A Comparative Life Cycle Assessment (LCA) of Water Treatment Plants using Alternative Sources of Water (Seawater and Mine Affected Water)

by

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PREFACE

The research contained in this dissertation was completed by the candidate while based in the School of Engineering of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Howard College Campus, South Africa. The research was financially supported by Umgeni Water and the Water Research Commission.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

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ABSTRACT

Water is a replenishing, yet at times scarce resource that is necessary for the growth and development of all organisms and plant life. In South Africa, the situation is challenging due to competing demands for limited fresh water reserves. Thus, the search for technological solutions is necessary to alleviate water shortages. Two of the potential measures to increase available water supply are desalination and reuse of water. As with any industrial operation, potable water production involves several processes which inherently impact the environment. These need to be taken into consideration in the design and management of water treatment operations. The purpose of the study was to conduct an environmental Life Cycle Assessment (LCA) of two water treatment membrane plants that use alternative feed sources namely seawater and mine affected water. The first plant will be located in the Southern area of the eThekwini Municipality and will utilise seawater reverse osmosis (SWRO) to produce 150 Mℓ/d of potable water. The second is a case study based on an existing mine water reclamation plant in Mpumalanga that is designed around a two stage ultrafiltration-reverse osmosis (UF-RO) process used to treat 15 Mℓ/d of mine affected water. The LCA guidelines, which were established by the International Organisation for Standardisation, were utilised for the purposes of this study. Design data was collected for both the construction and operation phases of the plants while SimaPro was used as the LCA analysis software with the application of the ReCiPe Midpoint method. The key findings from the assessment reveal that electricity production and consumption is responsible for the majority of environmental impacts that stem from the respective plants. A further analysis indicated that the South African electricity mix has greater environmental impacts than other energy sources such as photovoltaic and wind power. The integration of these energy systems with alternative water treatment processes has been proven to reduce environmental loads to levels associated with conventional water technologies. Based on these results, it is recommended that focus should shift towards energy minimisation techniques and the use of renewable energy sources in order to advance the environmental performance of water treatment processes.

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LIST OF ABBREVIATIONS

AD	Acidification Potential
AMD	Acid Mine Drainage
BWRO	Brackish Water Reverse Osmosis
CEB	Chemically Enhanced Backwash
CIP	Cleaning in Place
DWAF	Department of Water Affairs and Forestry
DWA	Department of Water Affairs
DWP	Drinking Water Production
DUP	Deep Bed Up-Flow
EIA	Environmental Impact Assessment
EMS	Environmental Management System
EPA	Environmental Protection Agency
FIEEC	Fédération des Industries Electriques, Electroniques et de Communication
GHG	Greenhouse Gas
HDPE	High Density Polyethylene
ILCD	International Reference Life Cycle Data
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
NF	Nano filtration
NCPC-SA	National Cleaner Production Centre of South Africa
NGO	Non-Governmental Organisation
NMVOC	Non-Methane Volatile Organic Compounds
NPP	Net Primary Production
NREL	National Renewable Energy Laboratory

ODP	Ozone Depletion Potential
PES	Polyethersulphone
PMFP	Particulate Matter Formation Potentials
PID	Process and Instrumentation Diagram
PVDF	Polyvinylidene Fluoride
REDISA	Recycling and Economic Development Initiative of South Africa
REPA	Resource and Environmental Profile Analysis
RO	Reverse Osmosis
RWQO	Receiving Water Quality Objectives
SCA	South Coast Augmentation
SEA	Strategic Environmental Assessment
SETAC	Society of Environmental Toxicology and Chemistry
SWRO	Seawater Reverse Osmosis
TDS	Total Dissolved Solids
UF	Ultrafiltration
UKZN	University of KwaZulu-Natal
UNEP	United Nations Environmental Programme
WC	Water Catchment
WDM	Water Demand Management
WMA	Water Management Area
WSS	Water Supply System
WSSD	World Summit on Sustainable Development
WTP	Water Treatment Plant
WWT	Waste Water Treatment

CHAPTER 1: INTRODUCTION

This chapter is dedicated to four aspects that provide a sound introduction to the content of this study. The first sub-chapter introduces the topics of water treatment and life cycle assessment tools which continues onto an explanation of the rationale behind the research project. This is followed by detailing the aims and objectives of the study. The chapter concludes with an outline of the structure of the thesis.

1.1 Introduction to the Study

Water is regarded as one of the most precious and critical resources worldwide. In South Africa, the scarcity of water presents various challenges mainly relating to efficient development, management and utilisation (Knüppe, 2011). To overcome these obstacles and ensure that South Africa has an abundant water supply, various water treatment techniques have been explored. As is the case with all industrial processes, there are substantial environmental impacts that occur from the construction of the plant through to commissioning, operation and decommissioning. In order to effectively evaluate the environmental burden of each water treatment system as well as its associated processes, a life cycle assessment (LCA) can be utilised. The use of such a sustainability tool provides a true reflection of the product's life cycle from 'cradle to grave' by systematically quantifying the amount of energy used, the consumption of raw materials, emissions to the atmosphere as well as the amount of waste generated (ISO, 2006a). By including all the impacts at each life cycle stage, the LCA provides a true reflection of the potential trade-offs in the selection of products and processes.

This study compares two water treatment processes in South Africa to produce potable water. The first study is based on a proposed desalination plant that will be installed by Umgeni Water. During the feasibility study phase, it was determined that the plant should be located on the South Coast of KwaZulu-Natal and will be designed to produce a total of 150 Mℓ/d of potable water (Umgeni Water, 2015a). The second study revolves around a water treatment process in Mpumalanga that treats mine affected water to potable water standards. The plant is currently treating 15 Mℓ/d of raw water via two processing trains (Golder Associates Africa, 2012). Both plants make use of membrane technologies to achieve the desired separation.

The LCA process consists of four phases namely goal and scope definition, inventory analysis, impact assessment and interpretation (ISO, 2006a). The first stage set the aims of the study and provided an outline of the functional unit, assumptions made and data requirements. The next stage consisted of the gathering of data which was used as inputs into SimaPro which was the selected LCA software. A series of scores for the various environmental impacts were obtained which provided an indication of the environmental contribution of the process parameters. Recommendations based on these results were then proposed.

1.2 Rationale for the Research

This study investigates the environmental impacts of two water treatment processes by employing the LCA as an environmental assessment tool. Currently, these alternative sources of water and associated technologies are in rare use (Department of Water Affairs, 2013). However, considering the increasing demand for a limited resource, such operations will become more widespread. Thus, it is imperative to shape the design process for future projects from the outset, so as to reach the best outcome locally. The findings from this study will provide guidance regarding focus areas to guide this process.

As water is an essential input in the production process of most entities, the environmental burdens associated with the generation of potable water are a key component in any national LCA database. Such databases should be planned under the umbrellas of both the United Nations Environmental Programme (UNEP) and the National Cleaner Production Centre of South Africa (NCPC-SA) (National Cleaner Production Centre of South Africa, 2012). This study aims to provide information of this nature which could assist in the marketing and export of South African goods abroad.

The various LCA studies undertaken locally and internationally have shown that the abstraction of water from the environment together with the energy usage within the water treatment process have the highest environmental burdens (Loubet et al., 2014 and Buckley et al., 2011). These studies have also demonstrated the flexibility of LCA as a decision making tool in the water industry as it has the capacity to assist in the comparison of technologies and different scenarios. In addition, the LCA provides an opportunity to improve the design and prioritise interventions before the actual construction process. Therefore, in South Africa, it is important to not only encourage the use of LCAs for the water sector but also to promote life-cycle based water footprinting. In addition, the inclusion of water usage data in life cycle inventories helps with the efficient utilisation of water as a resource (Buckley et al., 2011).

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 which reveals a gap in research centred around alternative water sources. Internationally, there is a strong body of literature with regard to desalination of seawater but a lack of similar information for the reuse of water affected by mining operations. Locally, there is only one study (Friedrich, 2001) 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 seawater. Therefore, it is imperative to utilise the LCA tool to its full advantage in order to positively shape future developments of these alternative technologies in South Africa.

1.3 Aims and Objectives

The overriding objective of this study is to quantify the overall environmental impact of each of the two water treatment technologies with the generation of local LCA data. In addition, the report aims to provide a comparison between the processes and their associated systems. It is envisaged that the outcomes of this report would be utilised for the purposes of process selection as well as improving the environmental performance of the process at the various stages of its life cycle. To summarise, the specific aims of the study are detailed as follows:

- to generate environmental information by investigating each of the water treatment processes (desalination and reclamation of mine affected water),
- to provide recommendations on how to improve the overall environmental performance of these technologies,
- to enlighten designers and owners regarding the potential life cycle environmental consequences of the selected technologies,
- to develop capability in undertaking life cycle assessments within research institutions and consulting companies.

The objectives of the research project are as follows:

- to conduct life cycle assessments for each of the systems investigated,

- to compare the environmental impacts of both technologies, and
- to focus on areas of potential environmental improvements for each process.

1.4 Outline of Dissertation

This thesis has been presented in a manner that ensures that the content of each chapter flows from one to another. As stated in the ISO 14000 series of documentation, the LCA process is a systematic approach which dictates that each step depends on the information gathered from preceding stages.

Following from Chapter 1, Chapter 2 is a discussion regarding available literature pertaining to the water situation in South Africa and membrane treatment processes to increase the water supply. Background related to the history and general structure of the LCA is also discussed.

Chapter 3 focuses on the two plants that were selected as case studies. Details regarding the location and motivation behind each plant was discussed together with a presentation of the key components for both treatment processes.

In Chapter 4, the methodology of the study is outlined with a description of the stages in LCA as it pertains to the two case studies.

Chapter 5 contains a presentation of the results. For each of the plants, the scores per impact category are analysed together with a comparative analysis of both processes. A discussion regarding the major process parameters is also included.

As the final chapter, Chapter 6 provides conclusions as well as recommendations that are based on the findings of the previous chapter. Future research possibilities that could add value are also mentioned.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This section provides a background to the study by firstly focussing on the water situation prevailing in South Africa elaborating on current supply and demand, future forecasts and various strategies. Water treatment technologies with a focus on membrane based processes will be introduced and detailed. Thereafter, a general discussion on the principles of a LCA will follow. The chapter will conclude with an insight into the applications of LCA for water systems.

2.2 Background into water and water treatment in South Africa

Water is increasingly becoming a topical issue worldwide with many countries facing water scarcity as an impediment to social and economic development. This sub-chapter starts off by detailing the water situation in South Africa in terms of demand and supply. In order to bridge the gap, several key strategies are highlighted. Lastly, a brief summary of the state of water treatment internationally is presented.

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 (Hedden & Cilliers, 2014). South Africa is not aloof to 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 with 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 235 l/day compared to 173 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 water. The water situation is aggravated by the fact that rainfall received is highly seasonal with short seasons of rainfall and long periods characterised by a lack of rain. (Department of Water Affairs and Forestry, 2004). Due to this disparity of rainfall, a substantial amount of water is transferred between the various Water Management Areas (WMA's) as illustrated in **Figure 2.1**. Large scale inter-basin transfers also facilitate the water resource management programme to supplement water to urban metropolitans like Johannesburg, Cape Town and Durban (Department of Environmental Affairs, 2012). Within these 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.

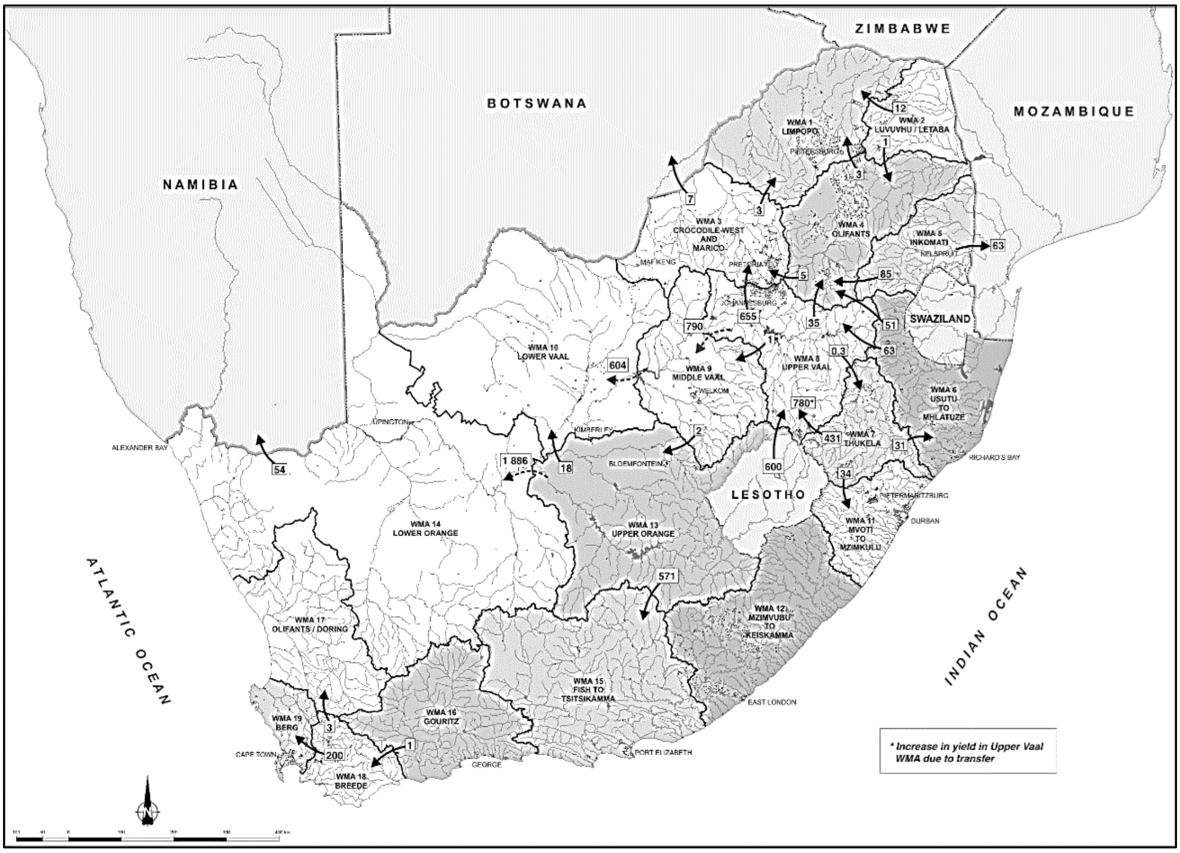


Figure 2.1 Location of WMAs and inter WMA Transfers (Department of Water Affairs and Forestry, 2004)

The majority of South Africa's water is supplied by surface water features such as rivers and dams. The 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 half of the country's average yearly runoff (Department of Environmental Affairs, 2012). This high percentage of total dam storage means that the construction of additional large dams would be inefficient. Multiple dams can also have a detrimental effect on the aquatic ecosystem integrity in inland waters. In the case of rivers, the potential yield is limited by water pollution originating from urban discharge, industrial, agricultural and mining activities. The above points to the fact that South Africa's current water resources are already being extensively utilised.

In the case of arid or rural areas where the supply of surface water is poor, groundwater is utilised to satisfy requirements. It is estimated that the country's available groundwater resource is approximately 10 343 million m^3/annum or 5 000-7 500 million m^3/annum under drought conditions (Department of Environmental Affairs, 2012). As in the case of surface water, groundwater availability varies with some WMA's 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, the current water demands need 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. 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 adequate quantities and at a satisfactory quality is vital. 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 sector that has the highest water consumption 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 constraint in the growth of this area as poor water quality has a detrimental effect on agricultural exports and derived foreign revenue. Although the mining sector was found to use 5 % of available water, it is a significant user in mining areas (Department of Water Affairs, 2013). 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 power stations and solar powered plants with a portion of South Africa's produced electricity exported to surrounding countries in Africa. In spite of the sector utilising approximately 2% of water, its contribution to the GDP and job creation is significant with the industry credited for providing an estimated 250 000 jobs (Department of Water Affairs, 2013).

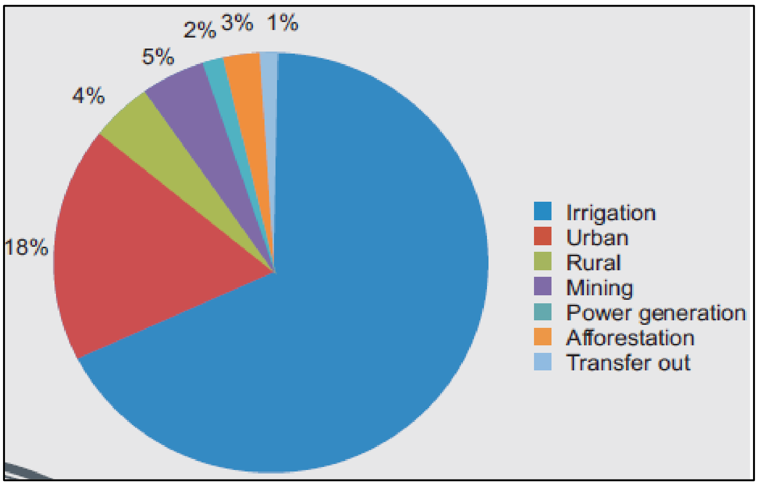


Figure 2.2 Major Water Users in South Africa (Department of Water Affairs, 2013)

2.2.3 Strategies to balance demand and supply

The Department of Water Affairs and Forestry (DWAF) has 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 (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 ground water flows with the authors of National Water Resource Strategy (2013 edition) estimating that South Africa uses approximately 2 million m^3/annum out of a possible 7 million m^3/a. Bearing the possibility of an underestimation in mind, this leaves around 3 500 million m^3/a that is available for further development. **Figure 2.3** is a presentation of the water balance in 2000 and the projected water balance in 2025. It is evident that as time progresses, water shortages are likely to become more prevalent in South Africa (Department of Water Affairs and Forestry, 2008). In general, it is probable that the country will experience a scarcity rather than a surplus of water.

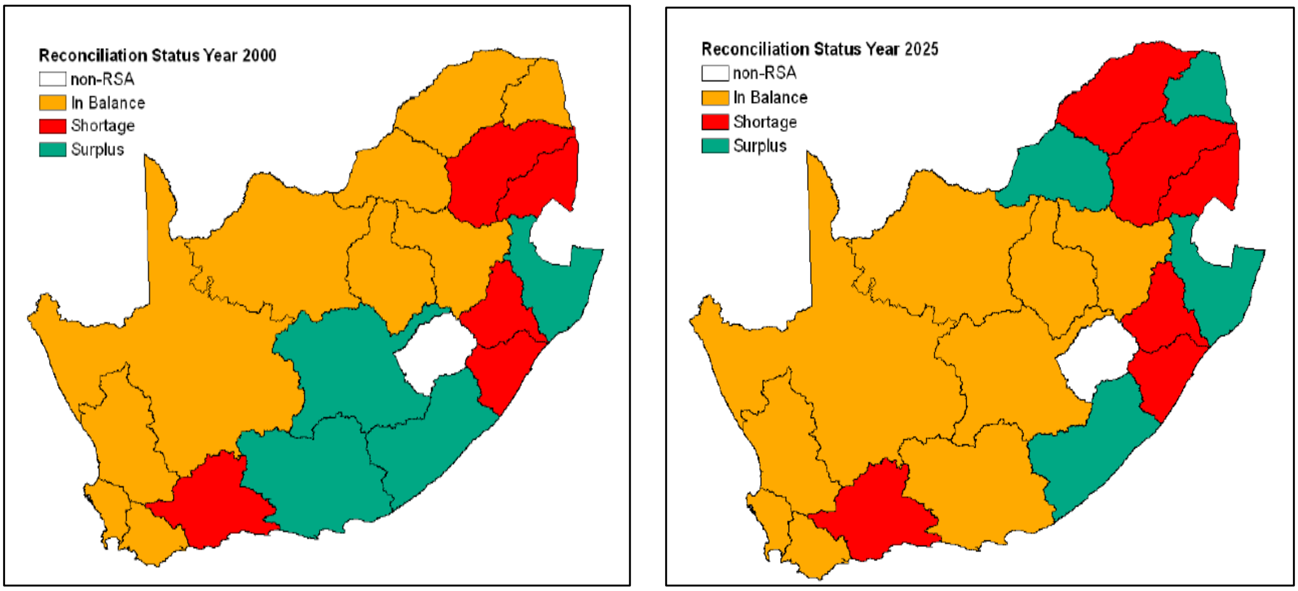


Figure 2.3 Water Demand and Supply Scenarios for 2020 and 2025 (Department of Water Affairs and Forestry, 2008)

Due to the burgeoning economy and social development prevailing in South Africa, an increase in demand is inevitable. Future burdens on water supply are expected to arise from an increase in population and economic growth due to development of new mines and power stations (Department of Water Affairs, 2013). Many of these pressures are location specific with future growth in water demands mainly concentrated in the large metropolitan areas.

In order to bridge the gap between demand and supply, various measures need to be implemented and are summarised below. In practise, a combination of factors is necessary depending on geographical location and suitability to the different WMA's.

- 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 (Department of Water Affairs and Forestry, 2004).

- Water Resource Management

The impending water scarcity situation has necessitated the development of reservoir management and inter-catchment transfer (Department of Water Affairs and Forestry, 2004). In addition, advances in the management of smaller water resources and revision of operating strategies for the larger water resources will assist in the alleviation of the present conditions.

- 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 (Department of Water Affairs and Forestry, 2004). This source of freshwater is advantageous as a result of a relatively low investment required for advancement.

- 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 (DWA) is supervising the implementation of over 150 development projects to increase water resources 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 investments with long payback periods which might diminish the economic viability of such ventures. An alternative is to induce changes in water-use patterns and to re-allocate water.

The practise of inter-catchment transfer is as a result of South Africa's geographical imbalance in water availability and unequal demand. It has been found in the 2006 edition of the report documenting South Africa's environmental outlook that more than 50% of the WMA's rely on transfers to prevent water shortages with approximately a third of the surface water yield in 2000 emanating from surface water sources (Department of Environmental Affairs and Tourism, 2006).

- Water Harvesting

This method of collecting rainwater and fog has proved successful with the eThekwini Municipality implementing 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 consistent supply 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 the industrial drainage is reused. Other metropolitans 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 available water supply in South Africa. At the water treatment 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).

Reclamation of water is becoming more common and practical due to the increasing demands, improvements in membrane technology and a decline in treatment costs. It is widely acknowledged that direct reuse of wastewater that is treated 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 is used to describe a range of water treatment technologies which facilitates the separation of salts from water thereby rendering a useful water product (Department of Water Affairs, 2013). The available desalination technologies can be applied to various water and wastewater streams from brackish groundwater to sea water thus providing an infinite source of water. This is especially true for coastal cities which are located downstream of catchments and may experience water shortages due to the utilisation of available water upstream (Department of Water Affairs, 2013).

Desalination is relatively expensive when compared to conventional treatment processes. Until recently, very little of South Africa's groundwater was considered as an economically viable resource due to high salinity levels. However, desalination is becoming more affordable due to the improvement of related technologies together with the rising cost of surface water. Desalination is already occurring on a small scale in South Africa with several plants located in the Western Cape Province and planning for future facilities ongoing (Department of Water Affairs, 2013). Du Plessis et al. mention that important factors to consider when considering desalination include the assessments of energy requirements, physical location of the plant and cost of distribution (du Plessis et al., 2006).

- Acid Mine Drainage Management

Mining in South Africa has always been crucial and is widely seen as one of the key drivers of the country's economy. However, since the 1970's 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). Acid mine drainage is highly acidic water and contains significant concentrations of salts, sulphides and metals. Major sources of AMD include drainage from underground mine shafts, runoff from abandoned mine dumps and open pits as well as tailings which contribute to 88% of the total waste produced in South Africa (Council for Scientific and Industrial Research , 2009).

The possibility of post-closure decantation of AMD is a major hazard and could 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 located near Witbank (Department of Water Affairs, 2013).

2.3 Background into Membrane Use for the Treatment of Water

In order to alleviate the strain on water supply, various measures can be implemented such as water preservation, maintenance of aging infrastructure as well as upgrading catchment systems. However, these methods possess the potential to improve the existing water supply quality rather than increasing it. The only approaches that are available to increase the amount of water beyond what is currently available is to employ desalination and water reuse (Elimelech & Phillip, 2011).

2.3.1 Introduction to Membrane-based Processes

Large-scale desalination plants that were constructed previously in the Gulf areas relied mainly on thermal desalination. These plants were responsible for emitting large quantities of greenhouse gases due to their significant use of thermal and electric energy (Elimelech & Phillip, 2011). In recent years, the majority of plants rely on membrane processes to desalinate both seawater and brackish groundwater with 63.7 % of the total global desalination capacity (Ghaffour et al., 2013). Such membrane technologies hold inherent advantages as they generally consist of stationary components with compact modular construction that are easy to maintain (Lee et al., 2016). Despite their capacity for excellent separation efficiency, membranes are prone to fouling which decreases process performance (Elimelech & Phillip, 2011 and Lee et al., 2016). Improvements in the fabrication of thin-film composite membranes have sought to reduce this tendency (Elimelech & Phillip, 2011). As a result of these significant technological advancements, the cost of desalination has decreased to the extent that in several locations, desalination is able to successfully compete with conventional sources of water such as dams (Ghaffour et al., 2013). Globally, desalination capacity has increased not just in the regions of North Africa and the Middle East but also in various other countries such as Spain and Australia (Ghaffour et al., 2013). In South Africa, desalination has been successfully executed in Mossel Bay, Sedgefield and Albany Coast along with the first desalination plant recently commissioned in KwaZulu-Natal (Turner et al., 2015 and Creamer, 2016).

Water recycling and the reuse of wastewater have also become a worldwide practice due to the deteriorating quality of natural water sources coupled with increasing instability of supply. It is estimated that the global capacity of these plants is approximately 50 000 Mℓ/day with actual output at roughly 60% of capacity (Burgess et al., 2015). A report by the European Union (2015) identifies more than 3 300 water reclamation projects with Japan having the majority (1 800) followed by the USA (1 600) and Australia (450). In Southern Africa, there are a few wastewater reuse plants that utilise membrane processes such as ultrafiltration and reverse osmosis to produce either industrial or potable water (Turner et al., 2015). The first direct water reclamation plant built in the region is in Windhoek, Namibia which comprises of an internationally recognised multi-barrier treatment system (Burgess et al., 2015). Plants in South Africa include the Beaufort West Reclamation Plant (2.1 Mℓ/d) and the George Plant (8.5 Mℓ/d) (Turner et al., 2015).

Due to an increasing focus on minimisation of water use in the mining industry and more rigorous environmental regulations, conventional treatment methods to reuse mine affected water are being tested. Amongst these techniques are precipitation, solvent extraction and ion exchange (Mortazavi, 2008). There are various disadvantages with respect to the above applications which include a lack of selectivity and production of large quantities of organic waste (Mortazavi, 2008). There have been a number of studies that have demonstrated the success of membrane separation processes for effluent and mine water treatment. Internationally, membrane processes have been utilised to treat mine affected water in France (iron mine), California (gold mine) and Australia (gold mine) (Mortazavi, 2008 and United States Environmental Protection Agency, 2014). In South Africa, Anglo Coal and Ingwe Collieries jointly developed the Emalahleni Water Reclamation Project in Mpumalanga. This plant was capable of treating 20 Mℓ/d of water affected by underground mining operations in the vicinity (Holtzhausen, 2006).

2.3.2 Types of Membranes

A membrane is defined as "a thin physical interface that moderates certain species to pass through depending on their physical and/or chemical properties" (Lee et al., 2016). They can be distinguished into two classes based on their composition and physical nature (Sagle & Freeman, 2004). As illustrated in **Figure 2.4**, isotropic membranes are homogenous in composition and structure whereas anisotropic membranes are non-uniform (Lee et al., 2016). Membranes can be constructed of inorganic materials (ceramics or metals) or synthetic organic polymers (Sagle & Freeman, 2004). The majority of membranes currently used are polymeric (Lee et al., 2016).

Common membranes such as reverse osmosis (RO), microfiltration (MF), ultrafiltration (UF) and nanofiltration (NF) are categorized based on varying pore sizes as per **Figure 2.4**. Due to their small size, RO membranes are effectively considered non-porous and can thus exclude low molecular weight species including salt ions and certain organics (Sagle & Freeman, 2004). For the purposes of desalination, the RO membrane consists of a semipermeable film capable of separating pure water from sea water. Such separation of salt and water is governed by a solution-diffusion mechanism which dictates the diffusion of species through a concentration gradient (Elimelech & Phillip, 2011). During the first few years of RO, operating pressures reached levels of 120 bar but currently range between 20 bar (brackish water) and 50 bar (seawater) (Van der Bruggen & Vandecasteele, 2002). In order to achieve these high pressures, substantial energy is required.

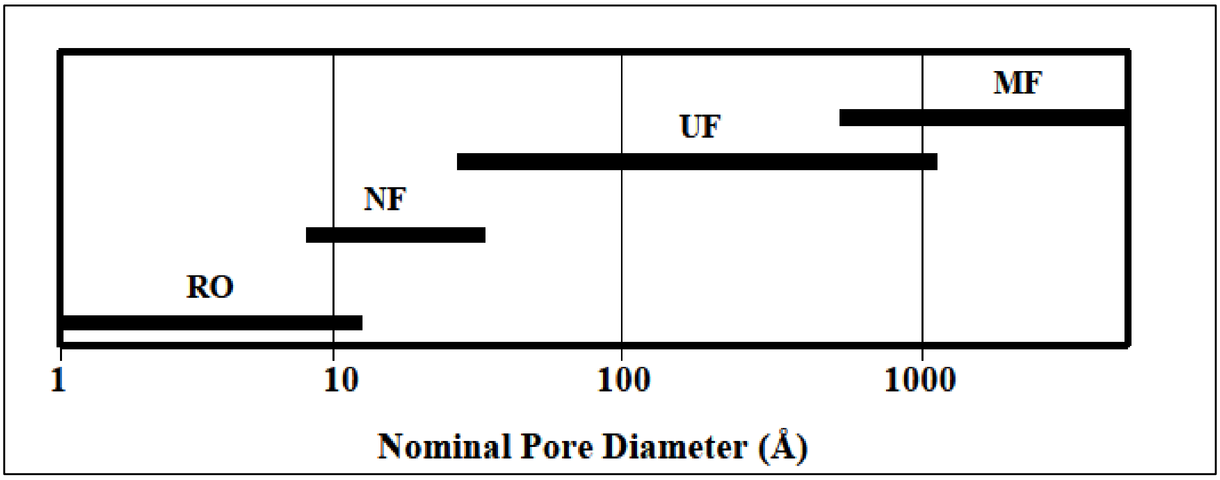


Figure 2.4 Range of Nominal Membrane Pore Sizes for Membranes (Sagle & Freeman, 2004)

2.3.3 Current Energy Requirements

During the last decades, reverse osmosis technology has evolved significantly with current research focussing on operational improvements to lower the cost and provide a more environmentally friendly process (Van der Bruggen & Vandecasteele, 2002). Amongst the literature, there are several articles that review the possible advancements (Elimelech & Phillip, 2011, Van der Bruggen & Vandecasteele, 2002 and Lee et al., 2016). In general, it is noted that the energy consumption of membrane processes has a significant effect on the overall operating and maintenance costs of operating these plants (Turner et al., 2015). **Table 2.1** provides an approximate range of energy usage values for various water treatment processes.

Table 2.1 Range of Electricity Consumption Values for Different Technologies (Vince et al., 2008)

Potable water production plant life cycle steps	Electricity consumption in kWh/m³ 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 vary with thermal desalination consuming the most amount of energy (6.5-20 kWh/m^3 of potable water). However, this technology does not make use of membranes. Seawater membrane desalination utilizing reverse osmosis without energy recovery devices is slightly less energy intensive with energy usage estimated to fall in the range of 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. Both Elimelech and Phillip (2011) and Subramani et al. (2011) state that the theoretical minimum energy required for seawater desalination with a 50% recovery is around 1.06 – 1.08 kWh/m^3. In practice, seawater RO systems consume between 2 – 6 kWh/m^3 with an average electricity use of 3.4 kWh/m^3 (Subramani et al., 2011). In the South African context, Turner et al. (2015) shows that for the SWRO plants, the electricity consumption varies between 3.97 kWh/m^3 (Sedgefield Plant) and 4.52 kWh/m^3 (Albany Coast Plant) with the Mossel Bay Plant using 4.39 kWh/m^3. The cost of electricity in rands for these plants comprises 40 – 50 % of the total operational and maintenance costs. Regarding alternative water treatment processes, water reuse has the lowest energy usage at 0.25 - 1.2 kWh/m^3. Locally, the energy consumption of three of the four Southern African reuse plants reviewed in the WRC report falls within this range (Turner et al., 2015).

2.3.4 Energy Minimisation Strategies

To date, important advances in desalination technology have been made in light of producing potable water at an affordable rate while having a minimal impact on the environment. Van der Bruggen and Vandecasteele (2002) consider an alternative to the traditional pre-treatment methods which consist of mechanical treatment in the form of cartridge or media filters together with chemical treatment to prevent scaling and corrosion. This combination often accounts for a significant portion of the total costs due to biofouling and the need for regular chemical cleaning. They review the use of pressure driven membrane technologies (MF, UF and NF) which have the capacity to lower both operational and capital costs while enabling the RO unit to function at a lower pressure and higher recovery (Van der Bruggen & Vandecasteele, 2002). The environmental impact of the discharge of contaminants as part of the brine solution can be minimised by making use of antiscalants with a lower potential for eutrophication (Morton et al., 1996). It is also suggested that the brine be diluted with waste streams such as backwash water or cooling water if available (Elimelech & Phillip, 2011). Furthermore, the development of fouling resistant membranes have the potential to decrease cleaning costs by 4% while providing energy savings of 25% (Van der Bruggen & Vandecasteele, 2002).

