than operational data had to be utilised. This was due to changes in the feed quality of the source water which affected the operation of the plant.

A set of assumptions had to be made in order to bridge data gaps. For certain inputs that were based on international data, it was assumed that the technology and equipment utilised performs in a similar manner to what is used in South Africa. Where construction material for components was unspecified, such as for the filter cells, various literature sources were perused and the most common materials were selected for the purpose of calculation. Super duplex stainless steel was chosen as the construction material of choice for any equipment that is in contact with ocean water. The working life of certain mechanical machinery, such as pumps, was assumed to be 10 years. It was also assumed that both plants will be operational for the entire year, i.e. 365 days, with no allowance for shut down periods. This was to account for the worst-case scenario. The results of the study will be reviewed by the organisations who have sponsored this research, namely Umgeni Water, Prentec, eThekwini Municipality's Water and Sanitation Department and the Water Research Commission of South Africa, through the review panel.

3.3.2 Inventory Analysis

As the second stage of the LCA process, the inventory analysis consisted of collecting environmentally relevant data and formulating calculations in order to quantify flows into and out of the system. For this particular study, the process of data collection and compilation was the most energy-intensive and time-consuming activity.

3.3.2.1 Data Collection for the Desalination Plant

The procedure for data collection started with compilation of a process flow diagram which highlighted the significant flows and operations within the system. From this point, a spreadsheet was drawn up which included material and energy inputs and outputs for each unit operation. As alluded to earlier, the process of data collection requires interaction and collaboration from all organisations linked to the study. A concerted effort was made to introduce the process engineers at Umgeni Water and the consultant engineers at Aurecon to the concept of life cycle assessments and the motivation behind gathering of specific data. For the construction phase, four major components were analysed, namely civil engineering structures, pipes, pumps, filters and membranes, as in Figure 3:5:. Civil engineering structures consisted of fixtures such as tanks, pillars and filter cells. The weight of these constituents was generally not stated and had to be calculated based on available dimensions provided in the feasibility reports. In the event that the construction material was not specified, technical literature was used to select the most appropriate building material. In the case of pipes, all pipes were specified to be constructed of high density polyethylene (HDPE) due to its higher durability, non-corrosive nature and lower construction and maintenance costs compared to other materials. The mass of these pipes was calculated using two methods: by firstly calculating the volume of a hollow cylinder (which represents a pipe) using the inside and outside diameters and using the density to obtain the mass. The second method used a HDPE pipe brochure to obtain the weight of the pipe, based on the outer diameter and standard dimension ratio (SDR) class which were stated in Appendix A of the Pipelines and Pump Stations Report (Umgeni Water, 2015b). The higher figure was then utilised in subsequent calculations. A similar approach was taken for pumps. For the intake pumps, options were provided for various pumps models in the above-mentioned report (Umgeni Water, 2015b).

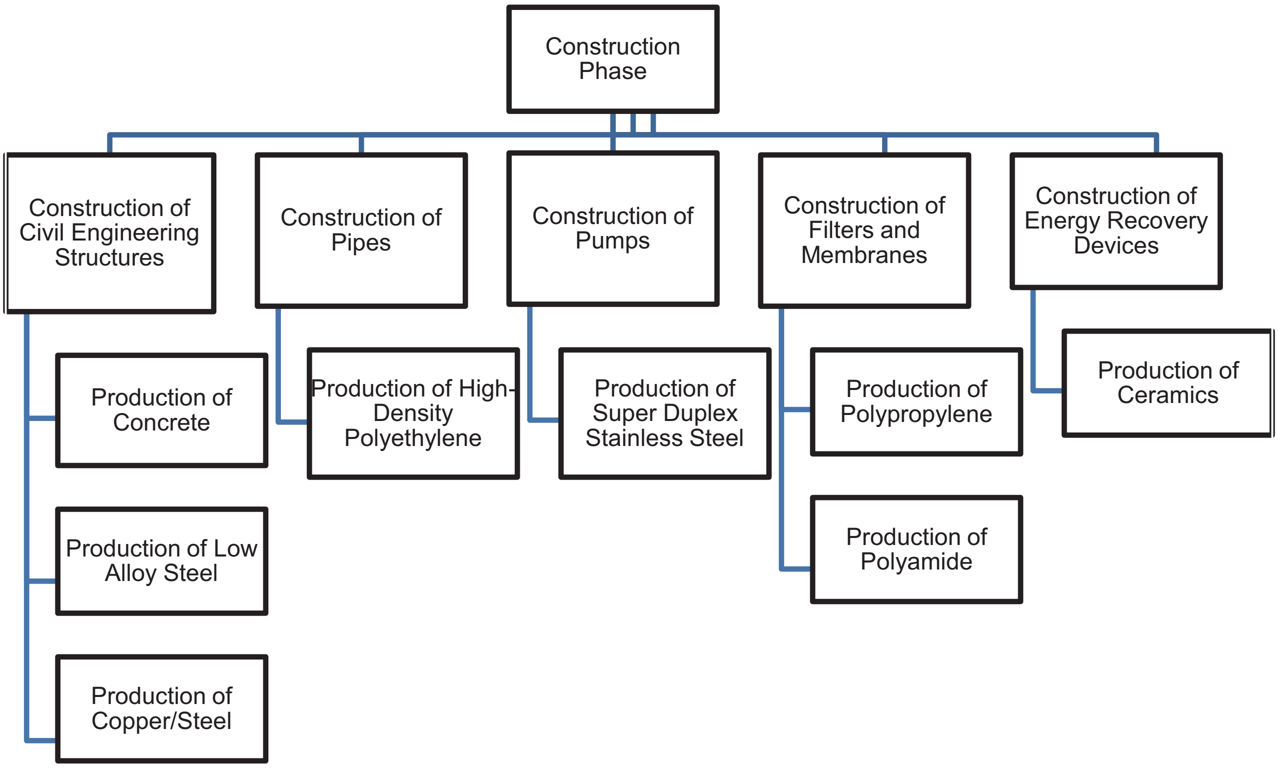

Figure 3:5: Components of the construction phase for desalination

The weight was then obtained by locating the pump specification sheets for the selected model. For other pumps where model numbers were unavailable, the installed motor size and pumping capacity, which was provided in the Desalination Options and Feasibility Report (Umgeni Water, 2015a), were used as guidelines to select an appropriate pump. This report also detailed that the pumps be constructed of super duplex stainless steel. As such a material was not available on the SimaPro database, steel which had a high chromite content (±25%) was selected. For the production of potable water, the main inputs into the system are the energy consumed, the chemicals utilised and the filter media, as displayed in Figure 3:6:.

Chemicals are used in water treatment for various purposes, namely disinfection, RO membrane cleaning, chlorination and re-mineralisation. The utilisation of chemicals was stated in terms of milligrams per litre of water (mg/ℓ) with the majority of the chemicals specified. For the chemicals that were not categorically stated such as the coagulant and antiscalant, research was undertaken to determine the most suitable chemical for the application. Table 3:1: provides a summary of chemical usage for the desalination process.

Table 3:1: Summary of Chemicals used for the Desalination Process

Chemical (Umgeni Water, 2015a)	**Unit Operation**	**Chemical (SimaPro)**
Sodium Hyphochlorite	Screening of Water	Sodium Hyphochlorite
Coagulant, Flocculant	Pre-Treatment – Both stages	Iron (III) Chloride (40% solution)
Sulphuric Acid	Pre-Treatment – Both stages	Sulphuric Acid
Sodium Hydroxide	Pre-Treatment – Second stage	Sodium Hydroxide (50% solution)
Sodium Bisulfite	Pre-Treatment – Second stage	Sodium Sulfite
Antiscalant	Pre-Treatment – Second stage	Phosphoric Acid
Membrane Cleaning	Reverse Osmosis	Hydrochloric Acid (30% solution)
Lime	Post-Treatment	Lime (hydrated)
Carbon Dioxide	Post-Treatment	Carbon Dioxide (liquid)
Chlorine	Post-Treatment	Chlorine (gaseous, membrane cell)
Sodium Hydroxide	Storage	Sodium Hydroxide (50% solution)

From the literature review, it is evident that the electricity requirement has always been one of the determining factors regarding life cycle assessment results. For the purposes of this study, this information was available in the Desalination Options and Feasibility Report and was expressed in terms of kWh/m^3 (Umgeni Water, 2015a). Electrical energy is used for pumping and the delivery of water and chemicals through the process. As electricity is such a fundamental element, it was imperative that a consistent and representative life cycle inventory (LCI) of electricity supply was utilised. The latest version of ecoinvent (version 3) offers new LCI data on power supply in 71 geographical locations, which includes South Africa (Paul Scherrer Institute, 2012). Thus, this inventory set was utilised for this study to account for the South African energy mix.

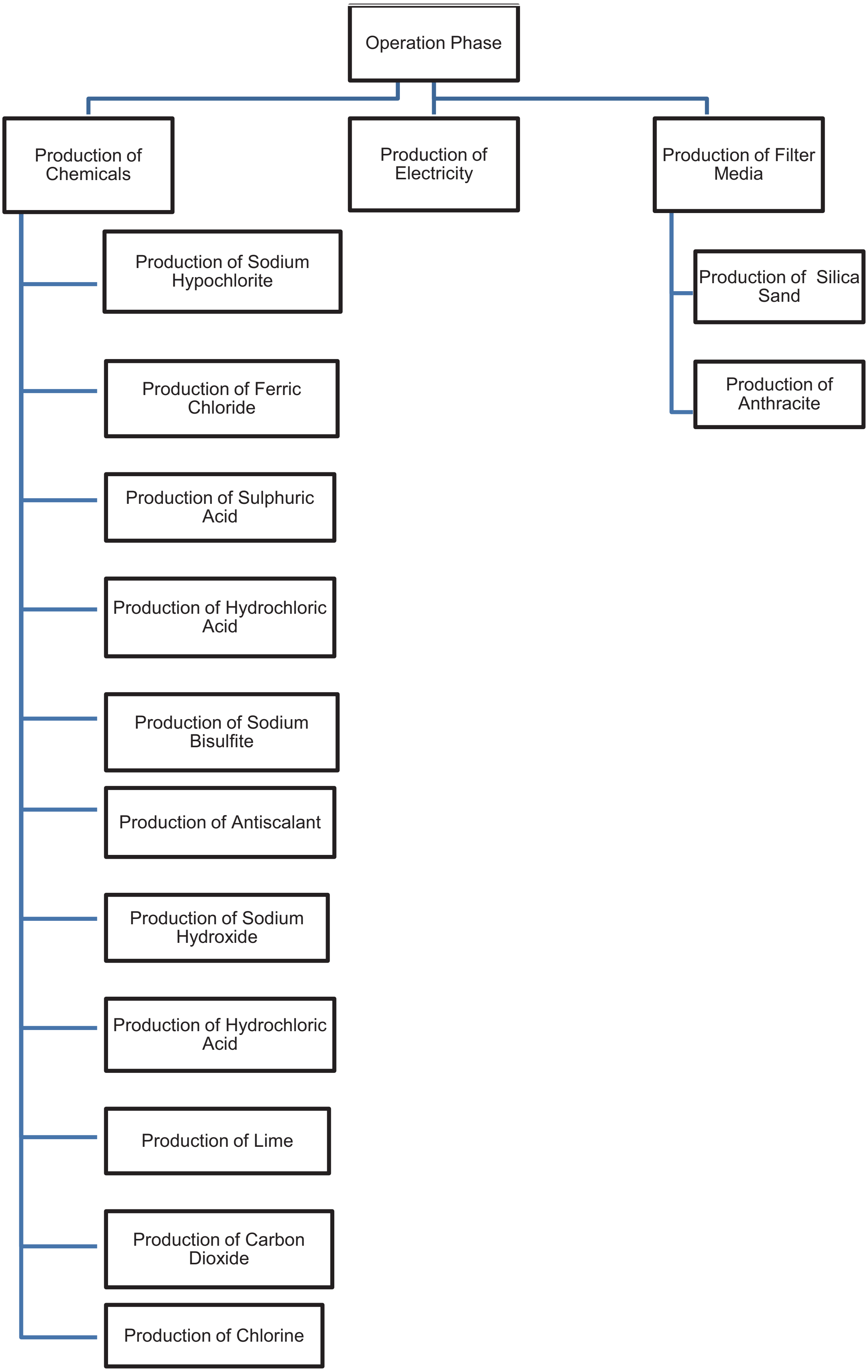

Figure 3:6: Components of operation phase for desalination

The filtration step forms part of the pre-treatment phase to protect the RO membranes further on in the process. As mentioned in Section 3.2.1, dual media filters were specified in both stages of pre-treatment containing silica sand, anthracite and garnet. SimaPro contains data for coal from extraction to point of sale in South Africa. This local data was utilised to represent the media layers for the filters.

3.3.2.2 Data Collection for the Mine Water Reclamation Plant

This procedure commenced with an initial meeting with the senior process engineer from Prentec. An overview of the treatment process was provided together with several Process and Instrumentation Diagrams as well as schedules for power use. This was followed by compilation of the spreadsheet that segregated the design data per unit operation and then further into the construction and operation phases. Average design feed flows into each sub-operation were stated in the design reports. In order to obtain clarification around certain technical aspects, several meetings were scheduled. The construction phase typically consists of infrastructure that is designed, built and commissioned as per project specifications. Figure 3:7: provides a summary of the major constituents of this phase, namely civil engineering structures, frames of the modules, grating, pipes, pumps, filters and membranes.

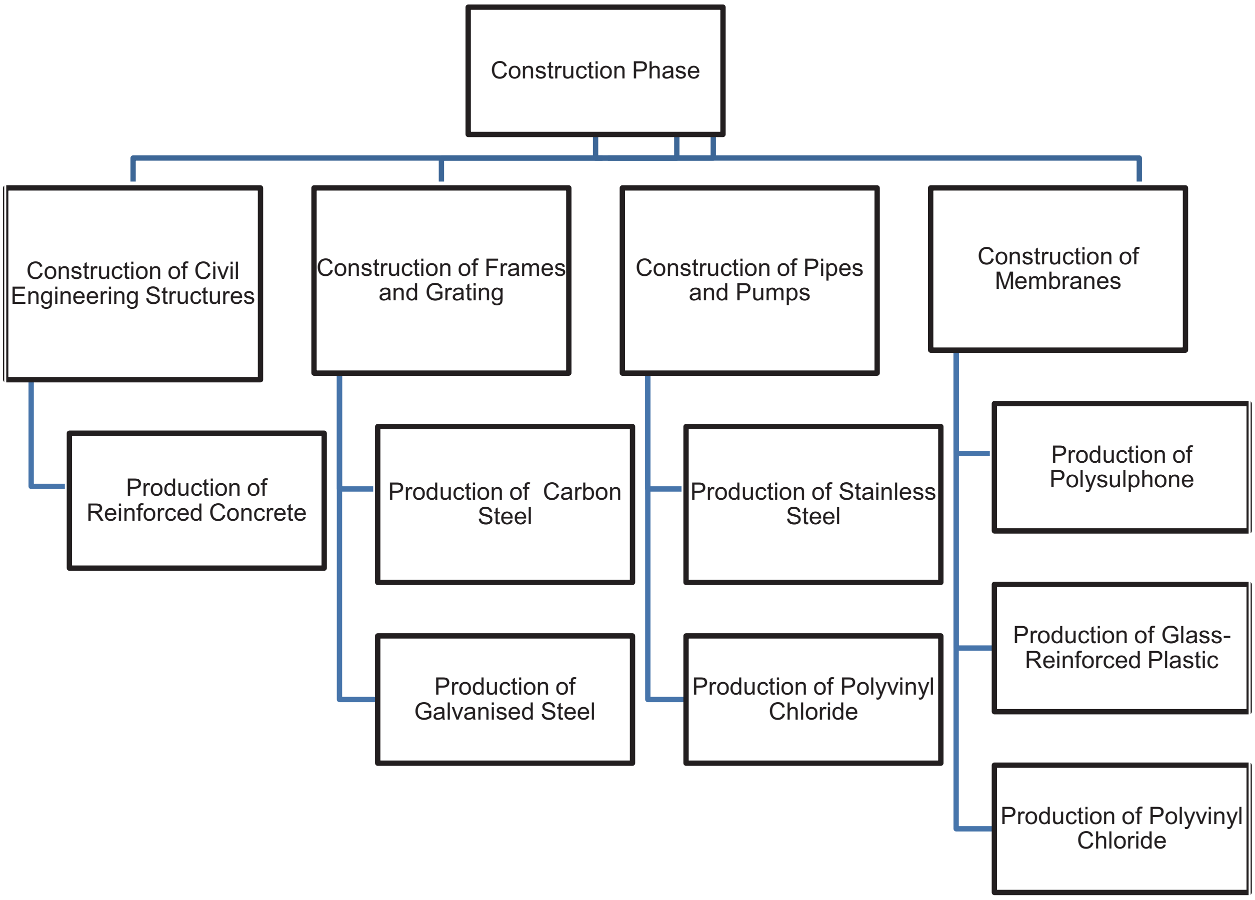

Figure 3:7: Components of the construction phase for mine water reclamation

The civil engineering structures for this case study consisted of tanks and filter cells. Design sheets for the various tanks provided the dimensions of the tanks such as the diameters and heights. These were utilised to calculate the circumference, and thereafter the number of panels that make up the wall of the tank. Together with the dimensions of the panels, the weight of the walls and base of the tank was calculated. From the design sheets, the material of construction for the base and walls was reinforced concrete to withstand pressures of 25 and 30 MPa respectively. With respect to working life, the senior process engineer was consulted and agreed that a reasonable working life for tanks would be 50 years.

For this second case study, the mass of components such as the frames of the skid, grating and pipes was obtained from Prentec. A 3D model of the plant, which collates the total mass of each skid, was utilised from which the mass of individual items was extracted. This data is extremely accurate as pipe mass would constitute the mass of all lengths of pipes, including all bends and tees. The frames and grating that form part of the skid are constructed from carbon steel and galvanised steel respectively, while the pipes are either assembled from PVC or stainless steel. The working life of the frames, grating and stainless steel pipes was taken as 25 years while the PVC pipes were assumed to last 20 years.

With respect to the pumps, product names were provided in the design proposal report. As the majority of the pumps were manufactured by Grundfos, the product centre on the Grundfos website was perused. As all the pumps were classified as End Suction Close Coupled (NB range), the pump catalogue was browsed by pump design to locate the mass of specific pumps. The working life of all pumps was stated as seven years.

The water treatment process for mine-affected water consists of two stages of treatment. Thus, there were two RO stages and two UF stages. For the RO membranes, the masses of 8" spiral-wound membranes were obtained from the Dow website, while the design sheets for the glass-reinforced plastic vessels were provided. According to the engineer, as well as figures from technical literature, the membranes, which are constructed of polysulphone, would last an average of five years while the working life of the outer shells was noted as 20 years. With respect to the UF membranes, product data sheets for the weight of the membranes were located on the supplier's website. These were constructed of polyvinyl chloride (PVC) with the same working life as the RO membranes.

The three components of the operation phase, as summarised in Figure 3:8:, are chemical use, energy consumption and the filter media used. There were numerous chemicals used in the treatment process to satisfy various objectives. Amongst them were coagulants, biocides, antiscalants, chemically enhanced backwash (CEB) and clean in place (CIP) chemicals. The major chemical constituents used were phosphoric acid as an antiscalant, ferric chloride as a coagulant and secondary antiscalant, sodium hydroxide, sodium hypochlorite and hydrochloric acid as CEB and CIP chemicals. The average concentrations in terms of ppm for each chemical were provided.

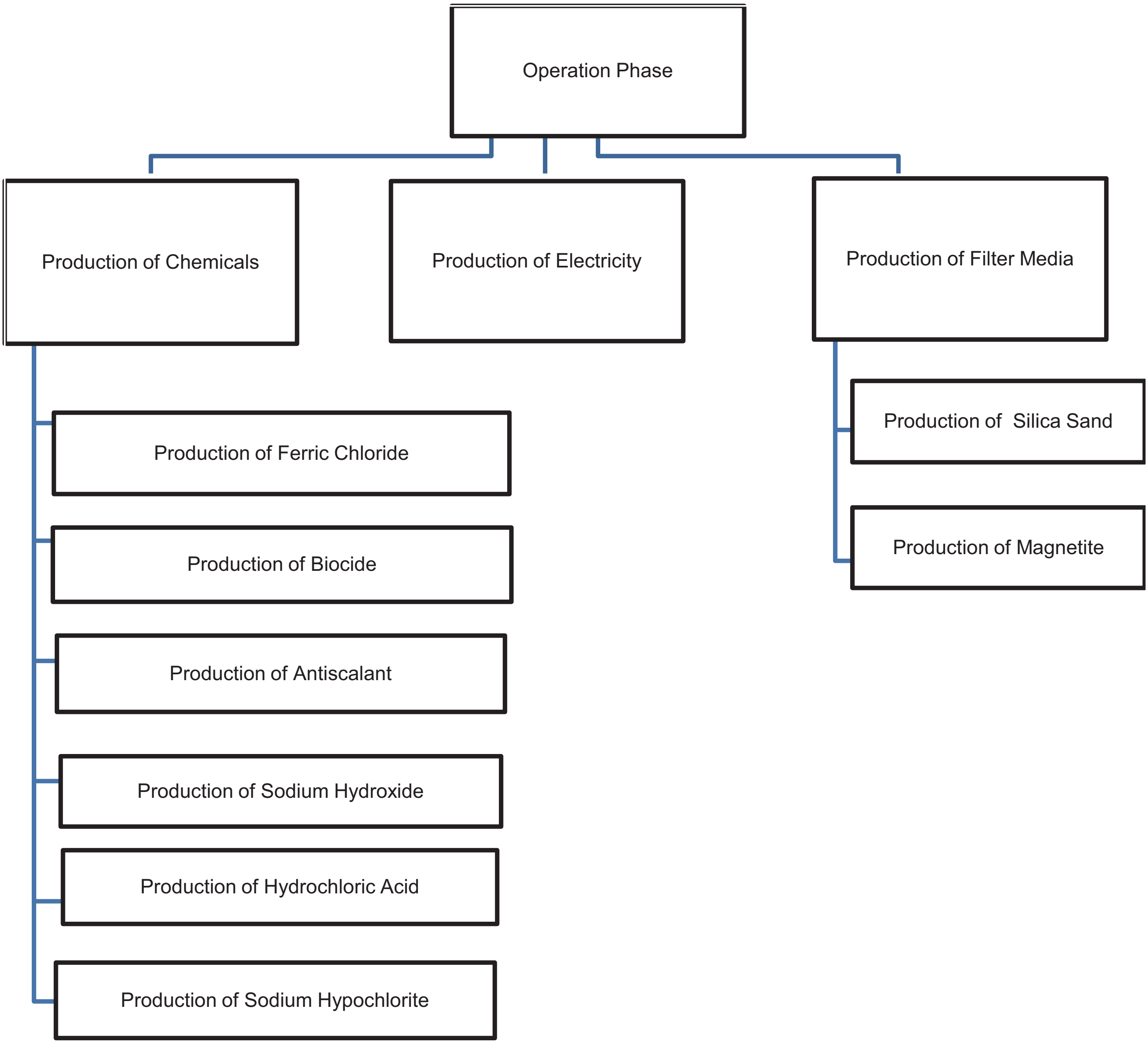

Figure 3:8: Components of operation phase for desalination

From the literature, it was evident that energy is of utmost importance. Thus, a concerted effort was made to obtain an accurate portrayal of electricity consumption within the process. The power used by each unit operation and the absorbed power of all power users was obtained from the design schedule, expressed in kWh. Together with the design feed rate into each area, the electricity requirement in terms of kWh/m^3 was calculated. As with the first case study, the South African electricity (medium voltage) dataset in SimaPro was utilised.

