An industrial ecology approach to salt-related environmental sustainability issues in a large industrial complex

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Declaration

I know the meaning of plagiarism and declare that all the work in the document, save for that which is properly acknowledged, is my own.

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Synopsis

South Africa is a developing country with aspirations for economic growth that rely to a large extent on growth in industrial manufacturing. Several large industrial hubs in South Africa add value to extracted mineral resources by means of chemical or metallurgical transformations into intermediate or useful products. Their activities do however lead to dissipative losses of vast volumes of freshwater for cooling purposes, which give rise to sustainability concerns as the catchment areas in which many of these industries were built are relatively water scarce, necessitating the need for environmentally damaging inter-basin transfers of water. Together with established concerns associated with emissions and the considerable resource use (*e.g.* global warming, acidification, destruction of natural ecosystems, land-filling of ash), the transfer of saline water from mines for desalination to supplement scarce raw water has resulted in further secondary effects which affect security of freshwater supply quality and quantity. The economic aspirations for expansion in the concerned regions cannot be realised in a sustainable fashion unless the current understanding and management of the complicated water networks and associated salts accumulation problems are improved. These problems are embodied in what is termed the “Secunda industrial complex”, the industrial hub selected for this research, in particular in the industrial activities at Eskom’s Tutuka power station near Standerton, the Sasol Synthetic Fuels and Sasol Technology production site near Secunda, and their associated coal mines.

Industrial ecology has developed into an established approach to improve waste reduction and resource use efficiency, explicitly using systems-based methods to improve the understanding and management of environmental concerns in the complicated real world of production and consumption. This thesis aims to demonstrate the application of industrial ecology (IE) theory to understand environmental sustainability problems relating to the accumulation of saline wastes and to study the potential for integrated technology interventions which take multi-party engagements and effects into account.

The work presented in this thesis forms part of a larger WRC commissioned project with the main objective to “assess the key factors that influence the long-term environmental sustainability of the Secunda complex and the potential synergy for reuse of waste products and opportunities for implementing of integrated technological solutions”. This dissertation serves this general objective by formulating responses to the following key questions:

i) Which environmental sustainability violations related to salts and water are expressed in the Secunda complex?

ii) Is there potential for multiparty engagement in synergistic exchanges of wastes in the Secunda complex?

iii) Does the implementation of such an intervention present favourable environmental performance compared to its base case?

The procedures of an IE assessment, consisting of a literature review and consultation process with industries, followed by options generation for potential symbiotic relationships, and a systems assessment of a preferred option, are employed in this thesis.

Recent and relevant literature is reviewed to provide insight into the current status of IE and salts management in the Secunda complex. An evaluation of technological interventions for water treatment within the complex found that while water balance problems have generally been sufficiently addressed by these attempts, the salts problem persists. Recent studies in which Life Cycle Assessment (LCA) was applied as a tool for assessing environmental performance of water treatment applications are reviewed to provide insight into the status of this technique for evaluating water applications and to learn from LCA studies of water desalination systems similar to those in the Secunda complex.

In response to the first key question, an environmental sustainability assessment is performed using the Natural Step Framework and from this several violations of sustainability principles are identified. Practical interventions, which are aimed at addressing these violations through the incorporation or consideration of multi-party engagements and effects, are developed through application of the principles of the waste-management hierarchy, thus fulfilling the second key question. By applying a ranking and rating procedure to these generated options, a membranes-based process (RO) as an alternative to the chemicals-intensive softening and ion exchange boiler feed water process at Sasol Synfuels is selected for further analysis.

In response to the final key question, LCA, a primary tool in IE, is used to compare the environmental performance of this proposed intervention to its base case and for assessing the shifting of salts burdens. The results of this assessment indicate that, while the RO intervention appears to not result in shifting of salts burdens (there is a 78% overall reduction in indefinite storage of problematic ions, from 599 kg/Ml boiler feed water produced to 133 kg/Ml boiler feed water produced), the RO option performs approximately 22% worse for environmental impact categories relating to the use of fossil energy for electric power generation (at 681 kg CO_2 equivalent per Ml boiler feed water produced for the RO option as opposed to 534 kg CO_2 equivalent of the IX per Ml boiler feed water produced). As indicated by a variation analysis, this finding is however subject to assumptions regarding the current status of marginal electricity production in South Africa and the availability of waste heat.

The findings from this study prompt extended research and practical recommendations to the Secunda industries. Further research into the viable recovery of water and salts from wastewater in the complex by means of Eutectic Freeze Crystallisation and carbonation are suggested, along with an investigation into the potential exchange of wastewater and waste heat amongst industries.

The findings from the literature review and the integrated salts management analysis lead to the recommendation that ion exchange processes for boiler feed water preparation in the complex be revised. An awareness of the life cycles of inputs to water treatment processes is suggested to avoid incurring detrimental effects in remote locations. Finally, it is suggested that the benefits of a holistic approach such as IE be embraced to complement present approaches to solving salts and water issues. Given that none of these issues are isolated to a specific company, this approach, which has demonstrated its strength and success elsewhere in the world, is especially relevant and should feature prominently in future agendas of the Secunda industries.

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List of Acronyms

ALCA	Accounting life cycle assessment
BFW	Boiler feed water
CAE	Clear ash effluent
CALCAS	Co-ordination Action for innovation in Life-Cycle Analysis for Sustainability
CEB	Chemically enhanced backwash
CIP	Cleaning in place
CLCA	Consequential life cycle assessment
CP	Cleaner Production
CSIR	Council for Scientific and Industrial Research
DEAT	Department of Environmental Affairs and Tourism
EFC	Eutectic freeze crystallisation
ES	Environmental sustainability
GWP	Gross Domestic Product
HLS	Hot Lime Softening
HTP	Human toxicity potential
IE	Industrial Ecology
IMS	Integrated membrane system
IS	Industrial Symbiosis
ISO	International Organisation Standards
IX/S	Ion exchange and softening
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
MIET	Extended input-output method
Ml	Mega litre
NaZ	Sodium Softening
ND	New Demineralisation
OD	Old Demineralisation

RO	Reverse osmosis membranes-based process
SA-DoH	South African Department of Housing
SRO	Spiral reverse osmosis
TNSF	The Natural Step Framework
UCT	University of Cape Town
UKZN	University of KwaZulu-Natal
WAIV	Wind Aided intensified eVaporation concept
WBCSD	World Business Council for Sustainable Development
WMH	Waste management hierarchy
WRC	Water Research Commission of South Africa
WSI	Water stress index
ZA	South Africa

CHAPTER 1

Introduction

The South African economy has grown positively after 1994 with an average real gross domestic product (GDP) growth rate of 3.0% for the decade of 1994 to 2004, representing a considerable improvement on the 0.8% average growth rate for the previous decade spanning 1984 to 1994 (Du Plessis and Smit, 2006). This trend continued between 2004 and 2007 with annual growth rates that varied between 4.9% and 5.3% (SA Government Information, 2010).

The basis of this growth has been the expansion of secondary and tertiary sectors to surpass the role of primary industries prior to 1994, as shown in Table 1 below.

Table 1: South Africa's sectoral growth performance (%of GDP at basic and 1995 levels) (adapted from Du Plessis and Smit, 2006)

	% of GDP			Average annual % change	
	1984	1994	2004	1985 - 1994	1995 - 2004
Primary sector	13.0 (17.5)	13.1 (11.9)	10.1 (10.4)	0.8	0.4
- Agriculture, forestry and fishing	2.7 (4.8)	3.7 (4.6)	2.8 (3.4)	3.9	0.3
- Mining and quarrying	10.8 (12.7)	9.5 (7.3)	7.3 (7.1)	-0.6	-0.4
Secondary sector	27.5 (30.5)	24.4 (27.7)	23.1 (24.7)	-0.4	2.5
Tertiary sector	59.1 (52.0)	62.5 (60.4)	66.8 (64.9)	1.3	3.8
GDP at basic prices	**100 (100)**	**100 (100)**	**100 (100)**	**0.8**	**3.1**

Table 1 indicates that the secondary and tertiary sectors experienced more favourable average annual percentage growth rates compared to the primary sector in the period spanning 1995 – 2004. In particular, the tertiary sector experienced an almost three-fold increase in its average annual change for the period 1995 to 2004 compared to the period spanning 1985 to 1994. The tertiary sector has also strengthened its position as the main contributor to GDP.

The secondary sector of the South African economy is characterised by several large, inland industrial complexes which centre around chemical or metallurgical manufacturing in close proximity to the mining activities from which raw material inputs are drawn. These complexes are located around Ferrobank in Witbank, Middelburg in Mpumalanga, Rustenburg, Secunda and the Steelpoort/Burgersfort area. While the importance of gold mining and processing has declined in recent years as a result of the resource having been largely exhausted (Hartnady, 2009), the role of coal has remained prominent in each of these complexes either due to electricity production (Ferrobank and Secunda), large-scale coal mining (Ferrobank, Middelburg and Secunda) or for direct and indirect uses of coal.

Little coal is used for direct energy needs as it is mainly used in its converted form to electricity to sustain the needs of energy-intensive mining and minerals processing (Fine and Rustomjee, 1996) of steel, ferrochrome and platinum group metals (Rustenburg, Steelpoort/Burgersfort). Manufacturing sector industries such as “plants in engineering, iron and steel and base metals and chemicals” have developed around these mining hubs (Fine and Rustomjee, 1996).