Regarding system design, investigations by Wilf and Bartels (2005) have led to the conclusion that the design and position of membrane modules have a tangible influence on the performance and financial situation of a RO plant. Whereas a two stage membrane configuration was used in the past, a single stage system has been reported to decrease the power usage by 2.5 % (Wilf & Bartels, 2005). An innovative design modification is to make use of a two-stage hybrid system where the first stage comprises of brackish water membrane elements followed by standard seawater elements (Veerapaneni et al., 2007). A two-pass NF system has also been discovered to reduce the energy requirements by 12% while the hybrid system is capable of a 5% reduction (Long, 2008). Another design method is to locate the membrane desalination plant in conjunction with an existing coastal power station (Voutchkov, 2004). A lower feed pressure is then required by the RO plant due the higher temperature (5-15°C warmer) of the cooling water discharged from the power generation plant compared to seawater. This has the advantage of increasing the water production by 40-50% (Subramani et al., 2011). In addition, capital savings can be achieved by sharing a common intake facility.

With respect to energy, it has been noted that pumping is the primary consumer of electricity. In order to improve the pumping efficiency, it has been suggested that three procedures are implemented namely:

a. the verification of the efficiency of the pumping system,

b. the utilisation of a premium efficiency motor, and

c. the installation of a Variable Frequency Drive (VFD) into the motor (Manth et al., 2003). These have been shown to increase energy savings of a desalination plant (Subramani et al., 2011).

The permeability of membrane materials can be enhanced by reducing the feed pressure while maintaining the salt rejection rate. Features of advanced membranes include a greater surface area and denser packing which results in greater fresh water capacity per membrane element (Subramani et al., 2011). Such membranes can be categorized as nanotube, nanocomposite and biomimetic with comparisons between each type made in **Table 2.2**.

Table 2.2 Comparison of innovative material based membranes for RO (Subramani et al., 2011)

Membrane type	Principle	Energy consumption	Advantages	Drawbacks
Nanocomposite	Zeolite nanoparticles incorporated in polyamide matrix creating enhanced transport of water molecules.	20% lower energy consumption than conventional seawater RO (NanoH2O, 2010).	More than double the flux of currently available seawater RO membranes (NanoH2O, 2010).	Chemical compatibility and structural stability is not known. Rejection of specific contaminants is not known. Long-term operational data not available.
Nanotube	Transport of water molecules through structured carbon and boron nitride nanotubes.	30–50% lower energy consumption than conventional seawater RO (Hilder et al., 2009).	Ten – fold higher flux than currently available seawater RO membranes (Hilder et al., 2009).	Only modeling results available. Rejection of specific contaminants is not known.
Biomimetic	Aquaporins used to regulate transport of water molecules.	Energy consumption is not known.	Hundred times permeable than currently available seawater RO membranes (AquaZ, 2010).	Inability to withstand high operating pressures. Rejection of specific contaminants is not known. Long-term operational data not available.

Elimelech and Phillip (2011) have reviewed several innovative systems that could potentially reduce the energy demand of desalination. A recent design focuses on the development of a hybrid system which combines treated wastewater effluent with RO for dilution of the feed. Another emerging technology centres around the implementation of forward osmosis which uses a solution of a lower chemical potential then seawater to “draw” water across a semipermeable membrane (Elimelech & Phillip, 2011). Together with the utilisation of waste heat which is a by-product of power plants and other operations, forward osmosis has the potential to become economically viable. Another advantage of the process is the potential for reduced fouling due to utilisation of thin film composite membranes and lack of hydraulic pressure (Mi & Elimelech, 2010). Pilot plants studies are necessary to obtain operational data for wide scale implementation of this technology. An alternative process to desalinate seawater is ion concentration polarization where an electric potential acts as a membrane for separation (Subramani et al., 2011). It has been reported by Kim et al. (2010) that a 50% recovery with an energy consumption of 3.5 kWh/m^3 was achieved which is similar to desalination utilising RO membranes. Due to the absence of membranes, the evident advantage of this process is the lack of fouling. Currently, only results emanating from modelling and bench scale tests have been stated for this technology (Subramani et al., 2011). Another advancement for separation lies in capacitive deionization technology which involves the flow of a saline solution through a capacitor type module. This process has been utilised mainly for brackish water desalination with a reported energy consumption between 1.37 and 1.67 kWh/m^3 (Welgemoed, 2005). Despite the low feed water recovery, this developmental technology could be utilised for seawater desalination with the implementation of improved process control and advanced electrode materials (Oren, 2008).

2.3.5 Renewable Energy Utilisation

Another concern surrounding desalination is the negative environmental impact that could occur as the energy source for SWRO plants is mainly thermoelectric which results in additional emissions of air pollutants (Elimelech & Phillip, 2011). To minimise these releases, renewable energy sources could be utilised in conjunction with traditional power sources to feed energy into the national grids (Elimelech & Phillip, 2011). Solar energy has been touted as an encouraging source of energy and can be classified into thermal and electromechanical operations. The former uses solar thermal energy while the latter uses photovoltaic cells. After solar energy, wind energy is the most popular source of sustainable energy for small scale desalination plants (Kalagirou, 2005). With wind turbines now commercially available, the common operations for wind-powered desalination processes include coupling of the wind turbines with the desalination plant or connecting both desalination system and wind turbines to the electricity grid. In certain localities where wind and solar profiles differ, wind-solar combinations have been used for desalination purposes (Karellas, et al., 2011). Hybrid systems have been implemented in countries such as Italy, Oman and Mexico (Subramani et al., 2011).

Wave energy and hydrostatic pressure as driving forces for electricity generation in the near future have also been explored by Charcosset (2009). She reviews instances where renewable energy systems have been successfully implemented either as prototypes or small scale processes. In other cases, it has been demonstrated that the possibility of implementation exists through modelling and simulation exercises (Charcosset, 2009).

The selection of suitable sources depends on factors such as feed water salinity, the proposed size of the plant and accessibility of electricity from the grid. Furthermore, policy determinations, economic and social factors need to be viewed as drivers for implementation of renewable energy (Subramani et al., 2011). A comparison of the various renewable energy sources listing the advantages and disadvantages of each supply is summarised in **Table 2.3**.

Table 2.3 Advantages and Disadvantages of Various Renewable Energy Sources (Subramani et al., 2011)

Renewable energy resource	Application	Advantages	Disadvantages
Solar	Solar still: Direct conversion of saline to potable water. Solar pond: Utilization of salinity gradient to store heat and produce steam for electricity generation. Concentrated solar power: Hot fluid used in turbine generator for producing electricity. Photovoltaic cell: Conversion of sunlight directly into electricity to power RO desalination.	Simple process. Inexpensive material of construction can be utilized (Qiblawey and Banat, 2008). Beneficial use of desalination brine (Qiblawey, 2008). Same equipment used in conventional power plants can be used for concentrated solar power plants (DOE, 2010). Hybrid designs with other (wind) renewable energy sources are easily achievable. Well suited for desalination plants requiring electrical power (Eltawil et al., 2009).	Energy loss in the form of latent heat of condensation (Mathioulakis et al., 2007). Large land area requirement (Kalagirou, 2005). Capital cost intensive. Output is intermittent (Trieb et al., 2009). Large land area requirement. Capital cost intensive. Output is intermittent (Kalagirou, 2005).
Wind	Wind turbine: Wind energy used to generate electricity to power RO desalination.	Well suited for desalination plants requiring electrical power (Eltawil et al., 2009).	Output is intermittent. Resource is location dependant and unpredictable (Kalagirou, 2005).
Geothermal	Geothermal steam to generate electricity to power RO desalination.	Continuous power output, predictable resource, thermal storage is not necessary (Barbier, 2002; EGEC, 2010).	Resource is limited to certain locations (Kalagirou, 2005).

With water needs constantly rising, a careful integrated approach between the water and energy sector is required in order to manage the multiple inter-relationships between the two areas. Conventional energy sources such as oil, coal and gas have come under increasing pressure recently due to their consequences on human health as well as the environment (Akella et al., 2009). The use of renewable energy sources for the provision of water will address the need for both water and energy services in developing countries (Prasad et al., 2012). Considering the aspects of climate change and sustainability, alternative energy technologies are increasingly favoured to decrease the environmental effects linked to the treatment and reuse of water.

2.4 Background into Life Cycle Assessment (LCA)

The diversification and expansion of manufacturing activities has led to an increased awareness of sustainability. This sub-section starts with a discussion around the effects of industrialisation and the emergence of sustainable development over a period of time. Common environmental management techniques are thereafter listed with a special emphasis on Life Cycle Assessment (LCA) as the favoured 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.

2.4.1 Industrialisation and Environmental Consequences

The environmental difficulties that exist today have been created by the development of society since the advent of the industrial revolution. Industrialisation assisted in the achievement of various social aims such as employment, labour standards and access to healthcare and education (European Commission, 2006). However, industrial processes also had detrimental environmental impacts such as climate change, air and water pollution and deforestation. Providing food, shelter, clothing and other basic needs of the global population has led to periods of consumption and production that are unsustainable. In addition, all the resources that are harnessed eventually end up as a waste product at some point and in some form, either to the air, water or land. The accumulation of these materials has far exceeded the Earth's available resources and carrying capacity (Daily & Ehrlich, 1992). With the increasing problems of declining biodiversity, growing water scarcity and other unresolved environmental issues, it was clear that drastic intervention was required.

The industrial revolution represented a major turning point in the earth's ecology and altered the relationship between human beings and the environment. Significant characteristics of this era included improvements in transportation, rapid increase in the production of goods, sustained population growth and a great increase in energy use from the burning of fossil fuels (Brauch, 2016). The movement of citizens from farms and rural areas to urban centres contributed to the increase of gas emissions from power plants, industrial plants and motor vehicles. This, in turn, led to consequences such as the production of acid rain and the advent of global warming. These adverse effects led to the realisation that environment and development need to be considered together in order to ensure the continued survival of both humans and other living organisms in the long term (Brauch, 2016).

2.4.2 The Advent of Sustainable Development

2.4.2.1 Background and Development

Industrial processes play an important part in the degradation of the environment. The more developed a country's industrial capacity, the greater it's 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 (Centre for Environment Education, 2007). The concept of sustainability emerged more than 40 years ago from the mandate adopted by the International Union of Conservation and Nature (IUCN) in 1963 (Adams, 2006). This idea, which was a central theme of the United Nations Conference on the Human Environment in 1972 in Stockholm, was created to introduce the possibility of economic growth without environmental damage. From this point onwards, sustainable development thinking progressed through the World Conservation Strategy (1980), the Brundtland Report (1987) and the United Nations Conference on Environment and Development in Rio (1992) (Adams, 2006). Over these decades, the definition of sustainable development has evolved with the most commonly quoted definition emerging from the Brundtland Report (1987) 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 focused on 3 aspects namely environmental, social and economic sustainability. These were termed the three governing themes of sustainable development at the World Summit on Sustainable Development (WSSD) in 2002 in Johannesburg, South Africa (Fien, 2010). **Figure 2.5** shows a well-known model illustrating the 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.

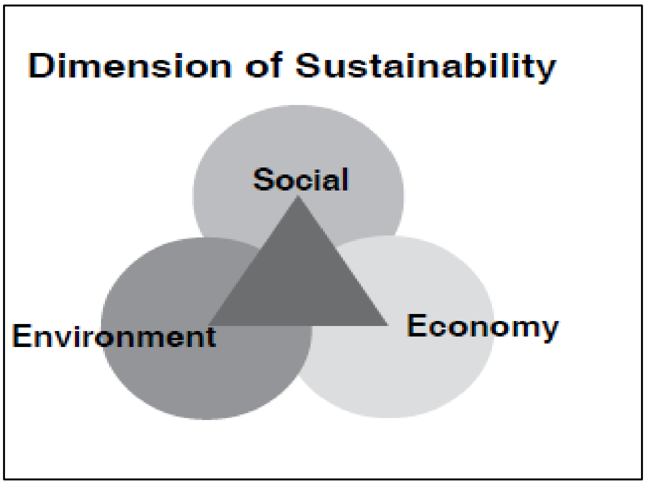


Figure 2.5 Visual Representation of Sustainable Development (Centre for Environment Education, 2007)

2.4.2.2 Tools to Achieve Sustainable Development

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 surrounding 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 the development of public awareness of significant environmental and social issues.

One of the significant themes of the Rio 2002 Conference focuses on the development of a green economy as a vital strategy to develop the relationship between the demands of the population on resources and the earth's diminishing capacity to replenish them. The United Nations Environment Programme (2012) states that a green economy is 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 investments, both private and public, are able to reduce carbon emissions, increase energy and resource efficiency and reduce the detrimental effects on the ecosystem while creating growth in income and employment (United Nations Environment Programme, 2012). To achieve this vision, society together with government need to formulate and implement strategies and supporting programmes.

The publication that emerged from 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, civil society and private sector) to guide the decision making process. A summary of common tools used in South Africa are listed in **Table 2.4** together with a brief description of each management technique and its reference in South African official documentation.

Table 2.4 Common Environmental Tools (Department of Environmental Affairs and Tourism , 2004a)

Environmental Tool	Brief Description	Reference in South African Documentation
Environmental Impact Assessment (EIA)	Aims to predict all environmental impacts of a project to find ways to reduce adverse impacts, shape projects to suit the local environment and present the predictions and options for decision making.	Information Series 13, Review in EIA (2004)
Life Cycle Assessment (LCA)	A tool for the evaluation of the environmental aspects of a product or service through all stages of its life cycle.	Information Series 9, Life Cycle Assessment (2004)
Environmental Auditing	This is a process whereby an organisation's environmental performance is tested against numerous requirements which are key performance indicators and legislated requirements.	Information Series 14, Environmental Auditing (2004)
Strategic Environmental Assessment (SEA)	It is becoming a common tool used to determine the environmental implications of decisions made at all levels.	Information Series 10, Strategic Environmental Assessment (2004)
Risk Assessment	Seeks to quantify the possibility and degree of an undesired effect. This procedure can be used in conjunction with the generic EIA procedure.	Information Series 6, Ecological Risk Assessment (2002)

2.4.3 Life Cycle Assessment as an Integrated Environmental Management Tool

2.4.3.1 Introduction

The increased awareness surrounding the issues of environmental protection and the potential impacts associated with the manufacture and consumption of products have prompted the need to develop techniques to understand and reduce such impacts. One such technique that is being more commonly utilised to achieve this purpose is that of the Life Cycle Assessment Tool (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 procurement through production, use, treatment, recycling and concluding with disposal (ISO, 2006a). Thus, an 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 certain phases. Other advantages of the LCA include the identification of relevant indicators of environmental performance. From a marketing perspective, a LCA could provide the substantiation required to state a claim based on environmental grounds or produce an environmental product declaration.

2.4.3.2 Historical Background to Life Cycle Assessment

The LCA as an environment management tool has its roots in the 1960's when concerns were raised regarding limitations of energy resources and raw materials. At the World Energy Conference in 1963, Harold Smith reported his calculation of energy needs 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 utilisation and production outputs in industrial processes. During this age, approximately a dozen studies were performed to estimate the costs and implications of using alternative energy sources.

In a landmark study in 1969, The Coca-Cola Company initiated a study to compare various 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 was identified as a Resource and Environmental Profile Analysis (REPA) or Ecobalance as it was termed in

Europe. Due to the oil shortages in the early 1970's as well as the formation of civil society groups encouraging industry to provide accurate information, approximately 15 REPA's were performed between 1970 and 1975.

From 1975 through to the early 1980's, interest in comprehensive environmental studies waned as a result of the diminishing influence of the oil crisis. It was not until the mid-eighties to early nineties that interest in LCAs was revitalised over a greater range of industries, retailers and design establishments (Jensen et al., 1997). In 1984, the Swiss Federal Laboratories for Materials Testing and Research (EMPA) published a report that contained a list of data required for LCA studies that also contributed towards the broader applications of LCAs.

In 1991, concerns over the unsuitable utilisation of LCA's for marketing purposes led to the issuing of a statement by 11 State Attorney Generals in the United States of America denouncing the use of LCA results unless uniform methods were developed (Curran, 2006). It was this action, together with pressure from other environmental bodies to provide a standardised methodology that led to the development of LCA standards in the International Standards Organisation (ISO) 14000 series which dates back from 1997. Another organisation of note is the Society of Environmental Toxicology and Chemistry (SETAC) which, through its European and American branches, started playing a leading role in the collaboration of LCA practitioners, users and scientists on the continuous improvement and coordination 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 standardization methods which led to the 1990's 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 the United Nations Environment Programme (UNEP). The 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) programme created awareness and improved skills of decision makers by producing informative material, establishing forums for sharing best practise 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 (Curran, 2006). The Life Cycle Impact Assessment (LCIA) program aimed to increase the quality and reach of life cycle indicators by promoting the exchange of views of 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 of life cycle data and methods to support reliable decision making (Jensen et al., 1997). It was during this period that environmental policy became increasingly life-cycle orientated 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.

2.4.3.3 Overview of the methodology of Life Cycle Assessment

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 (2006)

ISO 14041 - Life Cycle Inventory Analysis (1998)

ISO 14042 - Life Cycle Impact Assessment (2000)

ISO 14043 – Life Cycle Interpretation (2000)

ISO 14044 – Life Cycle Assessment – Requirements and Guidelines (2006)

According to the ISO 14040 (2006), the LCA process is a systematic approach which consists of four major components as illustrated in **Figure 2.6**. A brief description of each of the phases will follow noting that a LCA is generally an iterative process as stages are often repeated as more information is gathered.

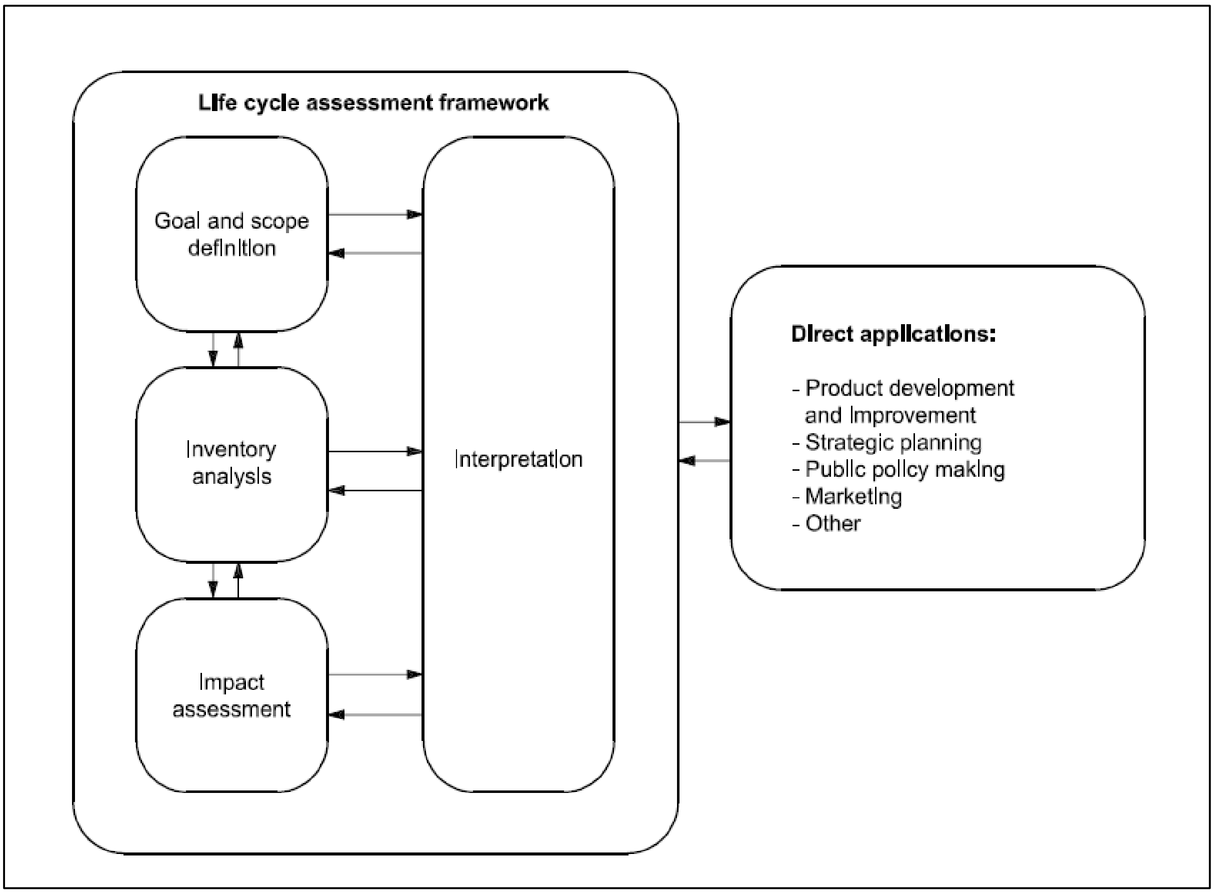


Figure 2.6 Life Cycle Assessment Framework - Stages of a Life Cycle Assessment (ISO, 2006a)

2.4.3.3.1 Goal Definition and Scoping

This is the initial phase of a LCA study and forms the basis of the assessment. In determining the actual goal of the LCA, the purpose and intended application of the assessment should be clearly specified. Furthermore, the initiator of the study together with the intended audience should also be stated (Heijungs, 1992). Jensen et al. (1997) comment that the goal definition is susceptible to change as a result of the findings during 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 the 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, 2006a). 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, various flows, life cycle stages and unit processes need to be taken into account as depicted in **Figure 2.7**. As in the case of the goal definition, the system boundary that was initially defined may need to be refined as the study progresses.

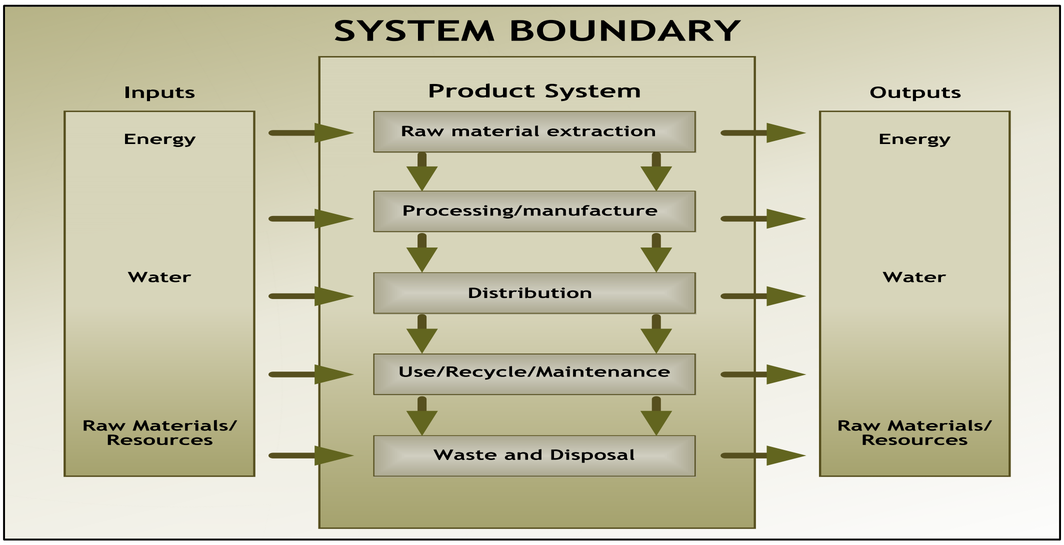


Figure 2.7 Components within a system boundary (Department of Environmental Affairs and Tourism, 2004)

2.4.3.3.2 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, 2006a).

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 recycle. **Figure 2.8** 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 provide an outline of all the relevant unit processes together with a list of flows and relevant data for operating conditions. 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, 2006a). The inventory analysis process 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 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 discharges identified in the inventory phase are evaluated.

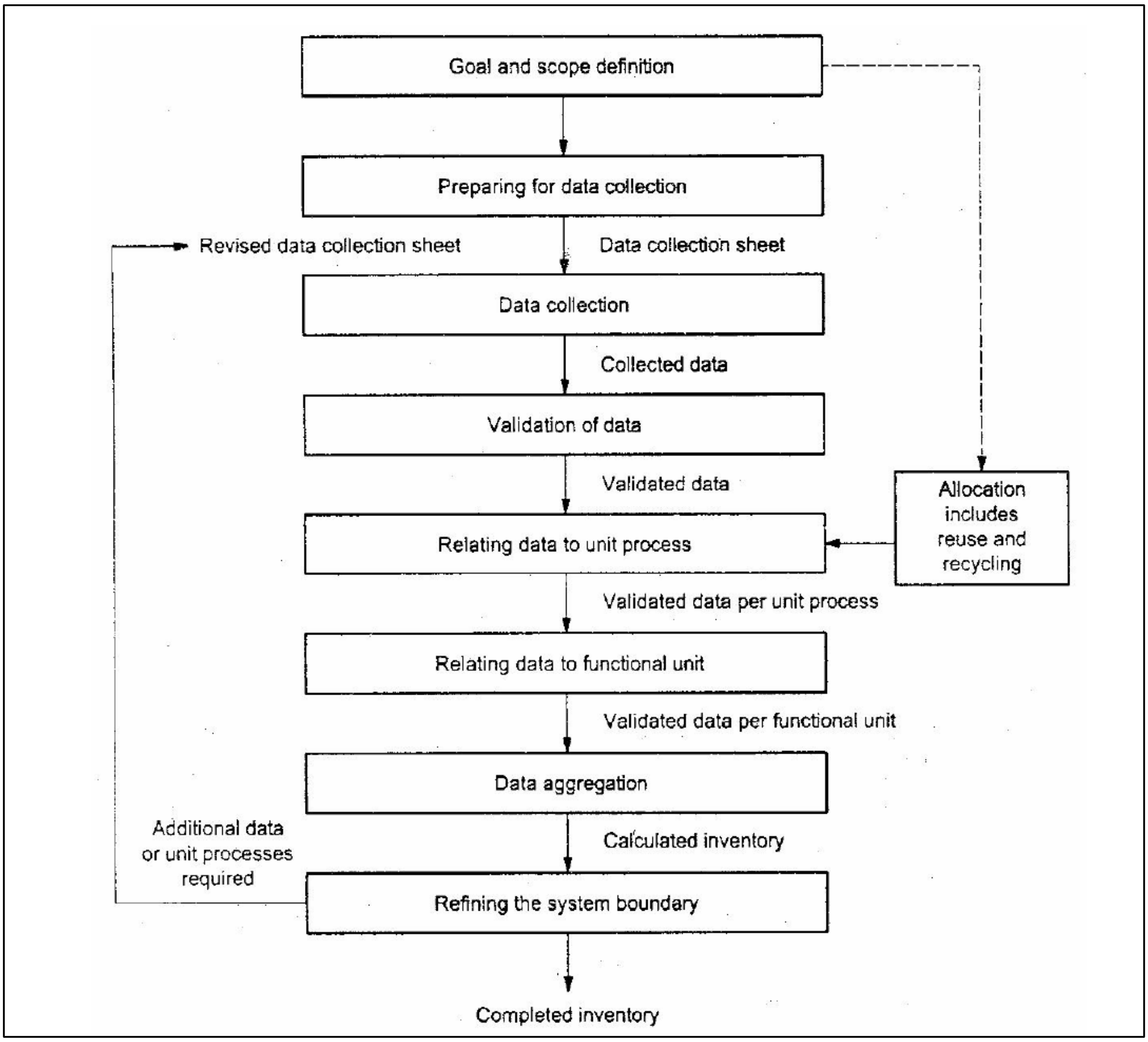


Figure 2.8 Basic procedure for Life Cycle Inventory Assessment (ISO, 2006b)

2.4.3.3.3 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 abridge 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 methods.

Figure 2.9 provides a graphical representation of the various elements. 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.

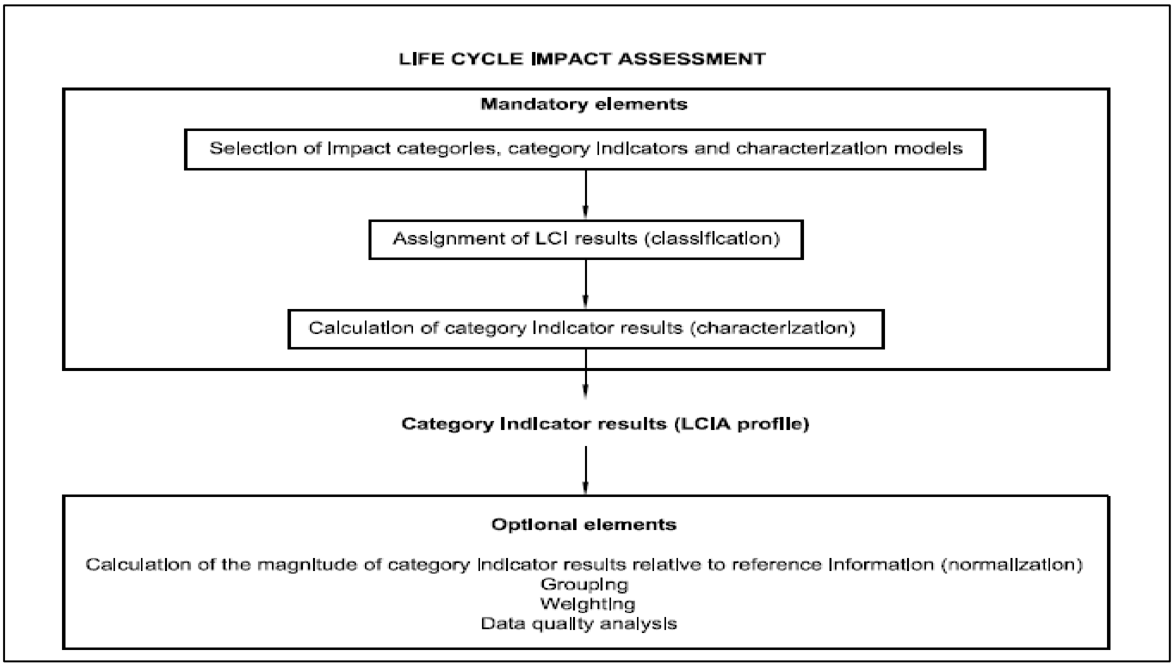


Figure 2.9 Elements of a LCIA (ISO, 2000a)

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

The first stage 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, flora and fauna or the availability of natural resources (Curran, 2006). Generally LCIAs focus on the potential impact to three major categories: human health, ecological health and resource depletion. **Table A1.1** in Appendix A lists a few common impact categories. In the majority of cases, existing impact categories, category indicators or characterisation models are chosen. 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 are a number of software on the market to complete this step. SimaPro contains many standard impact assessment methods where each method contains a number of impact categories (usually 10-20).

b. **Assignment of Life Cycle Inventory Assessment results (Classification)**

Classification is a qualitative step based on the 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 category. However, for elements that contribute to more than one category, the procedure is dictated by the ISO 14042 (2000) guidelines which states that there are two ways of allocating LCI results to several 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 that of 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 generally allowed when the effects are independent of each other. An example if that of 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) impacts, regional and local impacts. To date, there has not been any consensus reached regarding a single, standard list of impact categories. **Table A1.2** provides a number of suggestions for lists of impact categories with reference to the scale in which they are valid.

c. Calculation of Category Indicator Results (Characterisation)

Characterisation utilises science-based conversion factors, which are termed characterisation factors, to convert and combine LCI results into indicators of impacts that are representative of both humans 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, 2000a). Thus, Curran (2006) summarises that the process of characterisation provides 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 into impact indicators. This is typically calculated using the following equation:

$$\text{Impact Indicators} = \text{Inventory data} \times \text{Characterisation Factor} \qquad (2.1)$$

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

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 (Curran, 2006). 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 this where caution must be exercised is in the utilisation of European characterisation factors to American data.

d. **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 the 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 particular area which may be local, regional or global, the total emissions for an 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.

e. **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.

f. **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 (Curran, 2006). 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 various weighting factors and methods followed by a sensitivity analysis to assess the consequence on the LCIA results from the different choices.

2.4.3.3.4 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, 2000b).

Interpretation is performed in collaboration with the preceding phases of a LCA. In the event that the results of the inventory analysis or 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) advised that it is imperative to draw conclusions and provide recommendations based only on the facts. She adds that the communications of uncertainties and limitations should also be viewed as significant to the final report as such inclusions will enable the compilation of a comprehensive report containing all the necessary elements.

2.4.3.4 Strengths and Weaknesses of Life Cycle Assessment

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

2.4.3.4.1 Strengths

The LCA was developed in light of the 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 (Thorn et al., 2011). This characteristic differentiates the LCA from other assessment methods and goes beyond the scope of an Environmental Impact Assessment (EIA). Curran (2014) comments that without life cycle thinking, practitioners run the risk of focussing 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 data identifies the transfer of environmental impacts from one medium to another (e.g.

eliminating air emissions by creating a wastewater reject stream) or from one life stage to another (from use and reuse of the product to the raw material procurement stage). By including all the impacts at each life cycle stage, the LCA provides a true reflection of the potential environmental trade-offs in product and process selection (Curran, 2006). 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 database sets 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 utilising these and other standards, even criteria are developed which enables effective analysis and comparison (Department of Environmental Affairs and Tourism, 2004).

2.4.3.4.2 Weaknesses

Life Cycle Assessment is one of several environmental management techniques that can be utilised to evaluate 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 , 2013). While recognising the benefits of LCA, there are some limitations to LCA that cannot be ignored. For one, LCA traditionally only focuses on the environmental impacts with the social and economic impacts not being addressed. Thus, an environmental LCA combined with the results of another analysis e.g. an economic analysis, could 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, 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 practitioners alike.

Europe has been at the forefront of compiling LCI databases with Plastics Europe being one of the initial organizations to gather data on energy usage for plastics manufacturing (Rebitzer et al., 2004). Thus, the majority of default data originates from Europe. This can cause difficulties in the case of products manufactured in other parts of the world with older utility infrastructures such as South Africa (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 , 2013). In addition, these databases have been criticized for being inaccurate. Researchers have attempted to address the accuracy issue with the database ecoinvent offering data on individual technological processes. The Society of Environmental Toxicology and Chemistry (SETAC) is also collecting data on individual processes (raw materials, electricity and transportation) in an attempt to individualize LCA (Thorn et al., 2011). The large aggregated databases have also been criticized for outdated data. An example of this is the use of 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 which could ultimately contribute to unreliable environmental scores.