3.3.2.3 *Obtaining data for the Remix Wastewater Treatment Process*

As the eThekwini Remix plant is in the initial stages of design, the level of detail that is available is very low. Hence, the LCA performed on this system is a conceptual/simplified LCA. As noted earlier, this type of LCA is a basic LCA that can be utilised to assess the environmental impacts of a process with a limited inventory. As the major focus of the results from the previous two case studies was centred around the operations phase, a detailed LCA was performed for this life stage for the Remix plant too. However, due to lack of data on the planned construction of this plant, it was impossible to calculate the environmental scores for this stage. Therefore, a worst-case scenario was assumed in which, for each environmental score for each environmental impact category, 20% of that impact is due to construction.

This LCA took the operation phase into account by modelling the proposed electricity consumption and chemical usage of the reuse plant. The total electricity consumption of the entire plant was provided in the literature by Takabatake et al. (2013) as 2.9 kWh/m^3 of treated water; however, over the last three years, this figure had been reduced to 2.6 kWh/m^3 (Hitachi, 2016) due to increased energy-saving measures. For this study, the latest figure for energy was used. As this water treatment system includes a combined feed flow of treated wastewater and seawater, numerous chemicals were required. A list of chemicals, together with water mass flows, was provided by Hitachi (2016) in the form of a water mass balance sheet. The chemical concentrations were unknown and had to be sourced. The majority of the chemicals were the same as the ones proposed for use in the desalination case study with a similar chemical function. Thus, it was assumed that the dosages utilised by Umgeni Water and presented in the feasibility report (Umgeni Water, 2015a) for the desalination plant are the same in the case of the Remix system. In the case of the CIP and backwash chemicals, the concentrations were sourced from technical literature focusing on membrane use and maintenance.

Table 3.2 provides a summary of the chemicals utilised in the plant together with their respective dosages.

Table 3:2: Dosages of Chemicals in the Remix Plant

Chemicals	Dosage (mg/l)
Sodium Hypochlorite	2
CIP - Sodium Hydroxide	1200 [a]
CIP - Sodium Hypochlorite	200 [a]
Backwash - Sodium Hypochlorite	20 [b]
Chloramine	2.5
Sulphuric Acid	30
Sodium Metabisulphite Antiscalant - Ferric	15
Chloride	2
Sodium Hydroxide	20

[a] Procedure for Chemically Cleaning HYDRAcap® MAX Module(s)

[b] Savier Manual - Oltrecap P- Series Inside – Out Ultrafiltration Membranes

3.3.3 Data Validation

Validation of data was carried out for all processes deemed significant. Regarding the electricity consumption for the desalination process planned by Umgeni Water, questions were raised surrounding several figures provided. The design engineers then provided the original spreadsheet which illustrated the calculations used to obtain the final values. The design engineers were also provided with a list of queries regarding unknown information. Their responses were taken into account in the data collection process. In the SimaPro model, South African data was used in the case of energy consumption and mined anthracite used as filter media in the pre-treatment and filtration phases. In cases where such data was non-existent, data was chosen according to technical criteria such as the manufacturing process, and the function and composition of the material.

Validation for the mine-affected water treatment plant was carried out based on the design documents as well as the operation data provided by Prentec. In particular, attention was given to the energy consumption of the individual processes involved and the input data for energy was double checked by the company's engineers. Validation on the Remix system was not possible as this case study is still at the pre-feasibility stage. Therefore, the data from the literature was accepted without the possibility of validation.

3.3.4 Input of Individual Processes and Scaling Data to the Functional Unit

For an effective assessment, all data had to be scaled down in accordance with the functional unit. Thus, all material data was expressed in terms of kg/kℓ potable water, energy inputs as kWh/kℓ potable water and chemicals used as mg/kℓ potable water. Once this information was in the relevant format, it could be used as inputs into the SimaPro LCA software. Table 3:3: summarises the data in the inventory table for the desalination process and Table 3:4: for the mine water reclamation process. Within the SimaPro programme, new projects depicting both the processes were created. In addition, each unit operation was developed as an individual process together with the appropriate inputs and outputs.

Table 3:3: Direct Inputs Inventory Table for the Desalination Process

CONSTRUCTION PHASE			OPERATION PHASE		
Screening of Water					
High Density Polyethylene	1.57×10^{-3}	kg/kℓ	Sodium Hypochlorite	51.87×10^{2}	mg/kℓ
Chromium Steel	5.5×10^{-5}	kg/kℓ	Electricity	0.412	kWh/kℓ
Concrete (30-32 MPa)	3.0×10^{-6}	kg/kℓ			
Pre-treatment First Stage					
Concrete (30-32 MPa)	1.11×10^{-3}	kg/kℓ	Filter Media (Hard Coal)	1.37×10^{-2}	kg/kℓ
			Sulphuric Acid	38.9×10^{3}	mg/kℓ
			Ferric Chloride	32.4×10^{2}	mg/kℓ
			Electricity	0.126	kWh/kℓ
Pre-treatment Second Stage					
Concrete (30-32 MPa)	1.04×10^{-3}	kg/kℓ	Filter Media (Hard Coal)	1.39×10^{-2}	kg/kℓ
Chromium Steel	7.0×10^{-6}	kg/kℓ	Sulphuric Acid	37.9×10^{3}	mg/kℓ
			Ferric Chloride	31.6×10^{2}	mg/kℓ
			Sodium Hydroxide	39.7×10^{3}	mg/kℓ
			Sodium Sulphite	37.3×10^{3}	mg/kℓ
			Phosphoric Acid	49.7×10^{2}	mg/kℓ
			Electricity	0.257	kWh/kℓ
Reverse Osmosis					
Polypropylene	1.95×10^{-3}	kg/kℓ	Hydrochloric Acid	99.4×10^{2}	mg/kℓ
Polyamide	1.41×10^{-3}	kg/kℓ	Electricity	2.49	kWh/kℓ
Chromium Steel	1.66×10^{-4}	kg/kℓ			
Ceramic	1.06×10^{-5}	kg/kℓ			
Post-treatment					
Low-alloyed Steel	4.06×10^{-5}	kg/kℓ	Lime	63.0×10^{3}	mg/kℓ
Copper	9.49×10^{-7}	kg/kℓ	Carbon Dioxide	70.4×10^{3}	mg/kℓ
			Chlorine	25.0×10^{2}	mg/kℓ
			Electricity	0.003	kWh/kℓ
Water for Distribution					
Concrete (30-32 MPa)	1.36×10^{-3}	kg/kℓ	Sodium Hydroxide	20.0×10^{3}	mg/kℓ
Chromium Steel	2.35×10^{-5}	kg/kℓ	Electricity	0.414	kWh/kℓ

Table 3:4: Direct Inputs Inventory Table for the Mine Water Reclamation Process (continued on next page)

CONSTRUCTION PHASE			OPERATION PHASE		
Intake					
Reinforced Steel	4.77×10^{-5}	kg/kℓ	Electricity	0.103	kWh/kℓ
Galvanised Steel	8.2×10^{-6}	kg/kℓ			
Stainless Steel	3.46×10^{-5}	kg/kℓ			
Filtration					
Concrete (25 MPa)	1.23×10^{-4}	kg/kℓ	Filter Media (Anthracite)	9.62×10^{-2}	kg/kℓ
Concrete (30-32 MPa)	2.3×10^{-4}	kg/kℓ	Ferric Chloride	14.8×10^{3}	mg/kℓ
Reinforced Steel	1.10×10^{-3}	kg/kℓ	Biocide	10.2×10^{3}	mg/kℓ
Galvanised Steel	2.72×10^{-5}	kg/kℓ	Electricity	0.09	kWh/kℓ
Stainless Steel	9.25×10^{-5}	kg/kℓ			
Cast Iron	1.17×10^{-4}	kg/kℓ			
Polyvinylchloride (pump)	1.77×10^{-6}	kg/kℓ			
Pre-treatment					
Reinforced Steel	1.11×10^{-4}	kg/kℓ	Phosphoric Acid	17.35×10^{2}	mg/kℓ
Galvanised Steel	2.43×10^{-5}	kg/kℓ	Electricity	0.317	kWh/kℓ
Polyvinylchloride (pipe)	1.54×10^{-5}	kg/kℓ			
Stainless Steel	8.27×10^{-5}	kg/kℓ			
Polyvinylchloride (pump)	4.43×10^{-7}	kg/kℓ			
Stage 1 Ultrafiltration					
Polyvinylchloride (membrane)	3.46×10^{-4}	kg/kℓ			
Reinforced Steel	8.81×10^{-5}	kg/kℓ			
Galvanised Steel	1.91×10^{-5}	kg/kℓ			
Stainless Steel	6.00×10^{-5}	kg/kℓ			
Stage 1 Reverse Osmosis					
Polysulphone	3.86×10^{-4}	kg/kℓ	Hydrochloric Acid	345	mg/kℓ
Glass Fibre Reinforced Plastic	9.50×10^{-5}	kg/kℓ	Sodium Hydroxide	722	mg/kℓ
Reinforced Steel	1.10×10^{-4}	kg/kℓ	Electricity	0.489	kWh/kℓ
Galvanised Steel	1.06×10^{-5}	kg/kℓ			
Polyvinylchloride (pipe)	2.32×10^{-4}	kg/kℓ			
Stainless Steel	5.74×10^{-4}	kg/kℓ			
Stage 2 Reactors					
Reinforced Steel	9.10×10^{-4}	kg/kℓ	Ferric Chloride	72.9×10^{2}	mg/kℓ
Polyvinylchloride (pump)	8.85×10^{-7}	kg/kℓ	Electricity	0.079	kWh/kℓ

Stage 2 Ultrafiltration

Concrete (25 MPa)	3.94×10^{-5}	kg/kℓ	Sodium Hydroxide	25.1×10^{2}	mg/kℓ
Concrete (30-32 MPa)	1.34×10^{-4}	kg/kℓ	Hydrochloric Acid	25.1×10^{2}	mg/kℓ
Polysulphone	2.73×10^{-4}	kg/kℓ	Sodium Hypochlorite	25.1×10^{2}	mg/kℓ
Reinforced Steel	8.74×10^{-4}	kg/kℓ	Electricity	0.321	kWh/kℓ
Galvanised Steel	2.07×10^{-4}	kg/kℓ			
Polyvinylchloride (pipe)	7.68×10^{-5}	kg/kℓ			
Stainless Steel	1.46×10^{-3}	kg/kℓ			
Polyvinylchloride	6.37×10^{-7}	kg/kℓ			
Stage 2 Reverse Osmosis					
Concrete (25 MPa)	7.11×10^{-5}	kg/kℓ	Phosphoric Acid	18.1×10^{2}	mg/kℓ
Concrete (30-32 MPa)	1.77×10^{-4}	kg/kℓ	Electricity	1.46	kWh/kℓ
Polysulphone	1.29×10^{-4}	kg/kℓ			
Glass Fibre Reinforced Plastic	4.53×10^{-5}	kg/kℓ			
Reinforced Steel	8.74×10^{-4}	kg/kℓ			
Galvanised Steel	5.21×10^{-5}	kg/kℓ			
Polyvinylchloride (pipe)	2.51×10^{-6}	kg/kℓ			
Stainless Steel	1.82×10^{-4}	kg/kℓ			
Polyvinylchloride (pump)	2.12×10^{-7}	kg/kℓ			

3.3.5 Building the Basic Model in SimaPro

As mentioned in Chapter 2, a system consists of a collection of unit processes which are linked to one another by intermediate product flows. SimaPro defines seven types of process types: materials, energy, transport, processing, use, waste scenario and waste treatment. These can either be in the form of unit processes, i.e. describing a single operation, or a system process which is essentially one process containing a set of unit processes. The main purpose of all the processes is to quantify the flow of resources, products, co-products and emissions into and out of the system. Once processes have been modelled, product stages can be constructed. Such stages allow the definition of processes which are to be included in the different stages of the product. By default, SimaPro has five product stages: assembly, disposal scenario, disassembly scenario, reuse and recycle. The assembly stage describes the production stage of the process while the disposal scenario defines what could occur with the product if reused or disassembled. The disassembly scenario details what parts of the total product are to be disassembled, and their destination, while the reuse stage provides information as to the processes required to reuse parts of the product. As the name suggests, the life cycle stage links the various stages in order to describe the entire life cycle. For the purposes of this particular study, a “cradle-to-gate” analysis was conducted which focused on the assembly and life-cycle stages of the process.

3.3.6 The Inventory Table

The results of the inventory analysis was the generation of an inventory table. This is as a result of the ‘analyse’ function used in SimaPro which, through a reduced matrix, calculates the system inventory by constructing the process network and tracing the movement of materials from one stage to another. The software presents the table as a single list that is itemised alphabetically. This list is used as an input into the following phase, the impact assessment phase, which seeks to understand the contribution of the various processes to the overall environmental burden.

3.3.7 Impact Assessment

The impact assessment phase aims to establish a link between the product system and potential environmental impacts. To achieve this objective, inventory information is related to relevant impact categories and indicators. Furthermore, this phase provides a basis for the next stage, i.e. life cycle interpretation. The ISO 14042 (2000) document stated that there are three compulsory steps that need to be completed: selection and definition of impact categories, classification and characterisation. In addition, there are several optional elements that can be used dependent on the goal and scope of the study, namely normalisation, grouping, weighting and data quality analysis. For the purposes of this study, the three mandatory elements were deemed sufficient and were thus performed for the system. The optional steps were excluded due to the approaches employed which are based on value choices and thus introduce a degree of subjectivity to the study.

The SimaPro 8.1.1.16 software contains various impact assessment methods. For this study, the ReCiPe midpoint method was used. The primary aim of the ReCiPe method is to transform the list of inventory results into a limited number of indicator scores. To achieve this, ReCiPe makes use of an environmental mechanism as a foundation for the subsequent modelling. The term environmental modelling is used to describe a series of effects that culminate in a certain level of damage to human health, ecosystems or resources.

3.3.7.1 Category Definition

For the impact assessment stage, impact categories are selected to represent environmental issues that are relevant to the considered product system. Various environmental categories have been proposed, with most studies opting to select categories from previous assessments. Jensen et al. (1997) warn that the choice of categories should be consistent with the goal and scope of the study and should not seek to avoid environmental concerns. The overall recommendation from literature regarding selection is to include impact categories for which international consensus has been reached (Stranddorf et al., 2005). For this study, ReCiPe was selected as the impact assessment method of choice. It is the successor of two methods: Eco-indicator 99 and CML-IA (Institute of Environmental Sciences, Leiden University). The purpose of amalgamating the two was to integrate the “problem oriented approach” of CML-IA with the “damage oriented approach” of Eco-indicator 99 (PRé, 2015).
The first approach defines the impact categories at a midpoint level while the second approach defines it at the endpoint. The midpoint method was selected due to the relatively low uncertainty of the results. At this level, 18 impact categories are defined, namely: climate change, human toxicity, ionising radiation, photochemical oxidant formation, particulate matter formation, terrestrial acidification, ozone depletion, terrestrial ecotoxicity, agricultural land occupation, urban land occupation, natural land transformation, marine ecotoxicity, marine eutrophication, fresh water eutrophication, fresh water ecotoxicity, fossil fuel depletion, minerals depletion and fresh water depletion. A brief description of these categories together with some information regarding characterisation will be presented in the following sub-sections.

- Climate change

Climate change is the phrase used to describe the effect of changing temperatures in the lower atmosphere. Normally, the atmosphere is heated by radiation from the sun with a part of this radiation being reflected by the surface of the earth. When there is an increase in emissions of greenhouse gases (GHGs), the radiation is absorbed in the atmosphere resulting in an increase in temperature. There is now scientific consensus that such a situation would lead to climatic changes resulting in effects such as desertification and rising sea levels (Acero et al., 2014). Due to its complexity in modelling and broad scale, climate change is one of the most difficult categories to handle. The gases that are normally considered as contributors to global warming include carbon dioxide, methane and nitrous oxide (Stranddorf et al., 2005). In the majority of the LCA methodologies such as ReCiPe, the potential greenhouse effect is characterised in terms of global warming potential (GWP) for substances having the same impact as carbon dioxide in the reflection of heat radiation. The GWP of gases is measured in the reference unit of kg CO_2 equivalents where the effects of relevant gases are expressed relative to the effect of CO_2.

- Ozone Depletion

Ozone depletion refers to the damaging effect of various gases on stratospheric ozone or the ‘ozone layer’ (Acero et al., 2014). These gases include chlorofluorocarbons, hydrochlorofluorocarbons and tetrachloromethane. The combination of these substances reduces the ability of the ozone layer to prevent ultraviolet light from entering the earth’s atmosphere. The modelling for such an impact is complex as data required includes the stability of the gases, their lifetime and time horizon (Stranddorf et al., 2005). The characterisation model that has been developed by the World Meteorological Organisation (WMO) quantifies the potential depletion of stratospheric ozone in terms of ozone depletion potential (ODP) for gases having the same effect as chlorofluorocarbons (Acero et al., 2014). Chlorofluorocarbon-11 (CFC-11) has been selected as the reference substance due to the fact that it is well-studied and has one of the largest effects on ozone reduction (Stranddorf et al., 2005).

- Terrestrial Acidification

Terrestrial acidification is characterised by changes in soil chemical properties as a result of the deposition of nutrients in acidifying forms. As a result of this detrimental effect, plants suffer from reduction in biomass and unsuccessful germination and regeneration, to mention a few impacts (Azevedo et al., 2013). Acidification continues to be a problem of increasing concern in many developing countries such as South Africa which has one of the largest industrialised economies in the Southern Hemisphere (Josipovic et al., 2011). Substances are considered to possess an acidification effect if they result in the following two scenarios: they supply hydrogen ions to the environment and they leach corresponding anions from the system (Hauschild & Wenzel, 1998). Stranddorf et al. (2005) compiled a technical report which summarised the primary acidifying contributors. These were oxides of sulphur (SO_x), nitrogen oxides (NO_x) and ammonia (NH_3). In the Environmental Design of Industrial Products method, known as EDIP (Hauschild et al., 2009), acidification potential is characterised by using acidification potential (AP) which is expressed in terms of kg SO_2 equivalents (Stranddorf et al., 2005). It is imperative to note that the model is area independent and does not take into account regional differences, i.e. which locations are more or less susceptible to acidification (Acero et al., 2014).

- Depletion of Abiotic Resources

Within SETAC's working group on impact assessment, abiotic resources were considered as one of the major impact categories (Steen, 2006). In a general sense, this impact category refers to the consumption of non-biological resources, such as fossil fuels, minerals, metals and water (Acero et al., 2014). ReCiPe computes this in terms of the amount of the particular resource that is depleted. For water consumption, the reference unit is m^3, for metal and mineral resource depletion the unit is kg of iron, and for fossil fuel, consumption is expressed in terms of megajoules (MJ).

- Toxicity

This category aims to characterise and measure the impact of chemical emissions on human health or ecosystem functions (Hauschild et al., 2009). The model used in ReCiPe takes into account the fate of the chemical in the environment, the exposure of humans and the potential effect that exposure may have on human health or ecosystem health (Goedkoop et al., 2013). In the case of human health, the index utilised reflects the potential harm caused by a unit of chemical that is released into the environment (Acero et al., 2014). This is based on both the toxicity of a compound as well as the potential dosage. A range of different effects are covered, such as irreversible organ damage, carcinogenic effects and neurotoxicity which are incorporated into a single parameter (Stranddorf et al., 2005). Human toxicity does not incorporate indoor consumer exposure or work environment exposure (Stranddorf et al., 2005). Environmental toxicity or ecotoxicity is quantified in terms of three separate impact categories which examine freshwater, the marine environment and land. The chemical 1,4-dichlorobenzene was used as a reference substance in the midpoint calculations for all toxicity categories, i.e. to urban air for human toxicity, to freshwater for freshwater ecotoxicity, to seawater for marine ecotoxicity and to industrial soil for terrestrial ecotoxicity (Goedkoop et al., 2013).