Despite transcending the historic reliance on industries with inherently negative environmental impacts (*e.g.* mining), the growth pattern described above is not exempt from (in part unintended) environmental consequences such as severely compromised security of freshwater supply quality and quantity. Value added products and services require inputs from primary industries and incur environmental impacts throughout their life cycle prior to delivery to and/or use by end-users (Clift and Wright, 2000). While electricity and other products emanating from the complexes described above are imperative to the functioning of many other industries of the South African economy, their production is responsible for direct dissipative losses of vast volumes of freshwater (largely for cooling purposes) which, given the remote location of these complexes from the major river courses, are obtained from extensive inter-basin transfers of raw water (Basson *et al*., 1997; Rogers *et al.,* 2008).

Processing of mineral resources has also been marked by the continual transfer of water soluble salts from mine reserves to the industrial facilities. Salty mine fissure water is pumped from underground mine works to evaporation dams and salts are also transported to industrial facilities under the guise of coal-bound ash and mine water which is routinely desalinated to supplement raw water intake. The ongoing transfer of these salty wastes represents a containment problem for industries and exposure thereof to surface and groundwater water bodies adds to existing freshwater-pollution challenges.

The importance of the environmental sustainability of industrial activity has now been generally recognised, both globally (e.g. in the Millennium Development Goals (SA-DoH, 2005)), and nationally (e.g. in the Long Term Mitigation Strategy (DEAT, 2008; SA-DoH, 2005). Recent environmental law reform in South Africa has also placed new obligations on industrial activity, especially via the Air Quality Act (NEM: AQA, 2004) and the Waste Act

(NEM: Waste Act, 2008), which place emphasis on aspects of waste avoidance, waste minimization, reuse and recycling, and minimization of environmental impacts across all media.

A key aspect of the modernisation of industrial environmental management over the past two decades has been the development of the field of industrial ecology (IE) which places emphasis on the sustainability of energy and material flows. IE is described by Graedel (1997) to be a "study of all interactions between industrial systems and the environment" which "requires a systems view in which one seeks to optimise the total industrial materials cycle from virgin material to finished material to component to product to waste product to ultimate disposal". Industrial symbiosis, a subset of the field of IE, is defined by Chertow (2008) to "include physical exchanges of materials, energy, water, and by-products among diversified clusters of firms" which are located in relative geographic proximity for cooperation on resource management issues (Bain *et al.* 2010). Industrial symbiosis has enjoyed relative success in large industrial complexes abroad that resemble those in South Africa (*e.g.* Australia, see Bossilkov *et al*., 2005). Brent *et al.* (2008) describe examples of synergistic relationships which have recently become established in the South African economy. IE approaches and methods have been shown to be useful in understanding environmental sustainability problems whilst taking multi-party engagements and effects into account (Van Beers *et al.* 2007).

1.1 CONTEXT

The work contained in this thesis has contributed to of a larger, multifaceted project commissioned by the Water Research Commission (WRC) entitled 'An Assessment of the Key Factors that Influence the Environmental Sustainability of a Large Inland Industrial Complex' (K5/1833/3). The project commenced at the end of 2008 (see Rogers *et al.,* 2008) and in its inception phase selected the Secunda Industrial Complex out of a list of 10 such complexes for further study. As stated in the inception report of this project, "a benefit for this complex is the research opportunities associated with options for water supply and waste disposal in two water management areas and the availability of research data which this work can be linked to. Another benefit is the opportunity to apply the learning from this WRC project to the possible Waterberg complex" (Rogers *et al.* 2008).

The project was executed by the Council for Scientific and Industrial Research (CSIR), and was conducted together with the University of Cape Town (UCT) Chemical Engineering Department, the University of KwaZulu-Natal (UKZN) Chemical Engineering Department, Pollution and Waste Research Group and the Technical University of Delft, The Netherlands. The CSIR was responsible for coordination of the sub-research projects and integration of the findings into reports to the WRC.

The main objective of the WRC project was stated as follows:
To assess the key factors that influence the long-term environmental sustainability of an inland industrial complex and the potential synergy for reuse of waste products and opportunities for implementing of integrated technological solutions

Specific sub-objectives for the WRC project were to

- Compile a comprehensive inventory of input, output and on-site storage of products and waste within the Secunda complex;
- Evaluate the environmental sustainability of current practices with respect to water use efficiency and pollution of water systems as they relate to the compiled inventory;
- Assess the potential synergy within the complex for cleaner production opportunities by reusing water and waste with integrated technologies; and
- Identify barriers pertaining to Governance issues (regulatory) and Cleaner Production that impede on implementation of synergistic reuse options and integrated technical solutions.

This thesis is positioned to make definitive contributions to the achievement of the second and third objectives. It draws much of its evidence from work done jointly with project partners to address the first objective, and remains mindful of the non-technical contributions made by project partners in addressing the 4th objective.

1.2 PROBLEM STATEMENT

An unintended consequence of the extraction and processing of mineral resources is the continual transfer of water soluble salts from the lithosphere, via industrial facilities into the ecosphere. Salty wastes are often problematic to contain and their release or leakage to surface and groundwater water bodies adds to the already freshwater-stressed situation in South Africa. This environmental sustainability (ES) problem is embodied in the Secunda industrial complex as a result of the large scale extraction and further processing of coal into products and services that are fundamental to the South African economy.

Although a number of attempts have been made by industries in the Secunda complex to address ES issues relating to salts and water, these efforts have typically not been explicit about the systemic nature of such problems. In addition, despite its relative success in industrial complexes abroad, an IE -type approach such as industrial symbiosis has not featured strongly in their endeavours.

A WRC-funded research project has identified a need to understand ES problems relating to the accumulation of salty wastes and to study the potential for integrated technology interventions which take multi-party engagements and effects into account. IE approaches generally make use of systems analysis tools to quantitatively assess improvements and unintended consequences within proposed interventions.

1.3 OBJECTIVES OF THESIS

This research aims to act as vehicle for the development of options and scenarios for integrated technological interventions to salts problems in the Secunda complex which promote multi-party engagements and consideration for system wide effects. In particular, the purpose of this research is to achieve the following objectives:

i. To identify salts and water related environmental sustainability issues in the complex;
ii. To develop and demonstrate an approach for identifying appropriate integrated technological interventions to address these issues;
iii. To compare by means of life cycle assessment the environmental performance of a proposed intervention to its base case.

1.4 KEY QUESTIONS

The IE approach has been shown to succeed to different degrees of success at international industrial hubs similar to the Secunda complex, and there are examples of synergistic relationships which have recently become established in the South African economy (Brent *et al.,* 2008). It is proposed that the wastes produced within the Secunda complex represent a further, similar opportunity for industrial symbioses to be established in order to improve the environmental performance of these industries.

From this the key questions which flow from the objectives are

i) Which environmental sustainability violations related to salts and water are expressed in the Secunda complex?
ii) Is there potential for multiparty engagement in synergistic exchanges of wastes in the Secunda complex?
iii) Does the implementation of such an intervention present favourable environmental performance compared to its base case?

It is acknowledged that there may be economic, legislative and governance barriers to which may limit extensive integration of these exchanges. This is the topic of a separate component to the WRC project which this research forms part of (see Rogers *et al.,* 2010) and is not pursued in this dissertation.

1.5 METHODOLOGY AND APPROACH

In order to achieve the objectives and answer key questions, the methodology followed in this thesis is aligned with the methodology for an IE investigation. This includes data gathering through fieldwork and consultation with stakeholder industries, a literature review as well as quantitative analysis and substantiation of collected data by means of material and energy balances.

The nature of the work largely entails paper studies, flow-sheeting with Microsoft Excel and life cycle assessment (LCA) with an LCA software package. Experimental work and pilot studies are not included.

Chapter 3 will discuss the methodology in detail.

1.6 SCOPE AND LIMITATIONS

Generally, the scope of the research entails a rigorous assessment of environmental sustainability in the Secunda industrial complex (which will be defined in Chapter 2), focusing on water and salts issues. This includes, but is not limited to an assessment of potential synergies for reuse of water and waste products and opportunities for integrated technological solutions.

Such technological options should simultaneously be environmentally preferable as well as technically and economically feasible. Environmental aspects are assessed by Life-Cycle

Assessments while economic and technical feasibility are included as criteria in the assessment of proposed technological options for further study.

The assessments are conducted at a level which allowed feasible opportunities to be identified, but detailed, site-specific technological specifications necessary for the commissioning of the proposed interventions go beyond the scope of the dissertation and are therefore excluded. Where appropriate, further analysis is recommended or references to relevant parts of the WRC project are provided for clarification.

1.7 THESIS STRUCTURE

The dissertation of this thesis is presented in the following chapters as is illustrated by the schematic summary in Figure 1 below.