The broad scale practise of LCA is limited by both cost and time constraints with small companies unlikely to be able to afford to specialize in LCA or 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 databases. 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).

2.4.3.5 Applications of LCA

The principle of life cycle thinking implies that everyone associated with the 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) states that there are essentially 4 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 motivations 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 4 major applications namely (Jensen et al., 1997):

- internal use by industry for the purposes of product development and improvement,
- strategic planning and policy making in industrial settings,
- external use by industry for marketing, and
- governmental policy decision making in the fields of ecolabelling, green procurement and waste management prospects.

A LCA should always be holistically based in the sense that all inputs and outputs must be examined. However, there are varying levels of sophistication required for different applications. Jensen et al. (1997) presents 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 the detailed LCA, very few have been published.

2.4.3.5.1 Conceptual Life Cycle Assessment – Life Cycle Thinking

As the name suggests, the 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 the results. However, it can assist decision makers for the purposes of comparison between different products.

2.4.3.5.2 Simplified Life Cycle Assessment

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 simplified or omitted 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 the 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 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 the conceptual LCA in order to increase the representativeness of the results. (Gyetvai, 2012b).

Communication of the results for 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, 2012b). 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).

2.4.3.5.3 Detailed Life Cycle Assessment

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, 2012a).

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 an LCA e.g. neglecting minor components in a product. To ensure the accuracy of this form of study, the recommendations of the International Reference Life Cycle Data System (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, 2012a). **Table 2.5** provides an indication of the level of detail required in a few applications of LCA.

Table 2.5 Level of Detail in Various Applications of LCA. The "X" indicates the level that is most frequently used (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

2.4.3.6 <u>Position of Life Cycle Assessment in South Africa</u>

The LCA approach provides a systematic method to anticipate environmental problems and their potential solutions throughout the entire product life cycle. This approach is in line with South African environmental policy which advocates the adoption of cautious approach to development. The policy position is determined 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 sake of current and future generations (Ampofo-Anti, 2008).

South Africa was one of the first developing countries to utilise 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, 2004). Examples of LCA applications in the 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). Buckley et al. (2011) provided a review of LCAs undertaken within the South African water sector by summarising the various studies undertaken and highlighting the significant findings.

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 environmental impact assessment methodologies that are generally used have all originated in Europe thus decreasing their accuracy to predict conditions in South Africa. Another factor of note is the lack of regional and local characterisation factors that are developed for South African conditions (Brent, 2004). It was also discovered that environmental impacts due to land usage and water consumption are critical in the South African context but are only partially addressed by some of the European methods. Despite these limitations, the LCA has the capacity to contribute substantially particularly against the backdrop of the government's commitment to sustainable development. The National Cleaner Production Centre in South Africa (NCPC-SA) is a member of the United Nations Environmental Project (UNEP's) global resource efficiency and cleaner production network (National Cleaner Production Centre - South Africa, 2014). Their partnership aims to incorporate sustainability and eco-innovation based on life cycle thinking. As the NCPC-SA is an implementer of UNEP's life cycle management thinking, the organisation provides a framework to analyse, compare and disclose the environmental performance of products and processes that utilise freshwater (Raphulu, 2015). This assists with the identification of opportunities to improve water use during the production and manufacturing operations.

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 Life Cycle Assessment for Water Systems

The use of LCA as an assessment tool to gauge the environmental impacts of water technology has been increasingly used since the late 1990's. The earlier LCA's focussed on parts of the urban water system namely Waste Water Treatment (WWT) and Drinking Water Production (DWP). Since 2005, the number of case studies have 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 sections provide information regarding significant results found in case studies and highlight common problems encountered during the course of such studies.

2.5.1 Review of Case Studies

In order to compile a comprehensive inventory 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 source water, the construction material, chemicals and energy used for each operational element during construction, operation, decommissioning of process units and disposal of wastes (He et al., 2013).

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 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. Upon analysis of the construction phase, a difference in results was discovered with the former showing 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 focussing 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. These 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 emphasised by Ampofo-Anti's (2008) report which is based on the findings of LCA's conducted on the most commonly utilised construction materials and found 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 and Vince et al., 2008). He et al. (2013) in their study compared the energy consumed during operation of 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 significance of electricity usage 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 decreased with the use of 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 & Conway's (2011) review of energy use in the water sector, it was found that limited accessibility of water resources can greatly increase the energy use for supply, transport, and in the case of desalination, treatment of water. However, there can be serious shortcomings in comparing the results of various studies as most of the 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) notes that an appropriate inventory should be provided with water flows within the technosphere, water withdrawn and released to the local and 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 (Loubet et al., 2014).

One of the challenges of desalination is the disposal of the concentrated brine solution. Peters and Rouse (2005) aimed to assess the impact of such saline 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 situations were compared: brackish water reverse osmosis (BWRO), sea water reverse osmosis (SWRO) and water transfer from a river. Seawater Reverse Osmosis was shown to be the worst solution for the consideration of all impacts while BWRO and water transfer scenarios had comparable scores for electricity consumption.

With current focus on the environment, one of the major impacts that generate great interest is the impact of the process on climate change. Loubet et al. (2014) notes that the papers 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 as well as other environmental 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 greenhouse gases (Loubet et al., 2014).

2.5.2 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 methods (Eco-indicator 99, CML etc.). As a result, comparison of results on a common basis is unfeasible 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 choice of technologies 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) recommends 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 treatment industry is at a strategic level with the aim of providing a framework for GHG emissions and water footprint assessments. He et al. (2013) notes that it is quite rare for material and consumable data to be documented in detail. In particular, Landu (2005) found gaps of information for 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 database, a challenge exists regarding the location of equipment, processes and chemicals that are commonly used in the water industry. He et al. (2013) noted that such components are excluded from existing databases thus creating a barrier for 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 was noted by He et al. (2013) that certain components such as mixers, scrapers and flocculators are excluded. With respect to chemicals, the literature also reveals that a gap 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 (He et al., 2013).

2.6 Conclusion

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 the national rainfall patterns and temperatures. There are many strategies that have been put in place by the various departments to alleviate the situation. Two of the main technological developments that make use of membrane processes and which will be discussed in greater detail in **Chapter 3** are desalination and mine water 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. The LCA methodology enables the calculation of environmental impacts 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. Internationally and within South Africa, the use of LCA is increasing with a few studies undertaken. However, there is a need to investigate the environmental impacts of water treatment processes that utilise membrane technologies in the local context. This paper aims to satisfy this need by investigating the environmental burdens associated with membrane-based treatment processes that use alternative feed sources such as seawater and mine affected water in South Africa. As such, it is the first LCA study investigating the treatment of seawater and mine affected water by using membranes in South Africa.

CHAPTER 3: CASE STUDIES

3.1 Introduction

This chapter presents details regarding the various water treatment technologies utilised in the two case studies. The first case study centred around a proposed desalination plant in the Southern eThekwini area that makes use of RO technology. The second case study focused on a mine water reclamation process in Mpumalanga that was designed using both UF and RO.

3.2 The Desalination Plant in eThekwini Municipality

A graph presenting the water balance for the South Coast Water Supply System (WSS) 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 (SCA). 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, the implementation of either a desalination plant or the Lower uMkhomazi Bulk Water Supply Scheme is necessary.

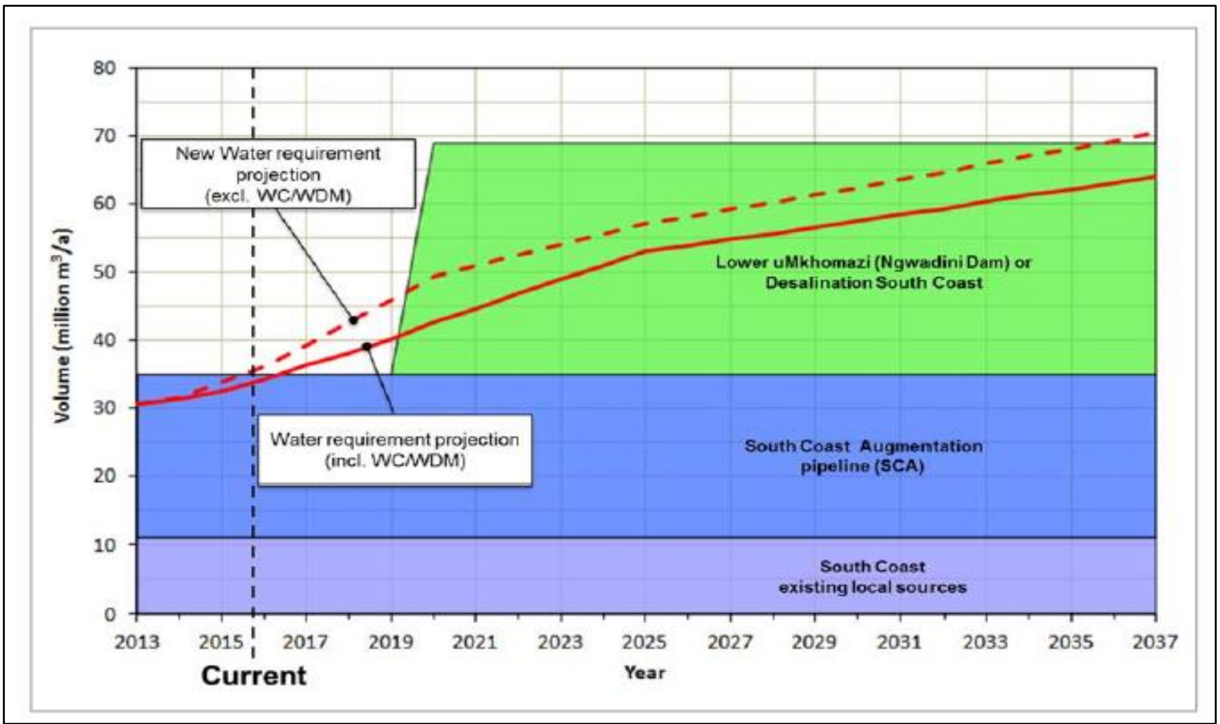


Figure 3.1 South Coast Water Balance (Department of Water and Sanitation, 2015)

To determine the feasibility of constructing a large scale desalination plant, an investigation by Umgeni Water was initiated by undertaking a desalination pre-feasibility study. The ultimate capacity of this plant was set at 450 Mℓ/d and would be servicing 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 an 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 and 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. 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 Umgeni 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 re-mineralization and disinfection,
- water storage tanks and pump stations, and
- electrical substations connected to power grid.

A diagram of the desalination process highlighting the key components are presented in **Figure 3.2**. The feed water will flow from an open ocean intake through initial screening before entering a two stage Gravity Granular Media Filter. The permeate then gets pumped by the 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 will be equipped with diffusers.

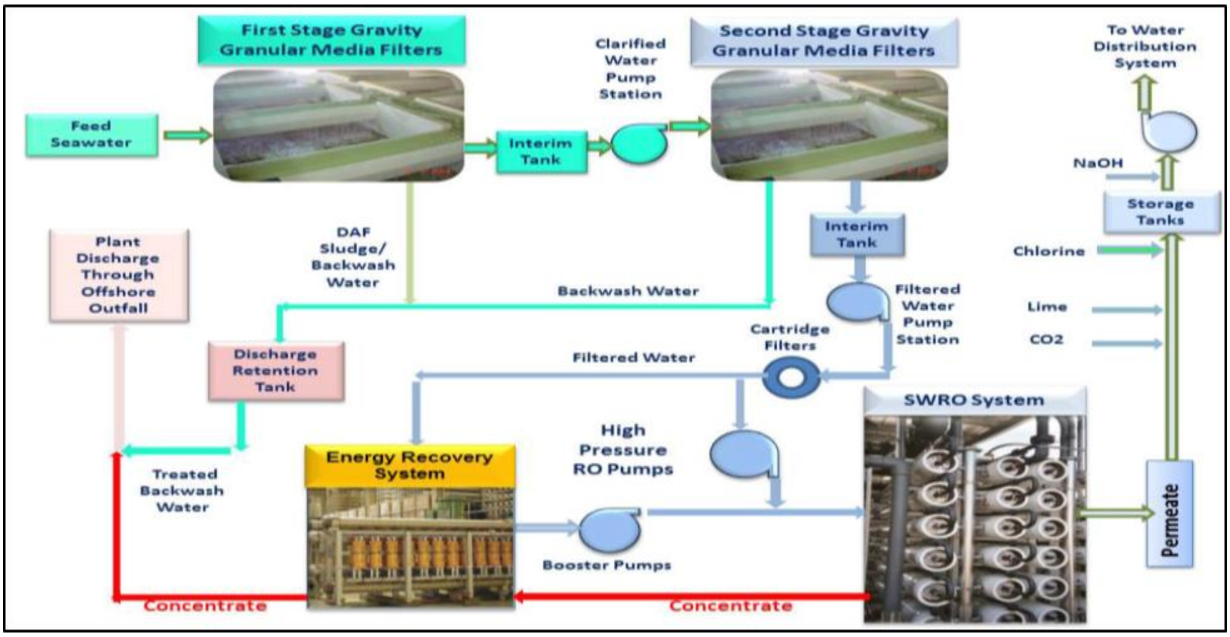


Figure 3.2 The Proposed Desalination Process (Umgeni Water, 2015a)

The aim of the pre-treatment process is to provide pre-treated seawater of a specified quality and quantity that is necessary for membrane desalination. In addition, the pre-treatment system would increase the useful life of the RO membrane elements as well as satisfy the customary performance warranties (Umgeni Water, 2015a). It is recommended that the RO system consists of 16 SWRO trains with one high pressure feed pump. This system must be designed to meet the specified product water quality and possess a certain degree of flexibility to accommodate potential increase in production or future changes in membrane technology (Umgeni Water, 2015a). Approximately 40 – 50 % of the energy requirements for desalination is 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 5 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 for the treatment of seawater are to be arranged in parallel modular units (e.g. RO membrane trains) to enable independent operation if necessary (Umgeni Water, 2015a). In particular, 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 meter per hour when the plant is operated at an average production rate of 150 Mℓ/d (Umgeni Water, 2015a).

3.3 The Mine Water Reclamation Plant in Mpumalanga

Various coal mines in Gauteng and Mpumalanga have been in existence 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 Environmental Impact Assessment (EIA) was undertaken prior to the commencement of the project in order to assess both positive and negative impacts as well as to propose potential mitigation measures.

It was proposed that the project will involve the construction and operation of the 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 of a raw water pond, pre-treatment and UF facilities as well as a two stage RO system. It was envisaged that the project will be carried out in three phases with the aim of abstracting and treating a total of 45 Mℓ/d. At this stage, 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.

Figure 3.3 is a simplified depiction of the mine water reclamation process. The mine affected water is pumped through Deep Bed Up-Flow (DUP) filters and treated with the addition of several chemical compounds (Prentec, 2013). 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. At present, 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 the 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 of three banks of membrane elements with a higher feed pressure then the first stage (Prentec, 2013). Special focus is reserved to achieve a balanced flux across all elements in the array together with a regular permeate flush.

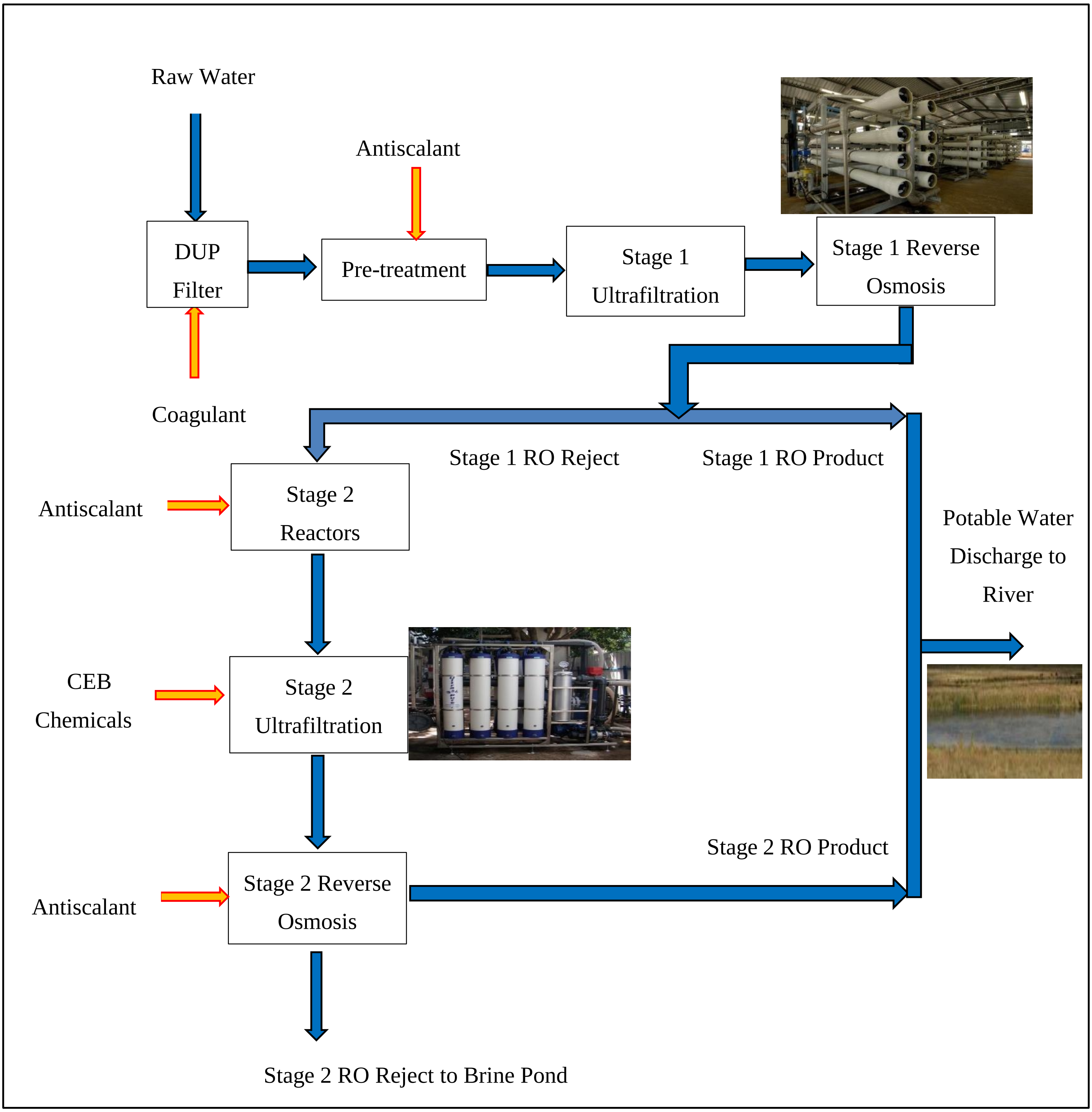


Figure 3.3 Process Flow Diagram Depicting the Mine Water Reclamation Process (adapted from Prentec, 2013)

CHAPTER 4: METHODOLOGY

4.1 Introduction

This chapter aims to provide a detailed account of the research process followed in this study. The project commenced with a thorough literature review to obtain background facts and figures along with the definition of concepts. This was followed by discussing two Life Cycle Assessment (LCA) software packages that are commonly used for the examination of water systems in particular. Once these subchapters have been covered, the various stages that encompass a LCA were elaborated upon with an in-depth analysis provided for each of the four phases. The methodology followed for this study is in accordance with the guidelines laid out in the ISO 14000 series of documentation for LCAs.

4.2 Literature Review

The literature review was undertaken to gain background information regarding four focus areas that were considered pertinent for the purposes of this study. The first part of the study centred around the water situation in South Africa. Details were provided regarding the available national supply of water as well as the current and forecasted growth. In order to counteract the growing need for water, various strategies are implemented which were elaborated upon. The second part of the review provides details regarding the use of membrane processes in water treatment. The different membranes are detailed together with common limitations experienced. Potential solutions sourced from literature articles are mentioned. The next section provides an introduction to LCA as an environmental management tool in response to the advent of sustainable development. The sub-section continues by highlighting the general structure of a LCA as well as the popular applications of the technique. The chapter concludes by focussing on the specific application of the LCA for various water system. A number of case studies were reviewed which provided a window into the application and expected results of such projects. Common limitations that occurred within the course of these studies were also mentioned.

The water situation in South Africa is outlined in several official documents such as the National Water Resource Strategy Document issued in 2013 and the South African Environment Outlook published in 2012. Reports of this nature are released by government departments such as Department of Water Affairs and Sanitation and Department of

Environmental Affairs and Tourism which also provide potential strategies to balance demand and supply of water.

The emergence of the theme of sustainable development as well as the introduction of LCA as a viable management tool was mentioned and elaborated upon in policy papers and documents presented by the World Conservation Union and United Nations Environment Programme amongst other organisations. The methodology of conducting a LCA is documented primarily in the ISO 14000 series (ISO 14040 – 14044) which details the major components of any LCA study. This was supplemented by guides circulated by the European Environment Agency, The Centre of Environmental Science in Leiden and the National Risk Management Research Laboratory in Ohio.

Regarding the application of LCA for water systems, information on literature sources was gathered from various databases such as ScienceDirect, SpringerLink, Scopus and ResearchGate. Conference proceedings and peer-reviewed journal articles provided an overview of the significant findings that emerged from other international case studies in the field of water treatment. Keywords utilised in the search include the terms life cycle assessment, desalination, mine water treatment and water treatment to mention a few. Articles were selected based on the number of citations, date of publication as well as relevance to the research theme.

4.3 Common Life Cycle Assessment tools

A wide variety of tools and modelling packages are available to assist in conducting a LCA. However, most of these programmes were developed to assess the environmental effects associated with the production of industrial products. Very few of these have been utilised in the fields of municipal water and wastewater (He et al., 2013). The tools that are most widely used for these purposes include GaBi and SimaPro. Both tools contain extensive databases and allow users to compare the environmental impacts arising from various situations (He et al., 2013).

4.3.1 GaBi Life Cycle Assessment Software

GaBi is a software package developed in Europe by PE International (now called thinkstep). With its first release in 1993, the programme is designed to fulfil numerous objectives such as the carrying out of LCAs, energy efficiency analysis and sustainability reporting. Menke et al. (1996) conducted a review of available LCA tools and found that the database within GaBi contained 800 different energy and material flows together with 400 specific industrial processes. The 10 process types in the database include industrial processes, transportation and mining processes. The development of a system can occur by making use of the graphic plan window of the program (Menke et al., 1996). Sub-processes within a particular system can be developed and then combined at a later stage. It was discovered that monetary, ecological and technical assessments are possible (Menke et al., 1996). In addition, weighting keys for the valuation criteria allow the user to input their individual preferences for specific results. In terms of outputs, a few balance sheets are available within the software such as mass and energy balances. These summary sheets can also be customised according to user specifications. GaBi has been used by studies such as the one carried out by Vince et al. (2008) to perform LCAs with the aim of comparing different potable water supply systems.

4.3.2 SimaPro Life Cycle Assessment Software

SimaPro is a commercial LCA software developed by PRé Consultants based in the Netherlands and adheres to the ISO standards. It contains various databases which in themselves comprise of various libraries. These libraries contain data for the most common materials and processes such as metal and steel production, electricity production and transportation processes. One of the most recognised series of libraries is the ecoinvent database which comprises over 10 300 inventory datasets in various sectors such as bulk and speciality chemicals, energy supply and construction materials (ecoinvent, 2015). Menke et al. (1996) concluded in their review that SimaPro has several elements that support its extensive usage as both a LCA management tool and for product development. Unique attributes of the software include the ability to link database entries as well as access to numeric and visual indications of impacts for each material and process in the life cycle (Menke et al., 1996). Compared to other LCA software packages, the database on processes that describes production of commodity materials was found to be more comprehensive (Menke et al., 1996). In the case of LCAs focussing on wastewater supply and treatment technologies, SimaPro has been successfully utilised as stated in the studies of Ortiz et al. (2007) and Lassaux et al. (2007).

SimaPro has been updated as time progresses and is available in various professional and educational versions. For this study, the '8.1.1.16 PhD' version was utilised which contains the latest update of ecoinvent data namely ecoinvent v3. This version includes the addition of over 80 new chemicals as well as updated cement datasets. In addition, the data for transportation is now systematically included in the market processes (PRé Consultants, 2013). Another feature that was particularly relevant to this particular study was the inclusion of new electricity mixes for certain countries such as South Africa. Such LCI data incorporated country-specific market activities which takes into account the domestic production mix as well as the imports from neighbouring countries (Paul Scherrer Institute, 2012). Another feature unique to SimaPro is related to the presentation of results. In the graphical mode, two views are possible where one shows the results as a bar chart according to impact categories while the other view displays a flow diagram. In South Africa, local software support for SimaPro is available from The Green House in Cape Town. It is for the reasons mentioned above that SimaPro was selected as the LCA tool for this study.

Table 4.1 summarizes the common databases and LCIA methods used in both packages. Both GaBi and SimaPro contain several assessment methods that allow the life cycle assessment of complex processes. The modelling packages contain various European and American impact analysis models.

Table 4.1 Databases and Impact Assessment Methods Used in SimaPro and GaBi (He et al., 2013)

	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

4.4 Goal and Scope Definition

As the initial stage of the LCA process, defining the goal and scope of the study forms the framework of the study. Generally, this phase provides details regarding the purpose and application of the study as well as the recipients of the final results (ISO, 2006a). Additional information such as the fixing of system boundaries and selection of the functional unit are also stated.

4.4.1 Defining the Goal

As presented in Chapter 1, the main objective of this study is 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.

The reasons for carrying out this study are varied, with the overarching motive being the generation of environmentally relevant data for each of the studied processes. By highlighting the environmental consequences of design decisions, the results could influence and ultimately guide future project plans for major water treatment plants.

4.4.2 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, and data requirements and assumptions and limitations made during the course of the study.

The systems under consideration are the two 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, 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 4.1** depicts the stages in the LCA with the black box depicting the system boundary.

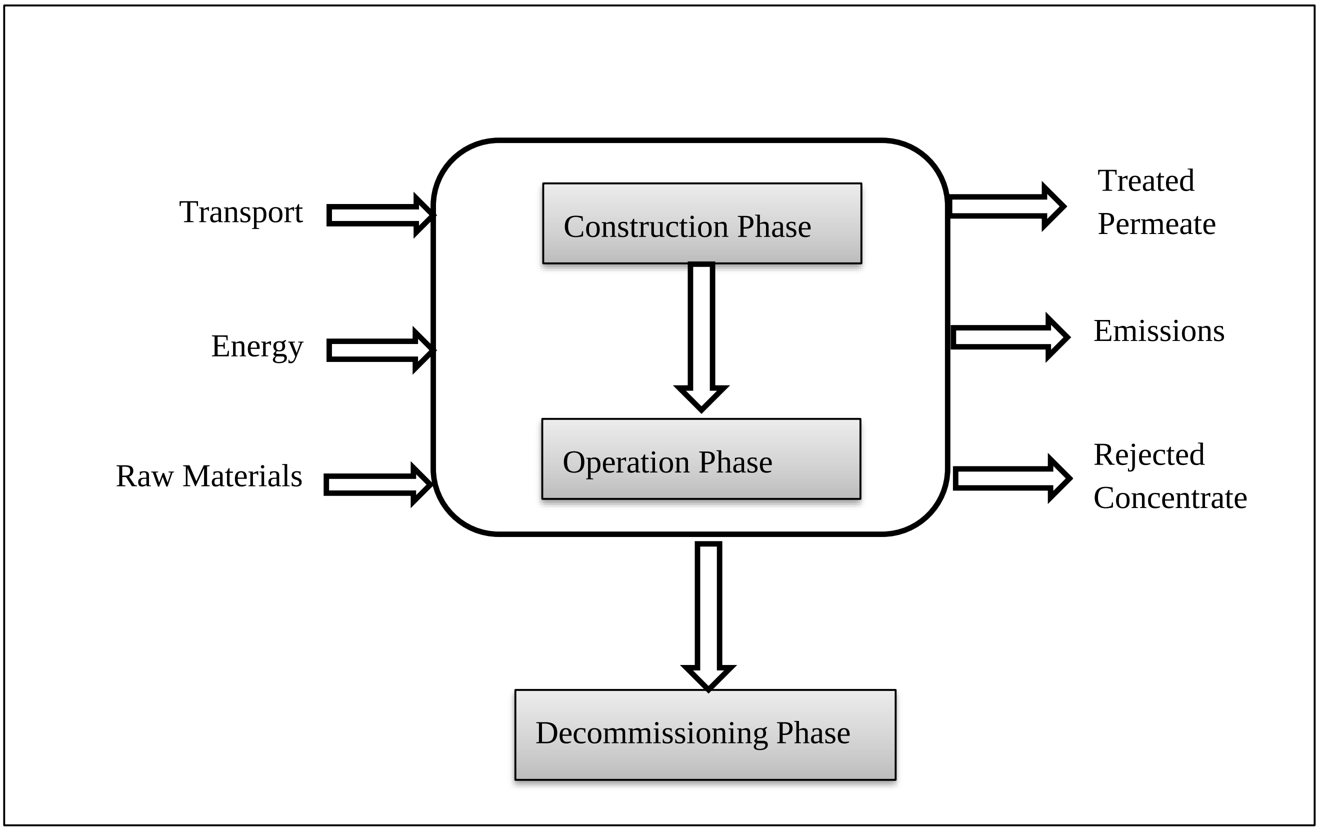


Figure 4.1 LCA Stages for Both Processes

The function for both 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 as well as providing the basis for comparison between the two processes.

Allocation continues to be a highly contentious issue in LCA circles. There is 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. However, the 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 for the study and thus affect the reliability of the results. For both case studies, 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 purposes of the study. Decisions regarding materials of construction as well as 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 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 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 that was encountered was that data was considered to be confidential and thus was not easily accessible. This was the case for both 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 in part 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 inputs 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 will perform in a similar manner to what is used in South Africa. Where the material of construction was unspecified for components such as the filter cells, various literature sources were perused and the most common materials were selected for the purpose of calculation. In other instances, super duplex stainless steel was chosen as the construction material of choice for any equipment that is in contact with the ocean water. Another assumption that was necessary, related to the working life of certain mechanical machinery such as pumps, which were assumed to function for 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 and the Water Research Commission of South Africa.

4.5 Inventory Analysis

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

4.5.1 Data Collection for the Desalination Plant

The procedure for data collection started off with a compilation of a process flow diagram (PFD) 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.

4.5.1.1 <u>Obtaining Data for the Construction Phase</u>

For the construction phase, four major components were analysed namely civil engineering structures, pipes, pumps, filters and membranes as in **Figure 4.2**. Civil engineering structures consisted of fixtures such as tanks, pillars and filter cells. The weight of these constituents were generally not stated and had to be calculated based on available dimensions provided in the feasibility reports. In the event that the material of construction 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 were calculated by firstly calculating volume of a hollow cylinder (which represents a pipe) using the inside and outside diameters, subtracting the volume of the inner from the outer and using the density to obtain the mass. The second method used a HDPE pipe brochure to obtain the mass 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.

Pumps are a fundamental part of the infrastructure of any plant and the design for the proposed desalination plant was no different. It was evident from the feasibility report that pumps were utilised in every stage of the desalination process with different types and positions. For the intake pumps, options were provided for various pump models in the above-mentioned report that detailed pipe specifications (Umgeni Water, 2015b). The mass was then obtained from 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. The masses of the respective pumps were taken as a single entity inclusive of parts such as motors, gears, bearings, casings etc. This was due to difficulty experienced in obtaining these figures. The Feasibility 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.

Once each unit operation was modelled in SimaPro, it became evident that the construction elements were of secondary significance to that of the operational factors. This was signified by the fact that the majority of the environmental burden was as a result of the operations phase. Thus, further detailed analysis and additional lengthy correspondence with the consulting company was not pursued.

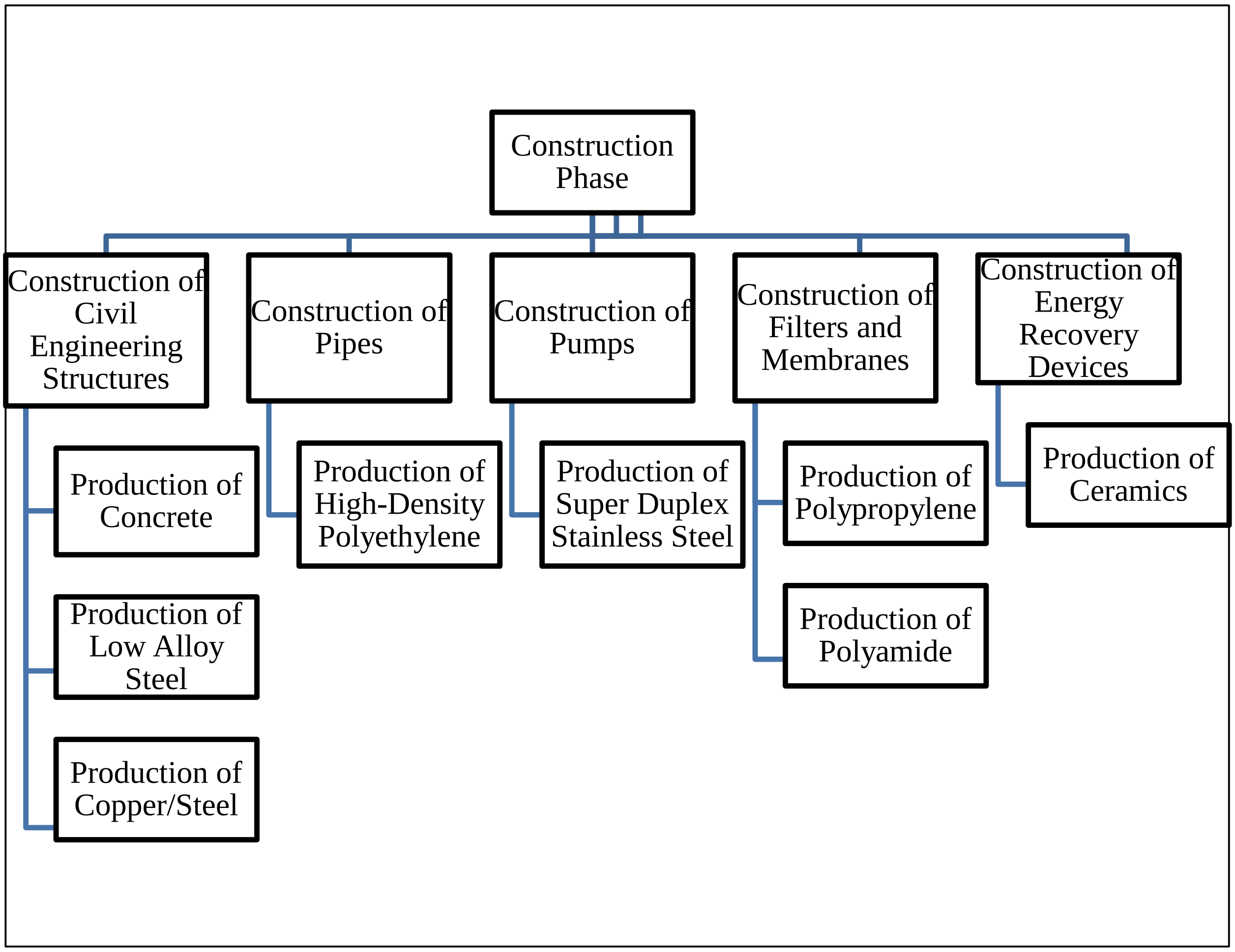


Figure 4.2 Components of the Construction Phase for Desalination

4.5.1.2 <u>Obtaining Data for the Operation Phase</u>

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 4.3**. There are a range of chemicals used in the production process with the majority being used in the pre-treatment and post-treatment phase. Chemicals were used for various purposes namely disinfection, RO membrane cleaning, chlorination and re-mineralisation. The utilisation of chemicals were 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 4.2** provides a summary of the chemical usage for the desalination process. The first and second column lists the chemicals mentioned in the Umgeni Water report as well as the unit operation. The last column states the chemical that was utilised in SimaPro based on technical literature.