- Eutrophication

Eutrophication is the process of nutrient enrichment which causes extreme plant growth in water bodies (van Ginkel, 2011). It forms a part of the natural ageing process of lakes and is speeded up by human impacts. In South Africa, freshwater resources are under tremendous stress from an increasing population and developing economy. Furthermore, most of the country's freshwater resources that have been fully allocated are subject to a collective increase in pollution from agricultural activities, power generation and mining (Oberholster & Ashton, 2008). A survey conducted by the DWAF indicates that the eutrophication issue in South Africa is widespread and varied (Walmsley, 2003).

Characterisation factors for aquatic eutrophication that have been proposed by Heijungs et al. (1992) are generally used. As in the EDIP 2003 methodology, Europe is considered the emitting region for ReCiPe where aquatic eutrophication can be caused by emissions to water, air and soil (Goedkoop et al., 2013). It has been found in practical scenarios that the particular substances emitted to water include phosphorus and nitrogen compounds. In mild and sub-tropical regions of Europe, freshwater resources are typically limited by phosphorus (P) while nitrogen (N) usually limits production of algal biomass in marine waters (Crouzet, et al., 1999). Thus, in ReCiPe, the limiting nutrient is N in all marine environments and P in all freshwater areas (Goedkoop et al., 2013).

- Photochemical Oxidation

Ozone is formed in the troposphere by the reaction of volatile organic compounds and nitrogen oxides under the influence of heat and sunlight (Acero et al., 2014). Photochemical ozone, which is also known as “ground level ozone”, is hazardous to human health at high concentrations but can cause some damage to vegetation even at lower concentrations (Stranddorf et al., 2005). In ReCiPe, the midpoint characterisation factor for ozone formation is representative for both environmental and human health effects. It is defined as the change in the average daily European concentration of ozone due to a marginal change in emission of substance *x* which is expressed as NMVOC (Non-methane volatile organic carbon) equivalents (Goedkoop et al., 2013).

- Land Use

The land use impact category reflects damage caused to ecosystems as a result of occupation and transformation of land. In ReCiPe, the following two mechanisms are used, namely occupation of a certain area of land during a certain time and transformation of a certain area of land (Goedkoop et al., 2013). The two mechanisms can be combined as occupation often follows a transformation, but occupation generally occurs in an area that has already been converted. For the midpoint characterisation, the ReCiPe method expresses land use impacts as a product of square metres and year (m^2 x year).

- Ionising Radiation

This impact describes damage to human health and ecosystems related to emissions of radioactive material throughout a product’s life cycle. In the building sector, such releases can be linked to the use of nuclear power in an electricity mix (Acero et al., 2014). This category takes into account the different ionising radiation types (α-, β-, γ-radiation and neutrons). The characterisation model used in ReCiPe utilised a calculation sequence which takes into account the radiation behaviour and burden based on detailed nuclear-physical knowledge (Acero et al., 2014). The results are given in terms of kilograms of uranium 235 (U235).

- Particulate Matter

Particulate matter with a diameter of less than 10 μm (PM_{10}) represents a complex mixture of extremely minute particles that are both organic and inorganic in nature (Goedkoop et al., 2013). Particle pollution has been linked to a variety of health problems particularly related to the respiratory tract as PM_{10} reaches the upper part of the airway and lungs when inhaled (Acero, et al., 2014). At the midpoint level, the intake fraction of PM_{10} is of importance as the effect and damage factors are substance independent (Goedkoop et al., 2013). Particulate matter forming potentials (PMFP) in ReCiPe are expressed in PM_{10} equivalents.

- Salination and Water Consumption

Salination is a significant factor in the South African context. According to van Rensburg et al. (2011), the salinity of South Africa’s water resources has been deteriorating slowly due to the quality of water distributed to the DWA. Thus, any environmental assessment tool that does not evaluate the effect of salinity has limited application in South Africa (Leske & Buckley, 2004). Leske and Buckley (2004) recommend that an impact category describing all effects of salinity be developed which would include damage to infrastructure, effects on plants and animals and aquatic ecotoxicity impacts. As there is no recognised impact assessment methodology for salination, it was decided not to include it in this LCA study. However, it is a significant regional problem and it is necessary to incorporate salinity impacts into LCAs in the future.

Water usage is another important consideration in South Africa, especially considering the current weather conditions. Landu and Brent (2006) undertook a LCA on water supply in Pretoria utilising a methodology developed by Brent that took water scarcity in the different regions of the country into account. The primary conclusion from the study was that the "actual extraction of the water from the ambient environment is in fact the most important consideration" (Landu & Brent, 2006). This result highlights the need for a South African impact assessment method that considers the environmental effects of water consumption in the local context.

3.3.7.2 Classification

As the second step in impact assessment, classification aims to assign the inventory input and output data to the categories selected in the previous stage. In the case of SimaPro, this process is automatically computed by the LCA software. As mentioned earlier, double counting of impacts should be avoided. For the ReCiPe method, upgrades to the method have been made in line with changes made in the ecoinvent database and other SimaPro methods. Such changes include the manner in which carbon dioxide is accounted for, to reduce double counting within the processes (ReCiPe , 2012).

3.3.7.3 Characterisation

Characterisation is the final mandatory step of the impact assessment phase. The objective of characterisation is to assign the relative contribution of every input and output to the chosen impact categories. In order to facilitate this, the substances that contribute to a particular impact category are multiplied by a characterisation factor that expresses the relative contribution of the substance. For characterisation at the midpoint level using the ReCiPe assessment method, the formula is given as (Goedkoop et al., 2013):

$$I_m = \sum_i Q_{mi} m_i \qquad \text{(Equation 3.1)}$$

where m_i represents the magnitude of intervention *i* (e.g. the mass of CO_2 released to air), Qm_i the characterisation factor that connects intervention *i* with midpoint impact category *m* and I_m the indicator result for midpoint impact category *m*.

This process is completed automatically by the SimaPro software and results in a table with values for each impact category expressed in terms of the category's reference unit.

3.3.8 Interpretation

As the final stage in the LCA study, the interpretation phase aims to analyse the results from the previous phase and draw appropriate conclusions and recommendations.

For the interpretation phase, one m^3 of potable water for distribution was analysed by the ReCiPe midpoint method, hierarchic version. As mentioned in sub-chapter 4.4, data was collected pertaining to the construction and operation phases. Thus, it was decided to firstly segregate the environmental impacts in terms of these two phases. This is possible through the "analyse groups" function in SimaPro which provides the user with an opportunity to select and compare the impact of various operations or inputs in terms of the available categories. This feature was also utilised to present the distribution of the individual impact categories per unit operation, e.g. RO was selected as an analysis group and the impacts attributed to this operation in terms of each impact were computed by the LCA programme. This was presented in a tabular format which provided an overview of the contributions of the individual sub-processes. In addition, each impact category was examined in greater detail, with the results depicted in a network diagram which produces a visual representation of each input's contribution to the overall impact of the process. This is useful for identifying the significant contributor(s) for each impact which will aid in the reduction of the system's environmental burden. **Appendix B** provides further details regarding the production of results in the two formats.

CHAPTER 4: **RESULTS AND DISCUSSION**

4.1 INTRODUCTION

This chapter presents the first part of the life cycle interpretation and is the final phase of the LCA methodology. Thus, this stage attempts to systematically identify, analyse and evaluate the results of the LCI and LCIA to reach suitable conclusions and provide relevant recommendations. This penultimate chapter will deal with the analysis of the results while the final chapter will present various conclusions and recommendations. The results from the three case studies of membrane water treatment will be presented in the form of process network diagrams which highlight the stages that carry the highest environmental contribution. This will be followed by a discussion of the main contributors to the major impact categories. A comparison between the findings of this study and similar studies undertaken globally will also be drawn.

4.2 DESALINATION PROCESS

As presented in Section 3.2.1, the two stages that were considered were the construction and operation stage. Once all the inputs and outputs had been evaluated, the environmental impact was calculated and characterised into the various impact categories in SimaPro. Figure 4:1: illustrates the contribution of the various inputs to the relevant impact categories, where the red bar represents the energy consumption, the blue bar represents the production of chemicals used in the process, the purple bar represents the filter media used and the orange bar represents the materials required for the infrastructure.

From the diagram, it is evident that electricity is an overwhelming burden in the majority of the categories, such as climate change and terrestrial acidification. However, in other categories such as water and metal/minerals depletion, the contribution of electricity is much lower (approximately 50%) with chemical usage becoming more prominent. It is also interesting to note that the infrastructure carries a relatively insignificant burden compared to the other two inputs. The following sub-sections will provide an examination of each of the impact categories in greater detail.

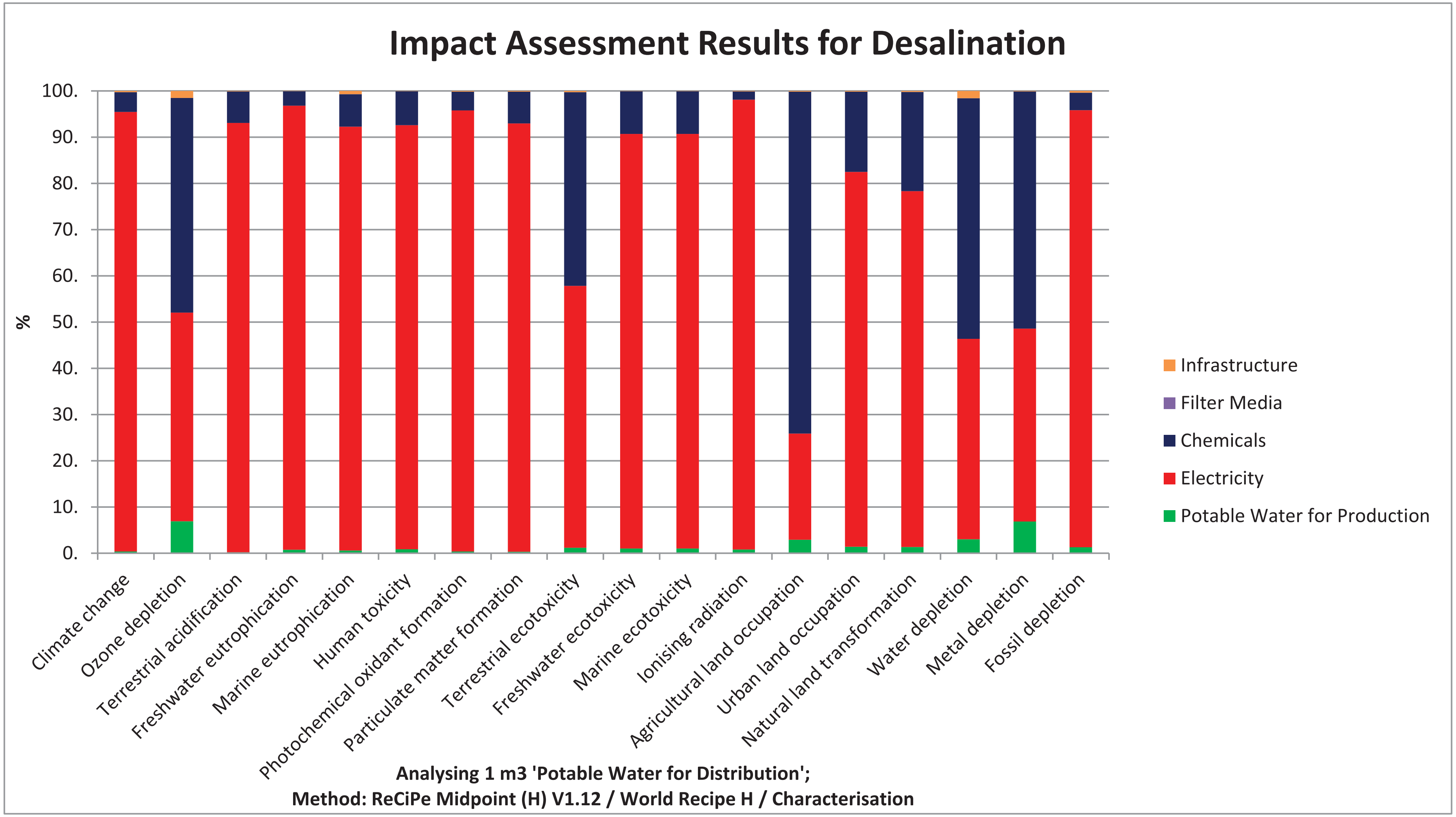

Figure 4:1: Overall impact assessment results for desalination

Figure 4.2 is a network diagram which visually represents the climate change distribution for the desalination process. The results show that the equivalent of 4.40 kg of carbon dioxide equivalents (CO_2 eq.) are emitted for the production of 1 kℓ of potable water.

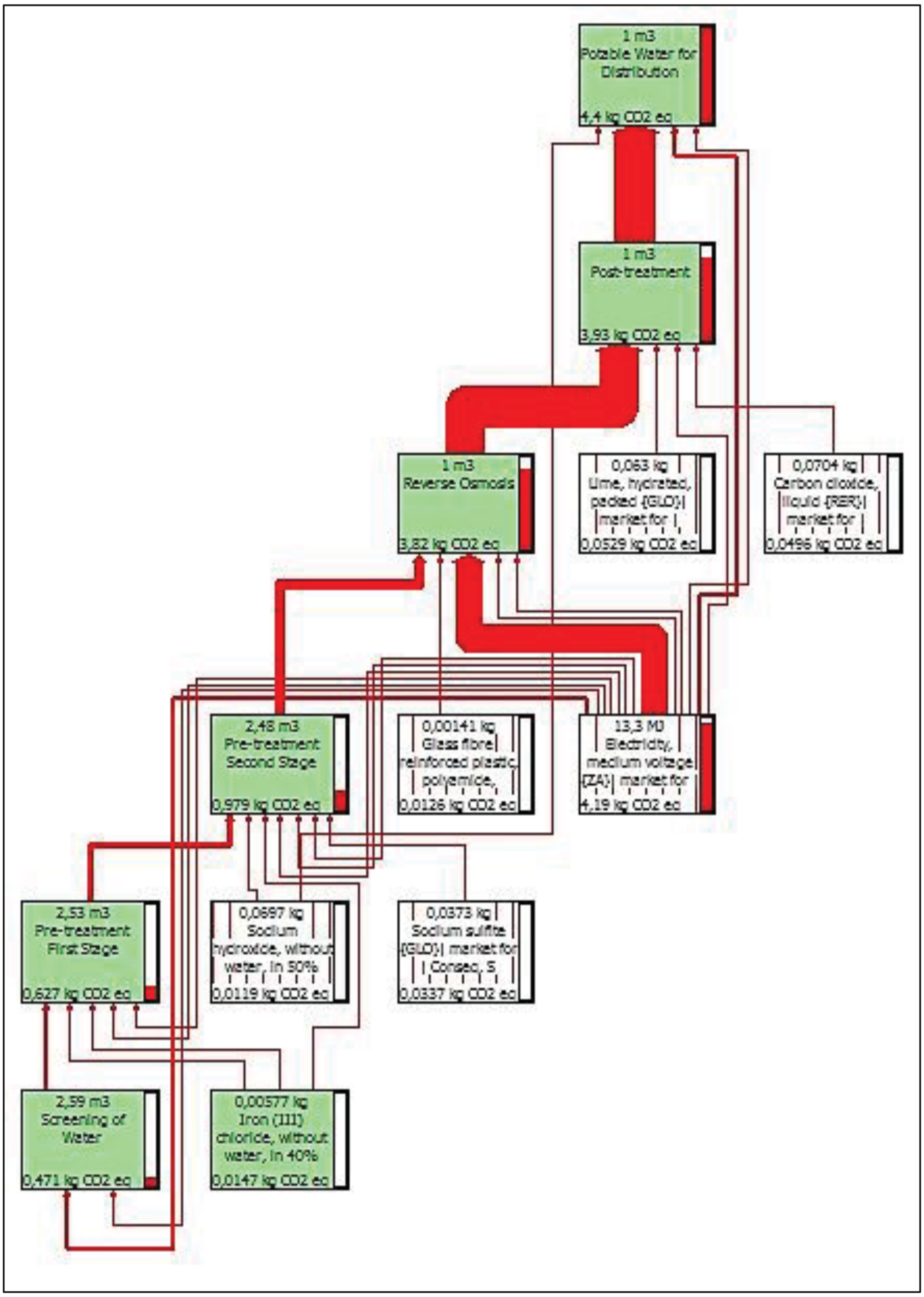

Figure 4:2: Network diagram illustrating climate change contribution for desalination

From the bars that are shaded in red, which are an indication of the extent of the environmental impact for each unit operation, it is evident that the RO process carries the highest contribution. This can be attributed to the high electricity input required for the high-pressure feed pumps which is highlighted in the diagram by the wide red arrow. Another pertinent point regarding energy is raised upon examination of the diagram – of the overall GHG emissions of 4.40 kg CO_2 eq., the electricity utilised within the system (13.3MJ) is responsible for 4.19 kg CO_2 eq. or 95.2%. This is a direct reflection of the conventional electricity mix in South Africa which is dominated by coal-fired power stations.

4.2.1 Ozone Depletion

The following figure provides insight into the contribution of each operation to ozone depletion. From Figure 4.3, one can ascertain that RO, the second stage of pre-treatment and post-treatment, is responsible for the majority of the emissions that contribute to ozone depletion. For RO, the release of gaseous compounds into the air is due to the energy input as well as the use of hydrochloric acid which is the CIP chemical required to clean the RO membranes. Regarding the second stage of pre-treatment, the significant contributors to ozone depletion include sodium sulphite and phosphoric acid which acts as an antiscalant for the process. The post-treatment phase, as the name suggests, requires chemicals such as chlorine gas, lime and carbon dioxide to condition the water for distribution. The use of these substances increases the contribution of this stage to ozone depletion. This breakdown ties in with the results in Figure 4:1: which shows the percentage contribution of the combined chemical usage to be slightly greater than that of energy consumption, which has an overall contribution of 45.1%.

4.2.2 Terrestrial Acidification

For the impact category acidification, gases that create acid deposition include ammonia, nitrogen oxide and sulphur oxide.

Figure 4:4: shows the individual elements that contribute to the total acidification profile. Electricity usage within the process has the highest impact as it contributes 92.8% to the potential for terrestrial acidification by the system. This is as a result of the electricity mix that emits quantities of nitrogen oxide and nitrous oxide.

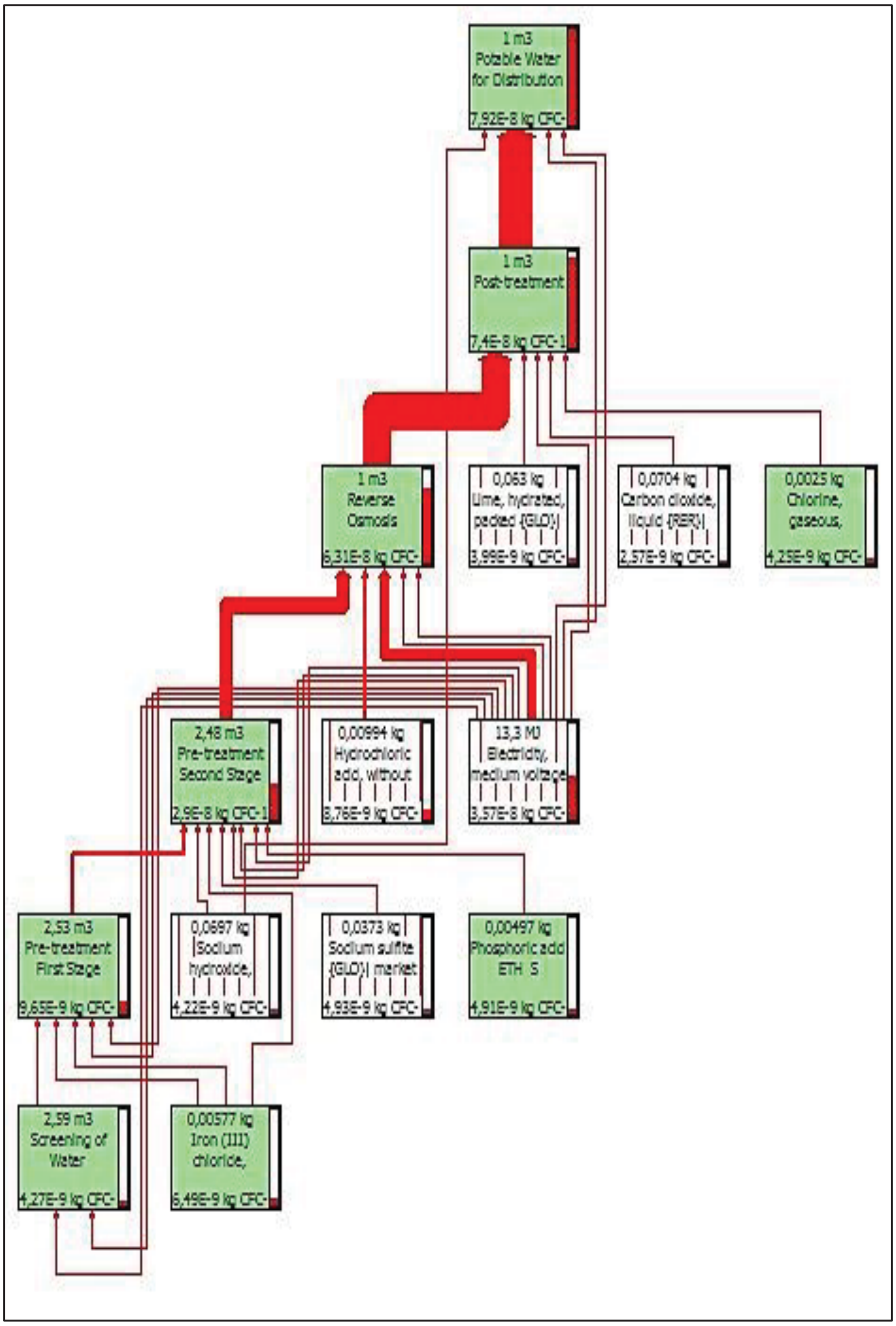

Figure 4:3: Network diagram illustrating ozone depletion for desalination

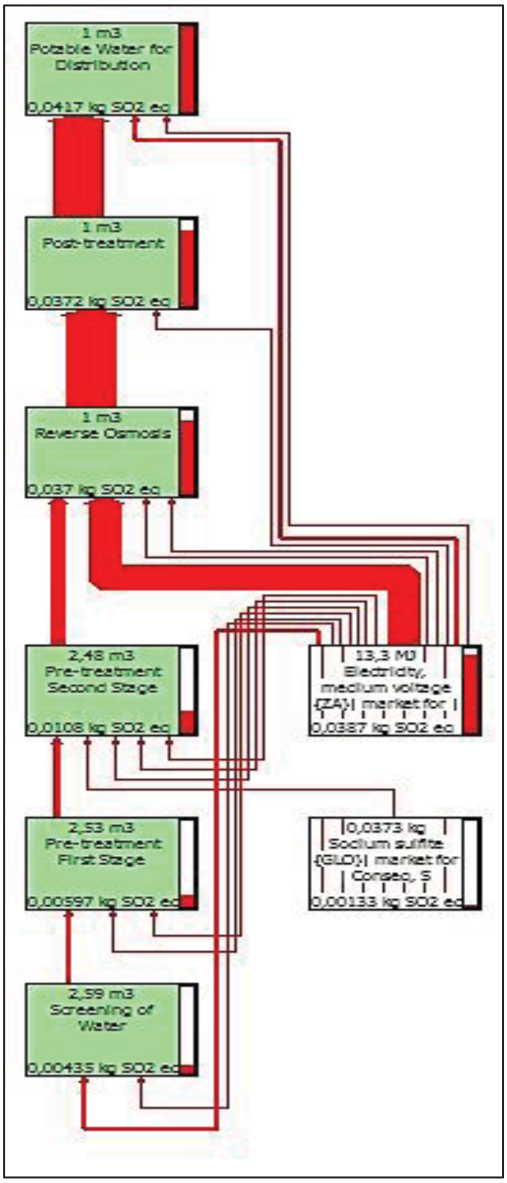

Figure 4:4: Network diagram illustrating terrestrial acidification for desalination

4.2.3 Depletion of Abiotic Resources

In a general sense, this impact category refers to the depletion of non-biological resources. In the case of SimaPro, the ReCiPe method takes into account the consumption of three components: water, metals and fossil. Figure 4:5: looks at the major contributors to such environmental impacts. From the graph, it is evident that electricity usage is the dominant contributor to fossil depletion with a contribution of 94.6%. However, the energy requirement of the system contributes less significantly to the categories of water and metal depletion. This is due to the use of chemicals such as sodium sulphite and sodium hydroxide which have a combined contribution of 32.2% and 24.2% for the depletion of water and metals respectively. This could be attributed to the use of water and minerals in the chemical production process.