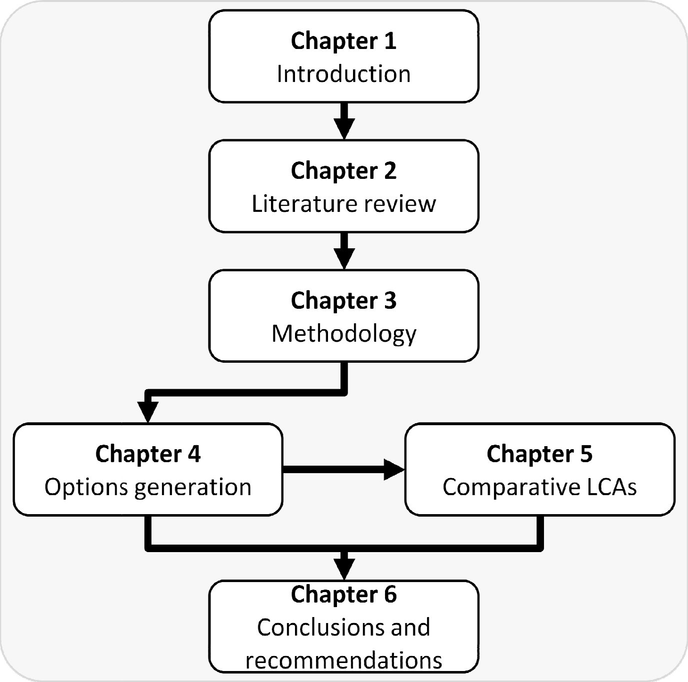

Figure 1: Thesis structure

Given the identification of a potential for intervention and the research objectives and key questions developed to support this, Chapter 2 presents a critical reflection on relevant literature and aims to demonstrate the stance of this research relative to that of others.

In response to the problem statement above and the findings obtained from Chapter 2, Chapter 3 commences with the development of hypotheses. The description and justification of the methodological approach which was employed to test hypotheses concludes Chapter 3.

Chapter 4 contains the results pertaining to the high-level investigation into technological interventions as developed from a sustainability assessment along the principles of the Natural Step Framework. Through a screening process a suitable intervention for further detailed study is identified.

Chapter 5 contains a complete and detailed comparative LCA of the selected intervention and its base case.

In Chapter 6, conclusions are drawn from the results and discussions in preceding chapters. The success of the thesis at addressing the key questions is evaluated and recommendations are proposed for both further investigation and the industries in the complex.

CHAPTER 2

Literature Review

The purpose of this chapter is firstly to provide further background information to the work contained in this dissertation, secondly to review relevant theory, and thirdly to gain insights from relevant publications on similar studies or studies which address relevant topics.

The chapter starts with a brief account of the general environmental impacts associated with the industrial activities within the Secunda area (Section 2.1.1). The findings from this section are applied in Chapter 5 to inform the selection of an impact assessment method and relevant impact categories in the Life Cycle Assessment (LCA).

An investigation into challenges experienced by the industries at managing specifically salts and water related problems is presented in Section 2.1.2.

Together with the review of the status of brine management in South Africa in Section 2.2, the findings from Section 2.1 provide context and background information to the development of detailed options for intervention in Chapter 4.

Given that an aim of this research was to develop interventions which involve multiparty engagement (see Chapter 4), Section 2.2 reviews international case studies on IE, the status of IE in South Africa in general and focuses on evaluating synergistic exchanges within the Secunda complex.

The literature which is reviewed in Section 2.3 informs several aspects of the LCA presented in Chapter 5. First, general methodology around LCA is reviewed to highlight the importance of appropriate methodological choices (Section 2.3.1), and then prior work on the use of LCA to investigate water systems is analysed (Section 2.3.2).

Section 2.4 summarises key findings obtained from this chapter and how these are applied in further chapters of this thesis.

2.1 ENVIRONMENTAL IMPACTS AND MANAGEMENT IN THE SECUNDA COMPLEX

2.1.1 Environmental sustainability problems in the Secunda area

Literature on environmental management in South Africa and its central themes is abundant and the purpose of this subsection is not to reproduce this but instead to guide the selection of impact categories in the impact assessment phase of the LCAs in Chapter 5.

Poor **air quality** in the Secunda complex results most notably from the emission of coal combustion gases and this results in several secondary effects which are described below (climate change, soil effects and human health *etc.*). As argued by von Blottnitz *et al.* (2009), although strides have been made to reduce particulate matter emissions, the real impacts of the transformation of carbonaceous fossil fuels into electricity and heat are still very much the emissions of SO_2, NO_x and CO_2. As determined by von Blottnitz (2006), Eskom's emissions of these gases are greater than those of European counterparts and so, for the results to be meaningful, data for the life cycle inventories relating to the use of electricity must be appropriately amended from datasets developed for foreign applications (Harding, 2008). Further relevant sources of these air pollutants for the Secunda area include the coal-to-liquids process of the Sasol Synfuels complex (Mulder, 2009) and physical processes such as blasting which release Nitrous gases from explosives (von Blottnitz *et al.,* 2009).

South Africa's unique vulnerability to **climate change** is investigated by Rumsey and King (2009). The fact that South Africa has one of the "highest per-capita greenhouse gas emission rates" coupled to the knowledge that the environmental consequences thereof are considered to be "complex and difficult to predict", this is deemed to be a relevant aspect of the environmental evaluation of interventions Rumsey and King (2009). In particular, the effects of "altered intensity and seasonality of rainfall" may result in exacerbated desertification and flooding in some parts (Rumsey and King, 2009). An impact category which incorporates climate change effects (which result from GHG emissions and potential to contribute to climate change) is thus essential in the analysis for comparative study.

The low annual per capita water availability and rainfall classify South Africa as a water scarce country (King *et al.,* 2009). Eutrophication, nitrification, salinisation and acid mine drainage are identified by Bosman and Kidd (2009) as "major **water pollution** problems in South Africa". Research to be conducted in the Mpumalanga province by Oberholster (2009) relates to specifically these aspects and appears to indicate that these are important environmental themes which need to be incorporated into the study.

Air and water pollution resulting from industrial activities exacerbate the general poor **human health** of the South African population (Boer *et al.,* 2009) and even more so for the Secunda region where several power stations as well as mines and Sasol Synfuels and Sasol Technology (hereafter referred to as Sasol Synfuels) are located. This calls for the inclusion of a suitable impact category for the LCAs in Chapter 5.

The extraction of **terrestrial minerals** at the expense of natural habitats is a well established ES problem in South Africa and in particular the Secunda complex where vast coal and goldmines are situated. The **use of coal** (an **abiotic resource**) for the generation of products and services such as synthetic fuels and electricity is a leading trait amongst the industries in the Secunda complex. While Strydom and Surridge (2009) focus on the impacts relating to the transformation and end-use of this energy source, given the "non-renewable" nature of this resource, it is important to consider the potential for alternative uses of coal bound energy that are yet to be unveiled through innovation studies and this is particularly true for the South African economy. The use of coal is anticipated to increase and thus these detrimental effects are anticipated to worsen. A problem of particular importance also to the Secunda complex is that of "dewatering". Salty mine fissure water is pumped from underground mine works to evaporations dams. It is estimated by Wells *et al.* (2009) that the last 40 years worth of mining activities in South Africa has resulted in the surfacing of some 3.7 million tonnes of salts and has resulted in "adverse land occupation effects, potential overflows and very local groundwater contamination".

South African soils exhibit vulnerability to exposure to gaseous emissions emanating from coal-fired power stations via acid rain, and to exposure to acid mine water (Verster *et al*., 2009). A study by Reid (2007) concluded that the long-term effects of coal-fired power station related air pollution on **soil properties** result in "detectable changes in soil chemical properties" and in particular the increased acidification over a 10 year period in the vicinity of the Arnot power station (situated near Ermelo). Acidic conditions affect the ability of plants to absorb nutrients and this may result in fruitless over-dosage of fertilisers (Verster *et al*., 2009), thus exacerbating a second problem relating to soil: **salinisation**. Salinisation may result from agricultural activities (over-irrigation and poor drainage) or exposure to emissions from industrial and mining activities (McNeill, 2001; Wells *et al.,* 2009). Salinisation affects fertility and productivity of soils. South African soils are thus affected by chemical deterioration and this represents an important impact category for the impact assessment of intervention options. Salinity problems pertinent to the industrial activities in the Secunda complex are described in detail next.

2.1.2 Salinity and water management in the Secunda Complex

In the following section, a brief review is presented on efforts by individual industries to manage salts and water balance problems experienced as a result of their operations. This information was obtained from publications and through personal communication with plant personnel during onsite interviews at Sasol Synfuels and Eskom Tutuka. Salts and water problems which have dogged these industries for several years have been studied internally and extensive databases have been established by these companies to better understand the issues. As stated in Chapter 1, one of the specific sub-objectives for the WRC project was to compile a comprehensive inventory of input, output and on-site storage of products and waste within the Secunda complex, which can be obtained in the publication by Brouckaert and Rogers (2010).

As discussed in this section, salts and water balance problems experienced by the Secunda complex industries are complicated and closely linked to each other.

2.1.2.1 Sources of salts

The first obvious source of salts is **raw water salts** which remain once raw water is evaporated through air cooling or once raw water is desalinated for use as boiler feed water. Ongoing deterioration of raw water quality in the complex and the desalination mechanisms employed play an important role in the magnitude of the salts problem associated with the desalination process. Several industries in the complex employ ion exchange, a chemicals intensive process, for raw water desalination to boiler feed water standards. The boiler feed water preparation circuit at Sasol Synfuels is considered to be particularly problematic by its operators as will be described below.

The second source of significant salinity problems is the brines that result from desalination of **saline mine water** with substantial dissolved salts component. As described Buhrmann *et al.* (1999), the Tutuka power station desalinates approximately 12 Ml of mine water from the Anglo Coal, New Demark coal mine daily. The success of a similar initiative by Sasol Synfuels to desalinate mine water from Sasol Coal Mines (see Burger *et al.,* 2004) and its contribution to the salts problems at Sasol Synfuels is critiqued below.