Table 4.2 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 of 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.

The filtration step forms part of the pre-treatment phase to protect the RO membranes further on in the process. As mentioned in **Section 3.3**, 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.

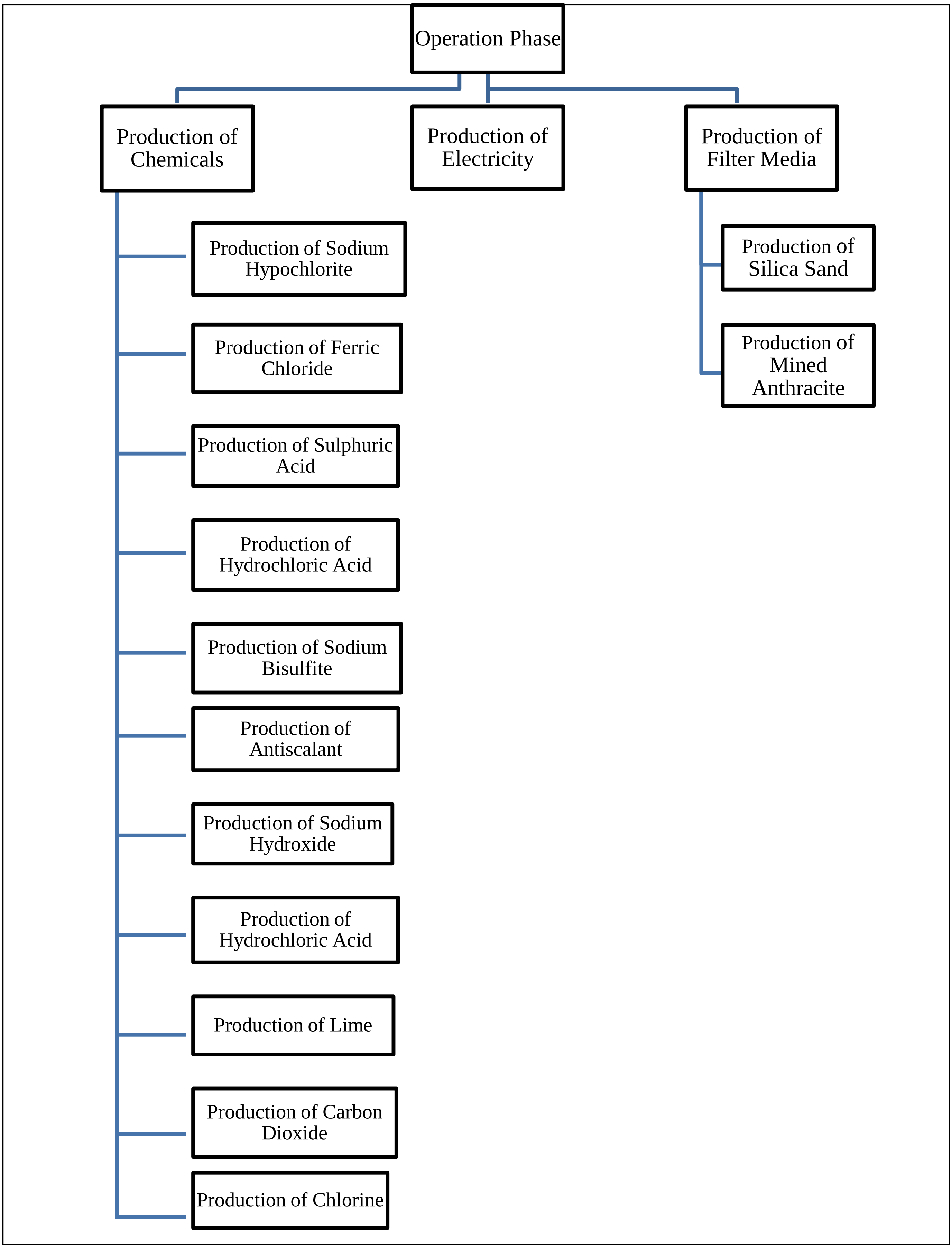


Figure 4.3 Components of Operation Phase for Desalination

4.5.2 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 (PIDs) as well as schedules for power use. This was followed by the 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 for this purpose.

4.5.2.1 Obtaining Data for the Construction Phase

The construction phase typically consists of infrastructure that is designed, built and commissioned as per project specifications. **Figure 4.4** provides a summary of the major constituents of this phase namely civil engineering structures, frames of the modules, grating, pipes, pumps, filters and membranes. The civil engineering structures for this case study consisted of tanks and filter cells. Design sheets for the various tanks provided dimensions of the tanks such as the diameters and heights. This was 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 panel, the weight of the walls and base of the tank can be 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 case study, the mass of components such as the frames of the skid, grating and pipes were obtained courtesy of the personnel at the drawing office of Prentec. A 3D model of the plant which collates the total mass of each skid was utilised from which masses of the individual items were extracted. This data is extremely accurate as pipe mass would include the mass of all lengths of pipe including all bends and tees. The frames and grating that form part of the skid are constructed of carbon steel and galvanised steel respectively while the pipes are either assembled from PVC or stainless steel. As advised by the engineer, the working life of the frames, grating and stainless steel pipes were 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 masses of the specific pumps. As in the initial case study, the masses of the respective pumps were taken as a single entity inclusive of all internal mechanical parts. The working life of all pumps was stated as 7 years.

The water treatment process for mine affected water consists of two stages of treatment. Thus, there were two stages of reverse osmosis (RO) and two stages of ultrafiltration (UF). 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 5 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 membranes were located on the supplier's website. These were constructed of polyvinyl chloride (PVC) with the same working life as the RO membranes.

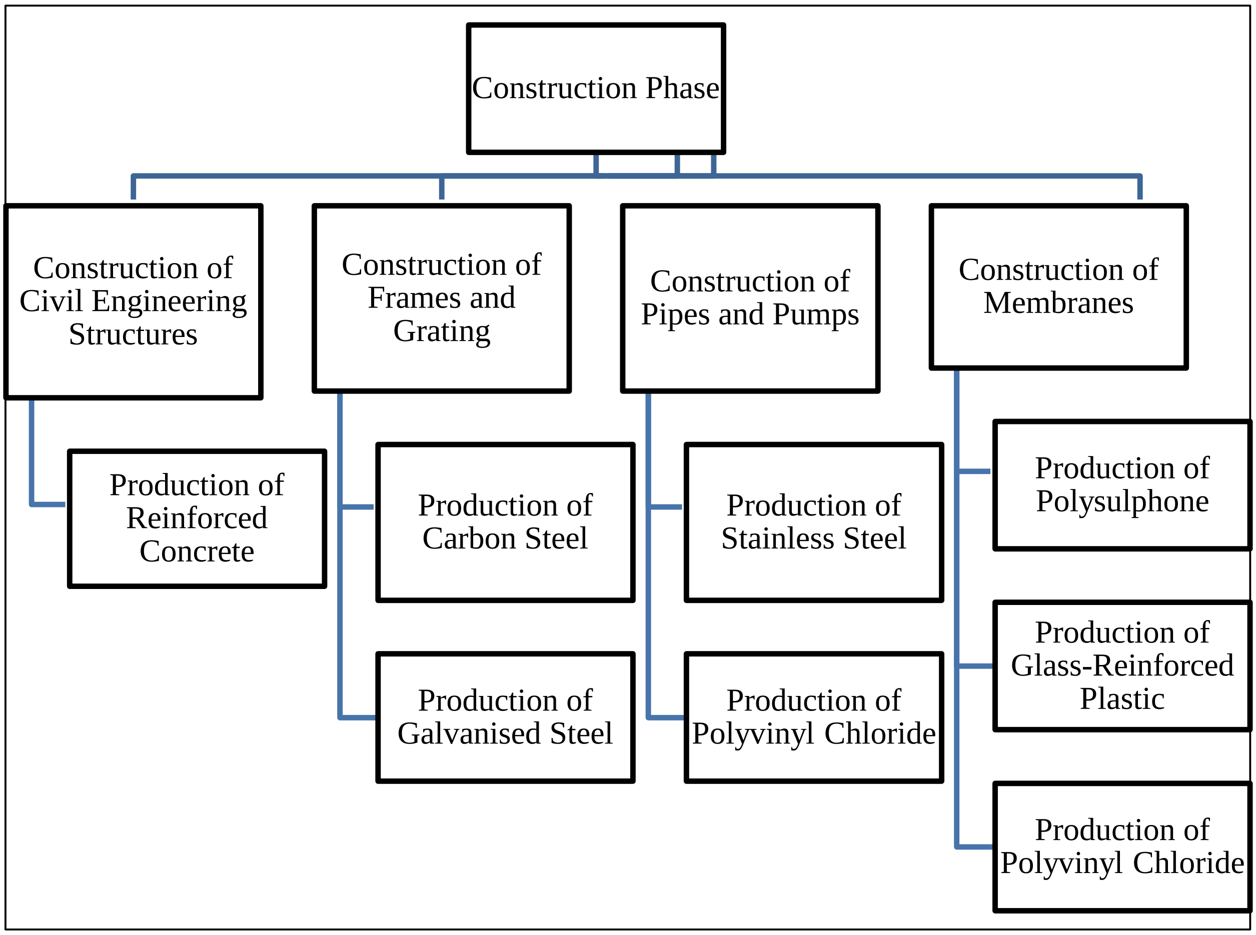


Figure 4.4 Components of the Construction Phase for Mine Water Reclamation

4.5.2.2 Obtaining Data for the Operation Phase

The three components in the operation phase as summarised in **Figure 4.5** include the chemical use within the process, the energy consumption as well as 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.

From the literature, it was evident that the energy was of utmost importance. Thus, a concerted effort was made to obtain an accurate portrayal of the electricity consumption within the process. The power used by each unit operation expressed as kW was obtained from a design schedule. 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.

As mentioned in **Section 3.3,** DUP filters are employed prior to the membrane treatment stages. The filter media consisted of two layers namely silica sand and magnetite. As in the case of the desalination process, the local data available in SimaPro was utilised to represent both media layers for the filtration process.

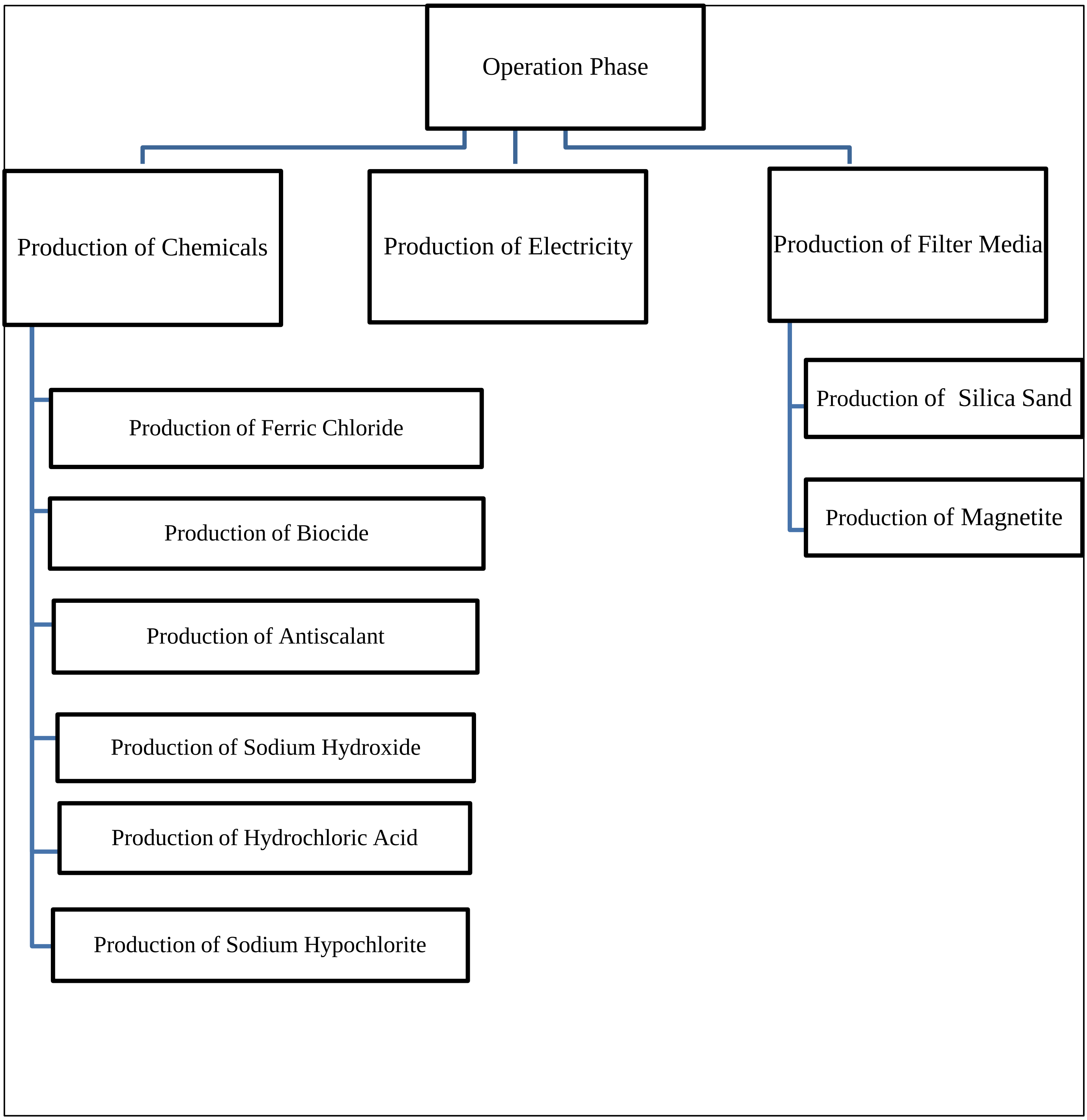


Figure 4.5 Components of Operation Phase for Desalination

4.5.3 Data Validation

Validation of data was carried out for all processes deemed significant. Regarding the electricity consumption for the desalination process, 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 the cases where data was non-existent, data was chosen according to technical criteria such as manufacturing process, function and composition of the material.

4.5.4 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 4.3** summarises the data in the inventory table for the desalination process and **Table 4.4** 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. The step-by-step procedure followed is illustrated in **Appendix B.**

Table 4.3 Inventory Table for 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 4.4 Inventory Table for the Mine Water Reclamation Process

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 (Hard Coal)	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 x 10^{-5}	kg/kℓ			
Stainless Steel	1.46 x 10^{-3}	kg/kℓ			
Polyvinylchloride pump	6.37 x 10^{-7}	kg/kℓ			
Stage 2 Reverse Osmosis					
Concrete (25 MPa)	7.11 x 10^{-5}	kg/kℓ	Phosphoric Acid	18.1 x 10^{2}	mg/kℓ
Concrete (30-32 MPa)	1.77 x 10^{-4}	kg/kℓ	Electricity	1.46	kWh/kℓ
Polysulphone	1.29 x 10^{-4}	kg/kℓ			
Glass Fibre Reinforced Plastic	4.53 x 10^{-5}	kg/kℓ			
Reinforced Steel	8.74 x 10^{-4}	kg/kℓ			
Galvanised Steel	5.21 x 10^{-5}	kg/kℓ			
Polyvinylchloride (pipe)	2.51 x 10^{-6}	kg/kℓ			
Stainless Steel	1.82 x 10^{-4}	kg/kℓ			
Polyvinylchloride pump	2.12 x 10^{-7}	kg/kℓ			

4.5.5 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 a life cycle stage. 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 being 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 focussed on the assembly and lifecycle stages of the process.

4.5.6 The Inventory Table

The result 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.

4.6 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 as presented in **Table 4.1**. For the 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.

4.6.1 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) warns 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).

ReCiPe is the successor of two methods: Eco-indicator 99 and CML-IA (Center of Environmental Science, 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 one 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:

- Climate change
- Human toxicity
- Ionizing 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
- Fresh water depletion

A brief description of these categories together with some information regarding characterisation will be presented in the following sub-sections.

4.6.1.1 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. Yet, when there is an increase in emissions of greenhouse gases, 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 potentials (GWP) for substances having the same impact as carbon dioxide in the reflection of heat radiation. GWP for gases are measured in the reference unit of kg CO_2 equivalents where the effects of relevant gases are expressed relatively to the effect of CO_2.

4.6.1.2 Ozone Depletion

Ozone depletion refers to the damaging effect of various gases on the 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 gas, its 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 the 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 is well-studied and has one of the largest effects on ozone reduction (Stranddorf et al., 2005).

4.6.1.3 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 into 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), the potential for acidification is characterised by using acidification potentials (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).

4.6.1.4 Depletion of Abiotic Resources

Within SETAC's working group on impact assessment, abiotic resources was 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, the consumption is expressed in terms of megajoules (MJ).

4.6.1.5 Toxicity

This category aims to characterize 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 (Stranddorf et al., 2005). On the other hand, environmental toxicity or ecotoxicity is quantified in terms of three separate impact categories which examine freshwater, marine 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).

4.6.1.6 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, the freshwater resources are under tremendous stress from an increasing population and developing economy. Furthermore, most of the country's 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 while nitrogen 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).

4.6.1.7 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. Thus, 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 then expressed as NMVOC equivalents (Goedkoop et al., 2013).

4.6.1.8 Land Use

The land use impact category reflects the 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). Both 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 number of years.

4.6.1.9 Ionising Radiation

This impact describes the damage to human health and ecosystems related to the emissions of radioactive material throughout a product life cycle. Within the construction 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).

4.6.1.10 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.

4.6.1.11 Salination and Water Consumption

Salination is a significant factor in the South African context. According to van Rensburg (2011), the salinity of South Africa's water resources has been deteriorating slowly due to the quality of water distributed to the Department of Water Affairs (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 the 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.

The ReCiPe impact assessment method was developed from two methods namely Eco-indicator 99 and CML-IA which both originate from 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.

4.6.2 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 in **Section 2.4**, double counting of impacts should be avoided. For the ReCiPe method, upgraded versions of 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).

4.6.3 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):

$$I_m = \sum_i Q_{mi} m_i \tag{4.1}$$

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.

4.7 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, hierarchist 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. the process of reverse osmosis was selected as an analysis group and the impacts attributed to this operation 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.

4.8 Conclusion

This chapter provided a detailed account of the execution of the study with a presentation of each of the four elements of the LCA. According to the LCA guidelines detailed in the ISO 14040 document, the LCA process follows a sequential method where each step provides sufficient information required for the following step. Thus, the study commenced by setting the goal and scope which was followed by the collection of data together with calculation processes. Constraints and limitations encountered during the study were documented as the study progressed. The resulting figures from the inventory stage were utilised as inputs for the modelling stage. This produced environmental scores according to the specified impact assessment method. This strategy was believed to be suitable in order to satisfy the original objectives of the study mentioned in **Section 1.3.**

CHAPTER 5: RESULTS AND DISCUSSION

5.1 Introduction

This chapter presents the first part of the Life Cycle Interpretation of the study 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 results while the final chapter will involve a presentation of various conclusions and recommendations.

The results from the two water treatment processes 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.

5.2 Results for the Desalination Process

As presented in **Section 4.5**, 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. These impact categories are pre-defined in the software package as part of the ReCiPe impact assessment method. **Figure 5.1** 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 has an overwhelming burden in the majority of the categories such as climate change and terrestrial acidification. However, in other categories such as water and minerals depletion, the contribution of electricity is much lower (approximately 50.0 %) with the 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.

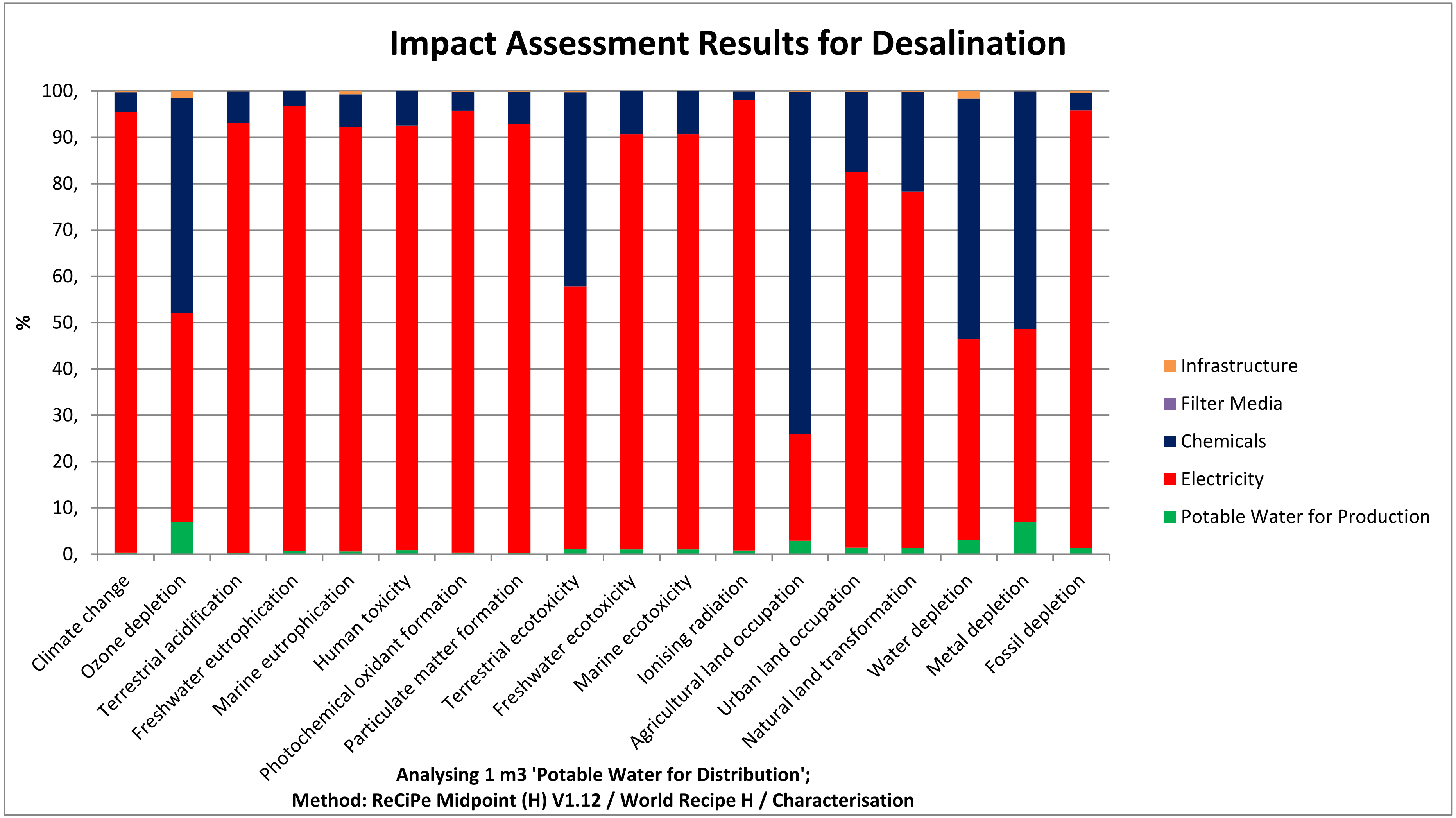


Figure 5.1 Overall Impact Assessment Results for Desalination

5.2.1 Climate Change

Figure 5.2 is a network diagram which visually represents the climate change distribution for the desalination process. The results show that 4.40 kg of Carbon Dioxide (CO_2) equivalents is emitted for the production of 1 kℓ of potable water. 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 reverse osmosis 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 greenhouse gas 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.

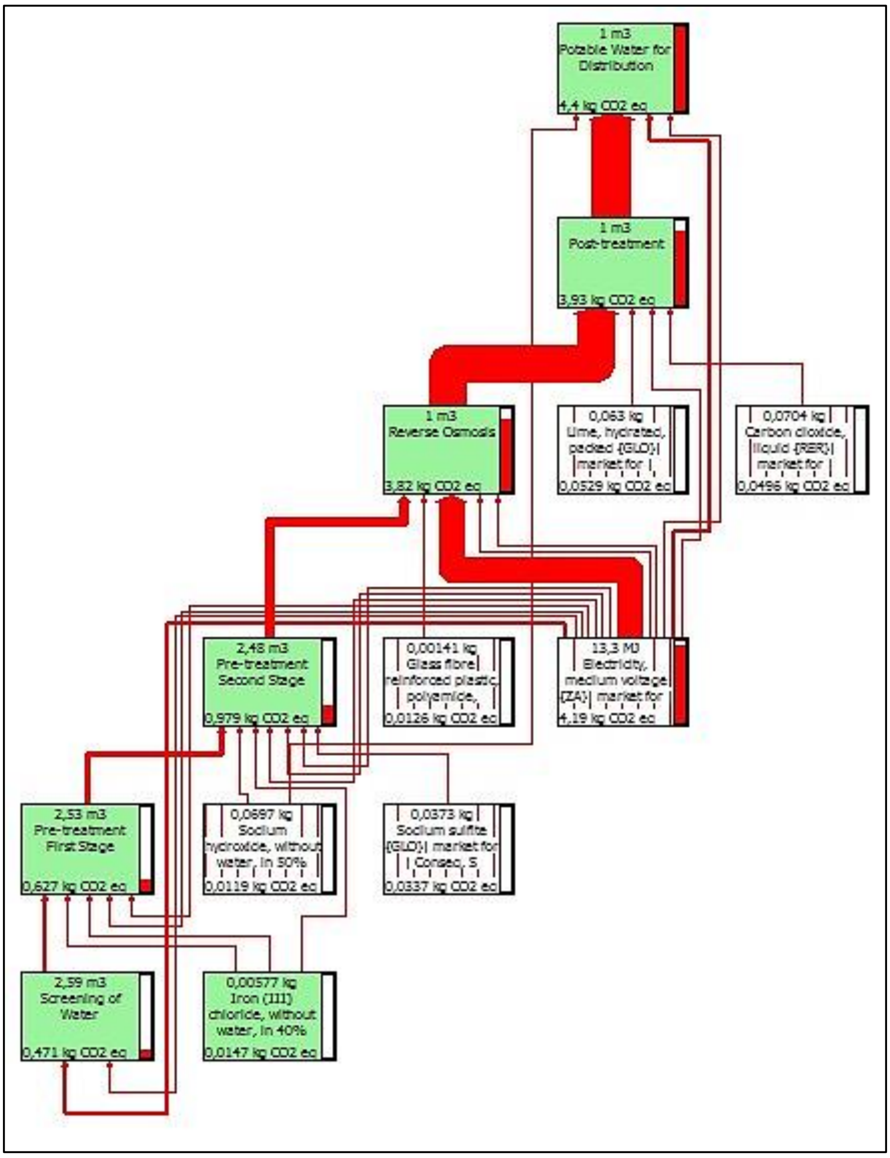


Figure 5.2 Network Diagram Illustrating Climate Change Contribution for Desalination

5.2.2 Ozone Depletion

The following figure provides insight into the contribution of each operation to ozone depletion. From **Figure 5.3**, one can ascertain that reverse osmosis, the second stage of pre-treatment and post-treatment are responsible for the majority of the emissions that contribute to ozone depletion. For reverse osmosis, the release of gaseous compounds in 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 the sodium sulphite and the phosphoric acid which acts as an antiscalant for the process. The post-treatment phase, which 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 5.1** 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 %.

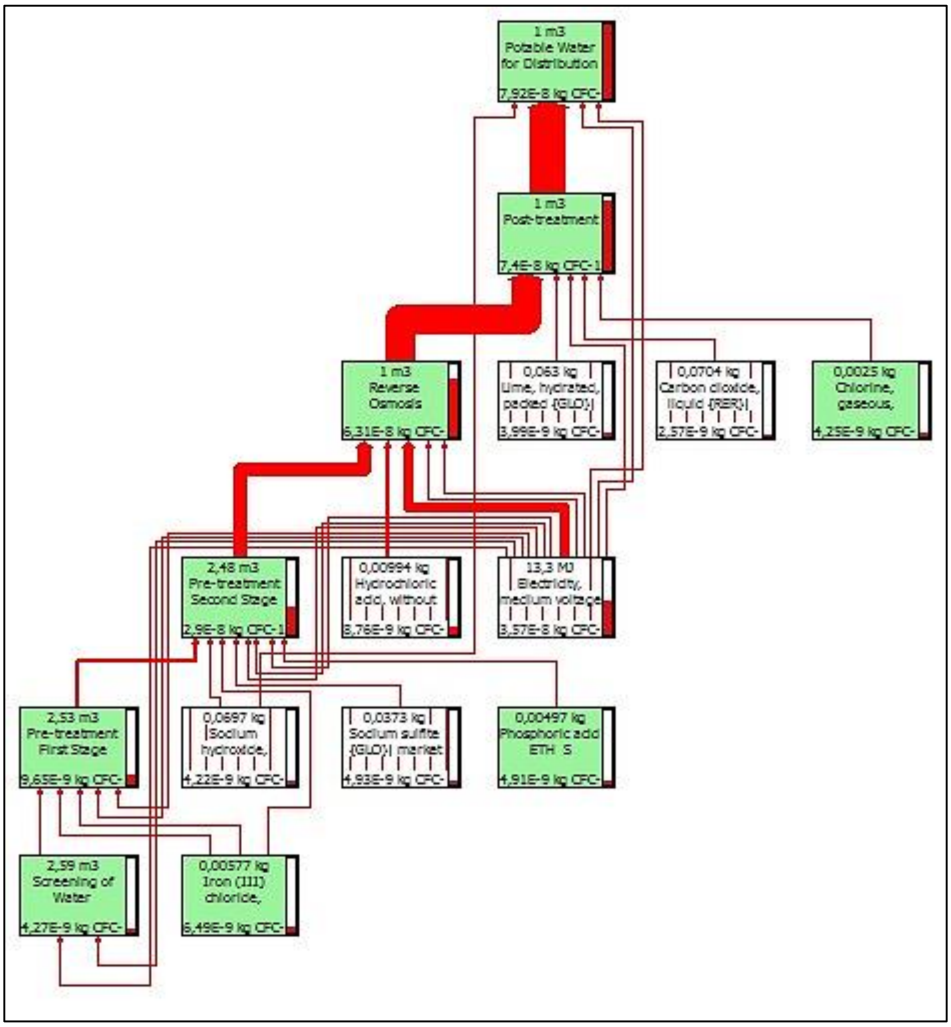


Figure 5.3 Network Diagram Illustrating Ozone Depletion for Desalination

5.2.3 Terrestrial Acidification

For the impact category acidification, gases that create acid deposition include ammonia, nitrogen oxide and sulphur oxide. **Figure 5.4** shows the contributors of individual elements 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, nitrous oxide and sulphur dioxide.

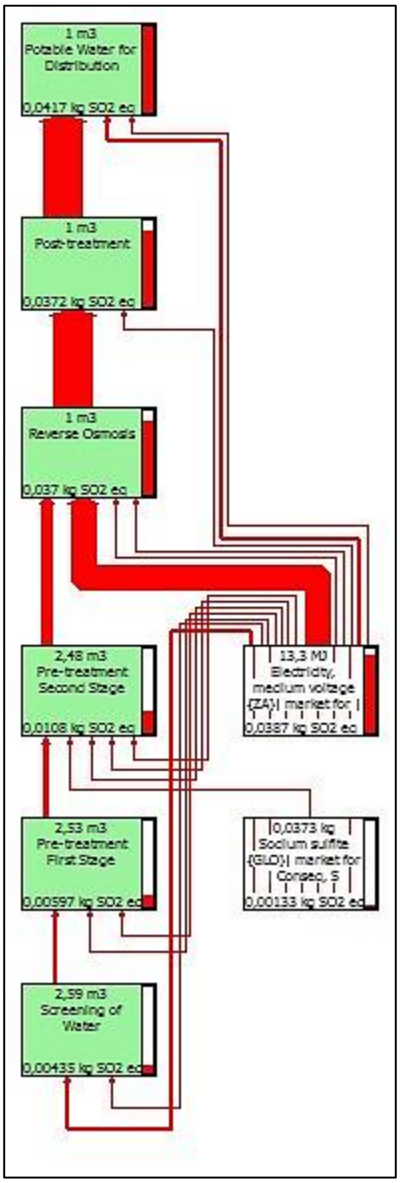


Figure 5.4 Network Diagram Illustrating Terrestrial Acidification for Desalination

5.2.4 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 5.5** 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. This could be attributed to the use of water and minerals in the chemical production process.