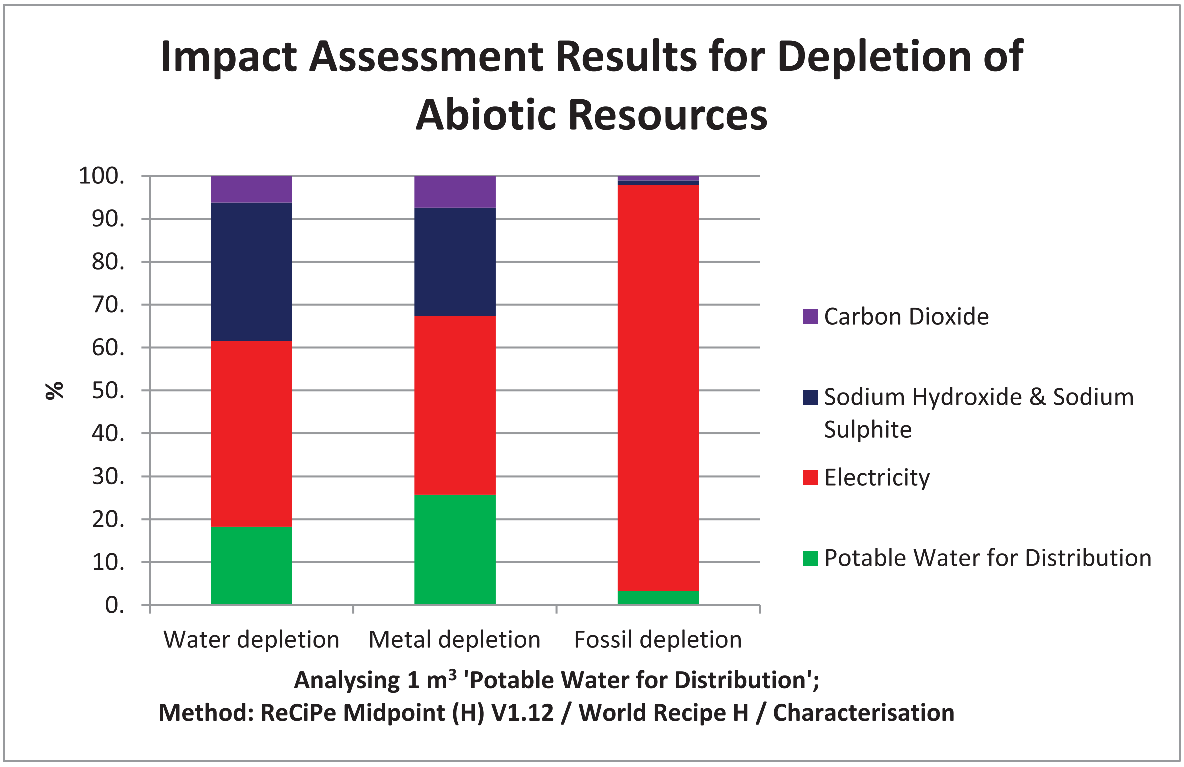

Figure 4:5: Impact assessment results depicting depletion of abiotic resources for desalination

4.2.4 Toxicity

It was decided to group the various toxicity impact categories together – human, terrestrial, freshwater and marine. The comparative graph in **Error! Reference source not found.** show that for human, marine and f reshwater toxicity, energy consumption is the major contributor. However, in the case of terrestrial ecotoxicity, electricity carries a lower burden of 56.6% while the production of chemicals used in the process has a noticeably higher impact. The chemicals that carry the highest burdens are carbon dioxide, sodium hydroxide and sodium sulphite. It has been noted that in the case of human toxicity, these by-products, mainly arsenic, sodium dichromate, and hydrogen fluoride, are caused, for the most part, by electricity production from fossil sources (Acero et al., 2014).

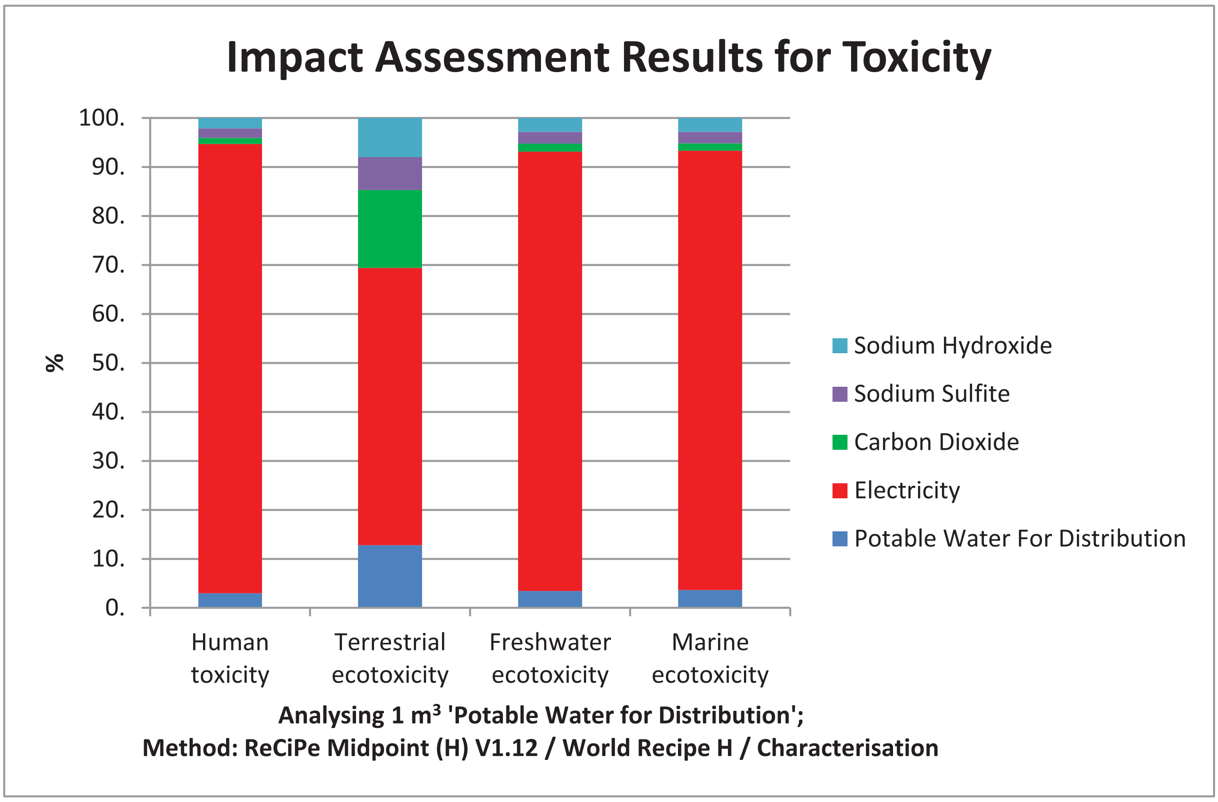

Figure 4:6: Impact assessment results depicting toxicity for desalination

4.2.5 Eutrophication

The effect of eutrophication on the environment has the capacity to decrease the benefits and increase the costs related to the use of natural resources. In the impact assessment, eutrophication was looked at from two perspectives – freshwater and marine. Both Figure 4.7a and Figure 4.7b show a similar trend – that of electricity being the greatest contributor. In addition, these figures also show that RO is the stage responsible for the highest impact. This can, in part, be related to electricity usage for the high-pressure feed pumps.

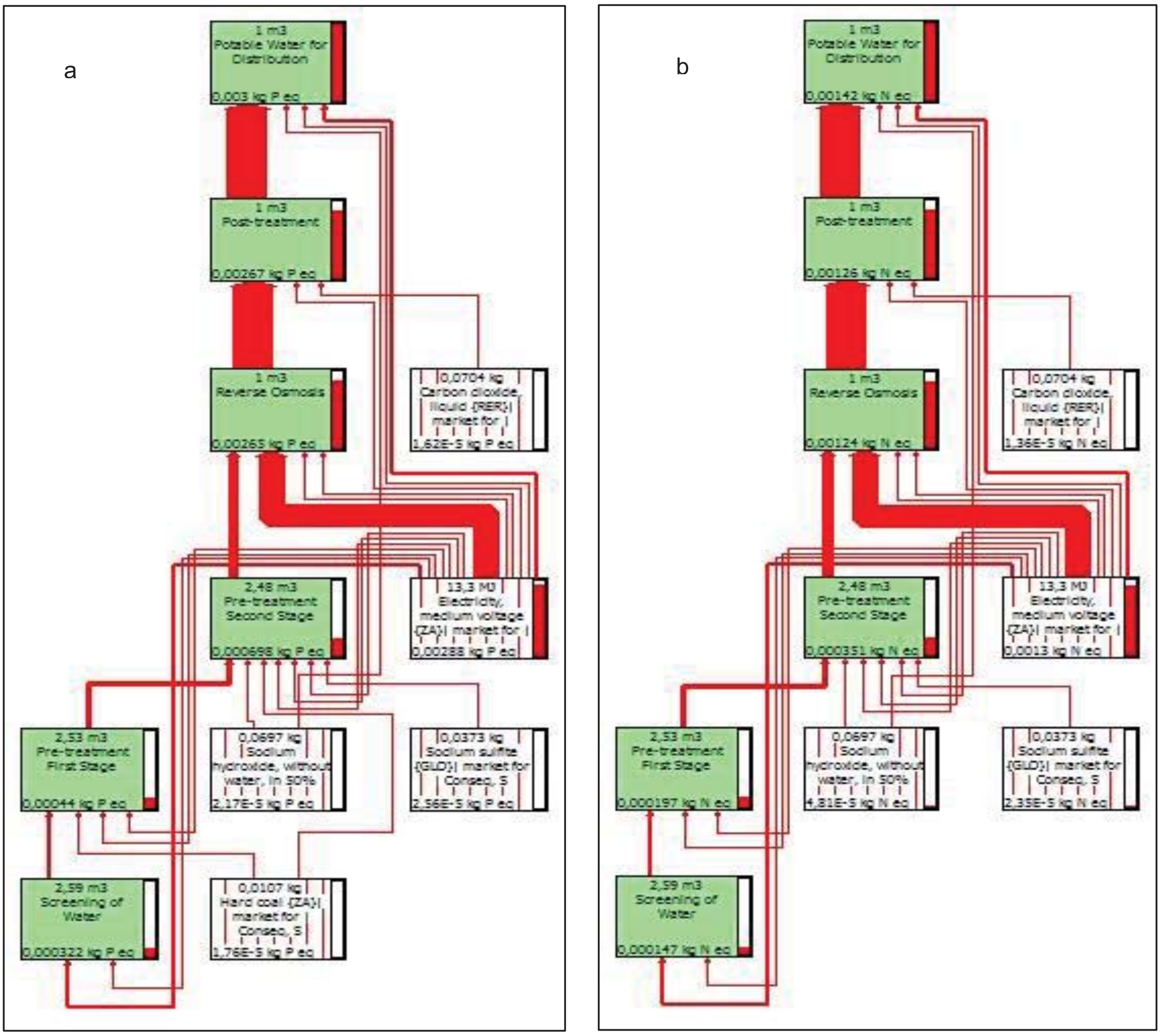

Figure 4:7: Network diagrams illustrating freshwater (a) and marine (b) eutrophication for desalination

4.2.6 Photochemical Oxidation

Photochemical oxidation, as in the case of ozone depletion, relates to the reaction of chemicals in the presence of heat and sunlight. Specifically, the category relates to the amounts of carbon monoxide, sulphur dioxide and nitrogen oxide emitted into the air. Looking at the inputs and outputs of the electricity mix in South Africa, one can gauge that emissions into the air as a result of the electricity production process include all the above-mentioned chemicals. Thus, it is not unexpected that Figure 4:8: shows electricity as the major contribution with a burden of 95.4%.

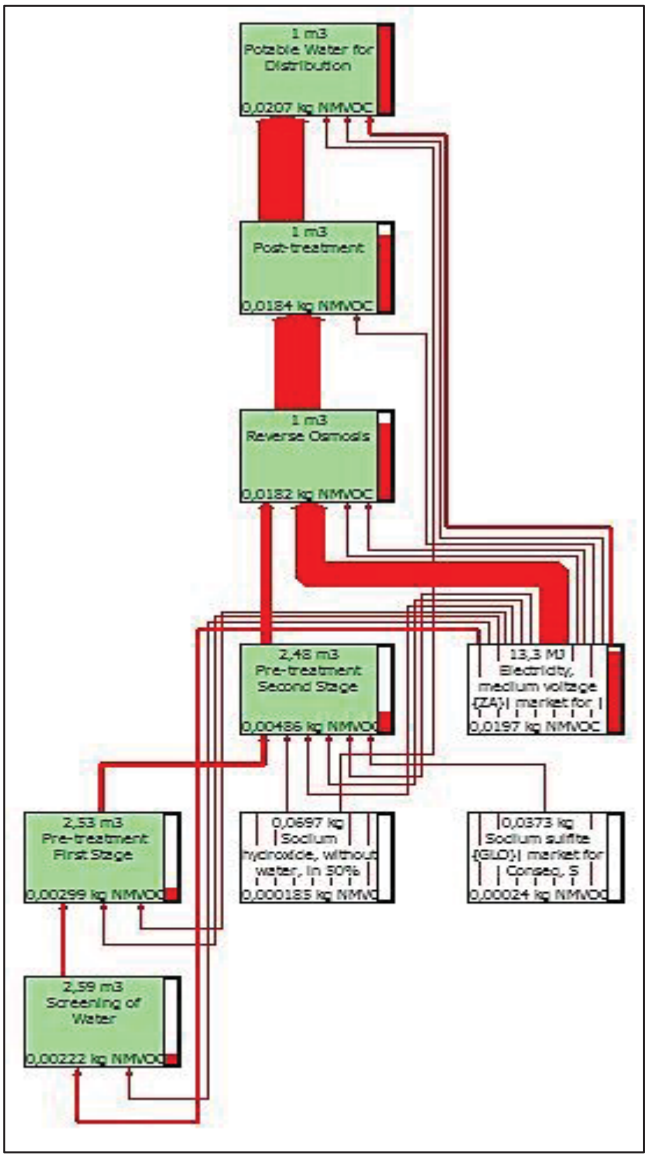

Figure 4:8: Network diagram illustrating photochemical oxidant formation for desalination

4.2.7 Land Use

The diagram below depicts land use in the form of agricultural land occupation, urban land occupation and natural land transformation. The impact of the product system on urban land occupation and natural land transformation can be traced to the production and consumption of electricity. However, the impacts on agricultural land use are dominated by the sodium hydroxide and sodium sulphite production process which are background flows.

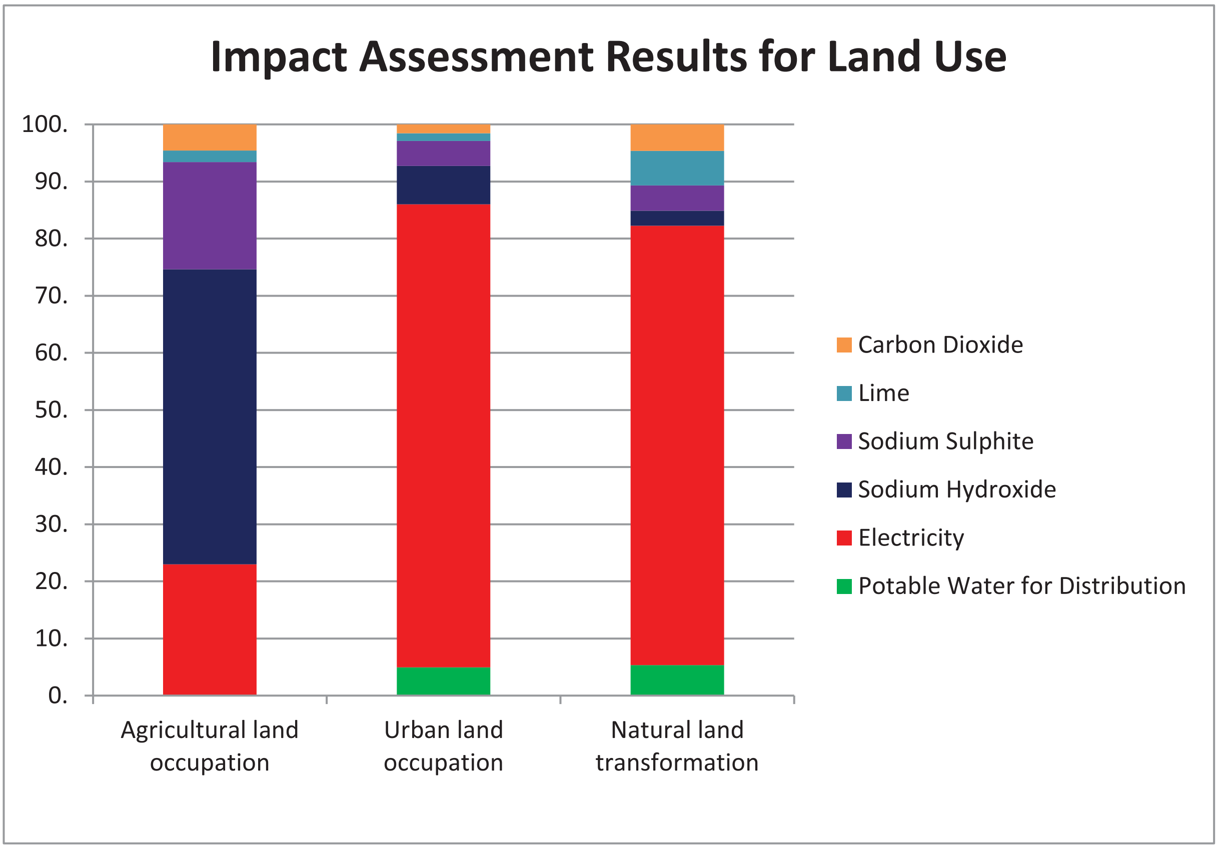

Figure 4:9: Impact assessment results depicting land use for desalination

4.2.8 Ionising Radiation

Figure 4.10 illustrates the contribution of the processes to the overall ionising radiation impact. The thick red arrow indicates that the majority of the emissions (97.3%) are caused by electricity use within the desalination plant. This could be linked to the portion of South Africa's electricity emanating from nuclear power (Acero et al., 2014).