A third source of salts is water soluble salts in coal which are eventually landfilled as part of the ash which remains after coal combustion and/or gasification. Upon contact with rainwater or waste water streams disposed of on these ash dumps, the **oxidation and dissolution**

processes of mineral material occurs (Carlson and Adriano, 1993). Moitsheki *et al.* (2010) investigate the dissolution of free CaO to produce $Ca(OH)_2$ when Sasol Mooikrans mine coal ash was in contact with water and how this phenomenon resulted in an increase in pH.

2.1.2.2 Water and salts balance problems at Tutuka power station

The Tutuka power station, commissioned in 1985, makes use of around 98Ml fresh raw water per day, of which 87% is evaporated in the wet-cooled system (Winkler *et al.,* 2007). The power station is operated as a zero liquid effluent discharge facility, *i.e.* “water is cascaded from good to poor quality uses until all pollutants are finally captured in the ash dams and the maximum mass of salts are removed in the smallest possible volume of water” (Coal Industry Advisory Board*,* 2006; WBCSD, 2006). Through the dry ashing system, the ash produced by the facility is moistened with these concentrated brines and conveyed to the ash dump on overland conveyors (Coal Industry Advisory Board*,* 2006; WBCSD, 2006). This circuit is depicted in the image below.

Figure 2: **Aerial image depicting overland ash conveyors which culminate in ash dumps (foreground), and cooling towers of wet cooling system shown adjacent ot the power station (background)**

A desalination plant built in 1985 treats excess blow-down water which is produced during low load factor operation (Coal Industry Advisory Board, 2006). The waste water desalination system at Tutuka was extended in 1998/99 to include the treatment of 12Ml/d mine water from the adjacent New Denmark colliery (Coal Industry Advisory Board, 2006; Buhrmann *et al.,* 1999).

The claim by the Coal Industry Advisory Board, (2006) that this initiative enabled the power station to better “control the salt load and water volumes to match the effluent sink available on the dry ash dump” was earlier made in reports by van der Walt and Wessels (2000) and Pather (2004). However, Brouckaert and Rogers (2010) report that, despite evaporation and incorporation of the resulting brines into ash conditioning, dust suppression and ash sluicing, an excess brine of around 0.89 Ml/d at 11.5 t/d salts results and this remains problematic in that it is returned to underground mine shafts, thus only relieving the mine water volume problem but not addressing the salts problem. This is confirmed in a recent report by Corbett and West (2010) as indicated in Figure 3 below.

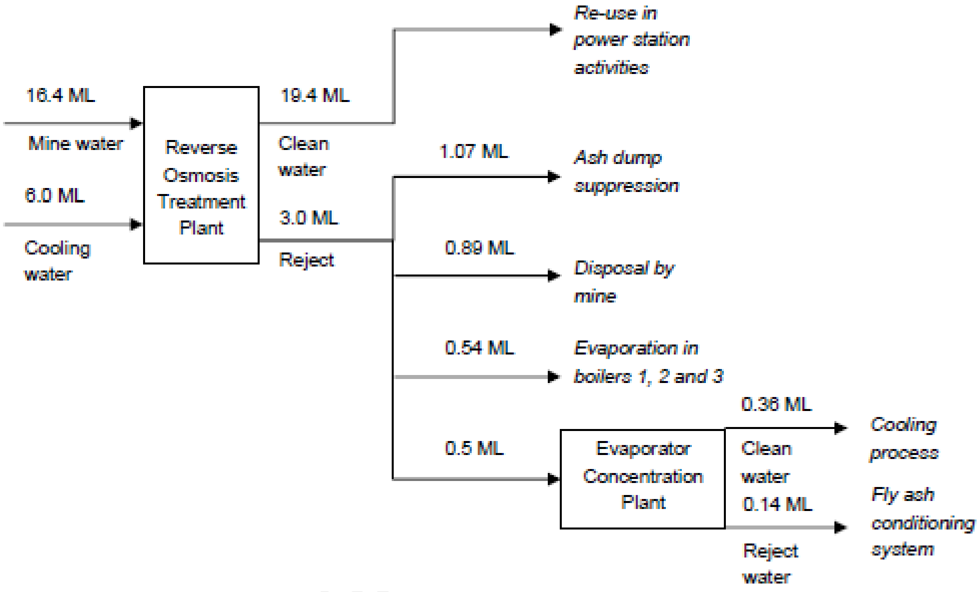

Figure 3: **Schematic representation of RO reject distribution at Tutuka (Corbett and West,2010)**

2.1.2.3 Water and salts balance problems at Sasol Synfuels

Depending on the quality, raw water intake is approximately 240 – 270 Ml/d, of which approximately 160 Ml/d is evaporated through the process and utility cooling systems (Roux, 2009; Brouckaert and Rogers, 2010).

Water and salts balance problems at Sasol Synfuels are manifold and characterised by a positive ash water balance, limited storage capacity for water volumes which could be recovered by desalination, poor housekeeping, and poor control over desalination units (Gilliland, 2008; Roux, 2009). These issues are largely interlinked and some are described next.

Storage capacity problems and poor housekeeping of streams with widely varied qualities (such as rain and storm water, water works resin regeneration effluent (10 Ml/d), fire water and boiler condensate (10 – 20Ml/d), cooling water blowdown etc.), results in the “indiscriminate” mixing and disposal of these streams to the ash system. This water, which could be recovered to supplement raw water intake, instead saturates the ash system and a **saline “clear ash effluent”** (CAE) of inferior quality is produced (Moitsheki *et al.*, 2010). This contradiction to the ‘zero liquid discharge to surface water streams’ for which the plant was designed necessitated the installation of several extensive desalination units. Furthermore, the configuration of these units exacerbates the salts balance problem by the potential liberation of minerals off the ash and due to the positive feedback nature of the desalination units. This is illustrated in Figure 4 below.

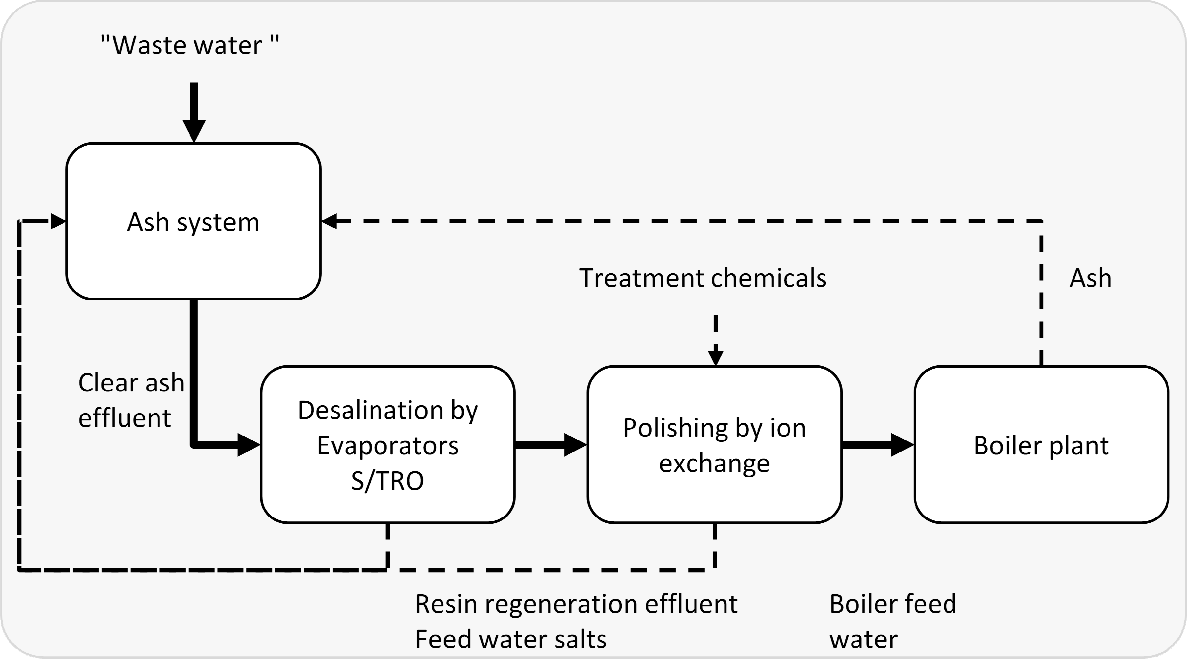

Figure 4: CAE desalination at Sasol Synfuels results in accumulation of salts in the ash through a positive feedback loop of salts (adapted from Gilliland, 2008)

The final treatment of CAE water recovered in this way is by **chemicals intensive ion exchange**, which itself represents a significant contributor to salts problems at Sasol Synfuels. Fouling problems have resulted in the use of excessive amount of treatment chemicals over and above that which is necessary for ion exchange resin regeneration at boiler feed water preparation units (Phillips and du Toit, 2001; Roux, 2009). Approximately 110 t of treatment chemicals results in the salts content of water works regen-effluents to be around 3 to 4 fold that of low salinity surface raw water which is desalinated (Rogers and Ras, 2009). This waste is integrated into the problematic ash system described above and it is considered by water engineers at Sasol Synfuels to be the major source of salts problems at Sasol Synfuels (Roux, 2009). The commitment to reduce these salts “at source” by means of a membranes based process is expressed in Sasol’s *Water and Salts Strategy* (Roux, 2009).