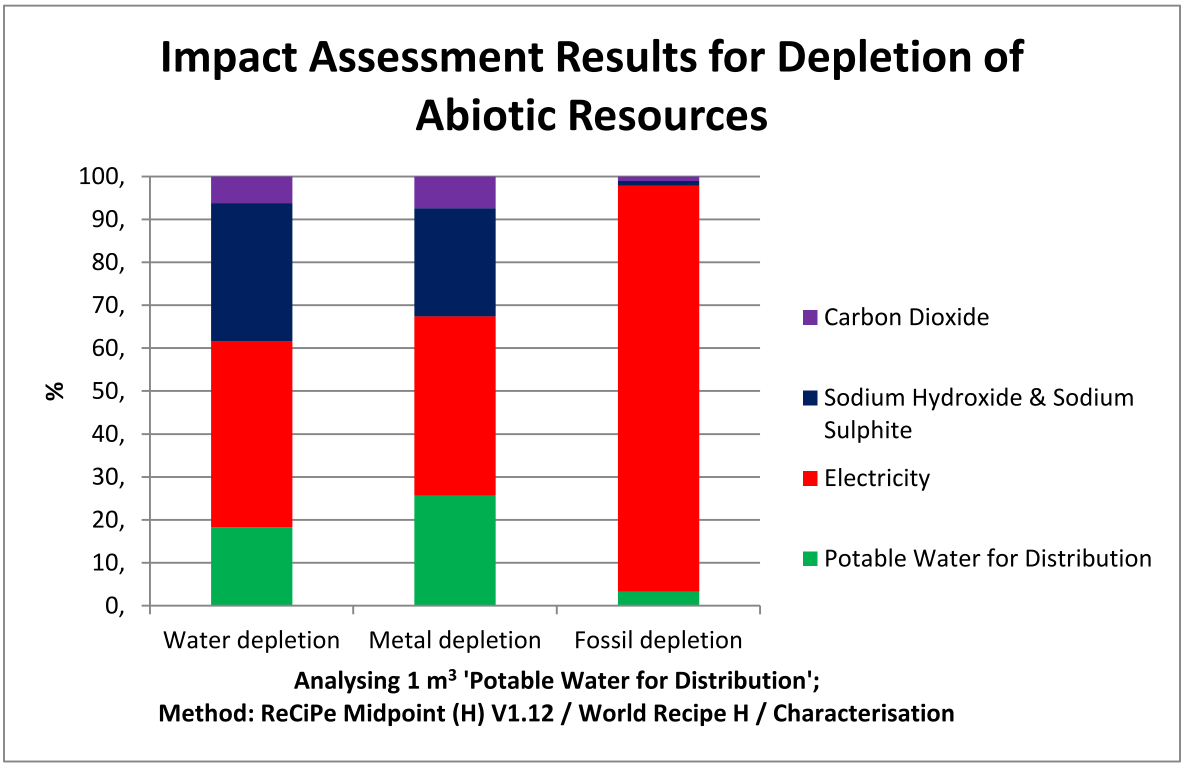


Figure 5.5 Impact Assessment Results Depicting Depletion of Abiotic Resources for Desalination

5.2.5 Toxicity

With respect to toxicity, it was decided to group the various toxicity impact categories together – human, terrestrial, freshwater and marine. The comparative graph in **Figure 5.6** show that for human, marine and freshwater 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 have 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).

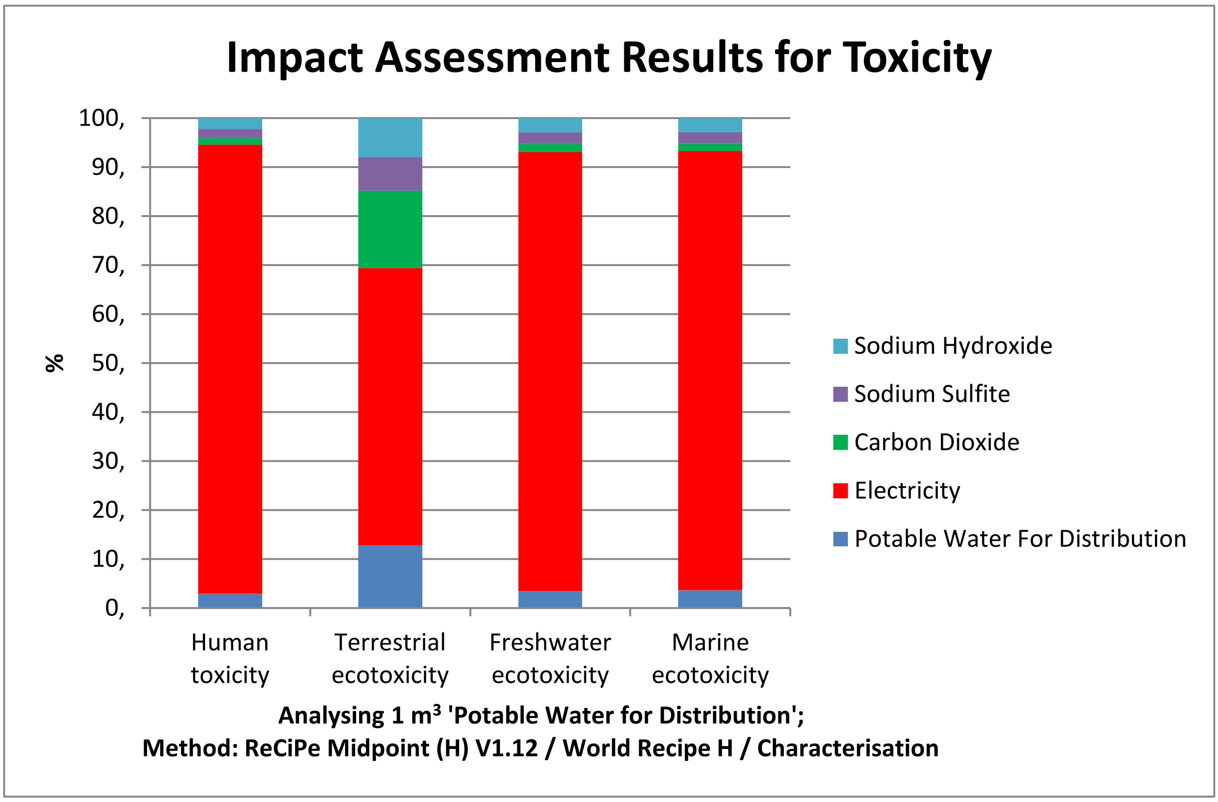
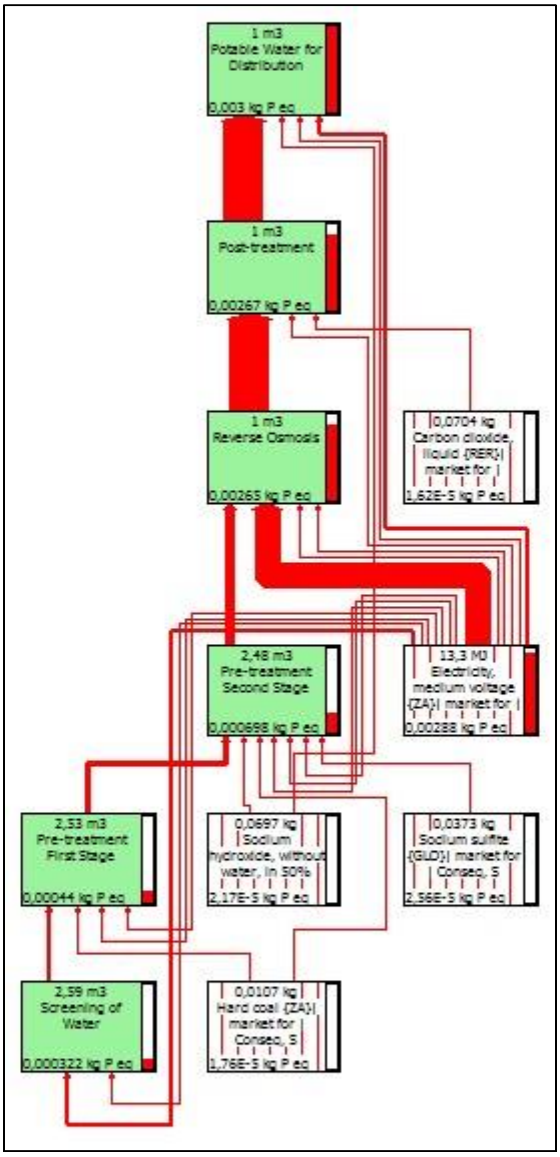


Figure 5.6 Impact Assessment Results Depicting Toxicity for Desalination

5.2.6 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 5.7** and **Figure 5.8** show a similar trend – that of electricity being the greatest contributor. In addition, these figures also show that reverse osmosis is the stage responsible for the highest impact. This can, in part, be related to the electricity usage for the high pressure feed pumps.



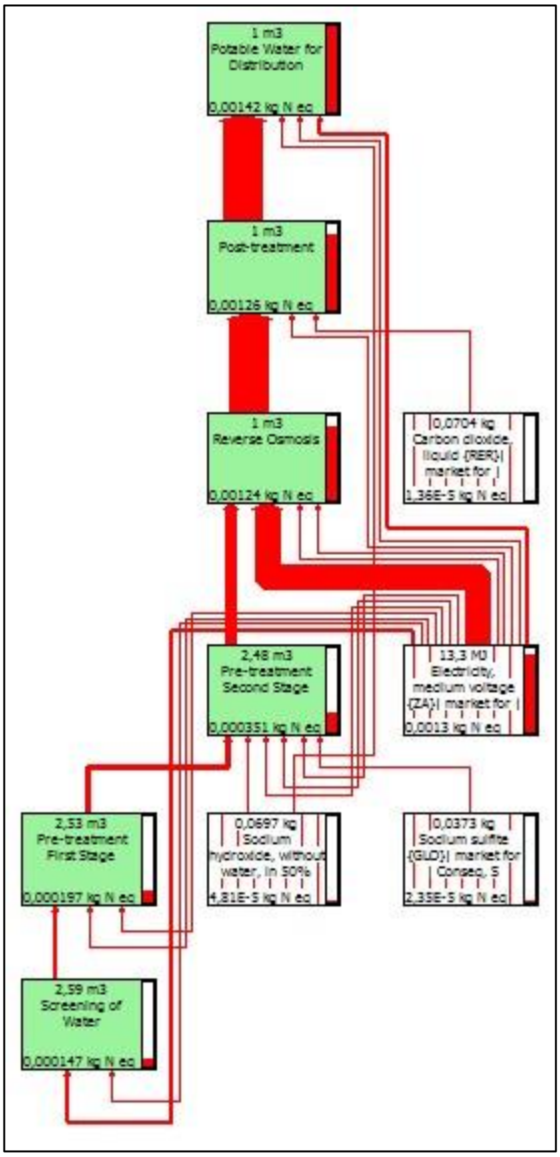


Figure 5.7 and Figure 5.8 Network Diagrams Illustrating Freshwater and Marine Eutrophication for Desalination

5.2.7 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 electricity mix in South Africa (see **Table A1.3** for detailed quantities of emissions per kWh), one can gauge that the 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 5.9** shows electricity as the major contribution with a burden of 95.4 %.

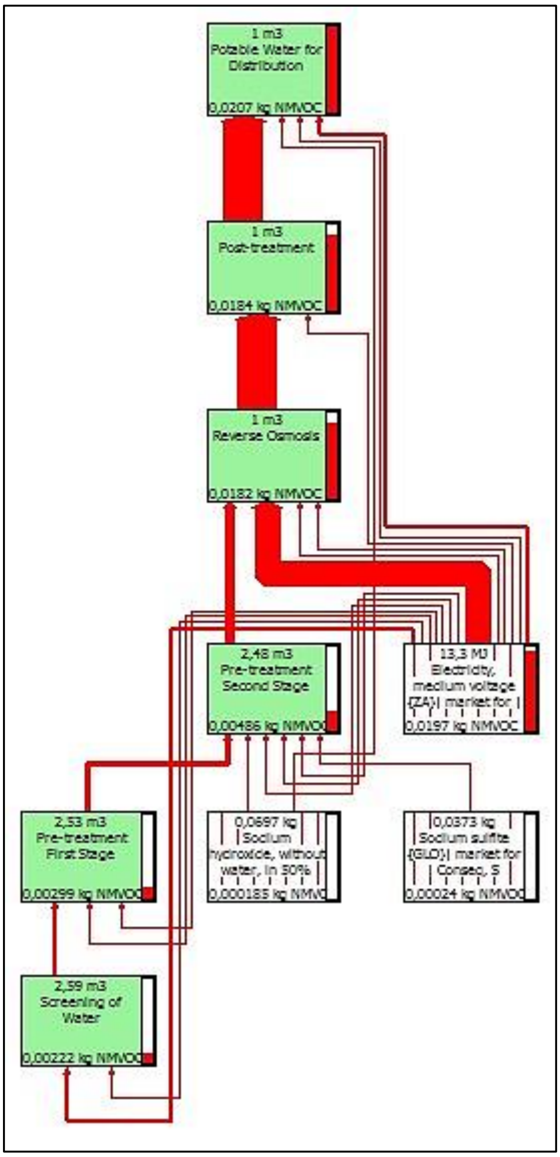


Figure 5.9 Network Diagram Illustrating Photochemical Oxidant Formation for Desalination

5.2.8 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 is dominated by the sodium hydroxide and sodium sulphite production process which are background flows.

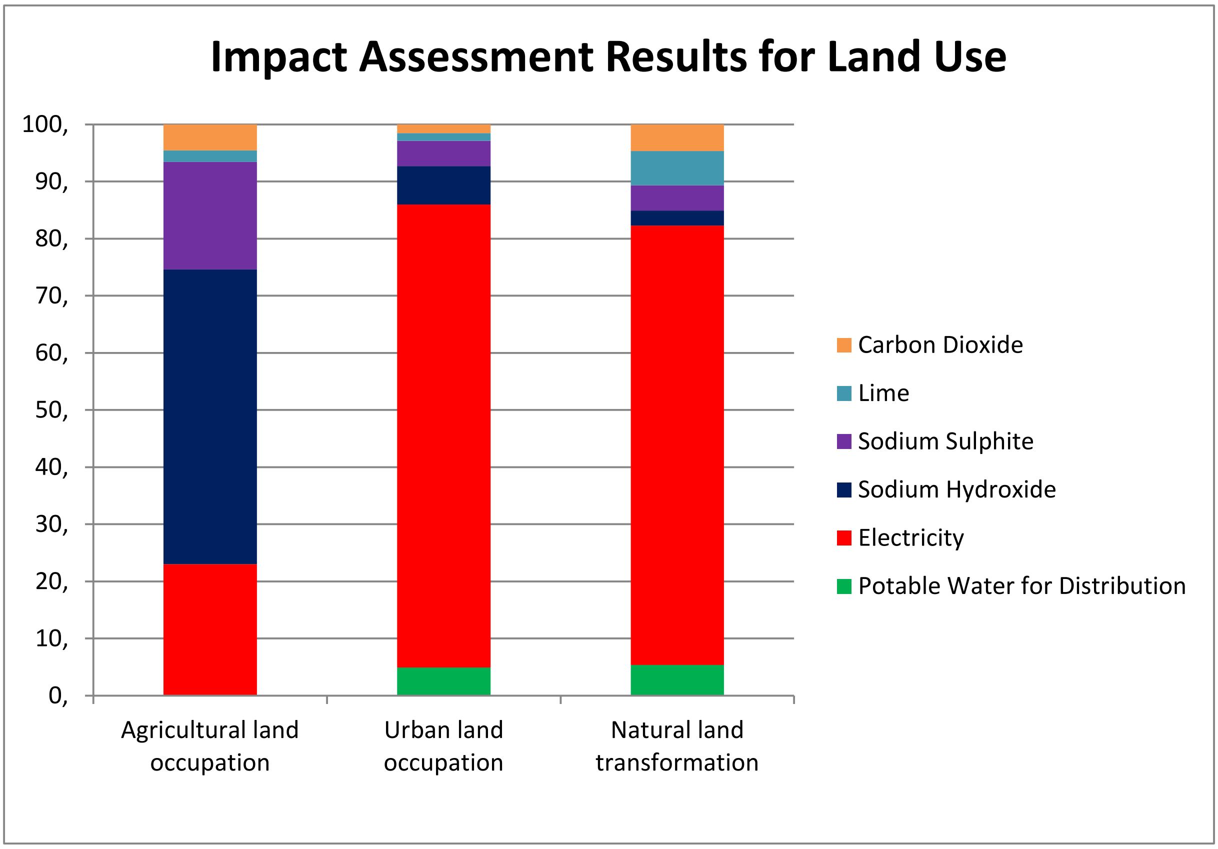


Figure 5.10 Impact Assessment Results Depicting Land Use for Desalination

5.2.9 Ionizing Radiation

The following image illustrates the contribution of the processes to the overall ionizing radiation impact. The thick red arrow indicates that the majority of the emissions (97.3 %) is caused by the 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).

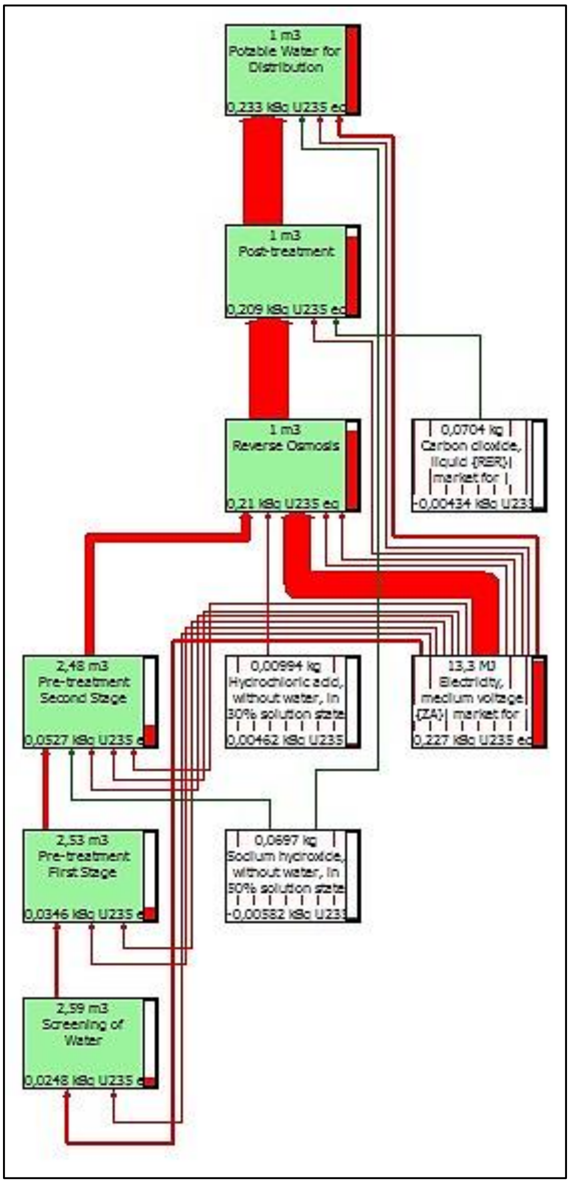


Figure 5.11 Network Diagram Illustrating Ionizing Radiation for Desalination

5.2.10 Particulate Matter

Figure 5.12 illustrates that the primary cause of particulate matter formation for the study is electricity – its production and use within the process. Generally, airborne 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 practise of burning coal for energy (Commission for Environmental Cooperation, 2011).

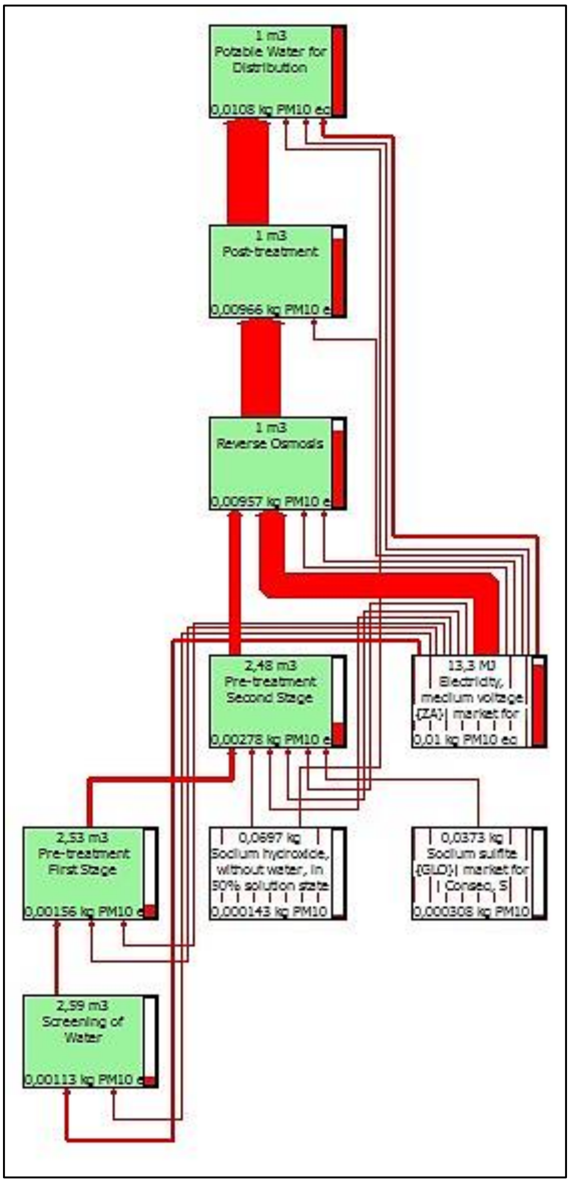


Figure 5.12 Network Diagram Illustrating Particulate Matter Formation for Desalination

5.3 Results for the Mine Water Reclamation Process

For the second case study, the two stages of the life cycle that were analysed were identical to the ones considered for the first case study namely the construction and operation phase. 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 5.13**.

Electricity consumption, which is shaded in red, has the greatest contribution to the bulk of the impacts. In the case of impacts categories such as climate change and terrestrial acidification, the 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. Unlike the operation phase, the environmental impact of the infrastructure phase, which encompasses materials used in the construction of the plant, is relatively less significant. An explanation of the contributing factors to each impact category will follow in greater detail.

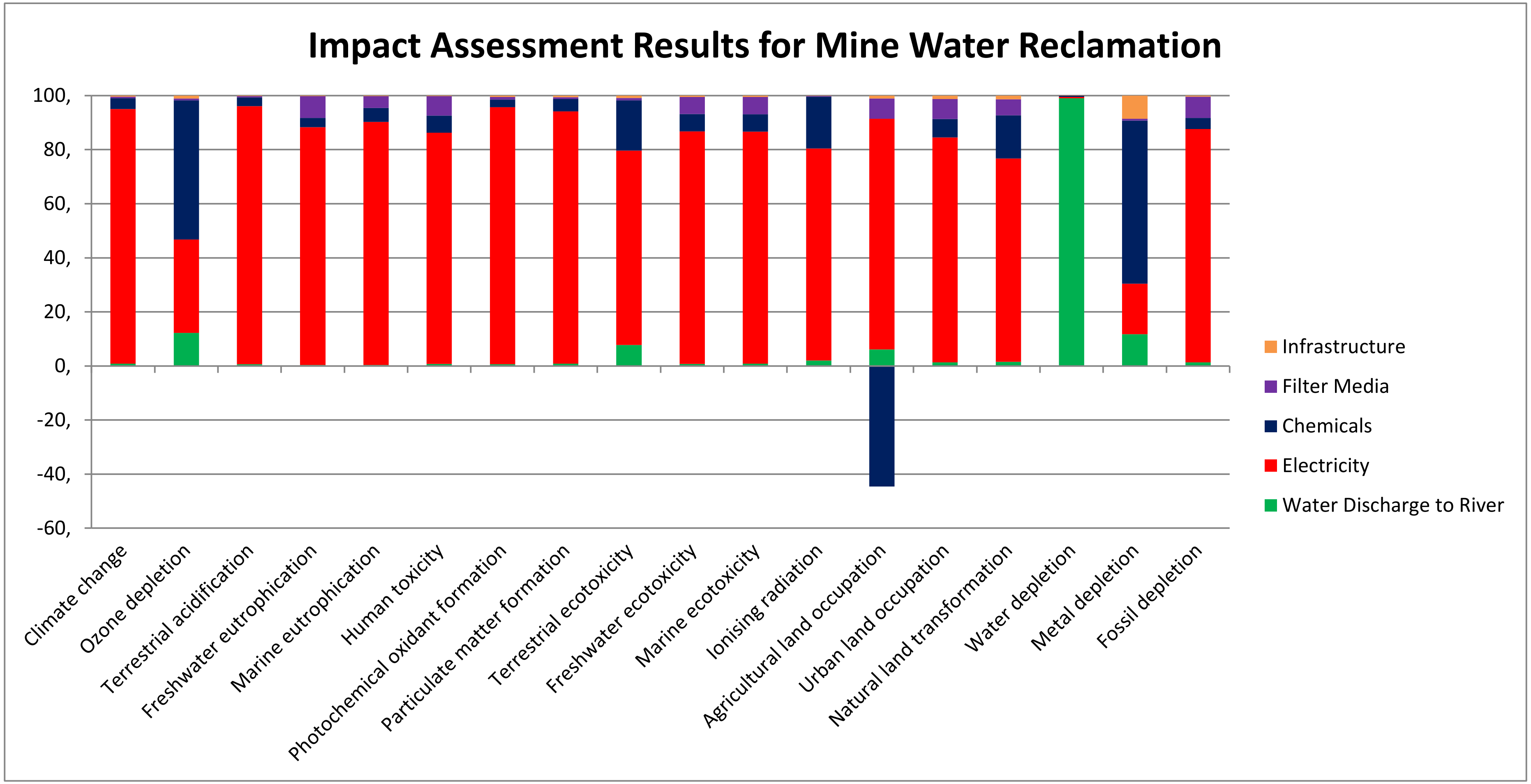


Figure 5.13 Overall Impact Assessment Results for Mine Water Reclamation

5.3.1 Climate Change

Figure 5.14 is a representation of the contributions of each unit operation to the overall impact category of climate change. The overall emission of Greenhouse Gases 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 reverse osmosis. Stage 2 reverse osmosis carries a marginally higher burden (1.54 kg CO_2 eq.) as opposed to Stage 1 reverse osmosis (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 reverse osmosis. This can be traced back to the higher feed salinity of the water entering Stage 2 reverse osmosis which originally emanates from Stage 1 reverse osmosis 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 results originates from the energy mix utilised in South Africa which relies on coal-fired power stations.

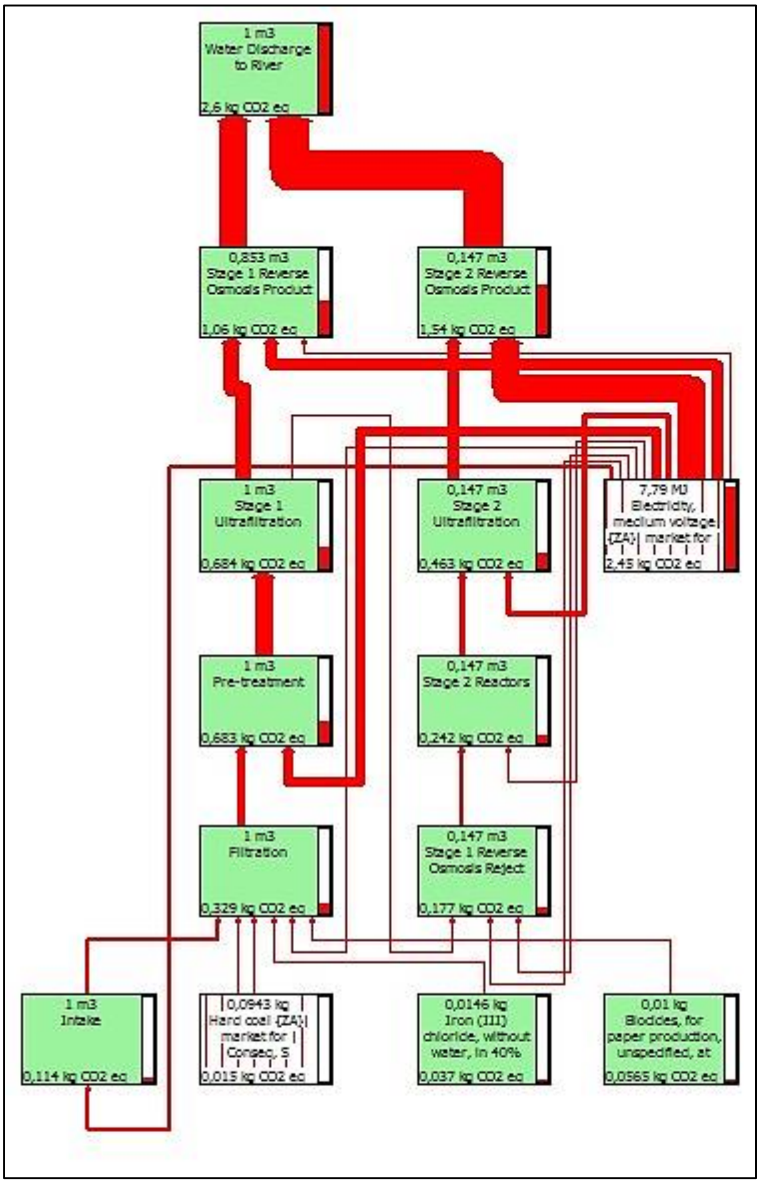


Figure 5.14 Network Diagram Illustrating Climate Change Contribution for Mine Water Reclamation

5.3.2 Ozone Depletion

The second impact category that will be discussed concerns ozone depletion. **Figure 5.15** shows an even distribution of this environmental impact from both sources of potable water i.e. product water from Stage 1 and Stage 2 reverse osmosis. Regarding the first stage of reverse osmosis, 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 the ferric chloride as a coagulant and biocide in the process which contributes 1.64×10^{-8} kg CFC-11 and 9.96×10^{-9} kg CFC-11 respectively. For the second stage of reverse osmosis, it is evident that the high energy usage carries 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 2.09×10^{-8} kg CFC-11 which equates to 34.6 % of the overall emissions of chlorofluorocarbons from the product system.

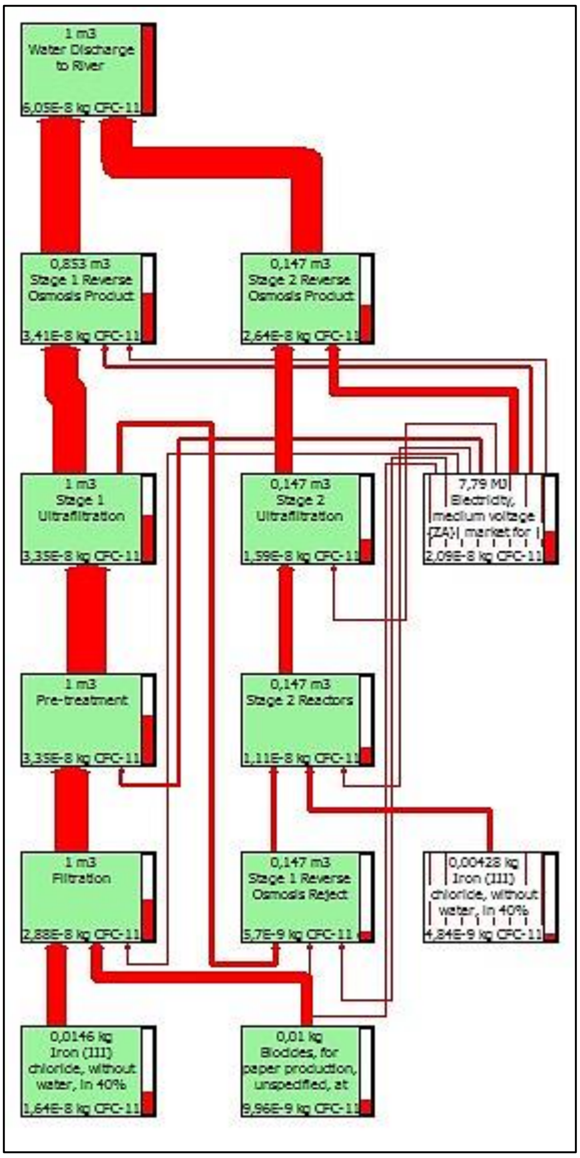


Figure 5.15 Network Diagram Illustrating Ozone Depletion for Mine Water Reclamation

5.3.3 Terrestrial Acidification

An analysis of the product system in terms of terrestrial acidification produces the diagram in **Figure 5.16**. 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.