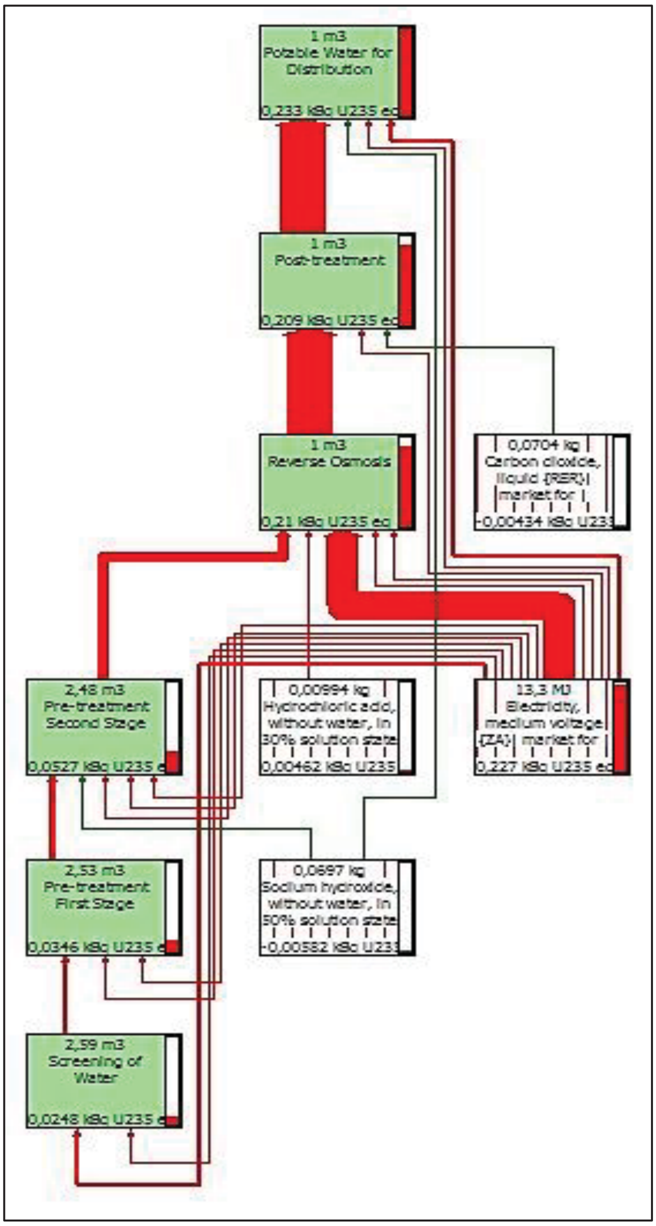

Figure 4:10: Network diagram illustrating ionising radiation for desalination

4.2.9 Particulate Matter

Figure 4:11: illustrates that the primary cause of particulate matter formation in this study is electricity – its production and use within the process. Generally, air-borne particles are composed of both solid and liquid substances and can arise from various sources such as combustion processes. A study conducted by the Commission for Environmental Cooperation found that in Canada, power plants burning coal accounted for 75% and 61% of PM_{10} and $PM_{2.5}$ emissions respectively which is a testament to the harmful practice of burning coal for energy (Commission for Environmental Cooperation, 2011).

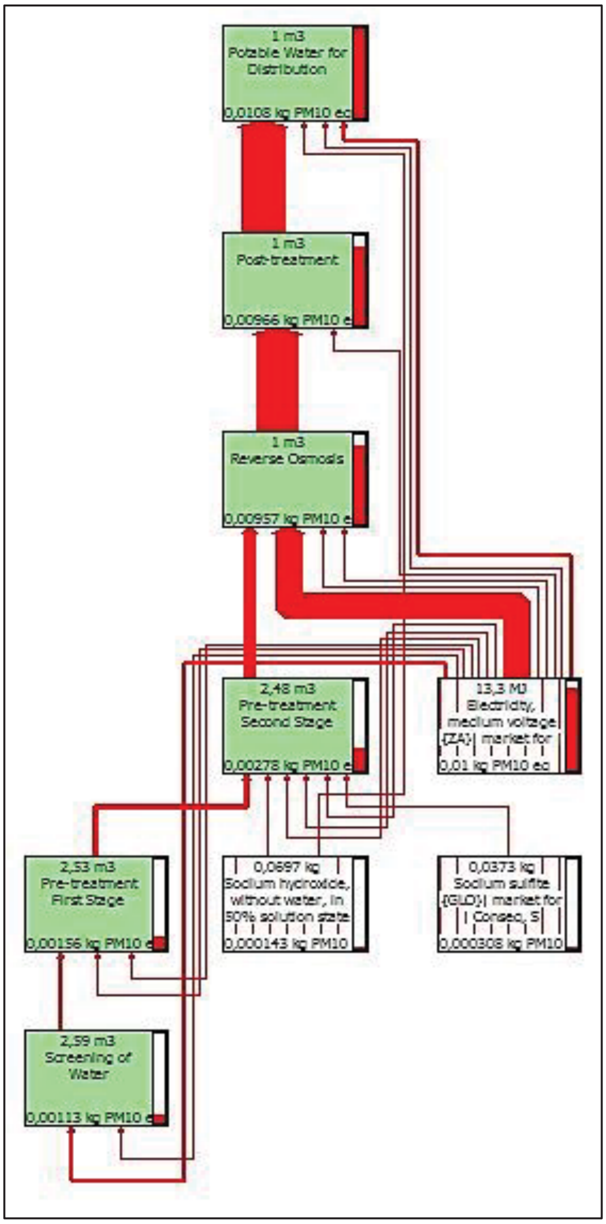

Figure 4:11: Network diagram illustrating particulate matter formation for desalination

4.3 MINE WATER RECLAMATION PROCESS

For the second case study, the same stages of the life cycle were analysed as for the first case study, namely the construction and operation phases. The application of a 0.01% node cut-off, together with a segregation of the results in terms of electricity, chemical usage, filter media and infrastructure, produces the graph in Figure 4:12:.

Electricity consumption, which is shaded in red, makes the greatest contribution to the bulk of the impacts. In the case of impact categories such as climate change and terrestrial acidification, energy usage is responsible for greater than 95% of the overall impact. In the case of other impacts e.g. ozone and metal depletion, chemical consumption within the water treatment process carries a much more significant environmental burden as it accounts for approximately half of the total impact. The environmental impact of the infrastructure phase, which encompasses materials used in the construction of the plant, is relatively less significant than the operation phase. An explanation of the contributing factors to each impact category will follow in greater detail.

4.3.1 Climate Change

Figure 4:13: is a representation of the contributions of each unit operation to the overall impact category of climate change. The overall emission of GHGs for the treatment of mine water amounts to a total of 2.60 kg CO_2 which is divided into the emissions from both stages of RO. Stage 2 RO carries a marginally higher burden (1.54 kg CO_2 eq.) than stage 1 RO (1.06 CO_2 eq.). This is as a result of the higher electricity consumption of the feed pumps required for the second stage of RO.

This can be traced back to the higher feed salinity of the water entering stage 2 RO, which originally emanates from stage 1 RO as the reject stream. Another important observation can be made by analysing the diagram, namely that the electricity usage within the treatment process which is equivalent to 2.45 kg CO_2 is responsible for 94.2% of the overall release of carbon dioxide. As in the first case study, this result originates from the energy mix utilised in South Africa which relies on coal-fired power stations.

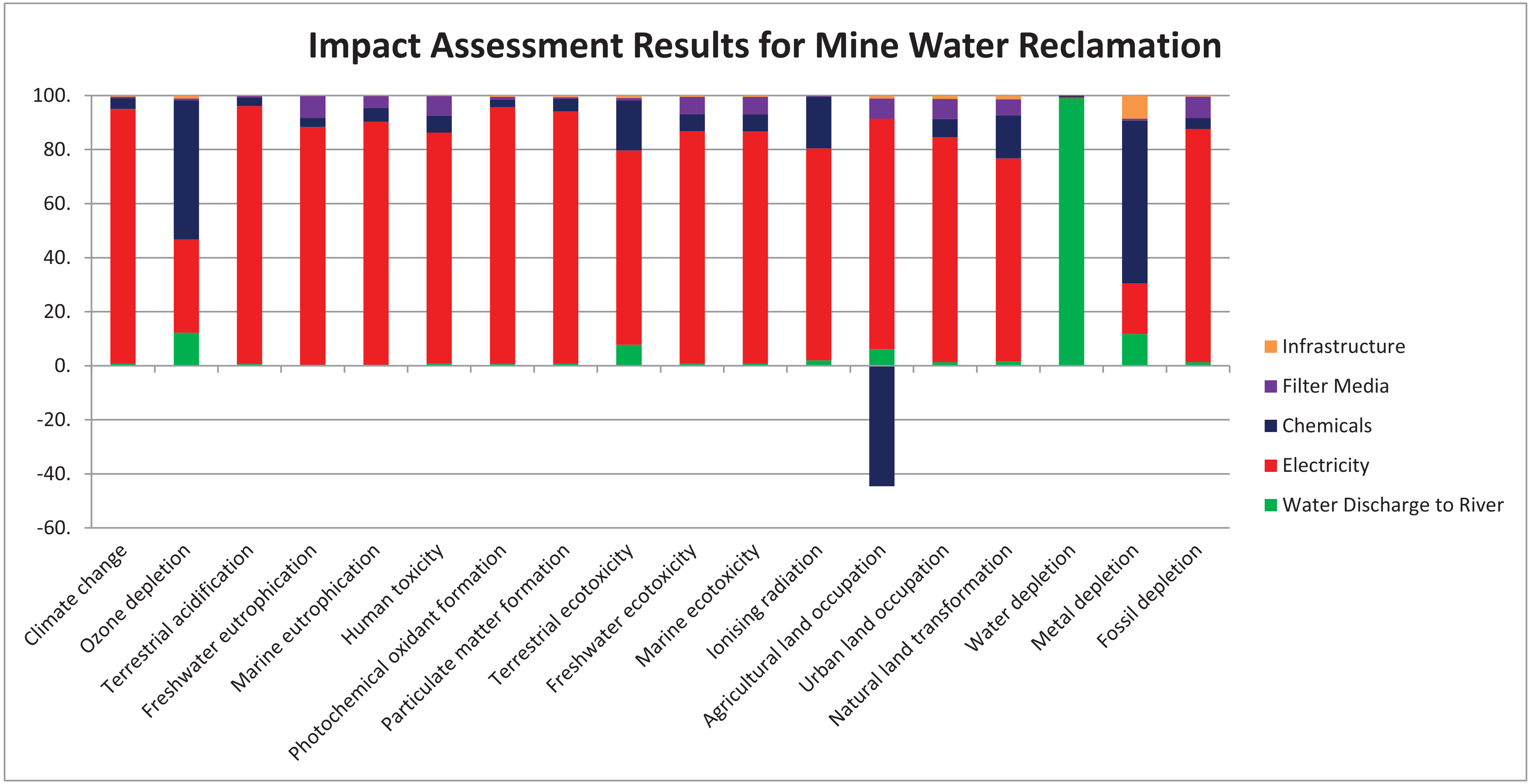

Figure 4:12: Overall impact assessment results for mine water reclamation

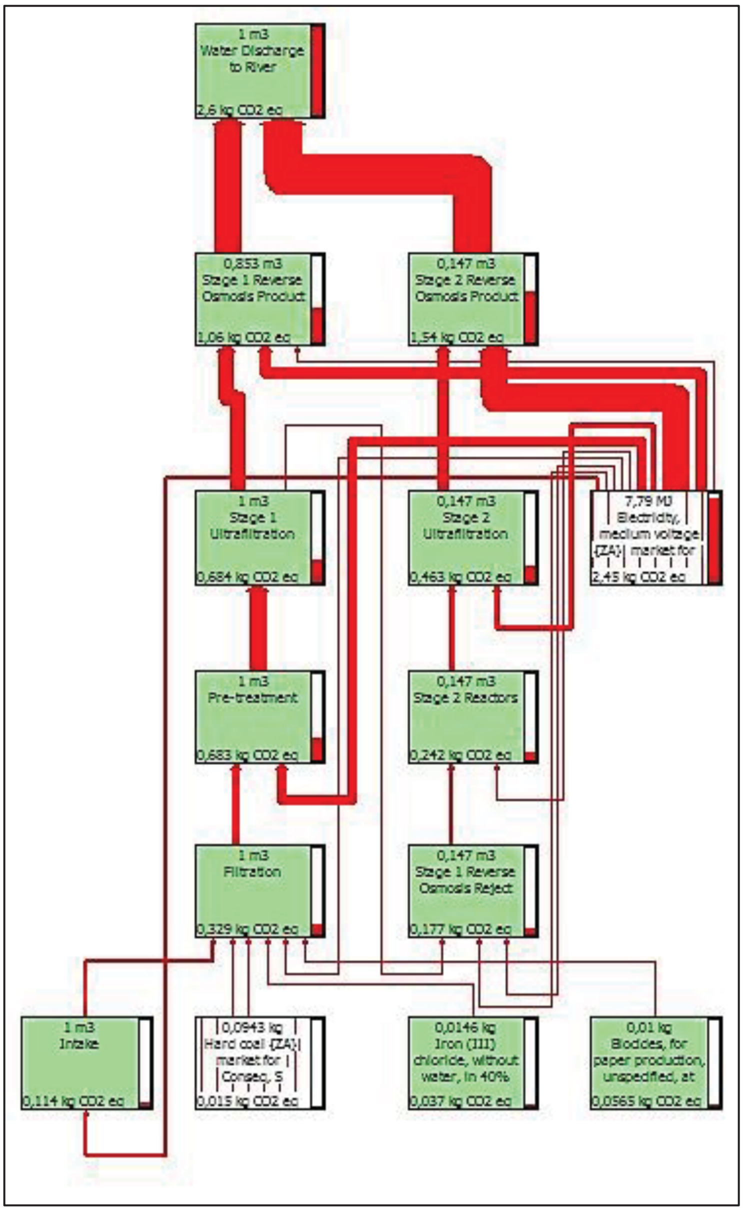

Figure 4:13: Network diagram illustrating climate change contribution for mine water reclamation

4.3.2 Ozone Depletion

The second impact category that will be discussed is ozone depletion.

Figure 4:14: shows an even distribution of this environmental impact from both sources of potable water, i.e. product water from stage 1 and stage 2 RO. Regarding the first stage of RO, the unit operation which carries a substantial impact is the filtration process. A more in-depth analysis indicated that this is due to the addition of ferric chloride as a coagulant and biocide in the process which contributes 1.64 x 10^{-8} kg CFC-11 and 9.96 x 10^{-9} kg CFC-11 respectively. For the second stage of RO, it is evident that the high energy usage has a substantial impact on ozone depletion. The chemical contribution to the second stage is less significant than in the first stage of processing.

Amongst the chemicals required in the second stage, ferric chloride as the secondary antiscalant appears to have the highest impact. Despite the fact that the chemical input into the process is significant as highlighted above, electricity consumption is still responsible for the production of 2.09 x 10^{-8} kg CFC-11 which equates to 34.6% of the overall emissions of chlorofluorocarbons from the product system.

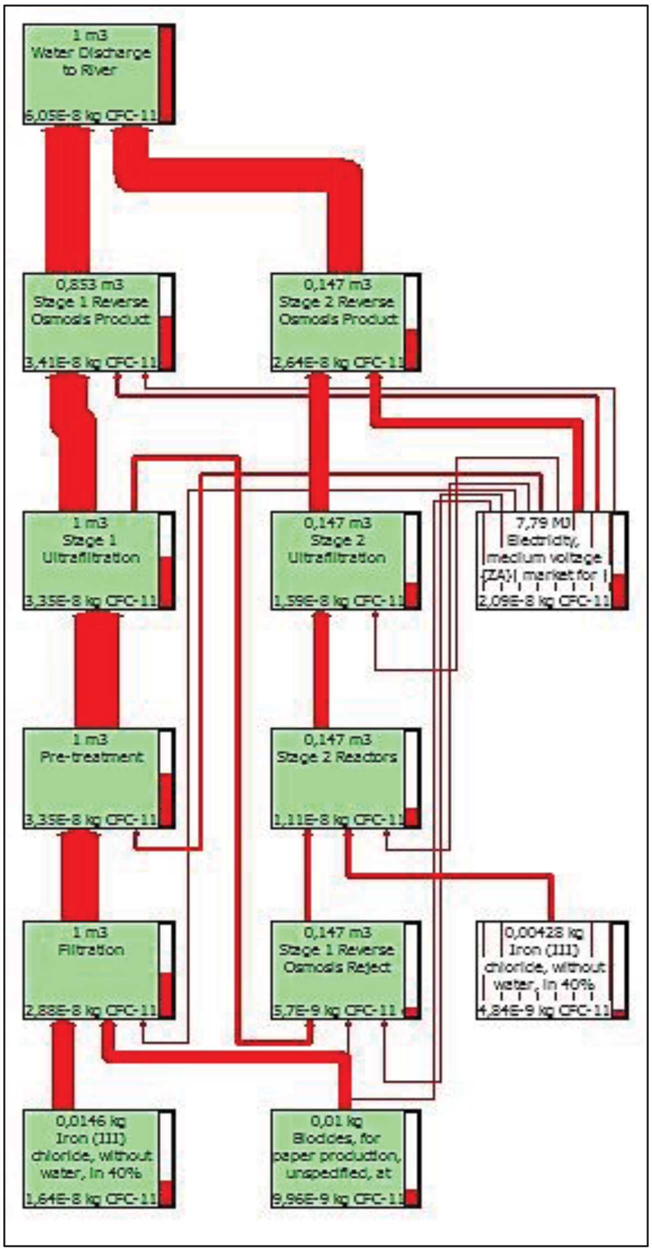

Figure 4:14: Network diagram illustrating ozone depletion for mine water reclamation

4.3.4 Terrestrial Acidification

An analysis of the product system in terms of terrestrial acidification produces the diagram in Figure 4.15. It is immediately evident that electricity usage is largely responsible for the resulting emissions of sulphur dioxide from the process, with a contribution of 95.4%. Rewlay-ngoen et al. (2014) investigated the effect of terrestrial acidification of a coal-fired power plant in Thailand where coal accounts for 19% of the total electricity production. The results indicate that there was a definite detrimental effect of such energy sources on plant growth. Furthermore, it was reflected that SO_2 has the capacity to cause the most damage, followed by NO and NO_2.

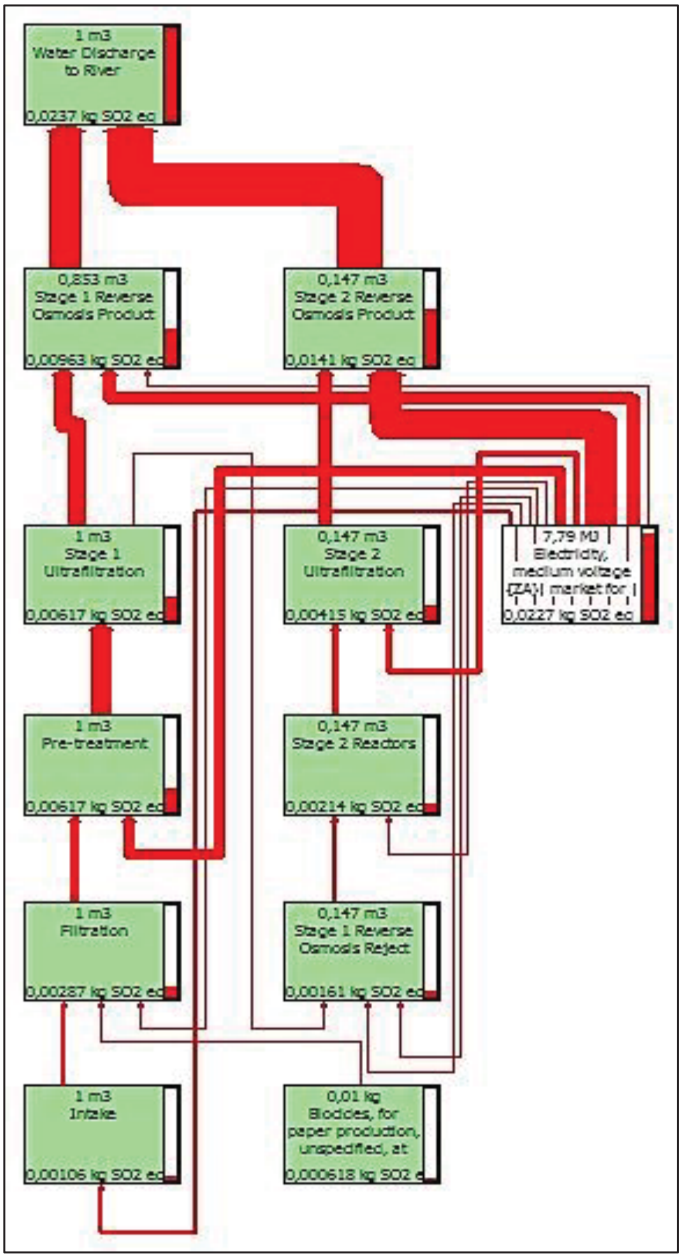

Figure 4:15: Network diagram illustrating terrestrial acidification for mine water reclamation

4.3.5 Depletion of Abiotic Resources

From Figure 4:16:, water depletion is mainly from use of the source water. As this is water accumulated in abandoned mining areas, this represents a decrease in available groundwater. In this situation, the groundwater is contaminated by previous mining activities and needs to be treated prior to discharge into surface water. Regarding metal depletion (see Figure 4.17), the results indicate that metallic substances are heavily used within the production process for biocides and iron chloride. As expected, a portion of the total metal depletion (1.18 x 10^{-2} kg Fe eq.) is due to the carbon steel frame used for each skid. The last category of depletion, namely fossil depletion, is dominated by electricity which has a contribution of 0.6 kg oil out of a total of 0.7 kg oil. This can be attributed to national electricity production which consists mainly of the combustion of fossil fuels.