Daily blowdown of 10 – 12Ml (at 600mg/l TDS) from process cooling towers reportedly represents the largest water balance problem and second largest salts problem at Sasol Synfuels (Roux 2009). The installation of a membranes based desalination process in 2006, **Project Landlord**, has allowed for the recovery of 12Ml/d from utility cooling tower blowdown to boiler feed water quality (Grant 2006). The relative success of this process at addressing water balance problems has inspired further intentions that focus on the segregation of ash water and process cooling blowdown (identified as a key focus area in the Secunda Water and Salt Strategy) (Roux, 2009).

The elaborate integrated membrane system (IMS) for **mine water desalination** system at Sasol Synfuels, which consists of electro-dialysis reversal, spiral reverse osmosis (SRO) and an evaporator-crystalliser, was established in 1995 and extended in the early 2000's with the intent to simultaneously alleviate water balance problems at the adjoined coal mines and to reduce raw water intake at Sasol Synfuels. This system is described by Burger *et al.* (2004) and von Gottberg, (2005). The brines resulting from this IMS are considered to be a major source of problematic salts (Roux, 2009). Operation of an evaporator-crystalliser, the unit responsible for final treatment of brines after mine water desalination, is reported to be severely limited by several constraints including significant feed concentration variation, deviation from design specification and design capacity (Roux, 2009). As a result, this unit is most frequently offline or operating at low capacity and instead brines are stored in dams or on the ash dams, thus adding to an already problematic water balance at Sasol Synfuels (Roux, 2009).

Two **carbonation plants** were installed in the 1980s with the intent to "precipitate calcium carbonate out of ash water (to reduce calcium levels) for reducing scaling in the re-use of the ash water" (Roux 2010). Several operational problems which arose and eventually lead to the decommissioning of the plant are detailed in a separate report (Ras *et al.*, 2010a). Recent studies indicate that there is international interest in the sequestration of CO_2 in brines through utilising ash as a source of alkalinity to maximise the reaction efficiency of the carbonation reaction. Montes-Hernandez *et al.* (2009) have demonstrated the ability to sequester up to 26 kg CO_2 in one ton of fly ash from coal combustion. Soong *et al.* (2005) suggest that ash-bound Calcium provides additional Calcium for the carbonation of brine in a multi-step conceptual process.

2.1.2.4 Water and salts balance problems Sasol Coal coalfields and Anglo Coal New Denmark coalfields

The "Long Wall" mining technique employed by coal mines in the complex to excavate shafts is associated with extensive fracturing of the rock overlaying the coal seam for up to 1.5 km from the compartment (Hodgson and Krantz, 1997; Vermeulen and Usher, 2005). Fissure water fills the mined/empty compartments and oxidises/dissolves mineral material. The effects of the "intermine flow" from such collieries as a result of hydraulic gradients have been described by Grobbelaar *et al.* (2004).

Phillips and du Toit, (2001) argue that "mine water will continue to remain a major challenge for the Secunda complex". Their predictive models have shown that the decant volume of mine water in the complex is expected to increase progressively in the next 40 years (to approximately 110 Ml per day) for as long as mining operations persist. A WRC project (K5/1669//3, 2008) predicts that the brine production in particular the Sasol Secunda Coal operations will remain similar to current volumes of close to 250 tons per day for the two decades after 2008.

Despite continued demand for additional water within the Complex and the considerable potential resource that this represents, it appears as though the disparity between raw water price and the capital and operating costs for treatment of poor quality mine water has prevented extensive integration of this waste material into the water systems of industries in the complex (Rogers *et al.,* 2010). Phillips and Du Toit, (2001) are of the opinion that, "due to the high capital and operating cost of current desalination technologies, the answer to the mine water problem is unlikely to lie solely in the implementation of treatment technologies, but rather in the innovative application of this water resource using existing infrastructure and processes".

Several collaborative efforts by these industries to address their individual salts and water problems by means of wastes exchanges with other industries are discussed in Section 2.2.2.

2.1.3 Recent developments in brine handling in South Africa

A recently concluded WRC project on the handling of brines in South Africa indicated that brine volumes produced by inland industries are expected to increase substantially during the next 20 years, in particular as a result of coal and gold mining (WRC Project K5/1669//3, 2008). Innovative approaches to the management of brines which were identified and tested in this study include technologies and approaches based on the Wind Aided intensified eVaporation concept (WAIV), evaporation techniques similar to "Dewvaporation", brine softening and recycling, and eutectic freeze crystallisation (EFC).

A recent publication by Lewis *et al.* (2009) reports on the ongoing research at the Crystallisation and Precipitation research group at the Department of Chemical Engineering, University of Cape Town, into the application of EFC for the treatment of multi-component brines and mine water. While the capital costs associated with this “new” technology is as yet unfavourable, operating costs for an EFC facility have been determined to be “approximately nine time less than that for evaporative crystallisation” (Lewis *et al*., 2009). Other favourable findings from thermodynamic modelling and successful laboratory scale investigations have propelled this research to the level of a pilot study which is presently in the planning phase (Randall, 2010).

2.2 INDUSTRIAL ECOLOGY

The development of industrial ecology (IE) from the 1970s to the late 1990s is documented comprehensively by Erkman, (1998). Bey, (2001) and O’Rourke *et al.* (1997) provide useful critical reviews of research work and applications in the field, and address some major controversies and limitations.

The formal definition of industrial ecology has traditionally been a controversial topic (Garner, 1995). In this dissertation IE is understood as a theory for resource use efficiency and waste reduction by which a state of sustainable development is approached and maintained through the use of systems-based methods to improve the understanding and management of environmental concerns related to industrial activities.

In this dissertation, Industrial symbiosis (IS) is understood as a subset of the field of IE. The following definition for IS is adopted here: a symbiotic relationship described as an IS exchange may “include physical exchanges of materials, energy, water, and by-products among diversified clusters of firms” (Chertow 2008) which are located in relative geographic proximity for cooperation on resource management issues (Bain *et al.* 2010). It is noted that industrial symbioses may result in unintended burden-shifting.

Section 2.2.1 reviews recent publications on international case studies at industrial complexes similar to the Secunda industrial complex and Section 2.2.2 describes the status of Industrial Ecology-type synergies in South Africa. Section 2.2.3 reviews the status of IE synergies in the Secunda Complex.

2.2.1 International case studies

Jacobsen (2006) provides an improved, quantitative account of the well-known IE example, Kalundborg. Unlike the oft cited paper by Ehrenfeld and Gertler (1997), he addresses several important aspects such the market sensitivity and threat of advancement in technology to IE type exchanges. The importance of adequate water supply to the industries at Kalundborg was recognised as being central to the success of the now well established industrial symbioses. As a result, Jacobsen (2006) chose to quantify the effects of selected water-related industrial symbioses exchanges and steam/heat related exchanges. Several opportunities for further industrial symbioses of wastewater and steam/heat were identified and quantified. He raises the question of whether industrial symbioses actually represent a “comprehensive strategy for environmental improvements” and recommends that an LCA could be used to quantify the significance of the raw material and energy savings and compare them to the potential for further exchange or utility sharing arrangements and the total flows of waste material, energy, and water (Jacobsen 2006). In addition, the possibility that industrial symbioses may result in unintended burden-shifting, or that they may introduce unintended complications to further optimisation opportunities, are considered.

Van Beers *et al.* (2007) have assessed the industrial symbioses at two of Western Australia’s major heavy industrial complexes, *viz.* Gladstone and Kwinana. A comparative review and assessment of the “drivers, barriers, and trigger events for regional synergies initiatives” in the two uniquely different areas is provided (van Beers *et al.,* 2007). In particular, a clear distinction between by-product synergy, utility synergy, and supply chain synergy is made to distinguish between ‘business as usual’ and real IE type exchanges that exist in the areas.

As explained by van Beers *et al.* (2007), “there is no standardized and internationally accepted methodology for defining and classifying industrial symbiosis and regional resource synergies”. Instead, it is suggested that new IE -type synergies can be identified through a step-by-step methodology based on the cleaner production approach. This is to be supported by a resource and process flow database, and opportunity identification workshops with industries (van Beers *et al.*, 2007). Similar to the study by Jacobsen (2006), the possibility of further regional synergy opportunities for in particular water efficiency and exchanges were also identified.

Due to “the level and maturity of the industry involvement and collaboration, and the commitment to future regional resource synergies”, van Beers *et al.* (2007) consider Kwinana and Gladstone to be comparable to the well known international example of regional synergy development at Kalundborg.

2.2.2 Status of IE synergies in South Africa and the Secunda Complex

Brent *et al.* (2008) conducted a survey of industrial efforts in South Africa in which elements of IE were identified at local and regional level. The status of these initiatives was considered underdeveloped and immature, yet it was indicated that the planning of future local development zones will be influenced by successful case studies at foreign locations (Brent *et al.,* 2008). Advancements of IE concepts in South Africa were recommended to be driven by the application of industrial symbiosis type strategies both at local and regional level. The drive for Clean Development Mechanism (CDM) projects in South Africa is anticipated to unveil some future IE opportunities. The report by Günther *et al.* (2008) on the **eMalahleni Mine Water reclamation project** provides useful insight in the form of "key learnings" into the multi-faceted nature of projects in the South African context which require multi-party engagement to transform waste into useful product. The eMalahleni Mine Water reclamation project is an existent industrial process and several of the key learnings identified by Günther *et al.* (2008) are considered to be pertinent to the work presented here. In particular, an understanding of the "feed water quality and the applicability of water treatment technology to produce the desired outcome" (Günther *et al.,* 2008) are incorporated in Section 5.1.2.1 and 4.3 respectively; raw water quality is considered in the design of the intervention and the technical feasibility of technology options is included as a criterion in the assessment of proposed technological options for further study. Similar aspects to the learnings relayed by Günther *et al.* (2008) around stakeholder engagement, regulatory processes and joint action between industries for the achievement of the desired outcome are considered by colleagues working on governance aspects for this project (Rogers and Mvuma, 2010).