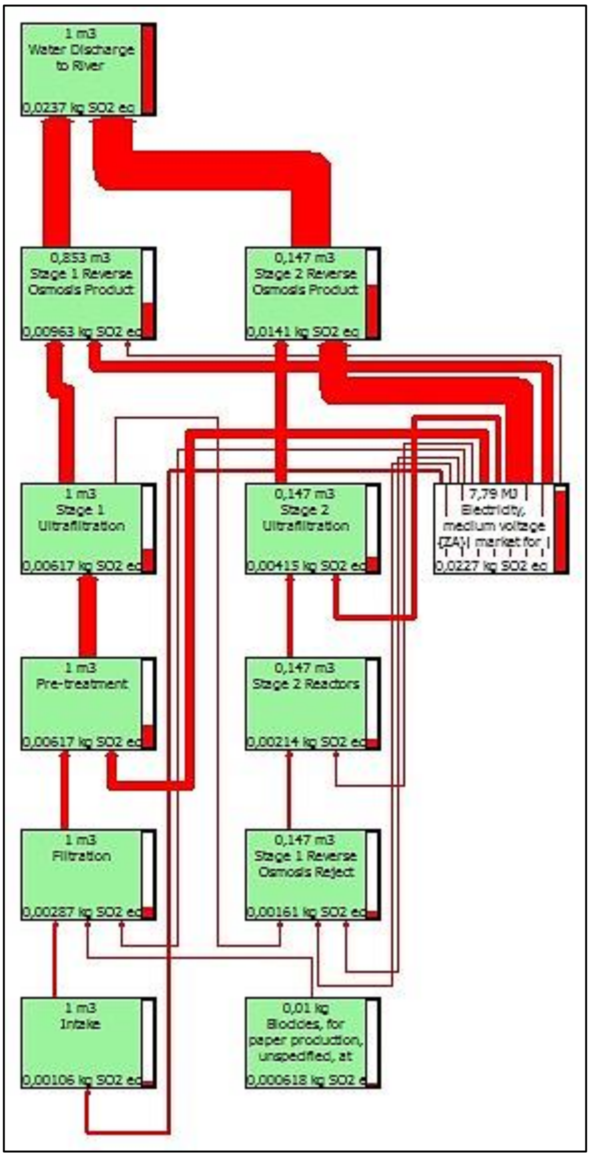


Figure 5.16 Network Diagram Illustrating Terrestrial Acidification for Mine Water Reclamation

5.3.4 Depletion of Abiotic Resources

From **Figure 5.17** below, the depletion of water is mainly due to the source water. As this is water accumulated in abandoned mining areas, this represents a decrease in groundwater that is available. In this situation, the groundwater was contaminated by previous mining activities and needs to be treated prior to discharge into surface water. Regarding metal depletion, 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 (1.18×10^{-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 0.60 kg oil out of a total of 0.70 kg oil. This can be attributed to the national electricity production which consists mainly of the combustion of fossil fuels.

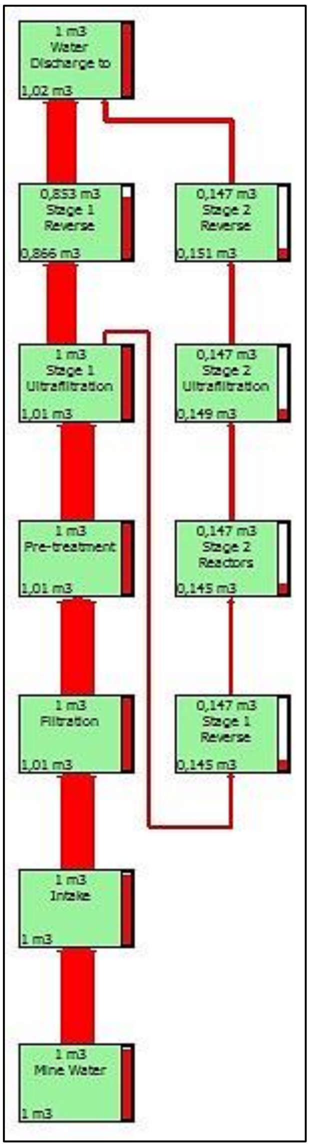


Figure 5.17 Network Diagram Illustrating Water Depletion for Mine Water Reclamation

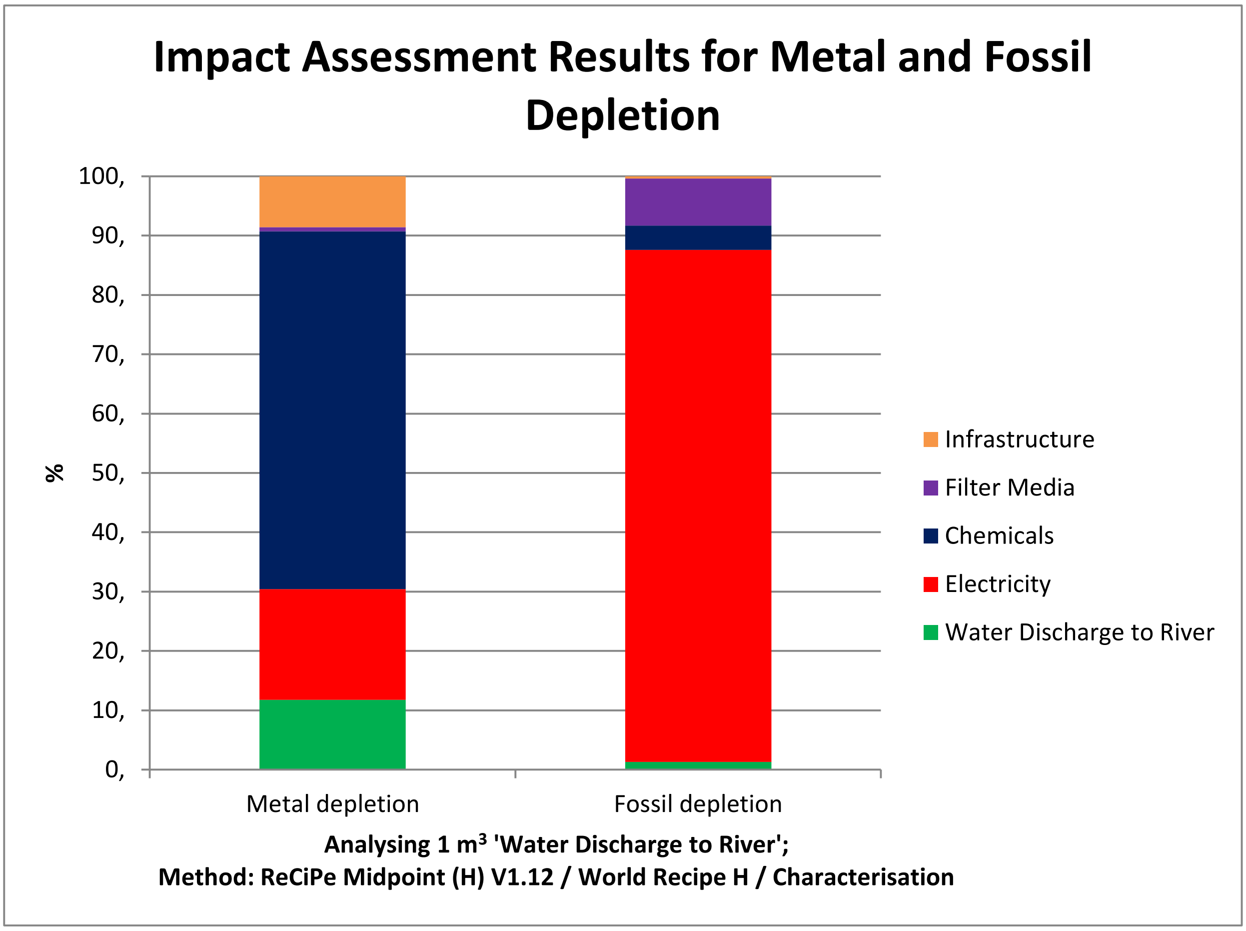


Figure 5.18 Impact Assessment Results Depicting Metal and Fossil Depletion for Mine Water Reclamation

5.3.5 Toxicity

As per the first case study, the 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 within the mine water reclamation process is responsible for the majority of the contribution 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 has a contribution of 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 has a much greater contribution of 17.3 %.

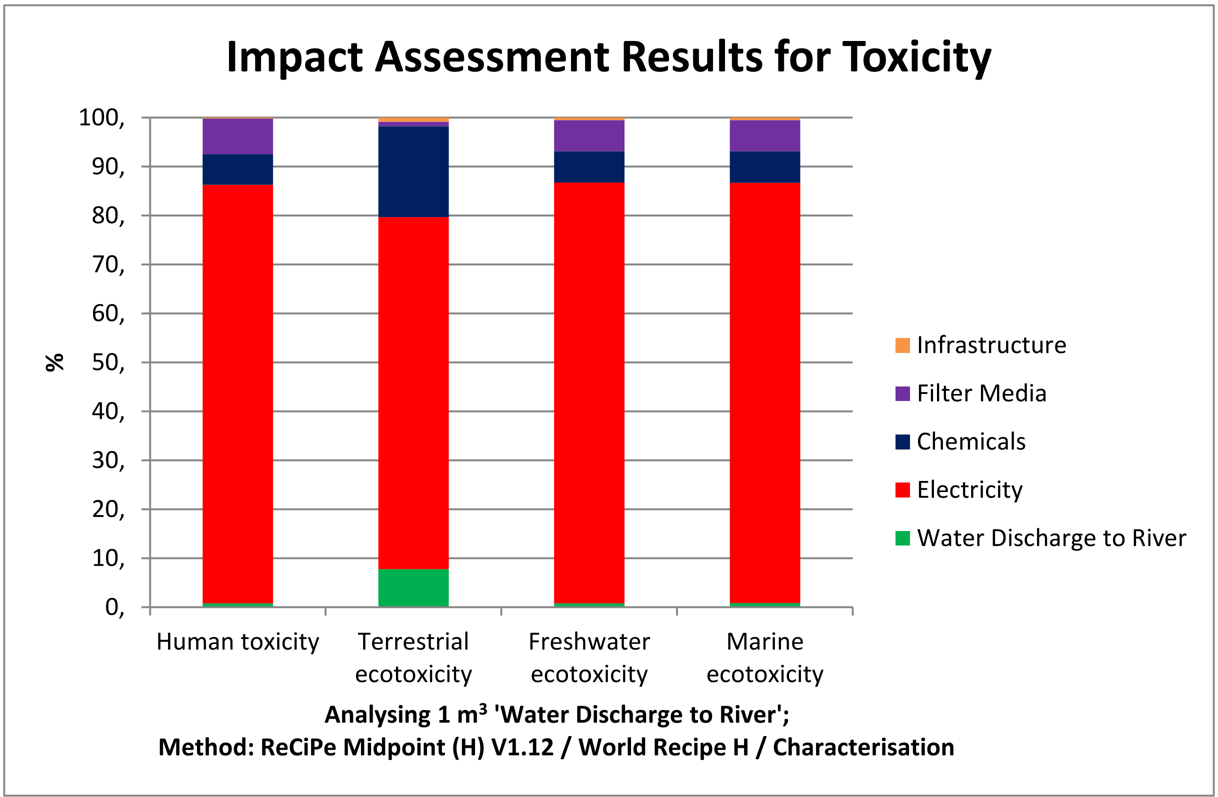
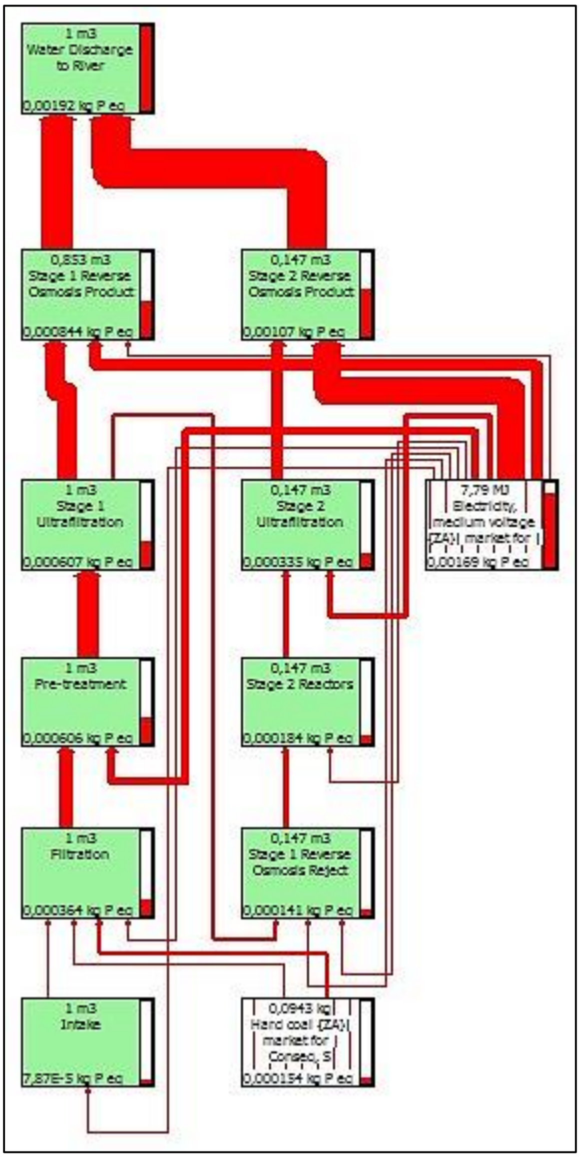


Figure 5.19 Impact Assessment Results Depicting Toxicity for Mine Water Reclamation

5.2.6 Eutrophication

Eutrophication is divided into two sub-sections: freshwater eutrophication which is illustrated by the diagram on the left and marine eutrophication which is depicted by the diagram on the right. For both impacts, the second stage of reverse osmosis 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 has 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.



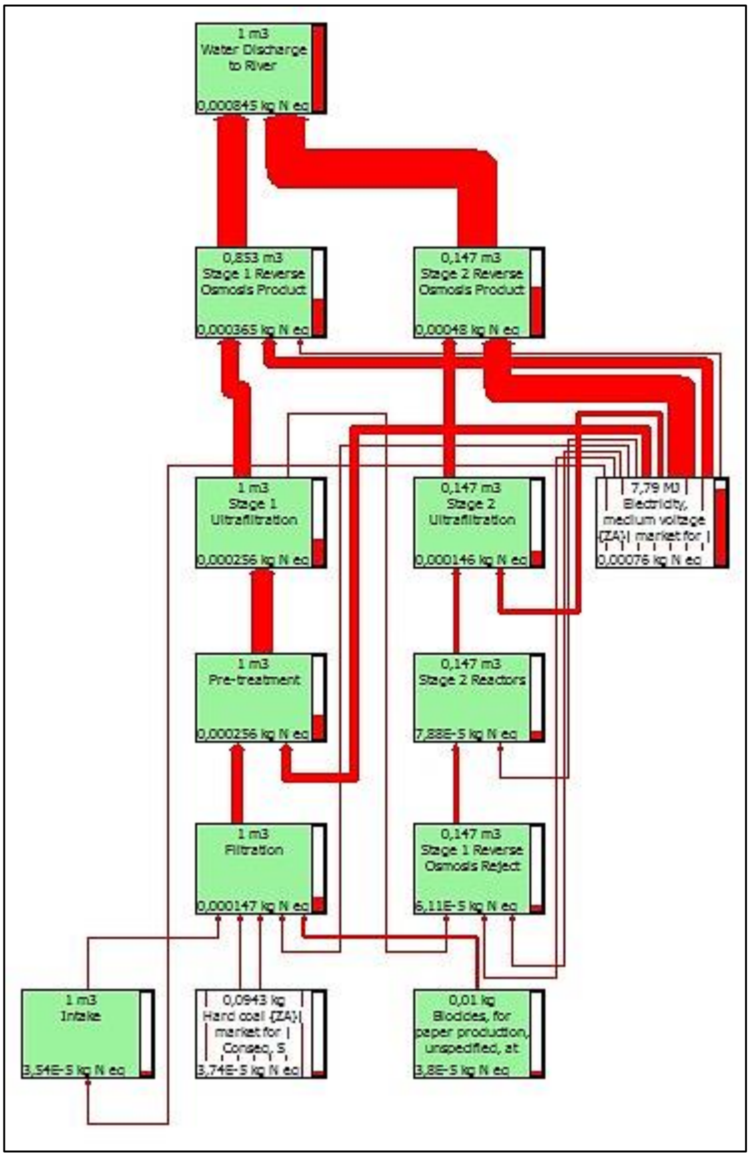


Figure 5.20 and Figure 5.21 Network Diagrams Illustrating Freshwater and Marine Eutrophication for Mine Water Reclamation

5.3.7 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 5.22** below clearly illustrate that the potential creation of smog from the product system is directly related to the electricity generation in South Africa which relies heavily on the combustion of fossil fuels.

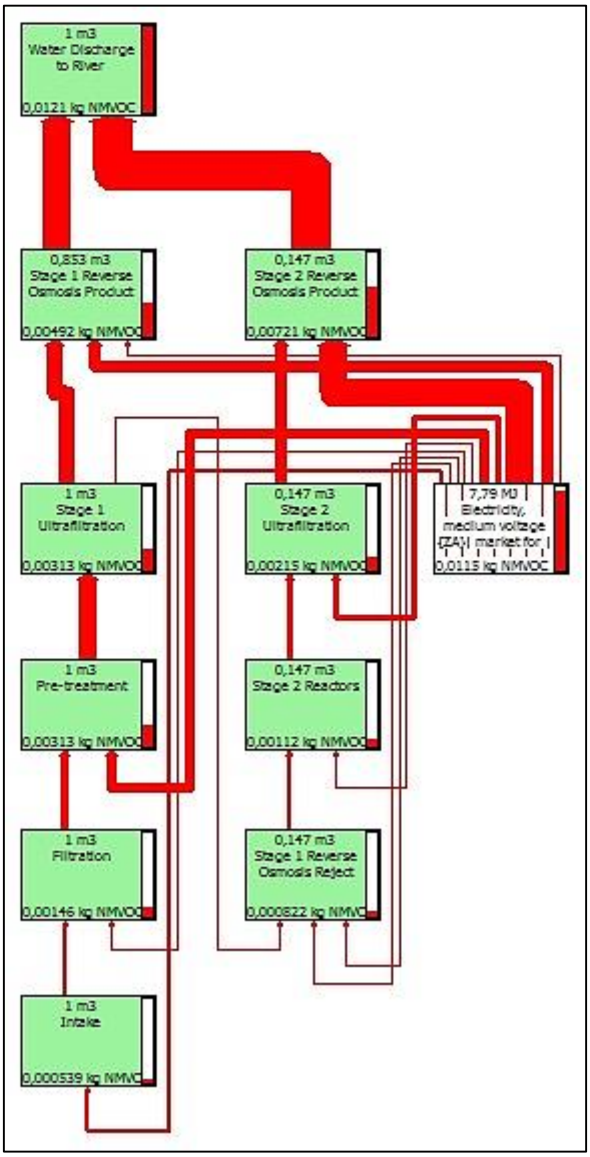


Figure 5.22 Network Diagram Illustrating Photochemical Oxidant Formation for Mine Water Reclamation

5.3.8 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 7.40 % 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.

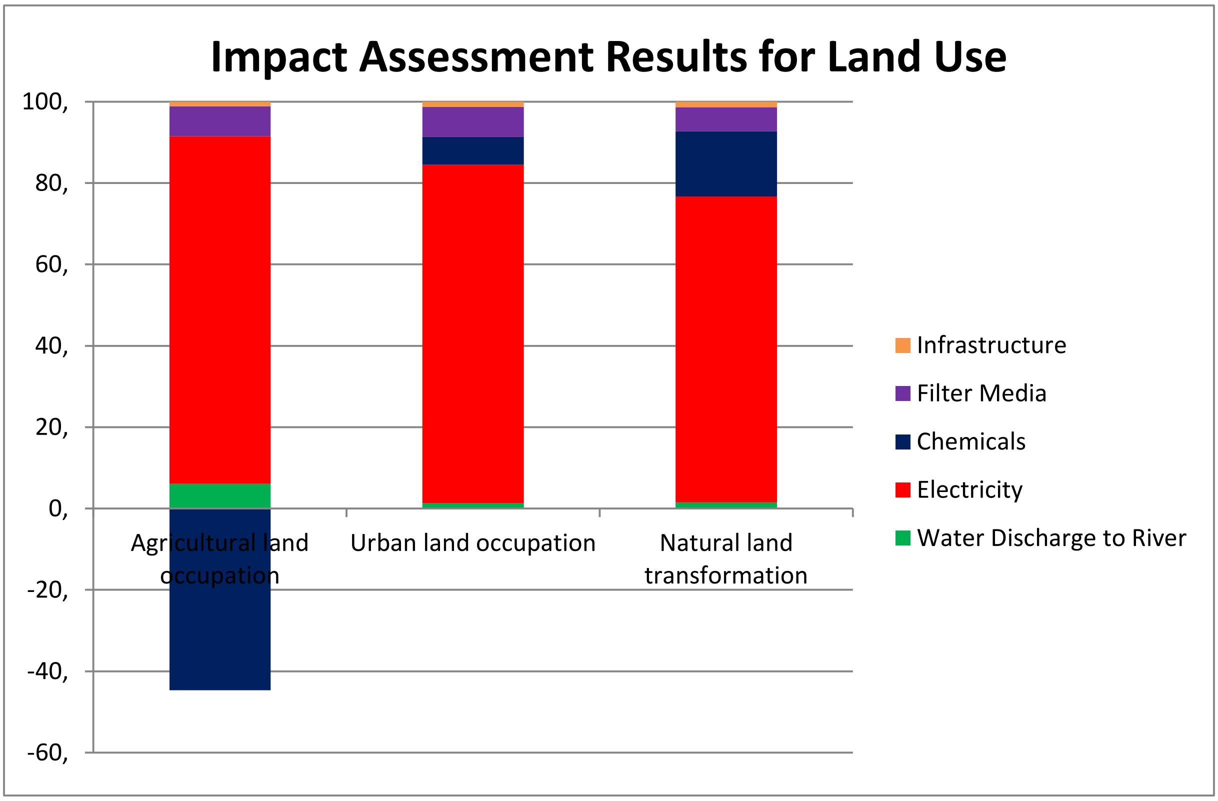


Figure 5.23 Impact Assessment Results Depicting Land Use for Mine Water Reclamation

5.3.9 Ionizing Radiation

Figure 5.24 illustrates the environmental impact of the mine water reclamation process on the potential for ionizing radiation. Electricity is responsible for the majority of the impact with 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 the electricity consumption.

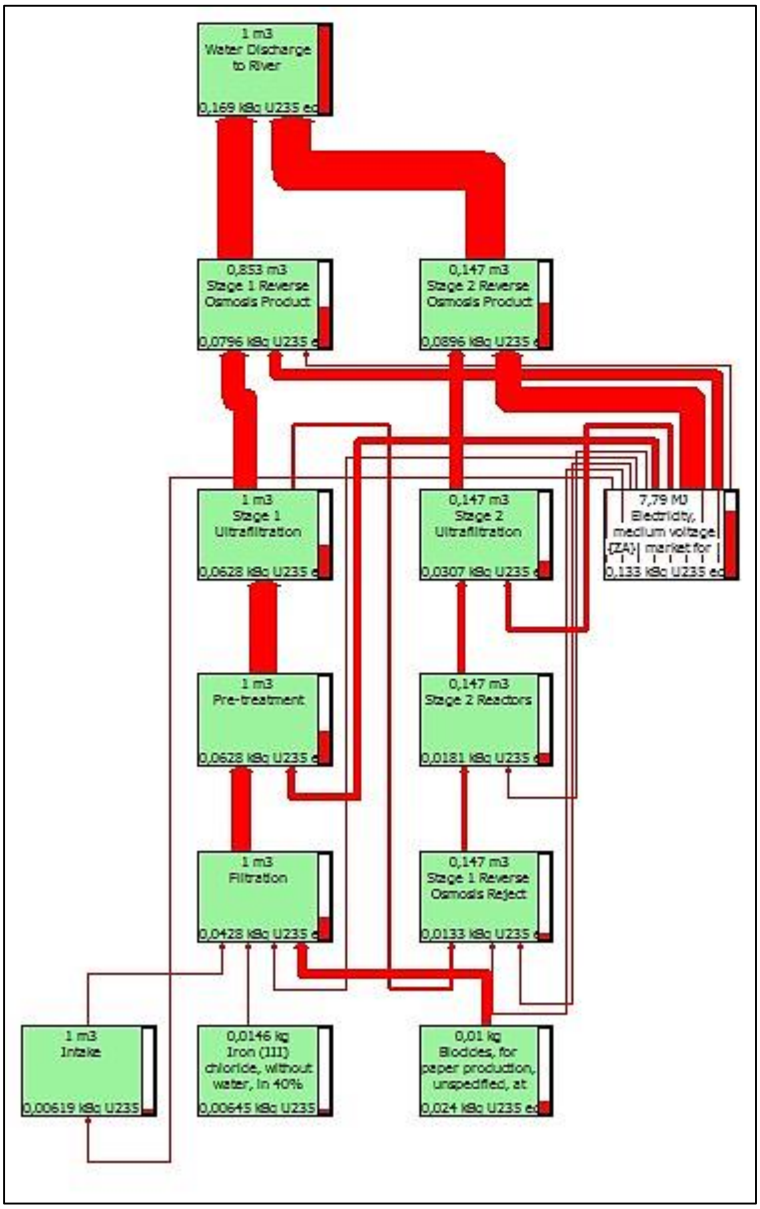


Figure 5.24 Network Diagram Illustrating Ionizing Radiation for Mine Water Reclamation

5.3.10 Particulate Matter

Particulate matter formation in terms of PM_{10} relates to the particles that are <10µm in diameter and have the capacity to cause harm to human health. **Figure 5.25** 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).

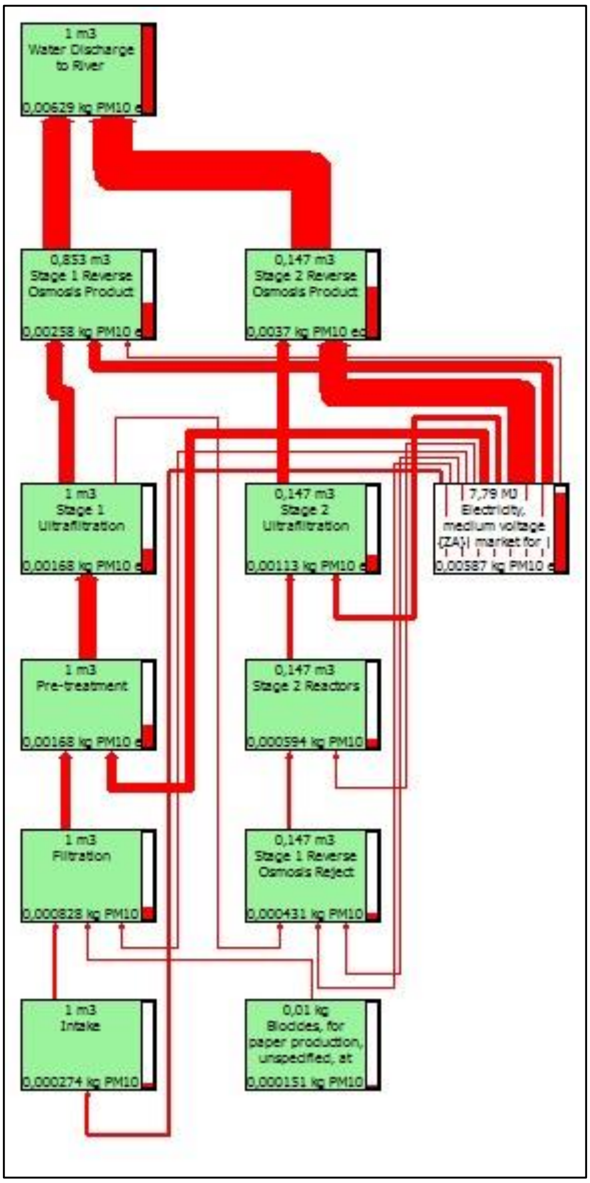


Figure 5.25 Network Diagram Illustrating Particulate Matter Formation for Mine Water Reclamation

5.3.11 Comparison between Design and Operation Data for Mine Water Reclamation

As mentioned in the Materials and Methods chapter, results obtained in **Section 5.3.1 – 5.3.10** 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 as well as changes in water chemistry. The process control philosophy can also be optimised to decrease inputs such as electricity. **Table 5.1** 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 the decreased electricity consumption.

Table 5.1 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 $x10^{-8}$	5.17 $x10^{-8}$
Terrestrial acidification	kg SO_2 eq	2.37 $x10^{-2}$	1.41 $x10^{-2}$
Freshwater eutrophication	kg P eq	1.92 $x10^{-3}$	1,21 x 10^{-3}
Marine eutrophication	kg N eq	8.45 $x10^{-4}$	5.24 x 10^{-4}
Human toxicity	kg 1,4-DB eq	1.29	8.23 $x10^{-1}$
Photochemical oxidant formation	kg NMVOC	1.21 $x10^{-2}$	7.26 x 10^{-3}
Particulate matter formation	kg PM10 eq	6.29 $x10^{-3}$	3.81 x 10^{-3}
Terrestrial ecotoxicity	kg 1,4-DB eq	4,61 $x10^{-5}$	3.21 x 10^{-5}
Freshwater ecotoxicity	kg 1,4-DB eq	3.70 $x10^{-2}$	2.36 $x10^{-2}$
Marine ecotoxicity	kg 1,4-DB eq	3.51 $x10^{-2}$	2.24 $x10^{-2}$
Ionising radiation	kBq U235 eq	1.69 $x10^{-1}$	1.13 $x10^{-1}$
Agricultural land occupation	m^2a	2.53 $x10^{-2}$	8.80 $x10^{-3}$
Urban land occupation	m^2a	1.15 $x10^{-2}$	7.50 $x10^{-3}$
Natural land transformation	m^2	7.63 $x10^{-5}$	5.21 x 10^{-5}
Water depletion	m^3	1.02	1.02
Metal depletion	kg Fe eq	1.38 $x10^{-1}$	1.27 $x10^{-1}$
Fossil depletion	kg oil eq	6.97 $x10^{-1}$	4.43 $x10^{-1}$

5.4 Comparison between Desalination and Mine Water Reclamation

Once the results for the individual categories for each case study had been analysed, a comparison between the two water treatment processes were made. **Table 5.2** provides a summary of the total environmental impact. The figures highlight the fact that the desalination process carries a much higher overall burden compared to the mine water reclamation process. For the bulk of the categories such as climate change and terrestrial acidification, desalination displays scores that are approximately double the impact associated with mine water reclamation. There are two categories where mine water reclamation performs worse than desalination namely water and metal depletion. This can be attributed to the process of extracting the groundwater from abandoned mines, thereby adversely affecting the water and metal content in the surrounding environment.

Table 5.2 Comparison between Impact Assessment Results for Desalination and Mine Water Reclamation (per m^3 potable water produced)

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

Although a comparison between the water treatment processes can be made, there are associated challenges and difficulties as the operations differ in many respects. **Table 5.3** highlights a few of the significant differences between the two 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.

Table 5.3 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) 12000 – 17000 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 non-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)

Both 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 also practical considerations that need to be taken into account prior to the design of these plants. Due to its feed source, the desalination plant has to be constructed in coastal areas with close proximity to seawater. As the mine reclamation plant will have to treat accumulated water from previously mined areas, the plant will reside close to the mines. The feed water quality for mine water reclamation is also a significant factor due to variances in source water. This occurs as a result of different minerals being mined as well as the age of the mine.

5.5 Improvement Analysis

The results up to this point indicate that electricity consumption in the water treatment process is responsible for majority of the environmental impacts in both the desalination and mine water reclamation process. 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 (electricity mix in South Africa), photovoltaic (solar) power and wind power.

The results presented in **Table 5.4** show that for most of the impact categories, the South African electricity mix has a higher impact when compared to the 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 eq. emitted by wind turbines. Looking at another impact category e.g. 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 in the case of climate change and terrestrial acidification, the energy mix used in South Africa generates the highest quantity of carbon dioxide and sulphur dioxide gases when 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 majority of the environmental impacts, conventional electricity has greater environmental consequences then other energy sources such as solar and wind power.

Table 5.4 Impact Assessment for Various Energy Sources (per kWh of electricity)

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}

5.6 Comparison with Conventional Water Treatment Technologies in the Local Context

The results and analysis thus far emphasise the fact that energy is the highest contributor to the environmental burdens associated with both the desalination and mine water reclamation plants. Thus, a further assessment regarding energy consumption was undertaken comparing the environmental impacts of alternative water treatment plants to conventional water treatment plant 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, the Wiggins Waterworks had the highest electricity consumption per kilolitre of water produced at 0.10 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 5.5**. 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 the emissions of 0.08 - 0.11 kg CO_2 eq/ kℓ water, which are calculated in **Table 5.5**, and would be released from a similar water treatment process to that employed at Durban Heights and Wiggins Waterworks.

Table 5.5 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

5.7 Comparison with International Studies

The use of LCA as an assessment tool to gauge the environmental impacts of water technology has been increasingly used since the late 1990s. 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., 2009). Vince et al. (2008) undertook a comparative LCA study of different water treatment processes for the production of potable water and details his results as per **Table 2.1**. 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 as 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 3 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 studies that involved LCAs on desalination plants. One such project revolved around conducting a LCA for a seawater desalinization 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 research paper was to quantify the amount of GHGs that are released from the Southern Seawater Desalinization Plant (SSDP) and determine the "hotspots" for water production. The SimaPro software was also utilised for computation purposes. In order to make the LCA results more representative, Australian databases and libraries had been used. Unfortunately, such databases are currently non-existent for South Africa. The library for Western Australian electricity generation was used to represent energy consumption. In his study, Biswas (2009) concluded that reverse osmosis contributes significantly higher greenhouse gas emissions than other stages of the desalination process with a 75.1 % contribution. This is comparable to the results from the first case study which quantify the GHG emissions from reverse osmosis at 64.6 % (2.84 of a total 4.40 kg CO_2 eq.). One of the reasons for the slight disparity is the fact that micro-filtration was used in the pre-treatment phase for the Australian plant. This reduces the amount of chemicals required for treatment prior to reverse osmosis 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 use of electricity for pumping, membrane operation and water delivery purposes account for 92.1 % of the greenhouse gas emissions during the life cycle of water production which is comparable to the figure of 95.2 % calculated for this project. A similar study carried out by Mrayed and Leslie (2009) found that the greenhouse gas emissions from the generation of electricity for the operation of seawater desalination plant accounted for a large proportion (95%) of the total greenhouse gas emissions.

In addition, an analysis was carried out by Biswas (2009) to determine the carbon footprints for different energy mixes for the desalination process. For this section, GHG emissions were quantified for energy sources that consist of various combinations of wind and national grid energy. The resulting figures emphasise the fact that greenhouse gas emissions can be reduced by a large margin i.e. 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 can be used to power the reverse osmosis system only. However, it is imperative to note that wind energy is normally used in conjunction with other energy sources as a hybrid system and not all sites are suited for the location of wind turbines.