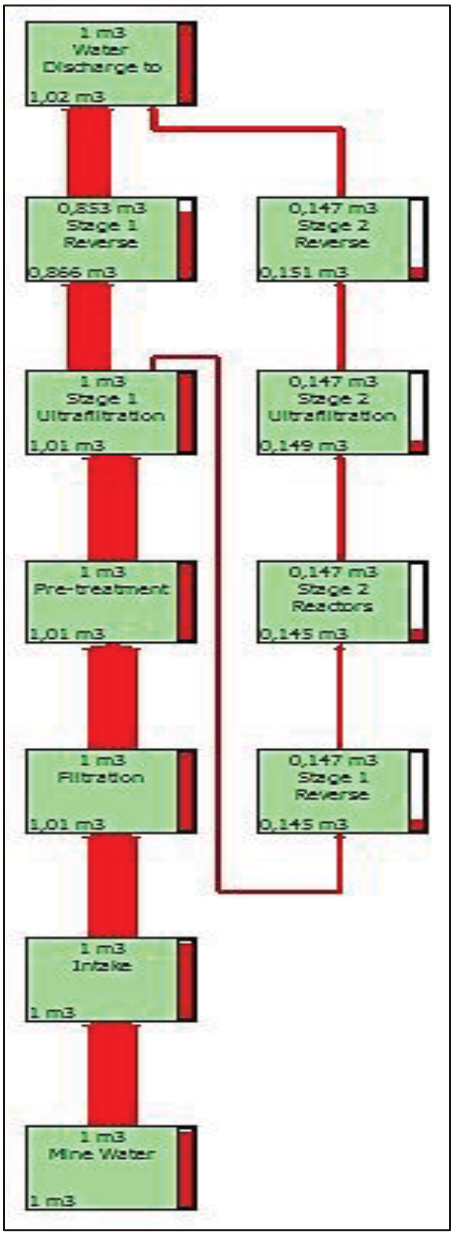

Figure 4:16: Network diagram illustrating water depletion for mine water reclamation

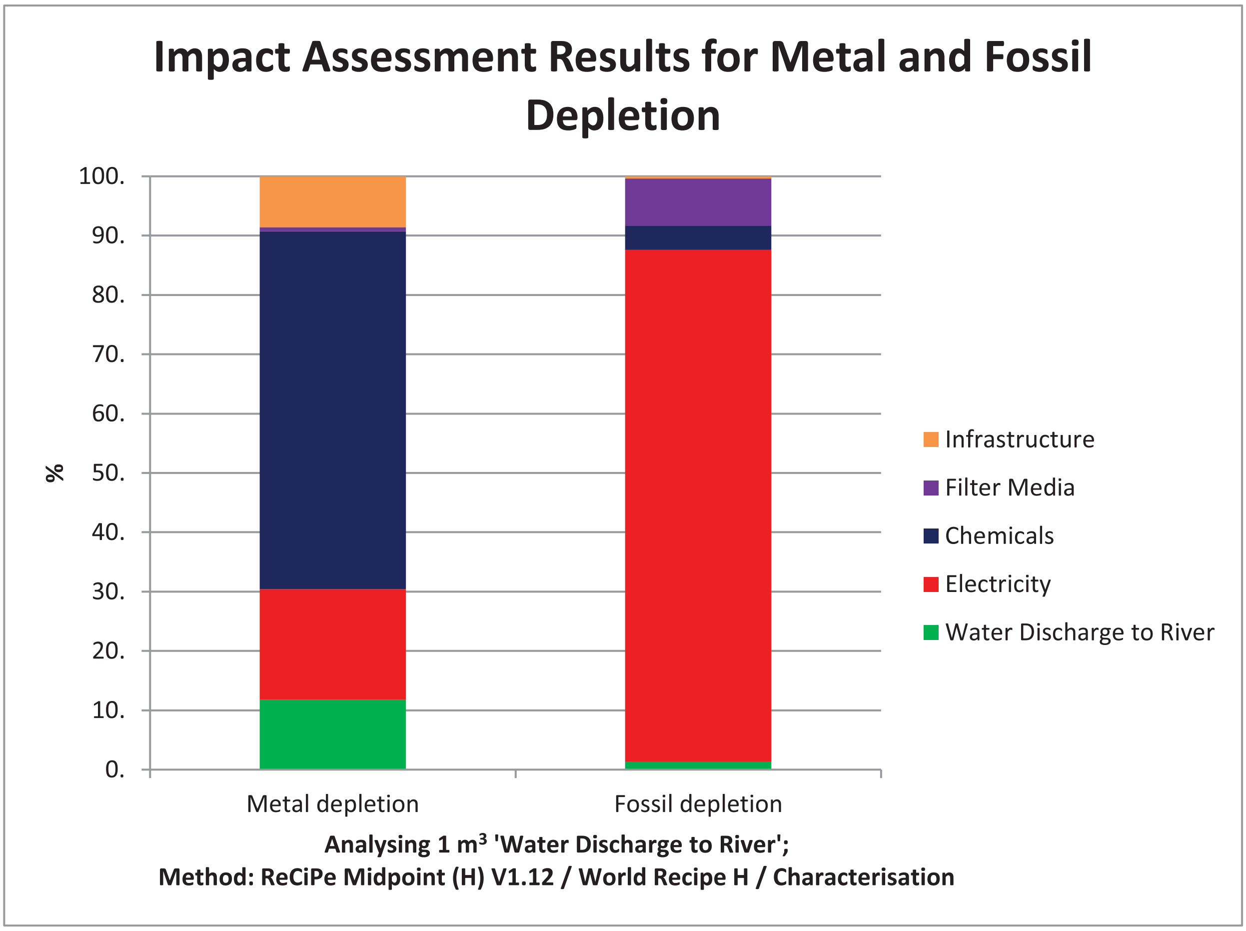

Figure 4:17: Impact assessment results depicting metal and fossil depletion for mine water reclamation

4.3.6 Toxicity

As per the first case study, toxicity values have been grouped together for analysis. The three impact categories are human toxicity, terrestrial ecotoxicity, freshwater and marine ecotoxicity. From the diagram below, it is evident that electricity usage is the major contributor to all four categories. For human, freshwater and marine toxicity, the contributions are fairly similar in magnitude. Electricity is responsible for 85.5, 86 and 85.9% of all three impacts, the filter media contributes 7.22, 6.31 and 6.34% and biocide carries a less signficant burden of 4.40, 3.21 and 3.20% respectively. For terrestrial ecotoxicity, electricity carries a comparatively lower burden of 71.9% while biocide usage makes a much greater contribution of 17.3%.

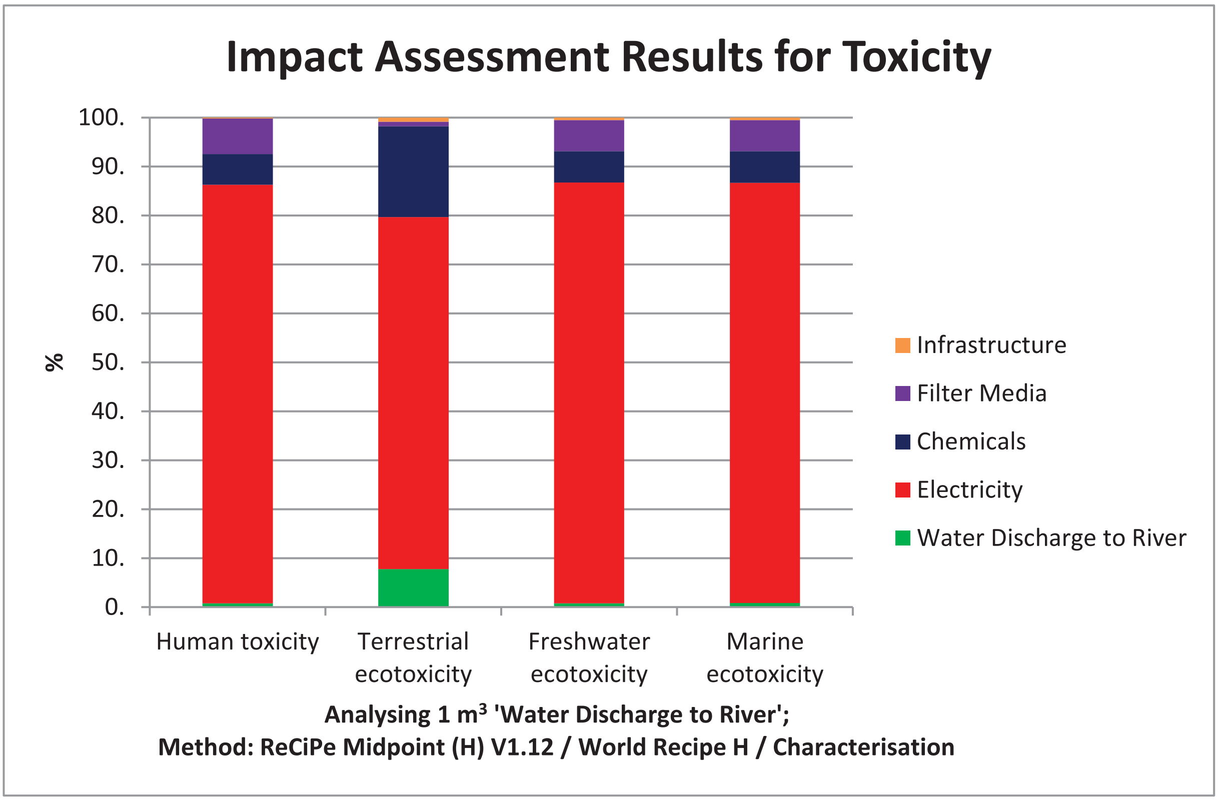

Figure 4:18 Impact assessment results depicting toxicity for mine water reclamation

4.3.7 Eutrophication

Eutrophication is divided into two sub-sections: freshwater and marine eutrophication, which is illustrated in Figure 4.19. For both impacts, the second stage of RO is responsible for 56–57% of the total environmental burden, with the first stage of treatment accounting for the remainder. This division can be attributed to the high electricity requirement (4.76 MJ) of the feed pumps that pump the concentrate from the first stage of RO through the secondary RO membranes in order to increase the overall recovery. In terms of individual inputs, electricity makes the greatest contribution with 87.9–89.9% of the total. For freshwater eutrophication, the life cycle of the filter media from the initial mining up to the sale of the product carries a burden of 8.05%. In terms of marine eutrophication, the contribution is shared equally between the filter media utilised and the biocide.

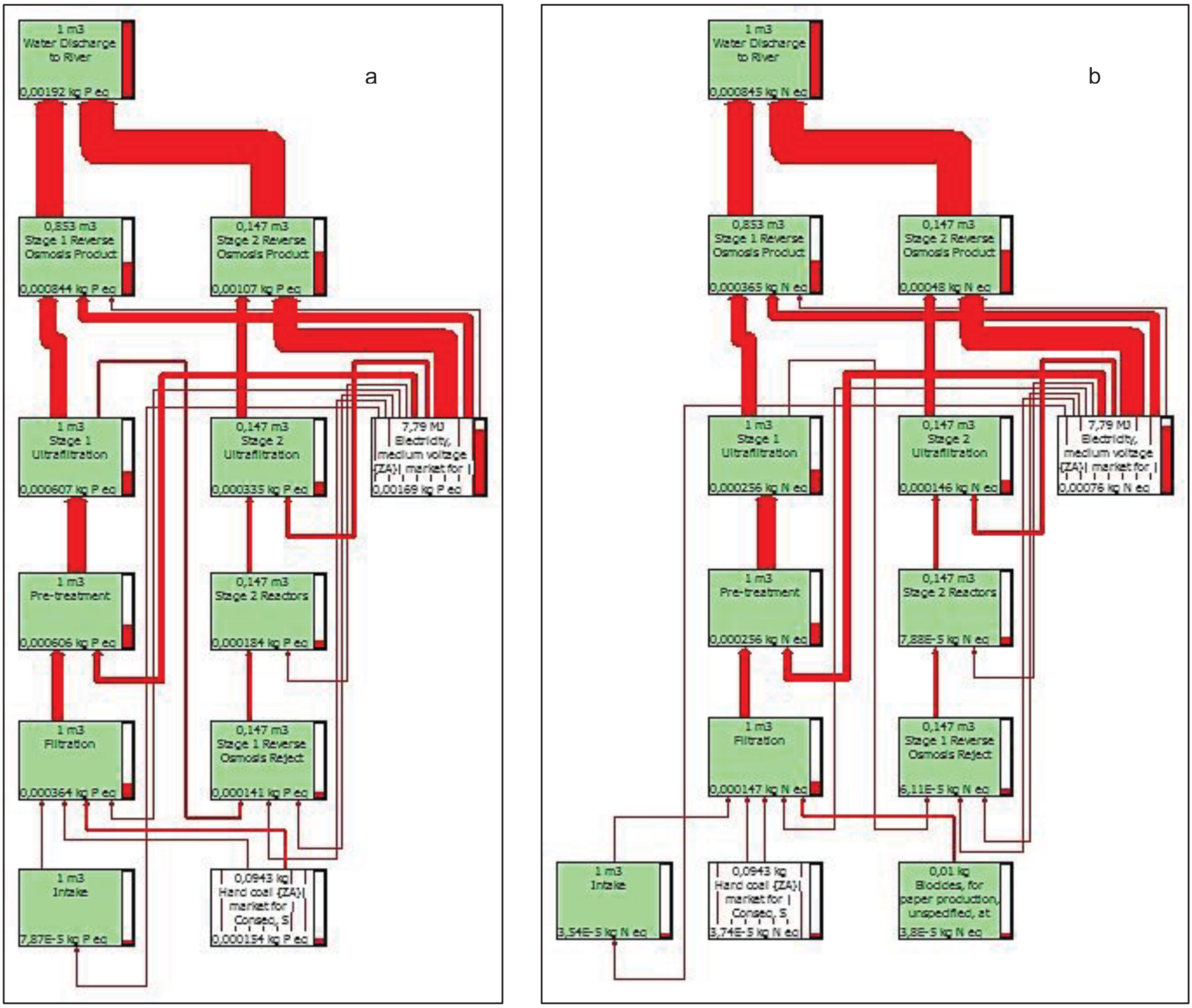

Figure 4:19: Network diagrams illustrating freshwater (a) and marine (b) eutrophication for mine water reclamation

4.3.8 Photochemical Oxidation

Photochemical oxidation or smog is related to the emission of air pollutants such as non-methane hydrocarbons. The width of the red arrows in Figure 4:20: below clearly illustrates that the potential creation of smog from the product system is directly related to electricity generation in South Africa which relies heavily on the combustion of fossil fuels.

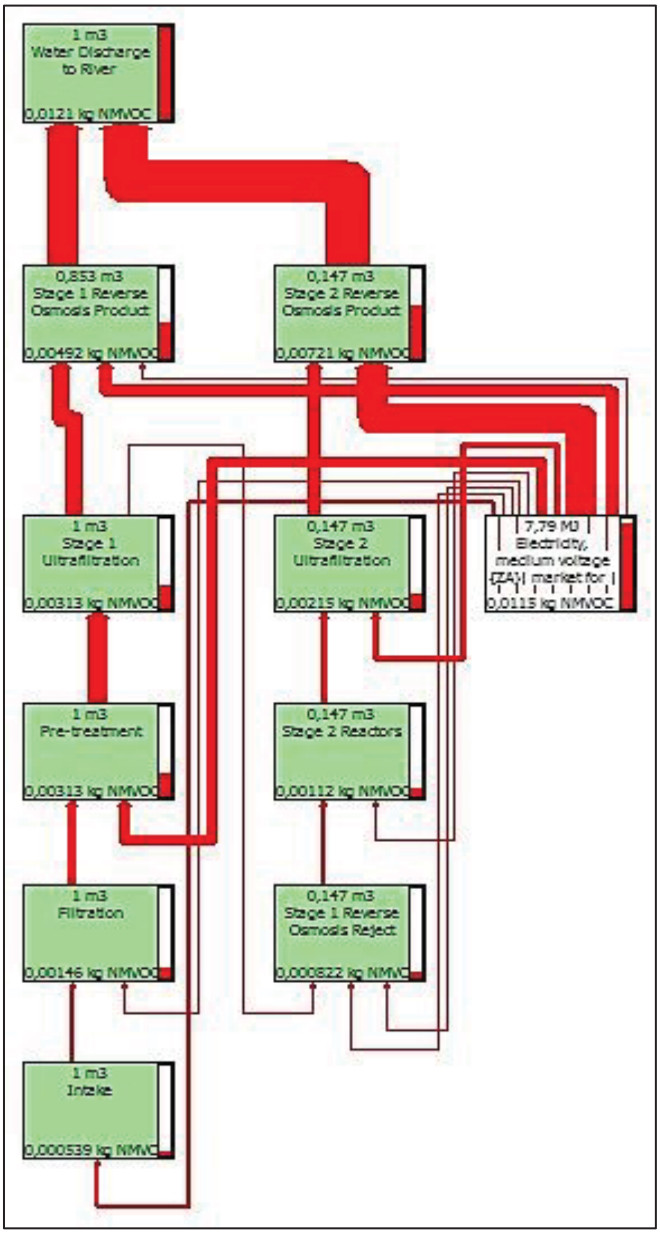

Figure 4:20: Network diagram illustrating photochemical oxidant formation for mine water reclamation

4.3.9 Land Use

The figure below illustrates the effect of the process on land use in both the urban and agricultural context. Natural land transformation and urban land occupation share a similar distribution, with electricity use responsible for contributions of 75.2 and 83.2% respectively. The next largest contributor for urban land occupation is the extraction and production of the filter media which accounts for 7.4% of the overall impact while the use of biocide is the second highest contributor to the category of natural land transformation. For agricultural land occupation, the use of two chemicals, namely ferric chloride and hydrochloric acid, has a positive rather than a negative impact on the use of farming land.

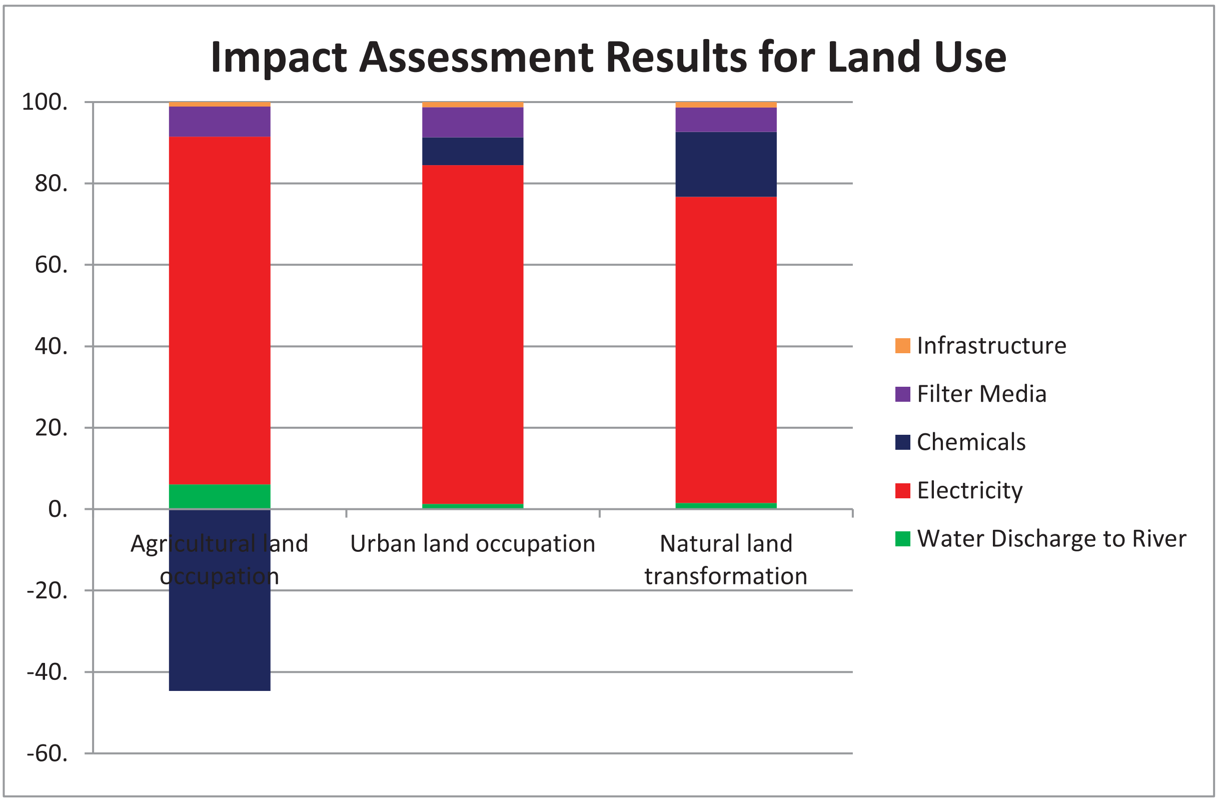

Figure 4:21: Impact assessment results depicting land use for mine water reclamation

4.3.10 Ionising Radiation

Figure 4:22: illustrates the environmental impact of the mine water reclamation process on the potential for ionising radiation. Electricity is responsible for the majority of the impact, contributing 78.4% of the total. This is due to the fact that coal-fired power stations, which provide the bulk of South African energy, are a source of radionucleide releases to the environment. Chemicals, in the form of biocide (14.2%) and iron (III) chloride (3.81%) are also contributors, albeit less significant than electricity consumption.