2.2.3 Status of IE synergies in the Secunda Complex

Aside from the crucial industrial exchanges of coal and electricity, some synergistic exchanges of wastes have been established within the Secunda Complex (see Chapter 3). These are described next.

2.2.3.1 Synergies involving water

"Project Libra" is an attempt by Harmony Gold's Evander mine to **recover gold from dormant slimes dams** (Harmony report, 2009). To achieve this, an alternative to additional raw water is required (Conradie, 2009). While coal mine water was initially considered as an option, this idea was not pursued as the liabilities associated with saline mine water were deemed undesirable (see below), (Conradie, 2009). The positive water balance and the low TDS of several waste streams at Sasol Synfuels, (see Section 2.1.2), favoured Sasol Synfuels as a potential alternative water source for tailings treatment at Evander. At the time of this research, the collaboration was stalled on the progress on environmental impact assessments and technology assessments (Roux 2010).

A detailed prefeasibility study was performed on the use of **mine water for cooling purposes** at Sasol Synfuels and two cooling systems were identified for a pilot study

(Jeevaratnam *et al.*, 2004). Despite the requirement for additional pretreatment steps and extensive modification of cooling tower coatings, the pre-feasibility study justified the extension of the study to the feasibility phase based on the financial benefits anticipated from this project. However, despite successful pilot scale testing, the project has not been extended (Roux, 2010).

The longstanding initiatives by the Tutuka power station and Sasol Synfuels to **desalinate problematic mine water** from adjacent coal mines (to supplement raw water usage and to alleviate mine water problems at the mines) represents a notable industrial symbiosis-type exchange. However, since typically, appropriate measures are not in place to manage the dissolved mine water salts that remain in brines after desalination (see Section 2.1.2), these salts accumulate on ash dams, in storage dams or are returned to underground storage cavities, thus contributing significantly to existing water and salts balance problems described for each of these industries in Section 2.1.2. Discussions around “the inequitable allocation of liabilities for salt management” and “defining ‘who’ is responsible for the liabilities associated with long term storage of soluble salts and saline solutions” are addressed by colleagues working on governance aspects for this project (Rogers and Mvuma, 2010). Corbett and West (2010) and Corbett and Lawson (2010) describe current developments and endeavours to address these problems at Tutuka through expanding existing desalination infrastructure.

2.2.3.2 Minor waste product synergies

At Sasol Synfuels Processing, **calcium carbonate rich lime sludge** is produced during cooling water blowdown treatment and this is presently disposed of in the alkaline ash dam system, an already alkaline system. Negotiations for the sale of this waste to a treatment facility which transforms acidic mine water into potable water on the West Rand of the Highveld were in progress at the time of this research (Roux, 2009).

Na_2SO_4 is recovered from Sodium and Sulphate rich mine water which is desalinated at the Sasol Synfuels waterworks. This was reportedly exchanged to such an extent with the vanadium industry, that imports of Na_2SO_4 were claimed to have been stopped (Roux, 2009).

2.2.3.3 Research and synergies pertaining to ash

In the attempt to collectively address salts, brines and ash wastes problems described in Section 2.1.2, pilot scale experiments on the **co-disposal of ash and brines** by means of pasting have been conducted at Sasol Synfuels in collaboration with Eskom and specifically the Tutuka power station. Seemingly apparent chemical and mineralogical interaction between brines and ash prompted an attempt to simulate these interactions with software so as to quantify salts and water binding processes (Pretorius, 2008). Experimentation with lysimetry is ongoing within Sasol Synfuels (Moitsheki *et al.,* 2010), at academic institutions which act as third parties (Muntingh *et al.,* 2009, Gitari *et al.,* 2008; Gitari *et al.,* 2008b) and its progress has been presented at several conferences (Pretorius 2008, Mooketsi *et al.,* 2007, Roux 2006, Mahlaba and Pretorius 2006, Gitari *et al.,* 2009). Similar studies have been performed in Australia (Ward *et al.,* 2006, Jewell *et al.,* 2002) and the United States of America (Joshi *et al.,* 1994).

Given the as yet unproven status, co-disposal is presently not considered to represent a sustainable solution to salts storage. The potential for long term solubilisation of salts from ash and the leakage into groundwater bodies is as yet poorly understood (Rogers and Mvuma, 2010).

Further published research initiatives by the complex's industries which pertain to an industrial synergy type approach at addressing the solid waste problem of ash dumps include the following

- Matjie *et al.* (2005) have studied a refractive extraction process for the **recovery of alumina** from coal fly ash to produce products that may be useful to the chemicals, refractory and paints industries;
- Matjie *et al.* (2005) have analysed **cement bonded products** such as "ash-bricks" and concrete that can be derived from solid waste products associated with fixed-bed gasification;
- Madzivire *et al.* (2010) who have proposed the "application of coal fly ash to circumneutral mine waters for the removal of sulphates as **gypsum and ettringite**";
- Swanepoel and Strydom (2002) investigated the potential for using fly ash as a component for **geopolymer production**.

2.3 LIFE CYCLE ASSESSMENT OF WATER SYSTEMS

In response to increasing pressures to reduce their environmental impacts, industries have moved from implementing end-of-pipe and cleaner technologies to adopting the integrated and sophisticated approach of cleaner production strategies for their processes (Clift 2009). LCA continues to evolve as a useful tool to assess the environmental performances of such efforts as well as existing plants or proposed changes to processes (Baumann and Tillman 2004). The holistic view of the environmental impacts due to a product, service or activity adopted by LCA methodology "avoids positive ratings for measurements which only consist in the shifting of (environmental) burdens" (Kloepffer, 1997).

Despite its popularity however, LCA is a tool that is still undergoing development and this is particularly true for water applications (Finnvenden *et al.,* 2009; Ridoutt and Pfister 2010; Koehler 2008; Renou *et al.,* 2008) in the South African context (Brent and Landu, 2007). In addition, as emphasised by Baumann and Tillman (2004), for the tool to be of use, considerable care should be taken in certain central aspects such as clarity in understanding the purpose for the study at hand. In particular, goal and scope definition and the use of an appropriate type of LCA are important.

As illustrated by the double arrows of Figure 5, the procedure for conducting an LCA is not strictly sequential. Instead, inputs, results and decisions are revised continuously on the basis of the goal and scope definition, interpretation of results and feedback from other sectors. The practise of LCA itself is undergoing ongoing changes that attempt to address its shortcomings and limitations (Reap *et al.,* 2008).

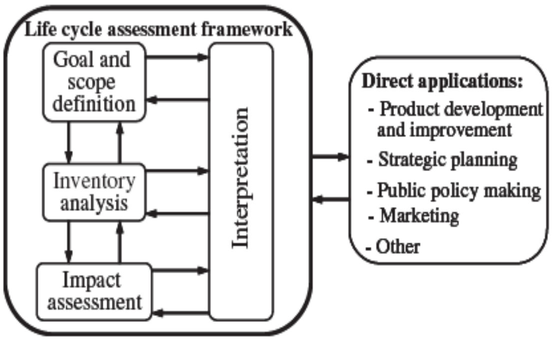

Figure 5: **LCA Procedure (ISO 2006)**

Since the framework underlying LCA practise is completely covered in literature it will not be presented in detail here. Instead, this review will focus on identifying the types of LCA that exist, why this distinction is important; how different types of LCA have been applied to systems similar to the research presented in this dissertation. In particular the review focuses on the methodology used in these studies.

2.3.1 Types of LCA

The distinction between attributional LCA (ALCA) and consequential LCA (CLCA) has been shown to be influential in success and transparency of a study and the interpretation of its outcomes (Thomassen 2008, Ekvall and Andræ 2006). This should come as no surprise since the type of LCA is inextricably linked to the goal and scope definition of a study, and together these aspects shape how a system is modelled in LCA and subsequently the outcomes of the study (Tillman 2000, Weidema 2003). Thus, correct or appropriate categorisation is crucial to the success of the LCA (Baumann and Tillman 2004).

LCAs are further categorised as either 'product assessments', that assess impacts of a certain product or process, or 'technology assessments', that identify the impacts of implementing a particular technology or process (Sanden and Kalström, 2007).

2.3.1.1 Attributional and consequential LCA

Although several terms such as 'attributional' (Ekvall, 1999 and Thomassen *et al.,* 2008), 'retrospective' and 'accounting' (Tillman, 2000) appear in the literature for describing this type of LCA, it serves a single purpose: to study the complete, *i.e.* 'cradle to grave', environmental burdens of all flows associated with an established process or product.
Consequential LCAs are also described as 'change-oriented', 'effect-oriented', 'comparative', 'prospective' (Ekvall, 1999). This family of LCA assesses the environmentally relevant flows from a technological system as a whole change in response to possible changes in the life cycle (adapted from Zamagni *et al.,* 2008).