Raluy et al. (2004) evaluated the environmental load associated with various electrical energy sources on the RO system. It was reported that a reduction of greater than 35 % is expected dependant on the origin of the energy i.e. cogeneration, internal combustion engine or a combined cycle (Raluy et al., 2004). In a follow-up report, Raluy et al. (2005) has reported that for a desalination plant using an energy source that is based on combustion of fossil fuel, carbon dioxide emissions of 1.78 kg/m^3 of desalted water and NO_x emissions of 4.05 g/m^3 of desalted water were released. Together with the integration of the RO system with photovoltaic energy, CO_2 emissions were reduced to between 0.6 and 0.9 kg/m^3 eq. and NO_x emissions to between 1.8 and 2.1 g/m^3 (Raluy et al., 2005). A further decrease in environmental impact is achieved when wind energy is utilised in conjunction with the desalination plant with CO_2 emissions of 0.1 kg/m^3 eq. and NO_x emissions of 0.4 g/m^3 (Raluy et al., 2005). Thus, a substantial reduction in emission of GHG is possible by substituting renewable energy sources in place of fossil fuels which can be seen in the results presented in **Table 5.5**. The use of such sources also have the capacity to decrease power consumption of the system where a proposed solar powered direct osmosis process by Khaydarov and Khaydarov (2007) was responsible for a 4 kWh/m^3 reduction.

Regarding desalination of mine affected water, Thiruvenkatachari et al. (2016) undertook an investigation evaluating the effectiveness of an integrated forward osmosis (FO) and reverse osmosis system. By utilising samples from three coal mines as feed, the system was able to achieve a combined recovery of greater 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.

As highlighted in **Section 2.3**, there are various options available in order to minimise 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 and Long, 2008). Pumping efficiency could be increased by installing a VFD 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 polarization and capacitive deionization technology are all advancements in the pipeline that could potentially have a positive impact on the energy consumption (Elimelech & Phillip, 2011 and Subramani et al., 2011). Other improvements include diluting the raw water with another stream to decrease the feed salinity.

5.8 Chemical Discussion

From the results presented in **Section 5.2** and **5.3**, electricity consumption in the operation phase is the main source of the overall environmental impact of both the systems. However, the chemical production and use also carries a significant burden. 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 as the chemicals with the highest impacts.

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).

Vince et al. (2008) carried out an analysis centred around various water treatment processes for particular local conditions. One of the conclusions that was reached was pertaining 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) goes on to 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 of similar chemicals may result in vastly different impacts. For 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 the 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 for the treatment of mine affected water is biocide. According to the details provided in SimaPro, the biocide used in the modelling stages comprises of 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.

As far as the toxicity of discharged concentrate is concerned, Mezher et al. (2011) mentions 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. As mentioned in **Section 2.3,** 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 recent 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 reverse osmosis, 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 savings can be maximised.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

This chapter represents the second part of the Life Cycle Interpretation phase. The first section provides a summary of the results obtained in **Chapter 5** highlighting the significant findings from the study. 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.

6.2 Conclusions

This research project is based on two water treatment processes that utilise alternative sources of water as feed. The first case study revolves around a proposed desalination plant in the Southern eThekwini district which will produce a total of 150 Mℓ/d of potable water. RO was chosen as the major component for separation of salts from the permeate. The second case study is centred around a water treatment process in Mpumalanga that uses mine affected water as the feed source. RO and UF are used in conjunction with each other in a two-stage treatment process to treat 15 Mℓ/d.

The LCA study followed the methodology and guidelines set out in the ISO 14000 series of documentation. The assessment was broken up into four phases namely goal and scope definition, inventory analysis, impact assessment and interpretation. The goal of the study was to determine the impact of the two processes via the generation of environmental LCA scores. The second phase of the analysis involved the collection of data which was the most strenuous constituent of the project. Two phases were considered for the LCA: the construction and operation phase. Design data was used as the basis for calculations with mass balance calculations and technical literature needed for supporting information. Once the inputs and outputs were scaled in terms of the functional unit, SimaPro software was used to undertake the modelling with the ReCiPe Midpoint Method chosen for the third stage of the assessment. The results were then analysed per impact category for each process with further examination undertaken in light of renewable energy use.

The results indicate that the operational phase is the predominant stage responsible for the majority of the environmental impacts attributed to both of the systems. Within this stage, the energy consumption is the greatest contributor with chemical use representing the second highest environmental burden. A comparison of both water treatment processes reveals that the desalination process has a greater environmental impact than the mine water reuse process mainly due to the increased energy requirement. As the results indicate that plant impacts are highly dependent on the electricity source and supply, further investigations on the substitution of fossil fuel based energy with renewable energy were undertaken. It was determined that the use of solar or wind energy could significantly reduce the climate change effect of alternative water treatment to levels that are comparable to conventional water treatment processes currently employed in the eThekwini Municipality.

6.3 Recommendations

As the results presented clearly highlight the high burden of electricity on the studied systems, an effort should be made to decrease the electricity 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 to be 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 by ecoinvent has been made 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 of salination and water consumption as local impact categories is required as these are environmental issues that are pertinent to South Africa in particular.

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. Together with assistance from governmental 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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APPENDIX A: ADDITIONAL TABLES

Table A1.1 Common Life Cycle Impact Categories (Curran, 2006)

Exhibit 4-1. Commonly Used Life Cycle Impact Categories

Impact Category	Scale	Examples of LCI Data (i.e. classification)	Common Possible Characterization Factor	Description of Characterization Factor
Global Warming	Global	Carbon Dioxide (CO_2) Nitrogen Dioxide (NO_2) Methane (CH_4) Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Methyl Bromide (CH_3Br)	Global Warming Potential	Converts LCI data to carbon dioxide (CO_2) equivalents Note: global warming potentials can be 50, 100, or 500 year potentials.
Stratospheric Ozone Depletion	Global	Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Halons Methyl Bromide (CH_3Br)	Ozone Depleting Potential	Converts LCI data to trichlorofluoromethane (CFC-11) equivalents.
Acidification	Regional Local	Sulfur Oxides (SOx) Nitrogen Oxides (NOx) Hydrochloric Acid (HCL) Hydroflouric Acid (HF) Ammonia (NH_4)	Acidification Potential	Converts LCI data to hydrogen (H+) ion equivalents.
Eutrophication	Local	Phosphate (PO_4) Nitrogen Oxide (NO) Nitrogen Dioxide (NO_2) Nitrates Ammonia (NH_4)	Eutrophication Potential	Converts LCI data to phosphate (PO_4) equivalents.
Photochemical Smog	Local	Non-methane hydrocarbon (NMHC)	Photochemical Oxident Creation Potential	Converts LCI data to ethane (C_2H_6) equivalents.
Terrestrial Toxicity	Local	Toxic chemicals with a reported lethal concentration to rodents	LC_{50}	Converts LC_{50} data to equivalents; uses multi-media modeling, exposure pathways.
Aquatic Toxicity	Local	Toxic chemicals with a reported lethal concentration to fish	LC_{50}	Converts LC_{50} data to equivalents; uses multi-media modeling, exposure pathways.
Human Health	Global Regional Local	Total releases to air, water, and soil.	LC_{50}	Converts LC_{50} data to equivalents; uses multi-media modeling, exposure pathways.
Resource Depletion	Global Regional Local	Quantity of minerals used Quantity of fossil fuels used	Resource Depletion Potential	Converts LCI data to a ratio of quantity of resource used versus quantity of resource left in reserve.
Land Use	Global Regional Local	Quantity disposed of in a landfill or other land modifications	Land Availability	Converts mass of solid waste into volume using an estimated density.
Water Use	Regional Local	Water used or consumed	Water Shortage Potential	Converts LCI data to a ratio of quantity of water used versus quantity of resource left in reserve.

Table A1.2 Selected Lists of Impact Categories (Jensen et al., 1997)

The "Leiden list" SETAC-Europe (1992)	SETAC "default list"[1] Udo de Haes (1996b)	"Nordic list" Lindfors et al. (1995c)	ISO preliminary list ISO (1997c)	Scale/comments
non-renewable	abiotic resources	energy and materials	abiotic resources	global
scarce, renewable	biotic resources		biotic resources	global
		water		
	land	land	land use	local
global warming	global warming	global warming	global warming / climate change	global
	depletion of stratospheric ozone	depletion of stratospheric ozone	stratospheric ozone depletion	global
human toxicity	human toxicological impact	human health, toxicological excl. work environment	human toxicity	global, continental, regional, local
		human health, non-toxicological excl. work environment		
occupational safety		human health impacts in work environment		local
environmental toxicity	ecotoxicological impacts	ecotoxicological impacts	ecotoxicity	global, continental, regional, local
photo-oxidant formation	photo-oxidant formation	photo-oxidant formation	photochemical oxidant formation (smog)	continental, regional, local
acidification	acidification	acidification	acidification	continental, regional, local
eutrophication	eutrophication (incl. BOD and heat)	eutrophication	eutrophication	continental, regional, local
COD (chemical oxygen demand) discharge				local
effects of waste heat on water				local
nuisance (smell, noise)	odour			local
	noise			local
	radiation			local, regional
space requirement				local
final solid waste (hazardous)				regional, local
final solid waste (non-hazardous)				regional, local
	casualties			local
		habitat alterations and impacts on biological diversity		local

1. The SETAC "default list" also mention some "flows not followed up to system boundary: input related (energy, materials, plantation woods etc.) and output related (solid wastes etc.)".

Table A1.3 Emissions to Air from South African Electricity Mix per 1 kWh

(Partial extract from SimaPro)

Ammonia	6,09E-05	kg
Benzene	4,37E-08	kg
Pentane	1,99E-10	kg
Acetaldehyde	2,14E-08	kg
Acetic acid	3,55E-09	kg
Acetone	1,47E-11	kg
Acrolein	5,07E-09	kg
Benzaldehyde	3,92E-09	kg
Benzo(a)anthracene	2,35E-15	kg
Benzo(a)pyrene	1,17E-10	kg
Butane	4,43E-10	kg
Cobalt	1,73E-11	kg
Ethane	1,11E-10	kg
Ethanol	5,49E-13	kg
Ethene	1,46E-11	kg
Ethylene oxide	6,7E-13	kg
Ethyne	1,11E-10	kg
Fluoranthene	2,14E-14	kg
Formaldehyde	4,23E-08	kg
Heptane	8,58E-10	kg
Hexane	8,31E-12	kg
Isoprene	1,01E-16	kg
m-Xylene	2,8E-09	kg
Methanol	1,79E-09	kg
o-Xylene	1,14E-09	kg
Phenol	2,65E-11	kg
Propane	3,01E-10	kg
Propene	1,14E-11	kg
Propionic acid	2,69E-13	kg
Styrene	1,6E-09	kg
Toluene	4,16E-08	kg
Xylene	2,86E-08	kg
Phenanthrene	3E-13	kg
Chrysene	2,57E-16	kg
Benzo(g,h,i)perylene	1,71E-16	kg
Ammonia	1,12E-07	kg
Ammonia	3,32E-06	kg
Benzene	2,57E-06	kg
Benzene	9,36E-08	kg
Benzene	3,14E-14	kg
Methane	5,12E-11	kg
Pentane	1,08E-06	kg
Pentane	2,08E-07	kg
1-Pentene	2,66E-13	kg
2,4-D	-1E-13	kg
Acetaldehyde	2,78E-09	kg
Acetaldehyde	6,46E-09	kg

Acetic acid	4,63E-09	kg
Acetic acid	1,15E-08	kg
Acetone	4,23E-08	kg
Acetone	3,79E-09	kg
Acetonitrile	9E-11	kg
Acrolein	2,64E-08	kg
Acrolein	2,71E-12	kg
Atrazine	-8,4E-15	kg
Benzaldehyde	1,43E-09	kg
Benzaldehyde	7,34E-13	kg
Benzo(a)pyrene	7,62E-09	kg
Benzo(a)pyrene	3,41E-11	kg
Butane	1,48E-07	kg
Butane	1,54E-07	kg
1-Butanol	3,55E-15	kg
Butene	3,4E-09	kg
Cobalt	3,87E-08	kg
Cobalt	8,64E-10	kg
Cobalt	6,59E-10	kg
Cyclohexane	1,02E-12	kg
Diethyl ether	5,8E-17	kg
Ethane	7,03E-07	kg
Ethane	4,22E-08	kg
Ethanol	2,63E-09	kg
Ethanol	4,69E-09	kg
Ethene	9,16E-09	kg
Ethene	1,59E-08	kg
Ethylene oxide	7,77E-14	kg
Ethylene oxide	3,89E-11	kg
Ethylene oxide	2,87E-13	kg
Ethyne	3,71E-11	kg
Ethyne	1,28E-09	kg
Formaldehyde	5,08E-07	kg
Formaldehyde	1,99E-08	kg
Formaldehyde	2,48E-13	kg
Formic acid	5,5E-10	kg
Formic acid	7,02E-12	kg
Heptane	3,43E-08	kg
Hexane	4,37E-08	kg
Hexane	8,29E-08	kg
Isoprene	8E-12	kg
m-Xylene	2,46E-14	kg
m-Xylene	8,08E-09	kg
Methanol	7,84E-09	kg
Methanol	7,66E-08	kg
Methyl ethyl ketone	5,55E-09	kg
Methyl formate	-1,4E-11	kg
Metribuzin	-1,4E-14	kg
o-Xylene	1,74E-12	kg
Phenol	2,28E-09	kg
Phenol	5,75E-10	kg

Propane	2,83E-07	kg
Propane	1,51E-07	kg
Propene	1,04E-07	kg
Propene	9,6E-09	kg
Propionic acid	3,11E-10	kg
Propionic acid	1,67E-10	kg
Styrene	2,28E-09	kg
Styrene	3,65E-11	kg
Toluene	8,34E-07	kg
Toluene	4,89E-08	kg
Trifluralin	-1,5E-13	kg
Xylene	5,96E-06	kg
Xylene	3,91E-08	kg
Carbaryl	-1,3E-15	kg
Cypermethrin	-6,4E-16	kg
Glyphosate	-3,3E-12	kg
Permethrin	-1,4E-15	kg
Acephate	-1,1E-14	kg
Metolachlor	-3,5E-14	kg
Phosphoric acid	2,46E-17	kg
Acrylic acid	8,43E-14	kg
2-Propanol	1,2E-09	kg
Diethylene glycol	4,91E-17	kg
Bentazone	-4,6E-15	kg
Benzene, 1,2-dichloro-	2,15E-13	kg
Benzo(k)fluoranthene	2,01E-15	kg
Chlorpyrifos	-5E-14	kg
Dibenz(a,h)anthracene	1,31E-15	kg
Hydrocarbons, chlorinated	1,19E-10	kg
Hydrocarbons, chlorinated	1,83E-08	kg
Hydrocarbons, chlorinated	2,2E-08	kg
Hydrocarbons, unspecified	-4,3E-12	kg
Indeno(1,2,3-cd)pyrene	5,14E-16	kg
Nitrogen, atmospheric	0,000541	kg
Parathion, methyl	-1,7E-15	kg
Phenol, 2,4-dichloro-	5,88E-13	kg
Phenol, 2,4-dichloro-	1,19E-14	kg
Sulfur trioxide	2,66E-12	kg
Sulfur trioxide	6,5E-12	kg
Sulfuric acid	2,59E-13	kg
Sulfuric acid	3,92E-16	kg
Sulfuric acid	6,49E-12	kg
Toluene, 2-chloro-	2,36E-13	kg
Actinides, radioactive, unspecified	0,187274	Bq
Aerosols, radioactive, unspecified	9,78E-06	Bq
Aldehydes, unspecified	3,59E-11	kg
Aldehydes, unspecified	8,68E-08	kg
Aldehydes, unspecified	1,14E-10	kg
Ammonium carbonate	1,13E-10	kg
Antimony	3,46E-08	kg
Antimony	1,65E-08	kg

Antimony	9,69E-11	kg
Antimony	2,72E-10	kg
Antimony-124	2,86E-08	Bq
Antimony-125	1,36E-06	Bq
Argon-41	0,000747	Bq
Arsenic	4,56E-11	kg
Arsenic	1,36E-07	kg
Arsenic	5,7E-09	kg
Arsenic	7,38E-10	kg
Barium	1,34E-08	kg
Barium	7,07E-07	kg
Barium	6,23E-09	kg
Barium	3,22E-09	kg
Barium-140	9,53E-07	Bq
Benzene, ethyl-	1,74E-15	kg
Benzene, ethyl-	8,5E-09	kg
Benzene, ethyl-	5,65E-09	kg
Benzene, hexachloro-	-4,6E-12	kg
Benzene, hexachloro-	2,39E-22	kg
Benzene, hexachloro-	2,95E-13	kg
Benzene, pentachloro-	7,44E-13	kg
Beryllium	4,6E-12	kg
Beryllium	1,9E-09	kg
Beryllium	1,36E-10	kg
Beryllium	3,41E-12	kg
Boron	4,89E-11	kg
Boron	4,19E-06	kg
Boron	1,81E-09	kg
Boron	1,78E-08	kg
Bromine	6,23E-11	kg
Bromine	3,41E-06	kg
Bromine	1,76E-08	kg
Butadiene	6,94E-14	kg
Butadiene	8,03E-15	kg
Butadiene	8,71E-14	kg
Butadiene	2,97E-14	kg
Cadmium	6,41E-11	kg
Cadmium	2,04E-08	kg
Cadmium	1,47E-10	kg
Cadmium	4,95E-10	kg
Cadmium	1,57E-17	kg
Calcium	3,26E-09	kg
Calcium	9,48E-10	kg
Calcium	3,5E-07	kg
Calcium	4E-07	kg
Carbon dioxide, biogenic	2,86E-05	kg
Carbon dioxide, biogenic	2,6E-05	kg
Carbon dioxide, biogenic	0,00699	kg
Carbon dioxide, fossil	0,007885	kg
Carbon dioxide, fossil	1,048887	kg
Carbon dioxide, fossil	0,004729	kg

Carbon dioxide, fossil	4,95E-09	kg
Carbon disulfide	1,15E-16	kg
Carbon disulfide	4,73E-07	kg
Carbon disulfide	7,35E-12	kg
Carbon monoxide, biogenic	2,87E-10	kg
Carbon monoxide, biogenic	6,33E-07	kg
Carbon monoxide, biogenic	1,39E-05	kg
Carbon monoxide, fossil	0,00017	kg
Carbon monoxide, fossil	0,000121	kg
Carbon monoxide, fossil	2,19E-06	kg
Carbon monoxide, fossil	5,82E-12	kg
Carbon-14	1,203155	Bq
Cerium-141	2,27E-07	Bq
Cesium-134	1,09E-08	Bq
Cesium-137	6,1E-07	Bq
Chlorine	5,16E-08	kg
Chlorine	3,06E-10	kg
Chlorine	1,33E-08	kg
Chlorine	3,22E-08	kg
Chloroform	5,23E-17	kg
Chloroform	8,85E-09	kg
Chloroform	1,13E-11	kg
Chromium	7,94E-10	kg
Chromium	2,27E-07	kg
Chromium	8,65E-10	kg
Chromium	7,86E-17	kg
Chromium VI	1,08E-12	kg
Chromium VI	1,87E-08	kg
Chromium VI	6,93E-10	kg
Chromium VI	4,61E-11	kg
Chromium-51	1,45E-08	Bq
Cobalt-58	9,62E-07	Bq
Cobalt-60	4,52E-06	Bq
Copper	2E-08	kg
Copper	1,7E-07	kg
Copper	9,11E-09	kg
Copper	3,43E-09	kg
Copper	2,67E-15	kg
Cumene	4,7E-18	kg
Cumene	4,92E-10	kg
Cumene	2,39E-09	kg
Cyanide	2,21E-15	kg
Cyanide	2,32E-07	kg
Cyanide	1,11E-10	kg
Dinitrogen monoxide	5,44E-05	kg
Dinitrogen monoxide	1,45E-05	kg
Dinitrogen monoxide	8,48E-06	kg
Dinitrogen monoxide	4,72E-14	kg
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	3,41E-10	kg
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	2,06E-10	kg
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	8,99E-14	kg

Ethane, 1,2-dichloro-	3,6E-09	kg
Ethane, 1,2-dichloro-	1,22E-09	kg
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	6,44E-09	kg
Ethane, hexafluoro-, HFC-116	8,01E-10	kg
Ethane, hexafluoro-, HFC-116	2,84E-13	kg
Ethene, chloro-	3,55E-17	kg
Ethene, chloro-	7,33E-10	kg
Ethene, tetrachloro-	7,67E-14	kg
Ethene, tetrachloro-	3,88E-09	kg
Ethene, tetrachloro-	2,07E-13	kg
Ethylene diamine	3,28E-12	kg
Fluorine	3,13E-12	kg
Fluorine	2,62E-09	kg
Fluorine	6,55E-08	kg
Fluorine	3,37E-09	kg
Fluosilicic acid	4,18E-09	kg
Heat, waste	0,000191	MJ
Heat, waste	7,21E-12	MJ
Heat, waste	0,002734	MJ
Helium	4,04E-11	kg
Helium	6,67E-09	kg
Hydrocarbons, aliphatic, alkanes, cyclic	5,22E-08	kg
Hydrocarbons, aliphatic, alkanes, cyclic	5,94E-10	kg
Hydrocarbons, aliphatic, alkanes, unspecified	3E-07	kg
Hydrocarbons, aliphatic, alkanes, unspecified	1,48E-06	kg
Hydrocarbons, aliphatic, alkanes, unspecified	8,76E-08	kg
Hydrocarbons, aliphatic, unsaturated	1,61E-11	kg
Hydrocarbons, aliphatic, unsaturated	1,4E-06	kg
Hydrocarbons, aliphatic, unsaturated	2,16E-07	kg
Hydrocarbons, aromatic	2,44E-08	kg
Hydrocarbons, aromatic	9,04E-10	kg
Hydrocarbons, aromatic	4,97E-09	kg
Hydrogen	2,46E-09	kg
Hydrogen	1,11E-07	kg
Hydrogen chloride	1,51E-07	kg
Hydrogen chloride	0,000289	kg
Hydrogen chloride	8,48E-07	kg
Hydrogen chloride	1,35E-15	kg
Hydrogen fluoride	5,81E-07	kg
Hydrogen fluoride	3,09E-05	kg
Hydrogen fluoride	7,04E-08	kg
Hydrogen sulfide	2,29E-08	kg
Hydrogen sulfide	1,7E-08	kg
Hydrogen sulfide	3,71E-09	kg
Hydrogen sulfide	1,09E-09	kg
Hydrogen-3, Tritium	1,903482	Bq
Iodine	1,82E-11	kg
Iodine	1,73E-06	kg
Iodine	6,94E-09	kg
Iodine-129	0,000483	Bq
Iodine-131	0,000284	Bq

Iodine-133	0,000106	Bq
Iron	8,28E-08	kg
Iron	2,83E-09	kg
Iron	1,17E-06	kg
Iron	1,5E-08	kg
Isocyanic acid	2,13E-09	kg
Krypton-85	0,002995	Bq
Krypton-85m	0,580063	Bq
Krypton-87	0,002991	Bq
Krypton-88	0,003955	Bq
Krypton-89	0,001684	Bq
Lanthanum-140	7,99E-08	Bq
Lead	9,5E-09	kg
Lead	4,8E-07	kg
Lead	9,63E-09	kg
Lead	4,39E-09	kg
Lead	3,15E-17	kg
Lead-210	7,58E-06	Bq
Lead-210	0,757642	Bq
Lead-210	0,002984	Bq
Magnesium	2,26E-11	kg
Magnesium	9,93E-07	kg
Magnesium	1,07E-07	kg
Magnesium	3,4E-08	kg
Manganese	2,97E-09	kg
Manganese	4,01E-07	kg
Manganese	2,42E-08	kg
Manganese	1,3E-08	kg
Manganese-54	7,44E-09	Bq
Mercury	-2,1E-10	kg
Mercury	2,96E-08	kg
Mercury	7,4E-11	kg
Mercury	1,12E-10	kg
Mercury	1,1E-19	kg
Methane, biogenic	8,75E-11	kg
Methane, biogenic	5,26E-06	kg
Methane, biogenic	1,92E-07	kg
Methane, bromochlorodifluoro-, Halon 1211	1,27E-11	kg
Methane, bromotrifluoro-, Halon 1301	1,3E-10	kg
Methane, bromotrifluoro-, Halon 1301	2,16E-16	kg
Methane, chlorodifluoro-, HCFC-22	3,23E-09	kg
Methane, chlorodifluoro-, HCFC-22	2,14E-12	kg
Methane, dichloro-, HCC-30	2,35E-11	kg
Methane, dichloro-, HCC-30	2,62E-08	kg
Methane, dichloro-, HCC-30	2,12E-12	kg
Methane, dichlorodifluoro-, CFC-12	9,43E-17	kg
Methane, dichlorodifluoro-, CFC-12	2,04E-14	kg
Methane, dichlorodifluoro-, CFC-12	2,95E-12	kg
Methane, dichlorofluoro-, HCFC-21	2,56E-16	kg
Methane, fossil	2,06E-06	kg
Methane, fossil	0,001737	kg

Methane, fossil	1,07E-06	kg
Methane, fossil	7,86E-14	kg
Methane, monochloro-, R-40	4,79E-08	kg
Methane, trichlorofluoro-, CFC-11	4,15E-16	kg
Methane, trifluoro-, HFC-23	8,14E-14	kg
Molybdenum	3,46E-09	kg
Molybdenum	1,26E-08	kg
Molybdenum	1,87E-09	kg
Molybdenum	2,8E-10	kg
Monoethanolamine	5,25E-09	kg
Nickel	5,09E-10	kg
Nickel	2,74E-07	kg
Nickel	1,97E-09	kg
Nickel	9,26E-09	kg
Nickel	1,1E-16	kg
Niobium-95	1,34E-06	Bq
Nitrate	1,52E-09	kg
Nitrate	3,17E-09	kg
Nitrate	9,22E-09	kg
Nitrate	2,23E-13	kg
Nitrobenzene	8,08E-13	kg
Nitrogen oxides	0,000396	kg
Nitrogen oxides	0,004153	kg
Nitrogen oxides	2,36E-05	kg
Nitrogen oxides	1,02E-08	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	6,82E-05	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	2,47E-05	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	1,45E-06	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	1,06E-12	kg
Noble gases, radioactive, unspecified	4646,117	Bq
Ozone	4,57E-06	kg
Ozone	4,06E-12	kg
PAH, polycyclic aromatic hydrocarbons	1,24E-08	kg
PAH, polycyclic aromatic hydrocarbons	8,49E-08	kg
PAH, polycyclic aromatic hydrocarbons	8,77E-10	kg
Particulates, < 2.5 um	9,93E-06	kg
Particulates, < 2.5 um	9,68E-05	kg
Particulates, < 2.5 um	8,6E-07	kg
Particulates, < 2.5 um	3,07E-06	kg
Particulates, < 2.5 um	5,98E-14	kg
Particulates, > 10 um	3,94E-06	kg
Particulates, > 10 um	0,001325	kg
Particulates, > 10 um	2,14E-06	kg
Particulates, > 10 um	1,09E-06	kg
Particulates, > 2.5 um, and < 10um	2,45E-06	kg
Particulates, > 2.5 um, and < 10um	1,9E-05	kg
Particulates, > 2.5 um, and < 10um	1,29E-06	kg
Particulates, > 2.5 um, and < 10um	6,86E-07	kg
Phenol, pentachloro-	5,02E-11	kg
Phenol, pentachloro-	3,35E-09	kg
Phenol, pentachloro-	6,07E-13	kg

Phosphorus	1,33E-13	kg
Phosphorus	1,46E-10	kg
Phosphorus	1,81E-09	kg
Phosphorus	2,04E-08	kg
Platinum	-6,9E-21	kg
Platinum	2,3E-17	kg
Plutonium-238	6,58E-11	Bq
Plutonium-alpha	1,51E-10	Bq
Polonium-210	1,38E-05	Bq
Polonium-210	1,343857	Bq
Polonium-210	0,005474	Bq
Polychlorinated biphenyls	7,13E-12	kg
Polychlorinated biphenyls	2,25E-16	kg
Potassium	3,65E-10	kg
Potassium	1,76E-10	kg
Potassium	1,84E-07	kg
Potassium	1,58E-06	kg
Potassium-40	1,86E-06	Bq
Potassium-40	0,251003	Bq
Potassium-40	0,000742	Bq
Propanal	3,36E-16	kg
Propanal	3,85E-10	kg
Propanal	8,43E-13	kg
Propylene oxide	1,54E-10	kg
Protactinium-234	0,011598	Bq
Radioactive species, other beta emitters	5,04E-06	Bq
Radioactive species, other beta emitters	0,007275	Bq
Radium-226	1,96E-06	Bq
Radium-226	0,212741	Bq
Radium-226	0,000774	Bq
Radium-228	5,94E-07	Bq
Radium-228	0,064457	Bq
Radium-228	0,000387	Bq
Radon-220	4,05E-05	Bq
Radon-220	5,534135	Bq
Radon-220	0,01539	Bq
Radon-222	2,27E-05	Bq
Radon-222	1157,653	Bq
Radon-222	41124,47	Bq
Radon-222	0,008667	Bq
Ruthenium-103	1,94E-10	Bq
Scandium	5,6E-16	kg
Scandium	7,15E-12	kg
Scandium	3,85E-09	kg
Scandium	3,24E-12	kg
Selenium	3,56E-11	kg
Selenium	1,83E-07	kg
Selenium	5,38E-10	kg
Selenium	4,32E-10	kg
Selenium	1,57E-17	kg
Silicon	2,47E-08	kg

Silicon	1,21E-08	kg
Silicon	2,39E-07	kg
Silicon	4,1E-08	kg
Silicon tetrafluoride	1,7E-12	kg
Silver	6,49E-14	kg
Silver	2,12E-13	kg
Silver	1,61E-10	kg
Silver	6,55E-14	kg
Silver-110	1,82E-07	Bq
Sodium	3,11E-09	kg
Sodium	2,06E-09	kg
Sodium	6,32E-08	kg
Sodium	1E-07	kg
Sodium chlorate	4,13E-11	kg
Sodium dichromate	2,32E-12	kg
Sodium formate	1,71E-11	kg
Strontium	1,96E-10	kg
Strontium	6,46E-07	kg
Strontium	3,91E-09	kg
Strontium	3,12E-09	kg
Sulfate	1,32E-08	kg
Sulfate	2,83E-08	kg
Sulfate	9,9E-07	kg
Sulfate	7,81E-07	kg
Sulfur dioxide	1,13E-05	kg
Sulfur dioxide	0,007706	kg
Sulfur dioxide	2,88E-05	kg
Sulfur dioxide	1,57E-12	kg
Sulfur hexafluoride	1,19E-07	kg
Sulfur hexafluoride	2,87E-13	kg
Sulfur hexafluoride	5,44E-17	kg
t-Butyl methyl ether	4,98E-10	kg
Thallium	1,97E-11	kg
Thallium	1,49E-12	kg
Thallium	4,09E-12	kg
Thorium	1,81E-15	kg
Thorium	4,86E-14	kg
Thorium	4,88E-12	kg
Thorium-228	3,15E-07	Bq
Thorium-228	0,035996	Bq
Thorium-228	0,000132	Bq
Thorium-230	0,012458	Bq
Thorium-232	4,91E-07	Bq
Thorium-232	0,05267	Bq
Thorium-232	0,000195	Bq
Thorium-234	0,011598	Bq
Tin	2,75E-09	kg
Tin	4,29E-09	kg
Tin	2,24E-10	kg
Tin	2,54E-12	kg
Titanium	1,52E-09	kg

Titanium	8,48E-12	kg
Titanium	7,02E-08	kg
Titanium	1,02E-09	kg
Uranium	2,88E-15	kg
Uranium	3,56E-14	kg
Uranium	6,5E-12	kg
Uranium alpha	0,021575	Bq
Uranium-234	0,025826	Bq
Uranium-235	0,00018	Bq
Uranium-238	1,63E-06	Bq
Uranium-238	0,177067	Bq
Uranium-238	0,000644	Bq
Vanadium	3,28E-10	kg
Vanadium	1,64E-07	kg
Vanadium	6,67E-09	kg
Vanadium	2,91E-08	kg
Xenon-131m	0,015713	Bq
Xenon-133	35,25012	Bq
Xenon-133m	0,000544	Bq
Xenon-135	9,759922	Bq
Xenon-135m	0,145384	Bq
Xenon-137	0,004609	Bq
Xenon-138	0,034339	Bq
Zinc	6,52E-09	kg
Zinc	4,92E-07	kg
Zinc	6,9E-09	kg
Zinc	2,36E-08	kg
Zinc	1,57E-15	kg
Zinc-65	3,71E-08	Bq
Zirconium	4,37E-13	kg
Zirconium-95	3,35E-06	Bq
Ethane, 1,1,1-trichloro-, HCFC-140	9,68E-17	kg
Ethane, 1,1,1-trichloro-, HCFC-140	1,81E-09	kg
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	1,8E-10	kg
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	1,86E-10	kg
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	3,98E-15	kg
Ethane, 1,1-difluoro-, HFC-152a	1,23E-11	kg
Ethane, 1,1-difluoro-, HFC-152a	4,4E-10	kg
Methane, bromo-, Halon 1001	1,42E-16	kg
Carbonyl sulfide	2,42E-09	kg
Aniline	6,05E-13	kg
Boron trifluoride	4,65E-15	kg
Chloroacetic acid	2,32E-11	kg
Dimethylamine	1,64E-12	kg
Methyl acrylate	9,53E-14	kg
Phosphine	3,18E-14	kg
Acetamide	-2,7E-15	kg
Alachlor	-1,1E-14	kg
Diflubenzuron	-1,4E-16	kg
Fomesafen	-1,7E-14	kg
Lactofen	-2,1E-15	kg