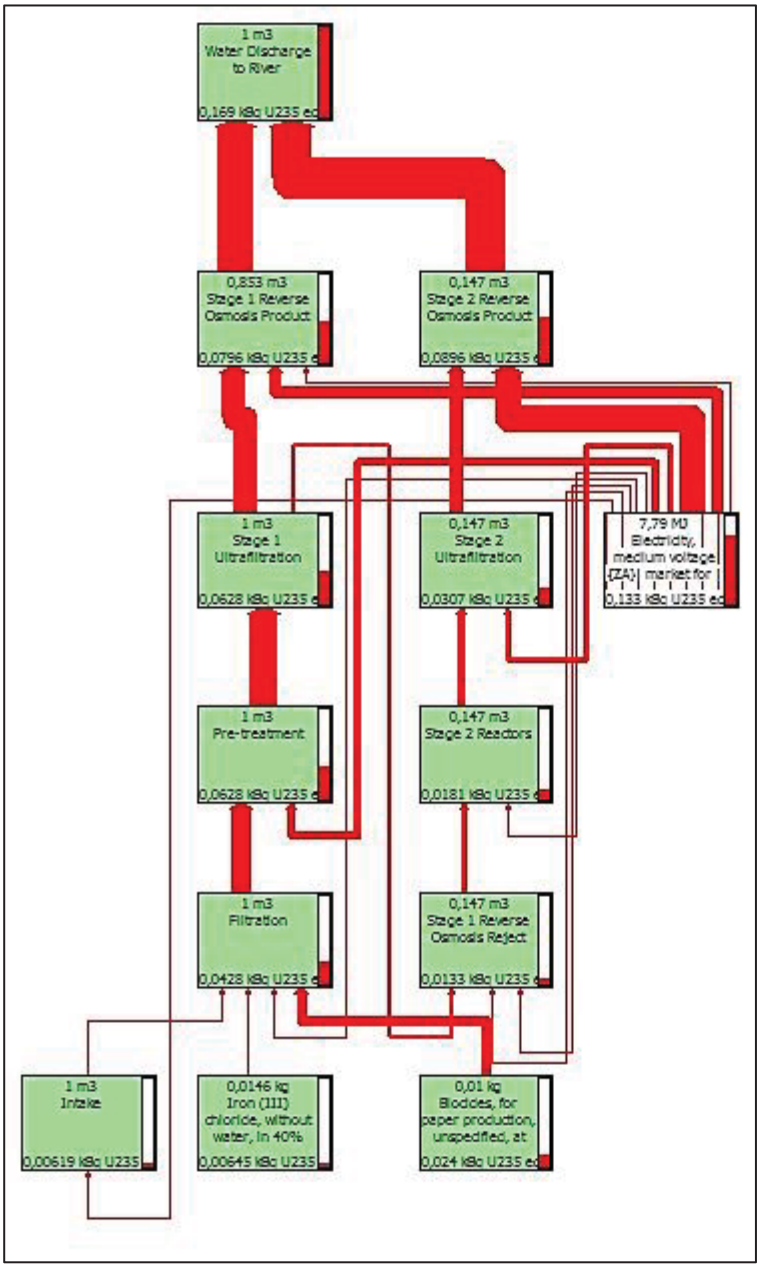

Figure 4:22: Network diagram illustrating ionising radiation for mine water reclamation

4.3.11 Particulate Matter

Particulate matter formation in terms of PM_{10} relates to particles that are <10µm in diameter and have the capacity to harm human health.

Figure 4:23: indicates that the quantity of particulate matter released from the process is directly related to the energy mix in South Africa. The burning of fossil fuels releases air-borne inorganic particles such as fly ash and suspended particulate matter (Mittal et al., 2012).

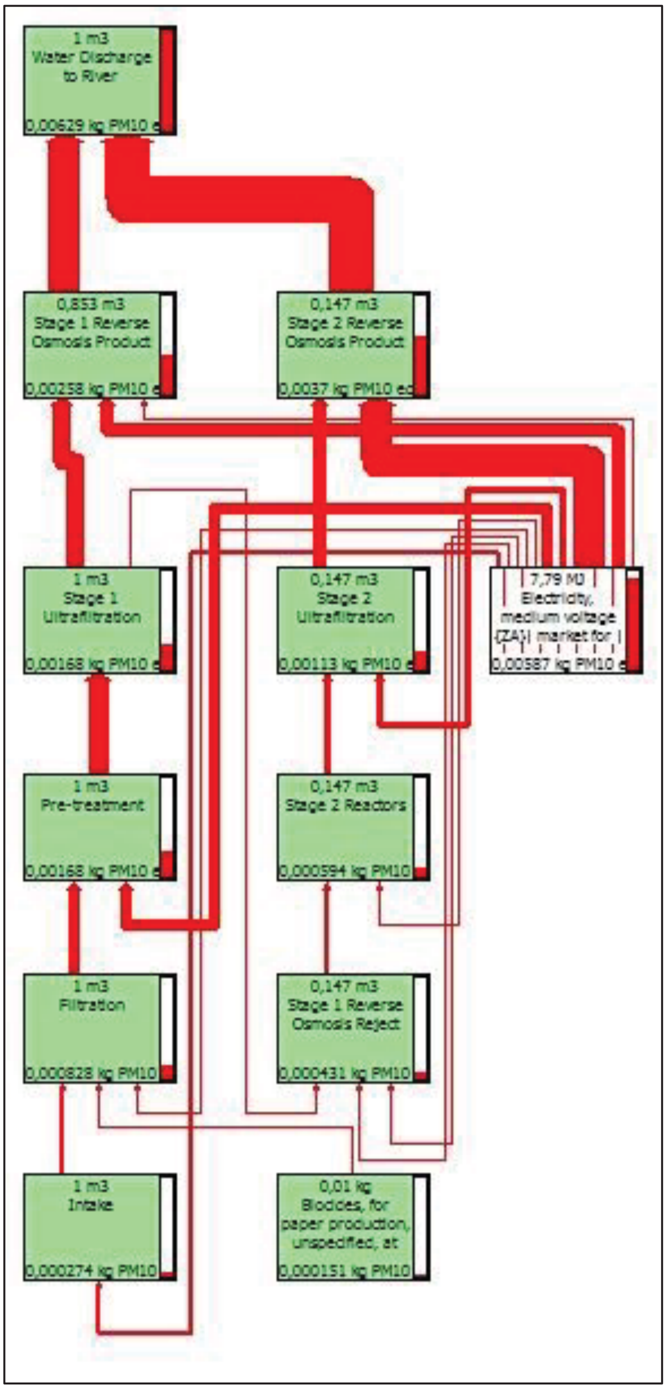

Figure 4:23: Network diagram illustrating particulate matter formation for mine water reclamation

4.3.12 Comparison between Design and Operation Data for Mine Water Reclamation

As mentioned in the materials and methods chapter, the results obtained in Sections 4.3.1–4.3.10 were based on calculations that utilised design data. However, during operation of the plant, variations in the system occur due to factors such as changes in feed and product water quality and changes in water chemistry. The process control philosophy can also be optimised to decrease inputs such as electricity. Table 4:1: presents a summary of the results from undertaking an impact assessment using design data as well as operational data. From the figures, it is evident that for the majority of the impact categories, the operational data results in an improved environmental performance. This can be attributed mainly to decreased electricity consumption.

Table 4:1: Comparison between Impact Assessment Results for Design and Operation Data for Mine Water Reclamation

Impact Category	Unit	Design Data	Operation Data
Climate change	kg CO_2 eq	2.60	1.56
Ozone depletion	kg CFC-11 eq	6.05 $\times 10^{-8}$	5.17 $\times 10^{-8}$
Terrestrial acidification	kg SO_2 eq	2.37 $\times 10^{-2}$	1.41 $\times 10^{-2}$
Freshwater eutrophication	kg P eq	1.92 $\times 10^{-3}$	1,21 $\times 10^{-3}$
Marine eutrophication	kg N eq	8.45 $\times 10^{-4}$	5.24 $\times 10^{-4}$
Human toxicity	kg 1,4-DB eq	1.29	8.23 $\times 10^{-1}$
Photochemical oxidant formation	kg NMVOC	1.21 $\times 10^{-2}$	7.26 $\times 10^{-3}$
Particulate matter formation	kg PM10 eq	6.29 $\times 10^{-3}$	3.81 $\times 10^{-3}$
Terrestrial ecotoxicity	kg 1,4-DB eq	4,61 $\times 10^{-5}$	3.21 $\times 10^{-5}$
Freshwater ecotoxicity	kg 1,4-DB eq	3.70 $\times 10^{-2}$	2.36 $\times 10^{-2}$
Marine ecotoxicity	kg 1,4-DB eq	3.51 $\times 10^{-2}$	2.24 $\times 10^{-2}$
Ionising radiation	kBq U235 eq	1.69 $\times 10^{-1}$	1.13 $\times 10^{-1}$
Agricultural land occupation	m^2a	2.53 $\times 10^{-2}$	8.80 $\times 10^{-3}$
Urban land occupation	m^2a	1.15 $\times 10^{-2}$	7.50 $\times 10^{-3}$
Natural land transformation	m^2	7.63 $\times 10^{-5}$	5.21 $\times 10^{-5}$
Water depletion	m^3	1.02	1.02
Metal depletion	kg Fe eq	1.38 $\times 10^{-1}$	1.27 $\times 10^{-1}$
Fossil depletion	kg oil eq	6.97 $\times 10^{-1}$	4.43 $\times 10^{-1}$

4.4 REMIX WASTEWATER TREATMENT PROCESS

Once the operational data for the Remix plant had been calculated in terms of the functional unit of 1 m^3 of potable water, the resulting numbers were used as inputs into the SimaPro software. Figure 4.24 is a depiction of the overall impact assessment results for the eThekwini Remix plant. From the figure, it is evident that electricity consumption within the plant, together with the South African electricity mix, is responsible for the majority of the system's environmental impacts. The figure also illustrates that sodium hydroxide and sodium sulphite are the greatest environmental contributors, of the chemicals utilised.

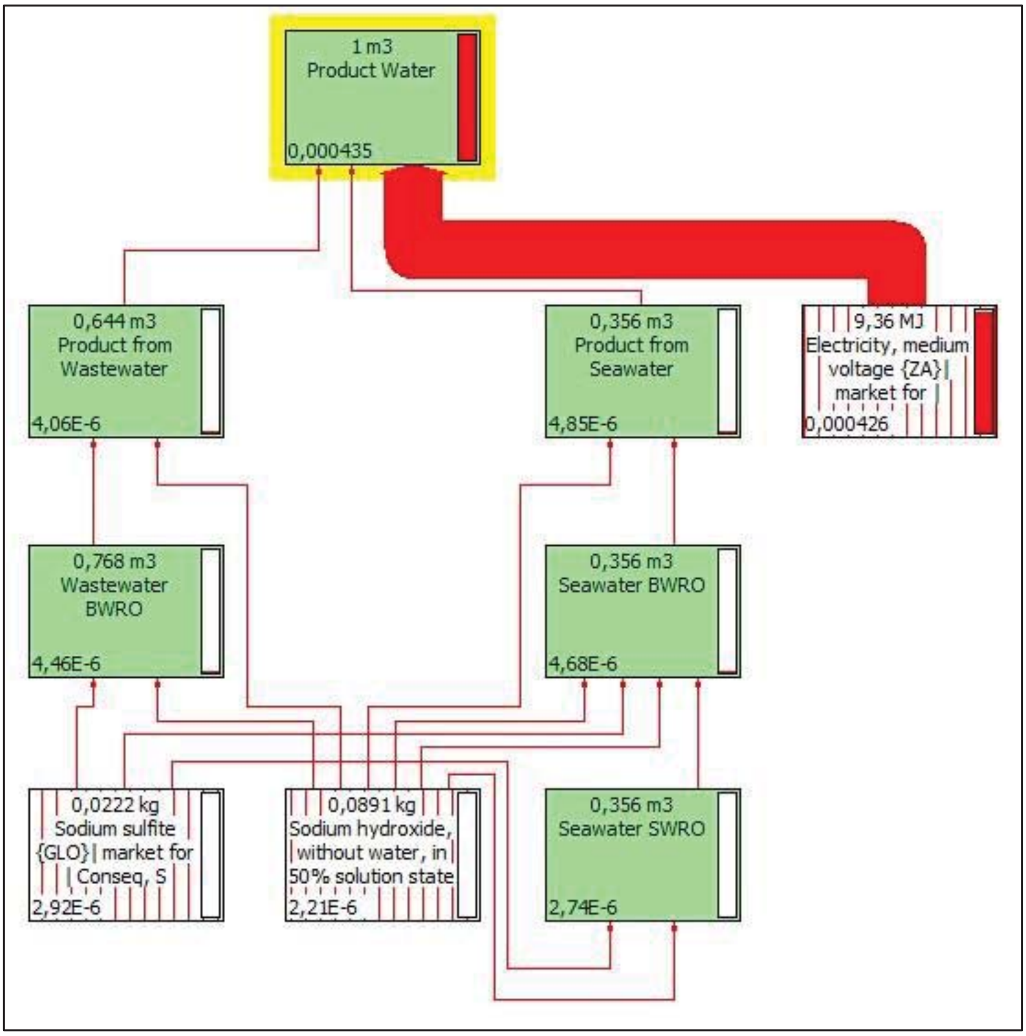

Figure 4:24: Network diagram for the eThekwini Remix Plant

Figure 4.25 is a representation of the results in terms of the individual impact assessment categories. Electricity, which is depicted in red, is the most significant contributor to environmental impacts associated with the atmosphere, such as climate change, photochemical oxidant formation, particulate matter formation and ionising radiation. In addition, fossil depletion is also greatly impacted by electricity with a 97.9% contribution. This is due to South Africa's reliance on the combustion of fossil fuel for energy generation. From a chemical usage aspect, sodium hydroxide has the greatest environmental impact, followed by sodium sulphite, iron chloride and chlorine. This is evident for categories such as agricultural land occupation, water and metal depletion. For the categories associated with toxicity and eutrophication, neither electricity nor chemical usage is the highest contributor. Instead, the source of the environmental burdens can be traced back to the wastewater feed from domestic and industrial applications.

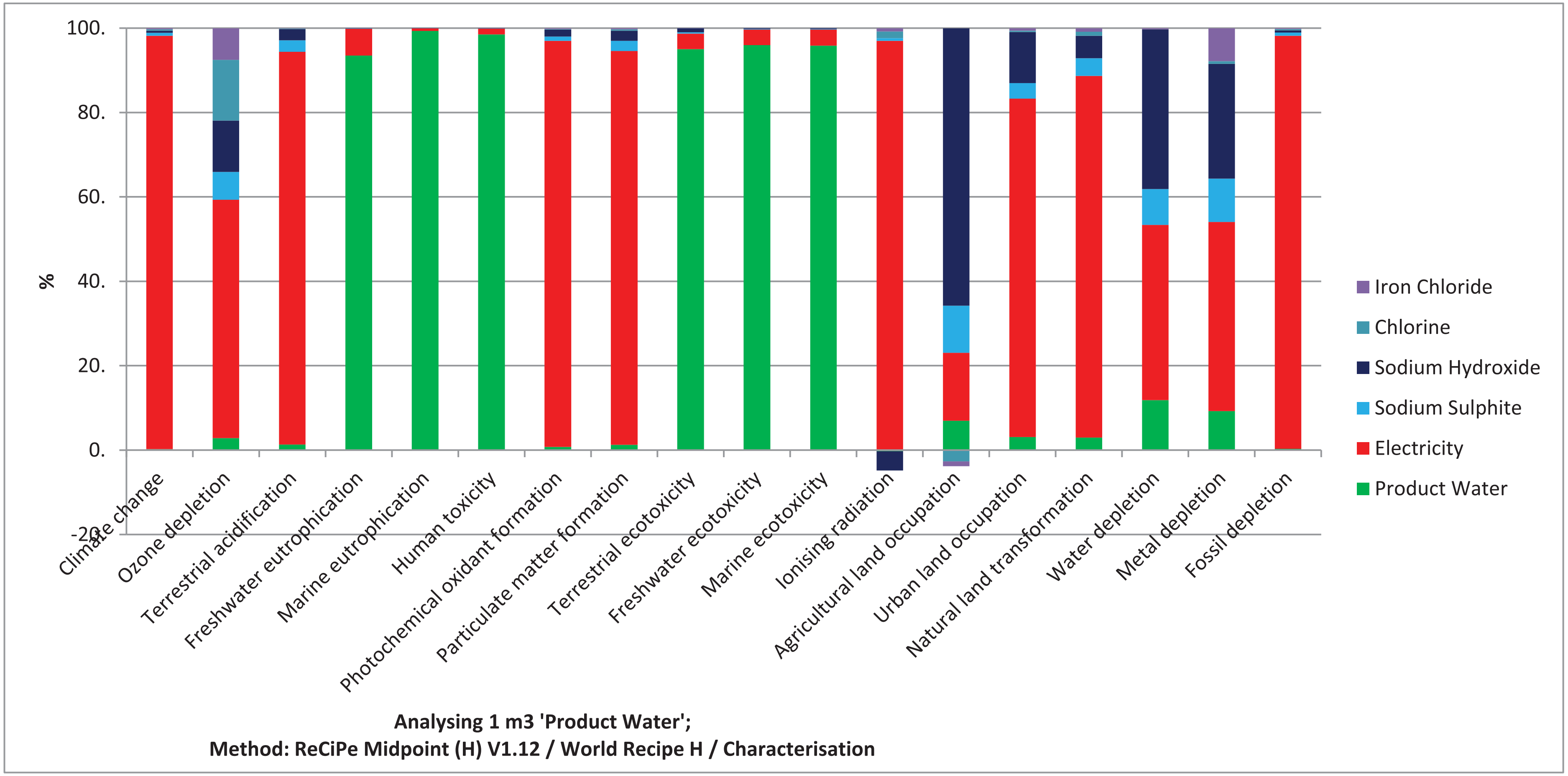

Figure 4:25: Overall impact assessment results for the eThekwini Remix plant

The individual scores for the impact categories considered for the operation of the planned eThekwini Remix plant are presented in Table 4.2. These scores have been calculated for the operation phase only and do not include the construction and the decommissioning of the plant due to lack of data at this stage. It has to be underlined that this project is only at the pre-feasibility stage and there were several delays in planning, which affected the data available for calculation. The only data available was some data on the membranes themselves but not on the additional infrastructure (tanks, pipes and the majority of the pumps) needed. Therefore, the construction phase was estimated to be 20%, based on literature and on the results of the other two case studies investigated. It has to be noted that a worst-case scenario was used, as in most of the literature studies the construction stage accounts for about 5–15% of the environmental performance for water treatment plants. This estimation allowed for the calculation of an approximation of the total score to be expected for the eThekwini Remix plant. As the project progresses and additional data on the infrastructure needed for this plant is generated, a more accurate modelling of the overall scores will be possible.

Table 4:2: Environmental Scores for the eThekwini Remix Plant

Impact Category	Unit	Remix Operation	Remix Approximated Total
Climate change	kg CO_2 eq	3.00	3.75
Ozone depletion	kg CFC-11 eq	4.44×10^{-8}	5.55×10^{-8}
Terrestrial acidification	kg SO_2 eq	2.92×10^{-2}	3.65×10^{-2}
Freshwater eutrophication	kg P eq	3.21×10^{-2}	4.01×10^{-2}
Marine eutrophication	kg N eq	1.55×10^{-1}	1.94×10^{-1}
Human toxicity	kg 1,4-DB eq	3.4	4.3
Photochemical oxidant formation	kg NMVOC	1.44×10^{-2}	1.8×10^{-2}
Particulate matter formation	kg PM10 eq	7.55×10^{-3}	9.44×10^{-3}
Terrestrial ecotoxicity	kg 1,4-DB eq	1.09×10^{-3}	1.36×10^{-3}
Freshwater ecotoxicity	kg 1,4-DB eq	1,03	1.29
Marine ecotoxicity	kg 1,4-DB eq	9.56×10^{-1}	11.95×10^{-1}
Ionising radiation	kBq U235 eq	1.56×10^{-1}	1.95×10^{-1}
Agricultural land occupation	m^2a	2.80×10^{-1}	3.50×10^{-1}
Urban land occupation	m^2a	1.44×10^{-2}	1.80×10^{-2}
Natural land transformation	m^2	$8{,}04 \times 10^{-5}$	10.05×10^{-5}
Water depletion	m^3	1.41×10^{-2}	1.76×10^{-2}
Metal depletion	kg Fe eq	6.87×10^{-2}	8.59×10^{-2}
Fossil depletion	kg oil eq	7.38×10^{-1}	9.23×10^{-1}

4.5 SUMMARY

Table 4:3: 3 provides a summary of the total environmental impacts for the three case studies investigated. The figures highlight the fact that the desalination process carries a much higher overall burden compared to the Remix technology and the mine water reclamation process. A direct comparison between these three case studies will be only valid as a general trend analysis and not as a detailed analysis of these processes. The lower environmental scores for the Remix plant are theoretical, expected based on existing literature. The scores for membrane treatment of mine-affected water show that the environmental burden of treating this water is potentially lower compared to desalination and Remix technology. However, the energy requirements and the subsequent environmental scores depend very much on the quality of the mine water to be treated. In the case study included in this research, the mine water treated is less polluted than was expected and planned for. Therefore, this trend cannot be generalised and another mine might have other water quality, other energy requirements and other environmental scores.

Table 4:3: Summary of Results for Desalination, Mine Water Reclamation and the Remix Technology

Impact Category	**Unit**	**Desalination**	**Mine Water Reclamation**	**Remix System**
Climate change	kg CO_2 eq	4.40	2.60	3.75
Ozone depletion	kg CFC-11 eq	7.92 x 10^{-8}	6.05 x10^{-8}	5.55 x10^{-8}
Terrestrial acidification	kg SO_2 eq	4.17 x10^{-2}	2.37 x10^{-2}	3.65 x10^{-2}
Freshwater eutrophication	kg P eq	3.00 x 10^{-3}	1.92 x10^{-3}	4.01 x10^{-2}
Marine eutrophication	kg N eq	1.42 x 10^{-3}	8.45 x10^{-4}	1.94 x10^{-1}
Human toxicity	kg 1,4-DB eq	2.05	1.29	4.3
Photochemical oxidant formation	kg NMVOC	2.07 x10^{-2}	1.21 x10^{-2}	1.8 x10^{-2}
Particulate matter formation	kg PM10 eq	1.08 x 10^{-2}	6.29 x10^{-3}	9.44 x10^{-3}
Terrestrial ecotoxicity	kg 1,4-DB eq	1.00 x 10^{-4}	4.61 x10^{-5}	1.36 x10^{-3}
Freshwater ecotoxicity	kg 1,4-DB eq	6.07 x10^{-2}	3.70 x10^{-2}	1.29
Marine ecotoxicity	kg 1,4-DB eq	5.75 x10^{-2}	3.51 x10^{-2}	11.95 x10^{-1}
Ionising radiation	kBq U235 eq	2.33 x10^{-1}	1.69 x10^{-1}	1.95 x10^{-1}
Agricultural land occupation	m^2a	2.91 x10^{-1}	2.53 x10^{-2}	3.50 x10^{-1}
Urban land occupation	m^2a	2.03 x10^{-2}	1.15 x10^{-2}	1.80 x10^{-2}
Natural land transformation	m^2	1.27 x 10^{-4}	7.63 x10^{-5}	10.05 x10^{-5}
Water depletion	m^3	1.93 x10^{-2}	1.02	1.76 x10^{-2}
Metal depletion	kg Fe eq	1.05 x10^{-1}	1.38 x10^{-1}	8.59 x10^{-2}
Fossil depletion	kg oil eq	1.09	6.97 x10^{-1}	9.23 x10^{-1}

In each of the three case studies, there are different associated challenges and difficulties as the operations differ in many respects. Table 4:4: highlights a few of the significant differences between the desalination and the mine water reclamation processes. The ISO 14040 (2006) document states that the results of various LCA studies can only be directly compared if the assumptions and context of each study are the same, which for this research, was not the case.