CLCA may make use of future-specific and market-related information, and in a recent study by Thomassen *et al.* (2008) it was concluded that "in general, outcomes of CLCA are more sensitive to uncertainties compared with ALCA, due to the inclusion of market prospects". Differences in outcomes of ALCA and CLCA are also reported by Ekvall and Andræ (2006) in their comparative CLCA and ALCA study on solder paste.

Depending on the application of the LCA, methodology is affected and specific conditions for methodological choices will apply: an ALCA approach is adopted for hot-spot-identification (identification of elements within the system that contribute most to a certain impact category), product declarations and for generic consumer information, whereas CLCA is used for product development and in public policy making (Weidema 2003).

Table 2 summarises the main differences between ALCA and CLCA. Weidema (2003), Tillman (2000) provide reviews of the two LCA types and their implications on the LCA methodology while Ekvall and Andræ (2006), Lesage *et al.* (2007) and Thomassen *et al.* (2008) provide illustrative case studies.

According to Thomasson (2008), a trend of ignorantly "[choosing] one methodology independent of research question" is a common problem in the literature on applied studies of LCA.

Table 2: Characteristics of accounting type and change-oriented LCI models (Tillman, 2000)

Characteristic	Accounting LCA	Change-oriented LCA

System boundaries	Additivity Completeness	Parts of system affected
Allocation procedure	Reflecting causes of system Partitioning	Reflecting effects of change System enlargement
Choice of data	Average	Marginal (at least in part)
System subdivision	None	Foreground and background

2.3.2 Recent LCA applications to water systems and desalination

In light of widespread local, regional and global current and projected global dilemmas related to water, Koehler (2008) considers LCA a useful and as yet underdeveloped tool in application to water systems. In analogy with the carbon footprint, it is suggested that information surrounding the “water footprint” of an industrial, agricultural or other production process or product may be obtained from an LCA study. The use of case studies is encouraged by Koehler (2008) to help develop a rigorous LCA methodology for water applications. Recent developments have been made in the methodology for assessing off-stream fresh water use in LCA by Bayart *et al.* (2010). Potential environmental problems relating to freshwater consumption are especially relevant for the South African setting, and work has been done by Brent and Landu (2007). In a study by Pfister *et al.* (2009), the concept of “water stress” is developed into a “water stress index” (WSI) which is used as a “simple screening indicator for the assessment of [fresh] water use, accounting for [fresh] water use and availability”.

Recent case studies in which an awareness of environmental issues relating to water is expressed include:

- The investigation by Fthenakis and Kim (2010) into “life-cycle water use factors per unit electricity generated across thermoelectric- and renewable technology options in the United States”. An interesting conclusion of their study was that “photo voltaic- and wind-technologies in addition to providing clean, abundant energy” would contribute to the protection of water availability at “local or regional levels, related to electricity supply”.
- Pineda-Henson and Culaba (2004) who identified “water resource depletion” as an important impact factor in their study of “green productivity” in the semi conductor industry.

Some useful reviews on the progress of LCA for water applications are included in the following papers:

- Vince *et al.* (2008) review how the use of LCA for analysing potable water production has developed in recent years.
- Friedrich *et al.* (2007) review miscellaneous water case studies in LCA while distinguishing between three different levels of applications: strategic/regional, process/project and material/specific.

Recent case studies in which desalination technologies are compared by means of LCA include:

- Raluy *et al.* (2006), Raluy *et al.* (2005), Raluy *et al.* (2004);
- Vlasopolous *et al.* (2006);
- Munoz and Fernández-Alba (2007).

Publications on case studies of LCAs performed on wastewater treatment systems and desalination plants which are relevant to the aims and objectives of this study are reviewed in detail in the following sections. The case studies are summarised in Table 3 and discussed in the following sections. Section 2.3.2.1 describes the objectives for using LCA in these studies and Section 2.3.2.2 discusses the methods and types of LCA contained in these studies. Section 2.3.2.3 describes an impact category for salinisation that has been developed by recent research. Key findings obtained from this literature are summarised in collectively with those relating to the chapter as a whole in Section 2.4.

Table 3: Recent literature on LCA water applications

Source	Type of LCA	LCIA Methods	Impact Categories
Brent and Landu (2007)	Product attributional	Resource Impact Indicator calculation procedure (SALCA regions in South Africa)	Mid points belonging to use of natural resources and ecological consequences
Renou *et al.* (2008)	Technological attributional	CML baseline 2000, Eco Indicator 99, EDIP 96, EPS and Ecopoints 97	Mid points: acidification, eutrophication, greenhouse effect, resource depletion and human toxicity
Friedrich *et al.* (2009)	Product and technological consequential	CML 2 baseline 2000	
Tangsubkul *et al.* (2005)	Technological consequential	Extended input-output method (MIET)	Global Warming Potential, Eutrophication Potential, Human Toxicity Potential, Freshwater Aquatic Ecotoxicity Potential, Marine Aquatic Ecotoxicity Potential, Terrestrial Ecotoxicity Potential, and Salinisation Potential
Ortiz *et al.* (2007)	Technological consequential	CML 2 baseline 2000, Eco-Points 97 and Eco-Indicator 99	Water- and airborne emissions; overall scores

2.3.2.1 Objectives for performing LCA on water systems

The study by **Brent and Landu (2007)** was aimed at addressing limitations of the available, ready-made Life Cycle Impact Assessment (LCIA) methodologies in the South African context, especially with respect to the life cycle inventory classification of water usage beyond extraction.

Renou *et al.* (2008) chose to investigate the influence of impact assessment method on the outcomes of the LCA for water treatment. This was done in order to address the apparent shortfall in literature with regard to rigorous discussion of methodologies and their differences when applied to water systems.

The main objective for a study by **Friedrich *et al.* (2009)** was the identification of the carbon footprint and associated environmental burdens due to the provision of potable water and sanitation from waterworks in the eThekweni Municipality.

The objective of another study was to provide support for decision making in water recycling **(Tangsubkul *et al.,* 2005).** LCA was used to compare and select a suitable technological solution and to identify opportunities to enhance the environmental performance of the water recycling train (Tangsubkul *et al.,* 2005).

The objective of an LCA by **Ortiz *et al.,* (2007)** was to provide a “broad perspective” for “rigorous and objective” decision making about environmentally preferable tertiary treatment technologies.

2.3.2.2 Methods used in selected literature on water system

As explained previously, classification of LCA type and the impact assessment methods used in a study is important to the understanding of both the LCA practitioner as well as the intended audience of the study.

Renou *et al.* (2005) have identified that several authors reporting on LCA on water systems make a selection of LCIA methodology/ies without declaring or justifying their choices. Furthermore, when practitioners make use of several different methods, results and differences in results are typically not compared or addressed sensibly. This may be due to the fact that LCA methodology and databases for water issues is as yet underdeveloped. Several critical issues regarding resource classification, LCI modelling and LCIA for water LCA have been identified (Koehler 2008). In particular, non-rigorous LCI databases, strict distinction between “utilisation and consumption” of water is recommended in order to meaningfully discuss dissipative losses (Koehler 2008). Brent and Landu (2007) have acknowledged this too and with particular reference to the South African context.

The following subsection identifies methodologies that were employed in the case studies on water treatment summarised in Table 3.

2.3.2.3 Types of LCA used in the selected literature

Brent and Landu (2007) studied the environmental impacts associated with water supply to a specific industrial region in the Tswhane municipality. The nature of their assessment is thus product attributional since the necessary infrastructure and delivery of this service was already in place at the time of their study.

Renou *et al.* (2008) performed a technological attributional assessment on a classical urban wastewater treatment plant for carbon and nutriment removal with the objective to illustrate the effect that selection of impact assessment methodology has on outcomes of the LCA (Renou *et al.,* 2008).

In light of recent interest in the carbon footprint of industrial activities, **Friedrich *et al.* (2009)** performed a combination of technological and product consequential analyses to assess the carbon footprint associated with providing freshwater and sanitation to an additional 200 000 persons. The nature of their study was product consequential in that it considered the delivery of a product that previously did not exist, and the study was technological consequential in nature since it considered the addition of new infrastructure as part of different options for provision of the water. The series of scenarios were modelled in order to find the best environmental options for increasing supply. An important question was related to the recycling operation and its associated environmental burdens

Due to the fact that **Tangsubkul *et al.* (2005)** present analyses and comparison of three different technologies for the treatment of water, *viz.* conventional wastewater treatment with additional membrane treatment, membrane bioreactor technology and wastewater stabilisation ponds, their LCAs are technological consequential in nature.

The objective of the case study employed by **Ortiz *et al.* (2007)** was to upgrade the quality of wastewater by complementary treatment for reuse while considering different electrical supply scenarios. Given that environmental aspects and potential impacts associated to future water treatment technologies were analysed, the studies are said to be technological consequential.

2.3.2.4 Methods of LCIA used and impact categories investigated

The LCIA phase of the LCA refers to the "translation" of resources use and emissions captured in the LCI of a process or product into environmental impact categories (Jolliet *et al.,* 2003, Baumann and Tillman, 2004). As explained by Baumann and Tillman (2004), this is done for a variety of reasons including ease of communication of the results of a study to non-LCA specialists, to improve the readability of the results in general and to give benchmarks for comparison of results between studies. The LCIA framework consists of obligatory elements by ISO 14042: classification and characterisation, as well as optional elements: normalisation, grouping, weighting and data quality analysis of the inventory entries. The intricacies and complexities of these and other LCIA aspects such as inventory – impact category mismatches, subcategory definition, and local/global impacts *etc.* are well described in the literature and will not be covered here (Baumann and Tillman 2004, ISO 14042, Goedkoop *et al.*, 2008).