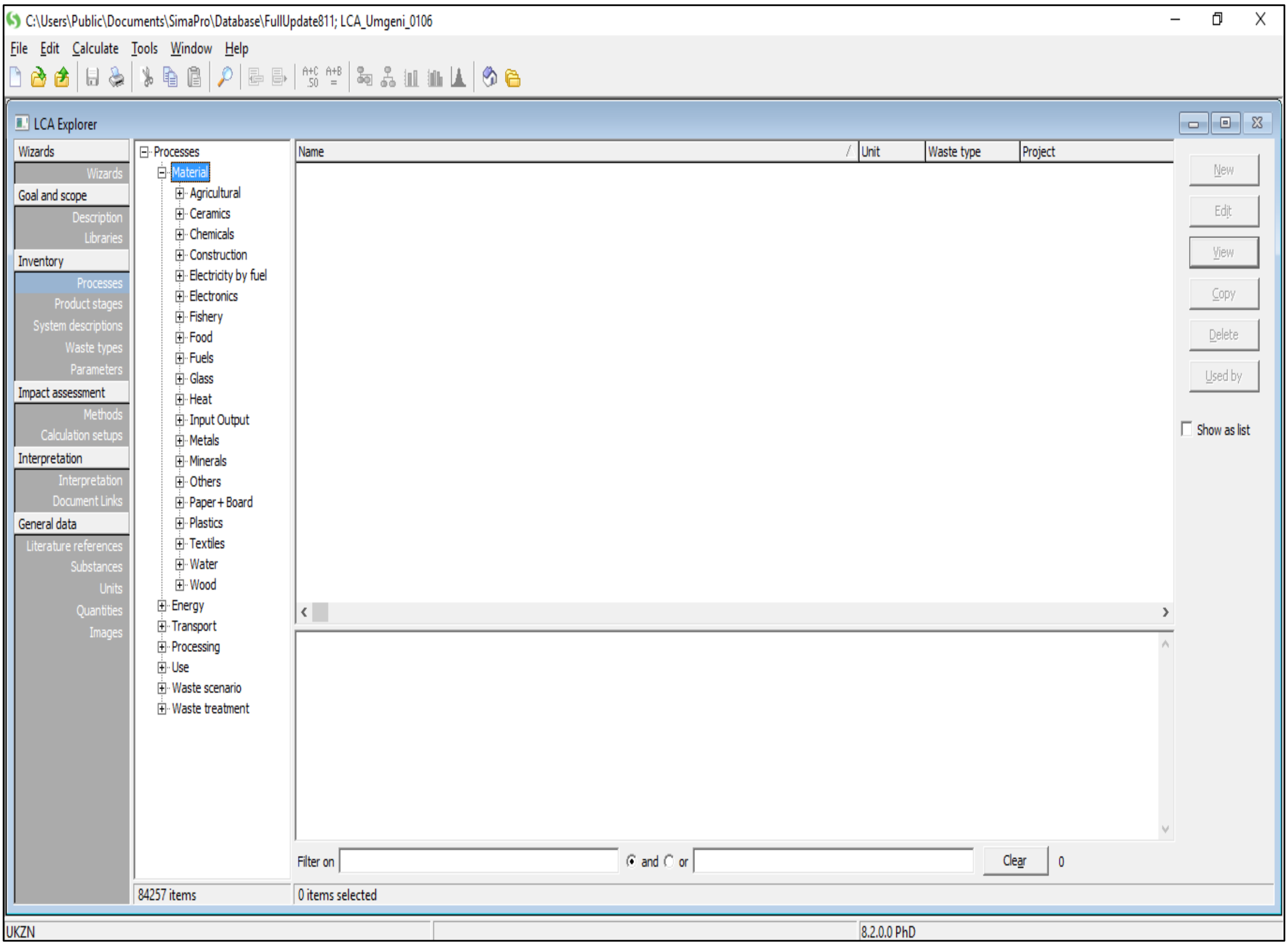
Pendimethalin	-9,4E-14	kg
Propiconazole	-1,6E-15	kg
Sethoxydim	-1,1E-15	kg
Thiodicarb	-5,4E-16	kg
Sodium hydroxide	-9E-19	kg
Sodium hydroxide	3,1E-11	kg
Tungsten	9,52E-13	kg
Tungsten	4,35E-10	kg
Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	1,8E-10	kg
Acenaphthene	8,52E-16	kg
Acenaphthene	4,6E-11	kg
Acenaphthene	9,68E-16	kg
Acenaphthylene	1,22E-13	kg
Acifluorfen	-1,5E-15	kg
Azoxystrobin	-5E-15	kg
Benzo(b)fluoranthene	2,78E-15	kg
Cyfluthrin	-2,6E-16	kg
Cyhalothrin, gamma-	-3E-15	kg
Dicamba	-8,4E-16	kg
Flufenacet	-1,1E-15	kg
Flumetsulam	-2,6E-16	kg
Flumiclorac-pentyl	-4,4E-16	kg
Fluorene	1,94E-14	kg
Furan	7,53E-18	kg
Furan	2,4E-09	kg
Hydrogen peroxide	8,32E-12	kg
Imazamox	-6,6E-16	kg
Imazaquin	-2,1E-15	kg
Imazethapyr	-4,4E-15	kg
Paraquat	-8,9E-15	kg
Pyrene	1,56E-14	kg
Sulfentrazone	-1,1E-14	kg
1-Pentanol	1,34E-13	kg
Benzene, 1-methyl-2-nitro-	-1,6E-15	kg
Ethylamine	1,69E-13	kg
Nitrogen fluoride	1,36E-17	kg
Trimethylamine	-8,9E-16	kg
Esfenvalerate	-1,6E-15	kg
Fluazifop-p-butyl	-3E-15	kg
Benzal chloride	6,2E-16	kg
Carbon dioxide, land transformation	6,2E-06	kg
1,4-Butanediol	4,33E-14	kg
2-Methyl-1-propanol	2,36E-13	kg
Arsine	9,79E-19	kg
Boric acid	6,95E-19	kg
Butyrolactone	3,31E-14	kg
Chlorosilane, trimethyl-	4,56E-12	kg
Ethyl acetate	5,55E-09	kg
Ethyl cellulose	1,12E-11	kg
Methyl borate	9,15E-14	kg
Sodium tetrahydroborate	9,02E-15	kg

Tetramethyl ammonium hydroxide	3,26E-13	kg
Carbon dioxide, land transformation	4,65E-05	kg
Terpenes	7,5E-11	kg
Chlorimuron-ethyl	-2,5E-15	kg
Quizalofop ethyl ester	-5,2E-16	kg
1-Propanol	9,44E-13	kg
Methane, tetrachloro-, CFC-10	4,22E-14	kg
Methane, tetrachloro-, CFC-10	2,52E-11	kg
Methane, tetrafluoro-, CFC-14	1,1E-08	kg
Methane, tetrafluoro-, CFC-14	2,03E-14	kg
Aluminium	0,000156	kg
Aluminium	7,39E-10	kg
Aluminium	1,08E-06	kg
Aluminium	2,75E-08	kg
Pentane, 2-methyl-	1,53E-11	kg
2-Butene, 2-methyl-	6,11E-17	kg
Methyl acetate	-4,2E-16	kg
Chlorosulfonic acid	1,2E-13	kg
2-Aminopropanol	-5,8E-16	kg
2-Nitrobenzoic acid	-1,8E-15	kg
Anthranilic acid	-1,4E-15	kg
Chloramine	4,7E-13	kg
Chlorosulfonic acid	-2,7E-15	kg
Cyanoacetic acid	-2,2E-15	kg
Diethylamine	2,68E-13	kg
Dimethyl malonate	-2,7E-15	kg
Dipropylamine	1,72E-13	kg
Formamide	2,46E-13	kg
Isopropylamine	2,19E-14	kg
Lactic acid	1,35E-13	kg
Methanesulfonic acid	-2,2E-15	kg
Methyl lactate	1,48E-13	kg
Phosphorus trichloride	9,68E-15	kg
Propylamine	7,83E-14	kg
t-Butylamine	1,42E-14	kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	1,59E-14	kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	1,18E-13	kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	5,2E-15	kg
Carfentrazone-ethyl	-1,4E-16	kg
Clethodim	-7,4E-15	kg
Flumioxazin	-4,5E-15	kg
Fenoxaprop	-2,1E-15	kg
Pyraclostrobin (prop)	-3,8E-15	kg
Thifensulfuron	-1,5E-16	kg
Trifloxystrobin	-9,7E-17	kg
Sulfur oxides	5,59E-10	kg
Methylamine	3,17E-14	kg
Cloransulam-methyl	-1,3E-15	kg
Carbon	1,62E-11	kg
Lithium	2,78E-15	kg
Argon-40	7,88E-06	kg

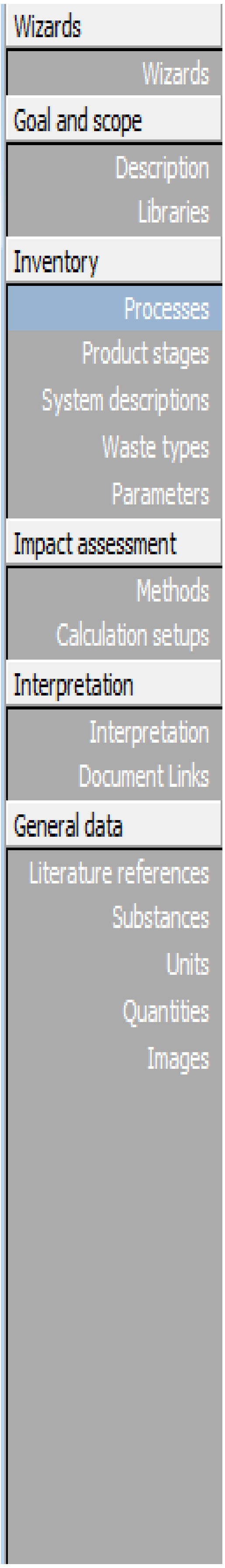
Perfluoropentane	3,19E-11	kg
Water/m3	0,002321	m3
Chromium IV	2,82E-17	kg
Organic carbon	4,04E-11	kg
Water/m3	4,45E-06	m3
Water/m3	1,77E-06	m3
Water/m3	1,95E-12	m3
Carbon monoxide, land transformation	5,2E-08	kg
Methane, land transformation	3,4E-09	kg
Chlorinated solvents, unspecified	7,74E-15	kg

APPENDIX B: SIMAPRO SETUP

1. This is the home screen of SimaPro.



2. The bar on the left hand side provides links to use for navigating the program. The following provides a brief description of the various functions within the LCA explorer.



- Wizards : Contains tutorials with step-by-step instructions.

Goal and Scope

- Description : Allows the user to load details about the specific project such as goal, functional unit and refernce flows.

- Libraries : This shows details of all the pre-loaded databases such as ecoinvent.

Inventory

- Processes : Indicates a list of processes within the various databases.

- Product stages : Allows the user to define the different stages in a LCA (assembly, life cycle, disposal, disassembly and reuse)

- System description : Provides a description of the various systems.

- Waste types : Displays a list of waste material.

- Parameters : Allows the user to input variables and calculation sequences.

Impact Assessment

- Methods: Displays a list of available methods

- Calculation setups: Displays a list of calculations within the project

Interpretation

- Interpretation: Allows the user to input summary and notes regarding the results.

- Provides links to the web sites for the various libraries

General Data

- Literature references: Lists literature references for the data in the libraries

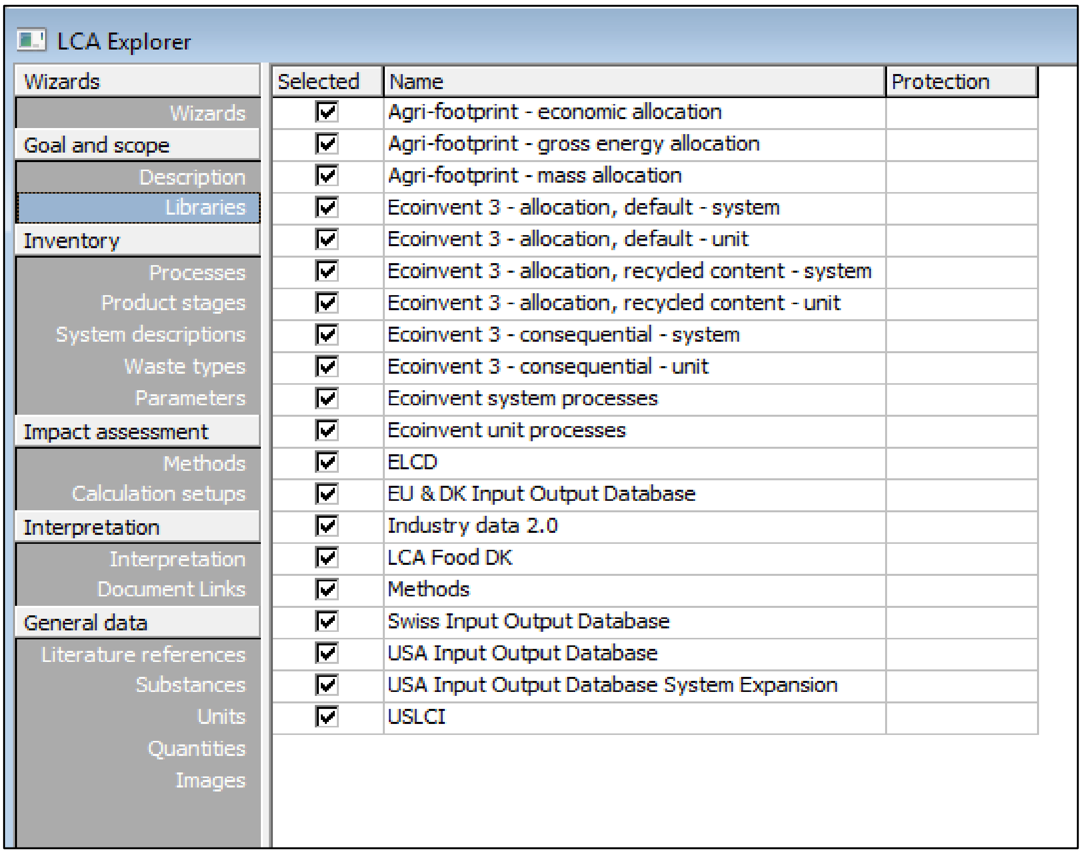
- Substances: Displays a list of available substances such as raw materials.

- Units: Displays a list of units in SimaPro

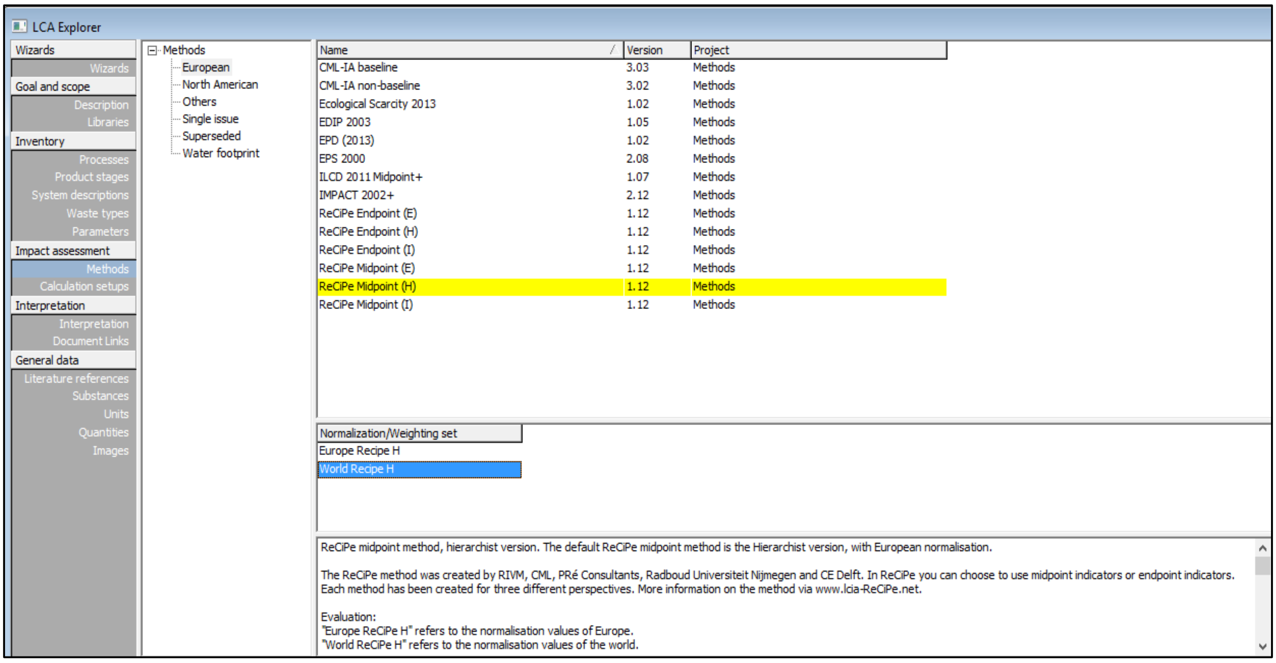
- Quantities: Indicates the dimensions used.

- Images: Displays various pre-loaded images.

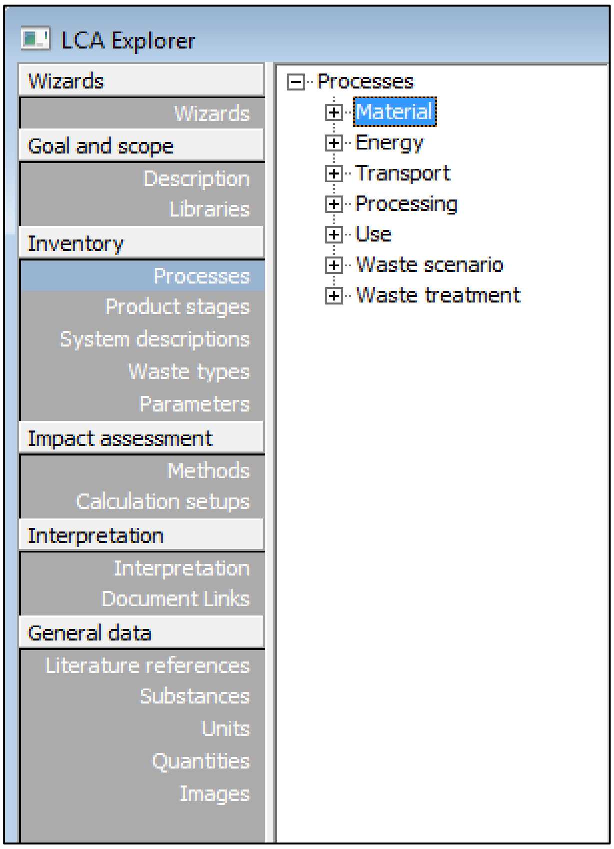
3. The libraries consist of databases that contain peer-reviewed data used by researchers. The checked boxes indicate that the library is active and in use.



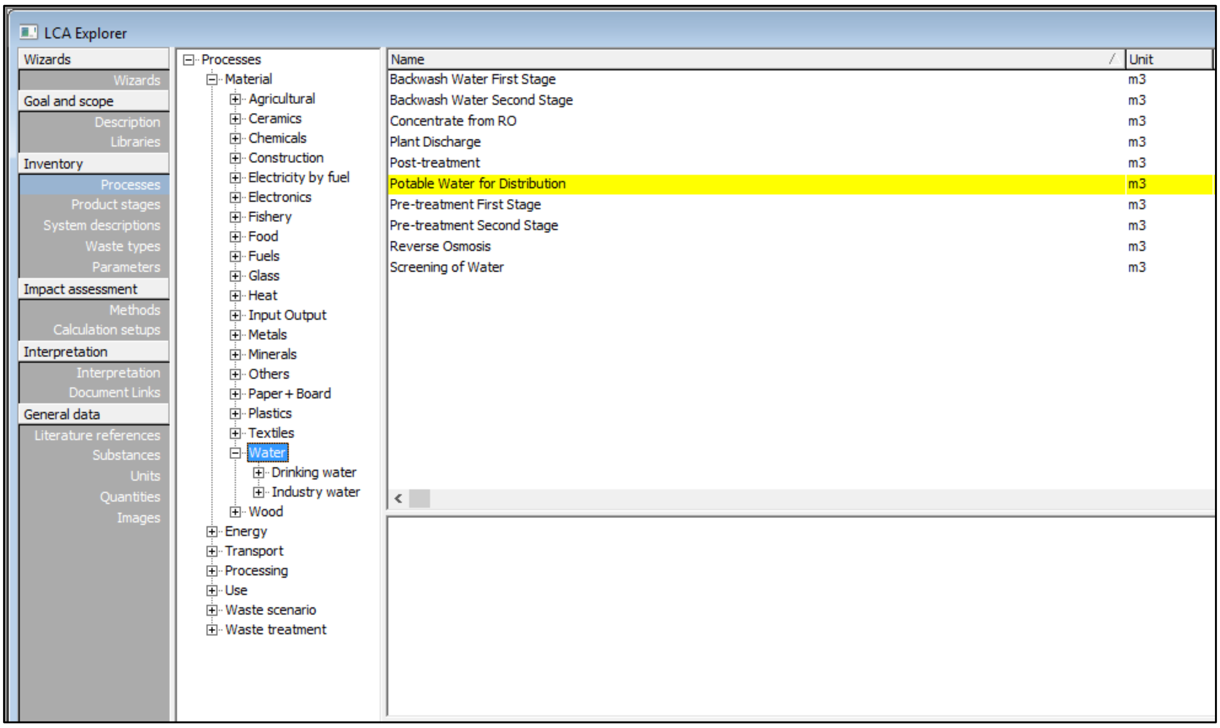
4. These are a list of the impact assessment methods in SimaPro. The ReCiPe Midpoint method was used for this study.



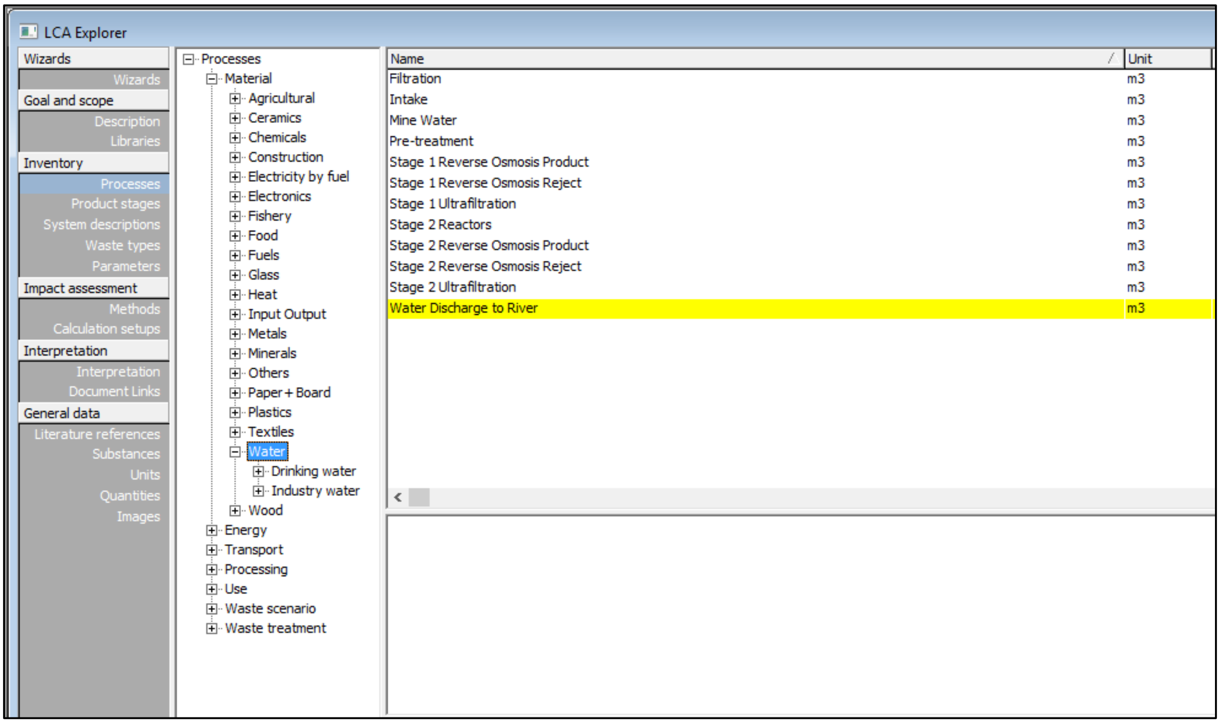
5. The processes are divided into sub-sections in terms of the various process categories.



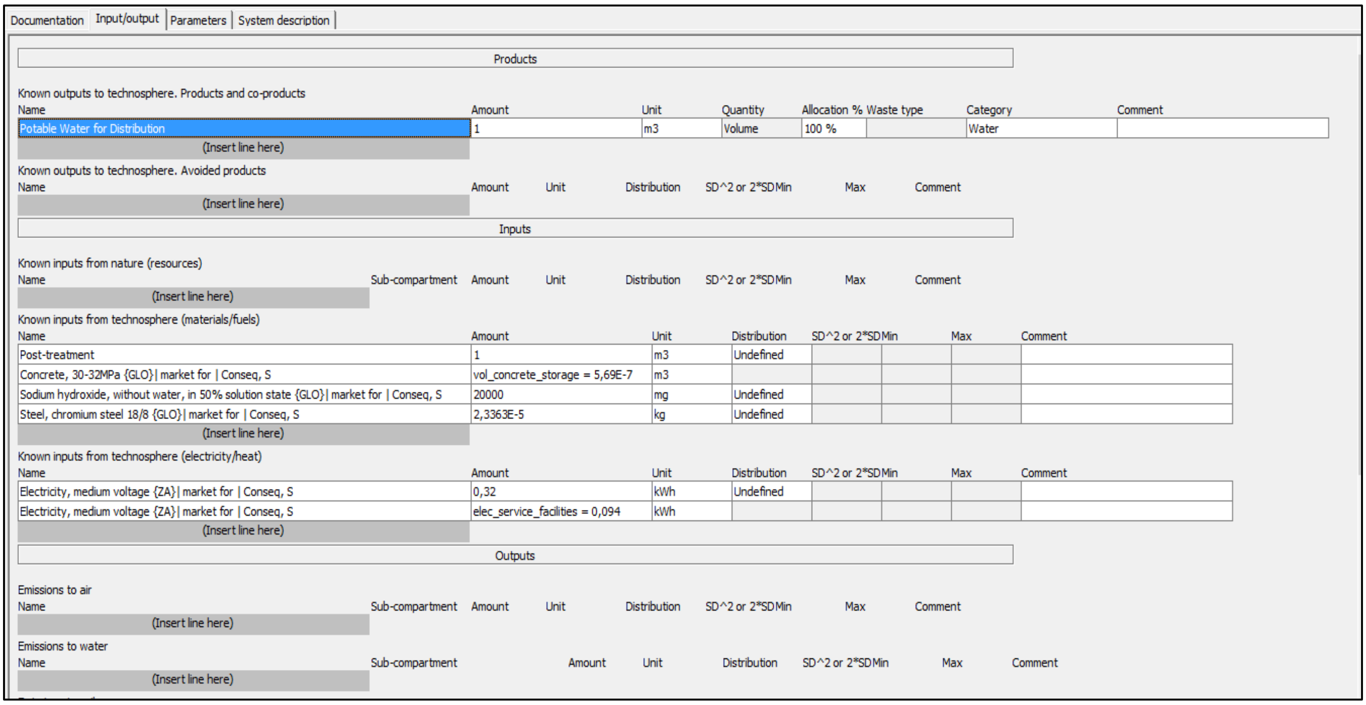
6. For the purposes of this study, new processes were compiled under the "water" sub-section. The first image shows the compilation of the various unit operations that make up the first case study i.e. the desalination process.



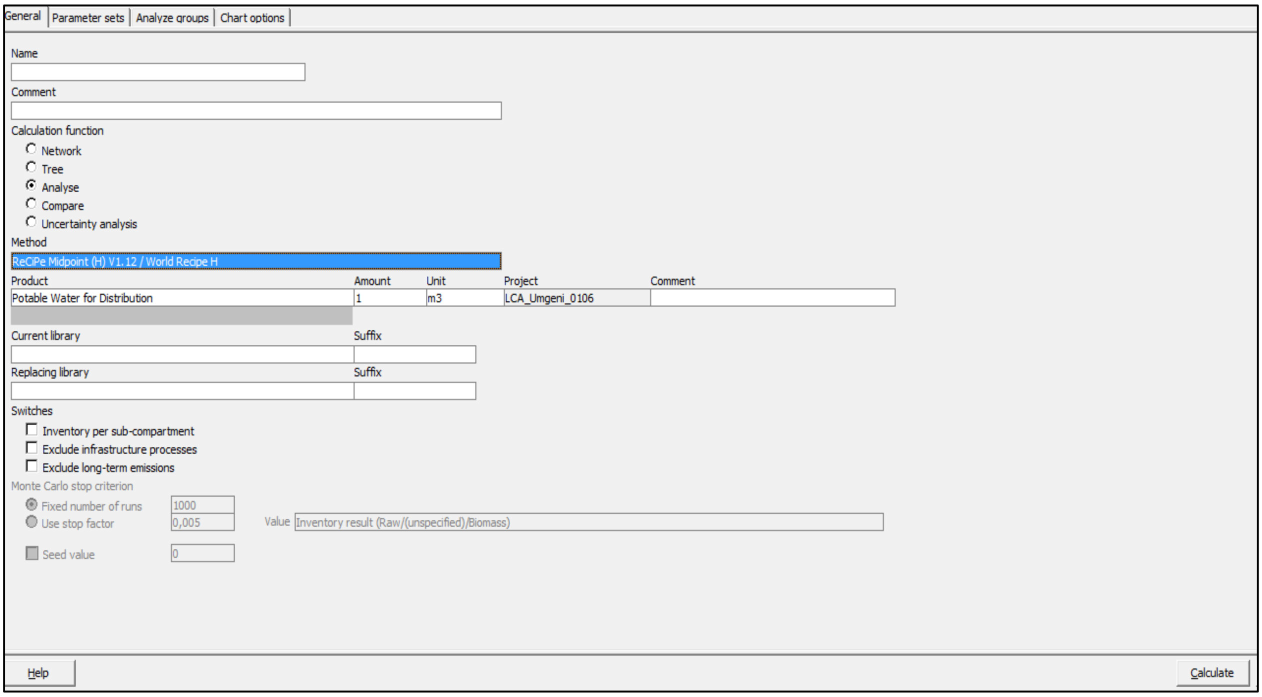
The image below shows the unit operations for the mine water reclamation process which was the second case study.



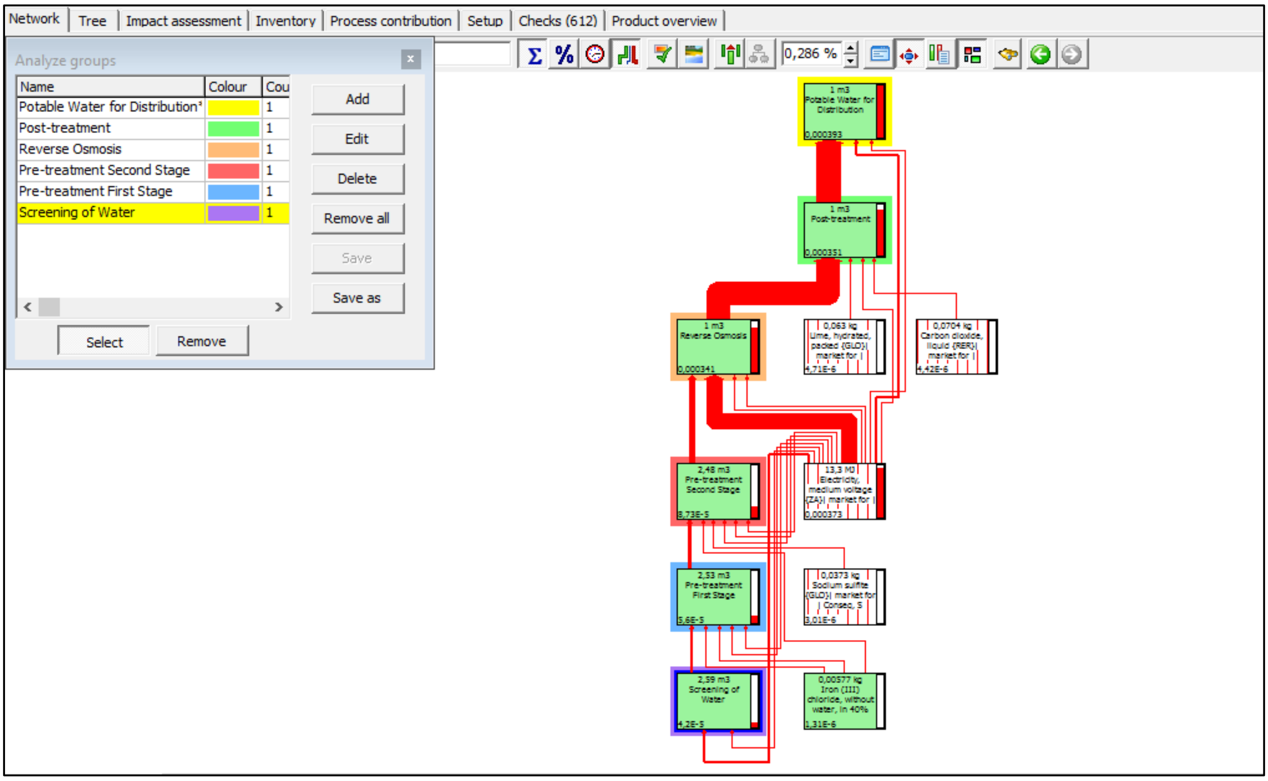
7. Each of the processes need to be described in terms of products, inputs and outputs. Products are divided into products and co-products and avoided products. Inputs consist of inputs from nature, inputs from technosphere in terms of materials and electricity. Outputs are divided into emissions to air, water and soil as well as waste flows.



8. Once all the processes have been the compiled, the final product flow was analysed in terms of the functional unit and the impact assessment method.



9. The resulting analysis is produced in two formats – either as a network diagram or as a bar graph. The network diagram is a graphical representation that indicates the parameters that have the highest contribution via the width of the red arrows.



The second diagram depicts the results in terms of the various impact assessment categories for the individual unit operations. This is possible by making use of the “analyse groups” function presented in the above figure. The chart can also be exported to Excel in a spreadsheet format.