Table 4:4: Summary of the Differences Between the Desalination and Mine Water Reclamation Processes

Aspect	Desalination	Mine Water Reclamation
Stages of Treatment	Single stage	Two stage
Feed Water Salinity	Feed Water Salinity: 38 000 mg/ℓ TDS	Feed Water Salinity (Stage 1) 3800 mg/ℓ TDS Feed Water Salinity (Stage 2) 12 000–17 000 mg/ℓ TDS
Water Treatment Recovery	40–45%	95–98 %
Infrastructure	Larger proportion of concrete construction	Larger proportion of steel construction
Post-treatment	Water stabilised before discharge into potable water supply network	Water not stabilised before discharge into river
Reject Stream	Brine is discharged to sea (55-60% of feed)	Brine to be treated further - not included in case study (2–5% of feed)

All three of the water treatment processes discussed in the study are secondary processes which are necessary to implement due to the scarcity of water. In addition, there are practical considerations that need to be taken into account prior to the design of these plants. Due to their feed source, the desalination and the Remix plants have to be constructed in coastal areas with close proximity to seawater. As the mine reclamation plant will treat accumulated water from previously mined areas, the plant will reside close to mines. The feed water quality for mine water reclamation is also a significant factor due to variance in source water. This variance occurs as a result of the different minerals being mined, the age of the mine and the different mining technologies used.

4.6 IMPROVEMENT ANALYSIS

The results indicate that electricity consumption in the water treatment process is responsible for the majority of the environmental impacts in all three of the processes studied. A further analysis was undertaken to compare the impact assessment results for the electricity mix in South Africa to alternative energy sources. The impact assessment was undertaken on SimaPro for 1 kWh of conventional electricity (the electricity mix in South Africa), photovoltaic (solar) power and wind power.

The results presented in Table 4:5: 5 show that for most of the impact categories, the South African electricity mix has a higher impact than renewable energy sources. This is evident in the case of climate change where conventional electricity is responsible for releasing 1.13 kg CO_2 equivalents per kWh which is 15 times greater than the equivalent amount of carbon dioxide released by solar power and over 60 times higher than the amount of CO_2 emitted by wind turbines. Looking at another impact category, terrestrial acidification, the numbers suggest that conventional electricity releases 1.05×10^{-2} kg SO_2 equivalents which is significantly higher than the 3.30×10^{-4} kg SO_2 equivalents released via the process of electricity generation through solar farms. Energy generated via wind releases the lowest amount of sulphur dioxide with 8.60×10^{-5} kg SO_2 equivalents released. The numbers above highlight the fact that the energy mix used in South Africa generates higher quantities of carbon dioxide and sulphur dioxide gases compared to renewable sources of energy. There are, however, certain impact categories where conventional electricity is not the most detrimental. For ozone depletion, photovoltaic energy is responsible for the greatest emission of chlorofluorocarbons (1.50×10^{-8} kg CFC-11 equivalents), followed by conventional electricity which releases approximately 0.64 of that amount and wind power with the lowest emission of 1.44×10^{-9} kg CFC-11 equivalents.

This analysis indicates that for the majority of environmental impacts, conventional electricity has greater environmental consequences then other energy sources such as solar and wind power.

Table 4:5: Impact Assessment for Various Energy Sources

Impact Category	Unit	Electricity, Conventional Electricity Mix	Electricity, Photovoltaic Energy	Electricity, Wind Energy
Climate change	kg CO_2 eq	1.13	7.52×10^{-2}	1.85×10^{-2}
Ozone depletion	kg CFC-11 eq	9.66×10^{-9}	1.50×10^{-8}	1.44×10^{-9}
Terrestrial acidification	kg SO_2 eq	1.05×10^{-2}	3.30×10^{-4}	8.60×10^{-5}
Freshwater eutrophication	kg P eq	7.80×10^{-4}	6.34×10^{-5}	1.20×10^{-5}
Marine eutrophication	kg N eq	3.50×10^{-4}	2.89×10^{-5}	6.58×10^{-6}
Human toxicity	kg 1,4-DB eq	5.09×10^{-1}	1.01×10^{-1}	2.67×10^{-2}
Photochemical oxidant formation	kg NMVOC	5.33×10^{-3}	2.70×10^{-4}	9.11×10^{-5}
Particulate matter formation	kg PM10 eq	2.71×10^{-3}	1.30×10^{-4}	6.13×10^{-5}
Terrestrial ecotoxicity	kg 1,4-DB eq	1.53×10^{-5}	1.50×10^{-4}	2.16×10^{-6}
Freshwater ecotoxicity	kg 1,4-DB eq	1.47×10^{-2}	1.95×10^{-3}	1.03×10^{-2}
Marine ecotoxicity	kg 1,4-DB eq	1.39×10^{-2}	2.21×10^{-3}	8.94×10^{-3}
Ionising radiation	kBq U235 eq	6.13×10^{-2}	2.28×10^{-2}	1.28×10^{-3}
Agricultural land occupation	m^2a	1.80×10^{-2}	2.99×10^{-2}	1.80×10^{-3}
Urban land occupation	m^2a	4.45×10^{-3}	5.70×10^{-4}	1.55×10^{-3}
Natural land transformation	m^2	2.65×10^{-5}	1.43×10^{-5}	2.16×10^{-6}
Water depletion	m^3	2.26×10^{-3}	7.21×10^{-3}	4.35×10^{-4}
Metal depletion	kg Fe eq	1.18×10^{-2}	2.68×10^{-2}	1.66×10^{-2}
Fossil depletion	kg oil eq	2.78×10^{-1}	2.12×10^{-2}	5.17×10^{-3}

4.7 COMPARISON BETWEEN CONVENTIONAL AND ADVANCED WATER TREATMENT TECHNOLOGIES

The results and analysis thus far emphasise the fact that energy is the highest contributor to the environmental burdens associated with the desalination, mine water reclamation and Remix plants. Thus, a further assessment regarding energy consumption was undertaken comparing the environmental impacts of two of the alternative water treatment plants to conventional water treatment plants in South Africa. At the outset, it must be acknowledged that the energy requirement for desalination and mine water reclamation is much greater than other water treatment technologies. When considering the treatment of raw wastewater in the local context, Wiggins Waterworks had the highest electricity consumption per kilolitre of water produced at 0.1 kWh/m^3 which represents the worst-case scenario for the eThekwini Municipality (Friedrich et al., 2009). The total energy consumption of the proposed desalination plant is 3.69 kWh/m^3 and 2.16 kWh/m^3 for the mine water reclamation plant. Taking the above two figures for energy usage and associating them with characterisation factors for climate change yields the results in Table 4:6: 6. The figures in the table demonstrate that desalination using wind and solar power will produce GHG emissions in the range of 6.83×10^{-2} –2.77×10^{-1} kg CO_2 eq/kℓ potable water. The release of GHG emissions for the mine water reclamation plant will be even lower with emissions between 4.00×10^{-2} and 1.62×10^{-1} kg CO_2 eq/kℓ potable water. These figures are comparable to emissions of 0.08–0.11 kg CO_2 eq/kℓ water, which are calculated in **6**, which would be released from a similar water treatment process to that employed at Durban Heights and Wiggins Waterworks.

Table 4:6: Comparison between Greenhouse Gas Emissions for Water Treatment Processes Employing Various Energy Sources

Plant	Energy Source	Characterisation Factors (kg CO_2 eq)	Climate Change (kg CO_2 eq/ kℓ water)
Desalination Plant	Conventional Electricity	1.13	4.17
	Photovoltaic	7.52×10^{-2}	2.77×10^{-1}
	Wind	1.85×10^{-2}	6.83×10^{-2}
Mine Water Reclamation Plant	Conventional Electricity	1.13	2,44
	Photovoltaic	7.52×10^{-2}	1.62×10^{-1}
	Wind	1.85×10^{-2}	4.00×10^{-2}
Wiggins Waterworks	Conventional Electricity	1.13	0.113
Durban Heights	Conventional Electricity	1.13	0.08

4.8 COMPARISON WITH INTERNATIONAL STUDIES

A series of studies have shown that energy consumption for the different water processing technologies is critical and is the source of many environmental burdens (Vince et al., 2008 and Barjoveanu et al., 2010). In South Africa, it has been proposed that electricity consumption be used as a crude environmental indicator for the performance of urban water systems with an electricity index (e.g. kWh/kℓ) applied to the treatment processes and pumping of water and wastewater (Friedrich et al., 2007). Vince et al. (2008) undertook a comparative LCA study of different water treatment processes for the production of potable water. In terms of energy requirements, seawater membrane desalination with energy recovery devices generally consumes about 3.5–4.5 kWh/m^3 of electricity. The proposed desalination process which is used in the first case study consumes a total of 3.69 kWh/m^3 which is within the above-mentioned range. Furthermore, it is lower than the stated electricity consumption of the three operational desalination plants in South Africa, namely the Sedgefield plant (3.97 kWh/m^3), the Albany Coast plant (4.52 kWh/m^3) and the Mossel Bay plant (4.39 kWh/m^3) (Turner et al., 2015).

There are several international LCAs of desalination plants. One project conducted a LCA of a seawater desalination plant in Western Australia (Biswas, 2009). As both Australia and South Africa are situated on similar latitudes and experience similar weather conditions, it was thought that this could be an effective comparison. The aim of the Biswas research paper was to quantify the amount of GHGs that are released from the Southern Seawater Desalination Plant (SSDP), and determine the “hotspots” for water production. SimaPro software, as in our study, was utilised for computation purposes. In order to make the LCA results more representative, Australian databases and libraries were used. The data for Western Australian electricity generation was used to represent energy consumption. In his study, Biswas (2009) concluded that RO contributes significantly higher GHG emissions than other stages of the desalination process, with a 75.1% contribution. This is comparable to the results from this study which quantify the GHG emissions from RO at 64.6%. One of the reasons for the slight disparity is the fact that microfiltration was used in the pre-treatment phase for the Australian plant. This reduces the amount of chemicals required for treatment prior to RO and would, therefore, result in a reduction of GHGs for the pre-treatment stages. Furthermore, the LCA analysis conducted by Biswas (2009) suggests that the emissions generated from the electricity for pumping, membrane operation and water delivery purposes account for 92.1% of the GHG emissions during the life cycle of water production, which is comparable to the figure of 95.2% calculated for this project for desalination. A similar study carried out by Mrayed and Leslie (2009) found that the GHG emissions from the generation of electricity for the operation of a seawater desalination plant accounted for a large proportion (95%) of the total GHG emissions.

In addition, the analysis carried out by Biswas (2009) showed that GHG emissions can be reduced by a large quantity, 90.6% in this case, if all the electricity was generated by wind turbines. The study also demonstrates that climate change impacts can be reduced by as much as 68% if electricity generated from wind turbines is only used to power the RO system. However, it is imperative to note that wind energy is normally used in conjunction with other energy sources in a hybrid system, and not all sites are suitable for the location of wind turbines.

Regarding desalination of mine-affected water, Thiruvenkatachari et al. (2016) undertook an investigation evaluating the effectiveness of an integrated forward osmosis and reverse osmosis system. By utilising samples from three coal mines as feed, the system was able to achieve a total recovery of more than 80%. Results also indicated that the forward osmosis process provided effective pre-treatment in preparation for the RO stage and could potentially replace conventional pre-treatment methods. Feini et al. (2008) studied the performance of both NF and RO membranes in the reuse of metallurgical effluent. By examining the water flux and salt rejection, they were able to conclude that NF would be more suitable for industrial conditions where treatment occurs on a large scale. These two studies indicate that for mine water treatment in particular, system advancements can aid the performance of the overall system.

There are various other options mentioned in the literature, for minimising the energy usage of a water reuse process utilising membrane technologies. System design developments include the implementation of a hybrid system which incorporates both brackish and seawater elements as well as a two pass NF system (Veerapaneni et al., 2007; Long, 2008). Pumping efficiency could be increased by installing a variable frequency drive on the electric motor of energy-intensive pumps (Manth et al., 2003). Investigation into innovative material based membranes that reduce fouling are currently underway (Subramani et al., 2011). In addition, emerging technologies such as forward osmosis, ion concentration polarisation and capacitive deionisation technology are all advancements in the pipeline that could potentially have a positive impact on energy consumption (Elimelech & Phillip, 2011; Subramani et al., 2011). These interventions can be classified as short-term and long-term interventions. Of the short-term interventions, pump efficiencies and the use of variable frequency drives on energy-intensive motors are of particular significance and the use of such devices should be encouraged for local RO plants.

4.9 DISCUSSION ON CHEMICALS USED

Chemical production and use carries a significant environmental burden, and after energy use, it is the second area which can be improved. In particular, the chemicals for post-treatment (lime and carbon dioxide) in the desalination process and the chemicals for pre-treatment (ferric chloride as coagulant and secondary antiscalant as well as biocide) in the mine water reclamation process appear in the modelling process to be the chemicals with the highest impacts.

Vince et al. (2008) analysed various water treatment processes for particular local conditions. One of the conclusions that was reached pertains to the detrimental effect of coagulant production and use (Vince et al., 2008). As is evident from the treatment of mine water, the usage of coagulant depends on the concentration of organic and suspended matter in the source water. Vince et al. (2008) state that the production of a kg of ferric chloride has an impact on ozone depletion that is equal to the impact of 35 kg of aluminium sulphate. This brings to light the fact that the choice among similar chemicals may result in vastly different impacts. In the second case study, ferric chloride is responsible for 35% of the total potential for ozone depletion of the system. Thus, it is recommended that the production process of ferric chloride be investigated together with consideration of other coagulants. In addition, it has been proven by Al-Mashharawi et al. (2012) that the use of low pressure membranes in the pre-treatment phase has the capacity to reduce the use of coagulants.

The other chemical that has a large environmental footprint in the treatment of mine-affected water is biocide. According to the details provided in SimaPro, the biocide used in the modelling stages comprises two oxidising agents and two highly toxic organics. One of the oxidising agents is chlorine dioxide. Lattemann and Höpner (2008) state that although chlorine dioxide effectively reduces biofouling, it may affect non-target organisms in surface water discharge. However, it presents a more appealing alternative to chlorine as it is assumed to form fewer organic by-products such as trihalomethanes (Lattemann and Höpner, 2008). Van der Bruggen and Vandecasteele (2002) make mention of the fact the fact that biocides are a necessity in water treatment processes and alternative chemicals with lower impacts have yet to be located.

It has been reported by Vince et al. (2008) that within a water treatment process, the remineralisation/neutralisation phase may lead to significant climate change impacts due to the production of chemicals such as carbon dioxide and lime. Large doses of chemicals are necessary in order to adjust the alkalinity of the demineralised water to potable water quality standards. For the selected desalination process, lime and CO_2 release the highest amount of GHG emissions after electricity use. These results necessitate an investigation into alternate chemicals as well as permeate blending of the product water with other mineralised water sources in order to decrease chemical use (Vince et al., 2008).

As far as the toxicity of the discharged concentrate is concerned, Mezher et al. (2011) mention that the overall temperature, density and total dissolved salts (TDS) of the discharge are of critical importance as they could potentially cause damage to the aquatic ecosystem. Increased temperature could have detrimental consequences while a rise in specific gravity would cause the contents of the reject stream to sink. The quantity of dissolved solids also increases with an increase in plant recovery. These factors need to be considered when debating the release of any concentrate into large bodies of water.

In order to decrease the detrimental impact of chemicals, it is necessary to develop environmentally friendly products that are biodegradable and possess low toxicity levels. The effect of the discharge of contaminants as a portion of the brine solution can be minimised by diluting the reject stream with other waste streams. An alternative solution is to substitute the traditional pre-treatment methods of mechanical separation and chemical treatment with pressure-driven membrane technologies such as MF, UF and NF. Ghaffour et al. (2013) have also stated that the addition of antiscalant is not always necessary, as demonstrated in the study by Waly et al. (2009) which showed stable operation of a SWRO plant without chemical usage. As a concluding note, Elimelech and Phillip (2011) note that other than RO, the other stages that account for the most energy use are the pre-treatment and post-treatment phases of desalination. Thus, by decreasing the chemical use within the treatment processes, the potential for energy saving can be maximised.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

This chapter presents the second part of the Life Cycle Interpretation phase. The first section summarises the results obtained in Chapter 4, highlighting the significant findings from the study and conclusions. The second section presents practical recommendations to decrease the environmental impacts of the studied systems. In addition, suggestions are also provided to assist future LCA practitioners to undertake similar assessments within the water sector in South Africa.

5.2 CONCLUSIONS

This research project should be seen as a base-line study for assessment of the environmental performance of treating alternative sources of water by membrane technologies. The case studies investigated are based on three membrane water treatment processes that utilise alternative sources of water as feed (i.e. seawater for desalination, mine-affected water for membrane treatment and seawater mixed with municipal sewage for the Remix technology). Environmental scores have been generated for the three case studies by employing the LCA methodology as set out in the ISO 14000 series of documentation. SimaPro software was used to undertake the modelling with the ReCiPe Midpoint Method chosen for the impact assessment. The results for each case study were analysed per impact category: climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial, freshwater and marine ecotoxicity, ionising radiation, agricultural land occupation, natural land transformation, fresh water depletion, metal/minerals depletion and fossil fuels depletion. The impact of using renewable energy was examined.

The results indicate that the operational phase is responsible for the majority of the environmental impacts attributed to desalination and the membrane treatment of mine-affected water. This is in line with other local and international studies. However, the magnitude of the impacts are unique for the case studies investigated. For example, for desalination, the operational stage contributes about 95.2% of the environmental burden for climate change and for most of the other impact categories considered, the operational contributions were all above 90% for this case study. A similar trend was established for the reclamation of mine-affected water. Within the operational stage, energy consumption is the greatest contributor and this is traced back to the energy demands of the RO stage of all of the three case studies investigated. Therefore, this stage should be targeted for improvement.

As the results strongly indicate that plant environmental impacts are highly dependent on the electricity source and supply, the substitution of fossil fuel-based energy with renewable energy was investigated. It was determined that the use of solar or wind energy will significantly reduce most of the impacts. With reference to climate change, using solar and wind energy reduced the impacts of membrane alternative water treatments to levels that are comparable to conventional water treatment processes currently employed in the eThekwini Municipality.

Chemical production and use represent the second highest environmental burden. The chemicals with the highest environmental burdens are those used for pre-treatment for mine-affected water (ferric chloride and biocide), for the post-treatment of desalination (lime and carbon dioxide), and sodium hydroxide in the Remix system.

5.3 RECOMMENDATIONS

As the results presented clearly highlight the high burden of electricity on the studied systems, an effort should be made to decrease electricity usage and its associated environmental impacts. Energy minimisation strategies include increasing pumping efficiency, implementing system design improvements, investigating evolving technologies for separation as well as utilising fouling-resistant membranes. To reduce the release of hazardous pollutants, renewable energy sources can be used for the provision of energy. Furthermore, as chemicals have been identified as being the second-highest contributor, alternative chemicals with lower impacts should be explored. The correlation between energy usage and chemical consumption for membrane processes should also be analysed in order to determine the possibility of a proportional relationship, i.e. if chemical usage increases, electricity consumption decreases and vice versa.

Within the current SimaPro database, there is a lack of local data representing South African conditions. An effort has been made by ecoinvent to tender for updated mining, agricultural and power generation processes pertaining to South Africa. Information of this nature will improve the accuracy of the results obtained from the environmental LCA model. In addition, development is required regarding salination and water consumption which are environmental issues that are pertinent to South Africa in particular. Furthermore, the ReCiPe impact assessment method used in this study was developed from two methods, namely Eco-indicator 99 and CML-IA, which both originate from the Netherlands. Salination and water consumption are only two of the environmental impacts that are significant in South Africa but are considered less relevant in Europe. Thus, an approach is required that incorporates these factors into existing procedures, taking South Africa's unique environmental conditions into account.

During the course of the research project, an endeavour was made to introduce the engineering community to the concept and purpose of LCA, particularly in the water sector. With assistance from government departments and research institutions, the use of this environmental management tool could become widespread. This could render the data collection process easier and make companies more comfortable with the sharing of sensitive data.

The environmental analysis points to the desalination process having a higher environmental impact then the mine water reclamation process. It is recommended that a LCA be carried out on the construction and operation of the uMkhomazi Dam which is an alternative option for supplementing the water supply in the eThekwini district. Other comparative LCAs should also be conducted on the existing desalination plants in the Western Cape as well as the new desalination plant located in Richards Bay. With respect to the mine water reclamation process, other treatment processes with similar inputs should be analysed and conclusions formed on the basis of the change in parameters. This would provide an indication regarding the relationship between the degree of contamination in the mine-affected water and the energy consumption and chemical usage of each process.

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