Some explanation with regard to characterisation is deemed necessary though. Traditionally, two types of impact categories exist: Midpoint and endpoint/damage impact assessment methodologies (Jolliet *et al.,* 2003). As explained by the Goedkoop *et al.* (2008), the use of endpoints typically simplifies the interpretation of results for decisions makers and clients not familiar with LCA terminology but is often associated with greater uncertainty than midpoint indicators which is in part due to a reduced modelling of environmental mechanisms. Typical midpoint methodologies are CML and EDIP; damage methodologies include Eco-Indicator 99 and EPS. More recent work has resulted in a methodology that combines these two: IMPACT 2002+ (Jolliet *et al.,* 2003). The selection of appropriate and essential impact categories is determined by the goal of the study and the LCA expert and the choices should be carefully motivated (Goedkoop *et al*., 2008), emphasising the iterative process illustrated by Figure 5.

However, as crucial as this step in the study is, there are still several problems associated with it in the literature for water studies.

In their LCA for water delivery to the Rosslyn industrial district in Tswhane, **Brent and Landu (2007)** used the Resource Impact Indicator (RII) calculation procedure using the South African LCIA framework to calculate impacts. The framework for this procedure is presented along with its impact categories in Appendix 2.1. LCA software package TEAM was employed in the study and the following conclusions were drawn from the outcomes: Toxicity impacts on water resources due to electricity requirements of the water supply system were concluded as being of far less importance than the direct impact of the extraction of water from the natural environment. It was also concluded that a lack of appropriate categorisation factors in the water use category resulted in untrustworthy and inadequate results relating to impacts due to water extraction.

The results were based on LCI database and associated LCIA profiles compiled specifically for the case study. Hence, the results of the LCA study cannot be generalised for any other region within or for South Africa.

In their case study on a water system to determine the influence of impact assessment methodologies on outcomes, **Renou *et al.* (2008)** used the following impact methods: CML 2000 was used as a characterization method while Eco Indicator 99, EDIP 96, EPS and Ecopoints 97 were used as weighting methods. The impacts that were considered were acidification, eutrophication, greenhouse effect, resource depletion and human toxicity. The study was conducted using SimaPro version 5.0 software and from the outcomes the authors concluded that similar and consistent assessment between the methods employed was obtained for all impact categories except human toxicity. The authors recommend further research into human toxicity impacts, as these did not conform in the same way between the impact assessment methods as for the other categories greenhouse effect, resources depletion and acidification.

Tangsubkul *et al.* (2005) performed LCAs to support decision making for comparison and selection of suitable technologies and identification of further opportunities for improvement. The LCA was conducted using GaBi3 version 2 software. Global Warming Potential, eutrophication potential, human toxicity potential, freshwater aquatic ecotoxicity potential, marine aquatic ecotoxicity potential, terrestrial ecotoxicity potential and the salinisation potential impact developed by Feitz and Lundie (2002) were employed. The Missing Inventory Estimation Tool (MIET) technique was employed to assess the “potential impacts associated with the construction phase”. The authors justify their choice of impact categories by stating that they “are most relevant to waste-water treatment and recycling practice”. Equivalency Factors were modified for Australian conditions. From the results of their LCAs, the authors conclude that wastewater stabilization ponds (WSP) present the environmentally most preferable solution of the three technological options considered. The authors suggest modification of the WSP system to reduce its unfavourable salinisation impact.

Ortiz *et al.* (2007) made use of the CML 2 baseline 2000 method for classification and Eco-Points 97 and Eco-Indicator 99 as weighting methods. SimaPro version 5.1 was employed to obtain their outcomes. Airborne and water borne emissions were assessed and were reduced to overall scores that were then compared. According to the authors, the outcomes of their assessments indicate that including additional tertiary treatment technologies did not contribute significantly to the environmental load of the waterworks and instead provides novel applications for the resultant purified water. The authors deem this as justification for “the intensive use of water reuse techniques in water scarce areas”. As anticipated, the use of renewable energy supply and producing biogas from sludge were found to be “forms of reducing the environmental load associated to energy consumption” and resulted in environmentally preferable options.

2.3.3 Salinisation impact category

CALCAS, Co-ordination Action for innovation in Life-Cycle Analysis for Sustainability, has recently recognised the initiatives of two research groups on salination impact categories for LCIA (Zamagni *et al.,* 2008).

Leske (2003) considers the inclusion of a salinisation impact category crucial to the relevance of environmental LCIAs performed in the South African context. The motivation for the work by Leske (2003) was the fact that “some salinity effects [can] not be described by existing impact categories”. The indicators that were developed in the research include ‘aquatic eco-toxicity effects’, ‘damage to man-made environment’, ‘loss of agriculture production’, ‘aesthetic effects’ and ‘effects to fauna and flora’. Total salinity potentials for emissions into the various initial release compartments were atmosphere, river, rural natural surface, and rural agricultural surface. Leske (2003) outlines several constraints on the use of the proposed category, including that it is only applicable to the South African context and that it needs specific knowledge for the collection of correct inventory data (Zamagni *et al.,* 2008).

Feitz and Lundie (2002) identify similar salination problems that are typically associated with irrigation in Australia. A preliminary soil salinisation impact indicator, the Sodium Adsorption Ratio, was developed as an indicator for potential land degradation from poor irrigation practices (Zamagni *et al.,* 2008).

The standardisation of impact categories and the categorisation of 'new' impact categories such as soil salinity, desiccation, and erosion are presently debated in the LCA community (Reap 2008).

2.4 SUMMARY OF LITERATURE REVIEW

The literature review identified literature and background information that serves to inform the development and assessment of integrated technological responses to the environmental sustainability risks and breaches identified in the Secunda complex. Three major sources of salts were identified, and water balance problems experienced at the industries are deemed to be complicated.

A review of **endeavours by industries to address salts and water balance problems** (installation of several expensive and elaborate desalination and brine handling technologies) revealed that although *water* balance problems were generally alleviated by these endeavours, frequently these have not been matched with proportionate alleviation of the *salts* balance problems. In general, it was found that, the salts recovery technologies failed or at best deferred the salts problem to indefinite storage.

Although the implementation of IE approaches is as yet immature in the South African context, the usefulness of such approaches to attempts at reducing environmental impacts of large industrial complexes and/or a number of industries in close proximity is evident from the international case studies discussed in Section 2.2.1. While ongoing research and existing examples of minor synergies within the Secunda complex and larger Highveld region seem to indicate potential for further opportunities (see Section 2.2.2), it is important to quantify the envisioned reduction in impacts associated with such interventions relative to the total impacts of these industries. As was identified in Sections 2.1.2 and 2.2.2, some of these approaches have been intimated as representing "silver bullets" to problems which are not straightforward or simple to solve. This falsely lends "green credibility" to the ongoing unsustainable practices whilst instead the problem is either exacerbated or only fractionally addressed.

Although the methodology for LCA applied to water systems appears to still be under development, the case study review in Section 2.3.2 reveals that this systemic approach has been applied to a variety of water and waste water systems including the South African context.

The discussion on LCA methodology in Section 2.3.1 illustrated that, while full comparison of alternative technical solutions is possible through LCA, it remains is an evolving tool from which meaningful results can only be obtained if methodological choices are made with the necessary care and insight.

The awareness of the unique environmental sustainability problems in the Secunda Complex expressed in Section 2.1.1 highlights the need for caution when making use of “ready-made” impact assessment methods that were developed for foreign geographies. In particular, as indicated in Section 2.1 and Chapter 1 of this thesis, salinisation of soil and water bodies is a significant environmental concern in the Secunda Complex and a central consideration of this thesis. The inclusion of a salinisation impact category from the two available approaches described in Section 2.3.2.3 in the LCA performed in Chapter 5 is thus essential for meaningful comparison of technology interventions with the base case.

CHAPTER 3

Methodology

This chapter provides a detailed account of the methodology and approaches adopted to generate and analyse the results obtained in subsequent chapters. The methodology is developed with the aim to achieve the research objectives and to address the relevant hypotheses.

In the attempt to investigate salts and water related environmental sustainability problems in the Secunda complex, the approach adopted in this thesis is that of marrying concept level techniques of sustainability study (such as The Natural Step Framework, Industrial Ecology, Cleaner Production, Design for the Environment) with quantitative level techniques (such as Life Cycle Impact Assessment, Total Material Flow Analysis, *etc*., (Heijungs *et al*. (2010) and Robèrt *et al*. (2002)).

Given the motivation for adopting a systems approach (see Chapter 1), this chapter commences in Section 3.1 with a description of the Secunda complex, the case study for the larger WRC project.

Section 3.2 contains the formulation of relevant hypotheses from the problem statement in Chapter 1 and literature reviewed in Chapter 2. An overview of the research approach is presented in Section 3.3. A hybrid consultation procedure together with the Natural Step Framework is proposed in Section 3.4 as the methods for identification and development of relevant technology interventions to address the environmental sustainability problem in the complex. The points-allocation method described in Section 3.4.1 is eventually employed in Chapter 4 to select from the set of options generated an intervention for further detailed analysis.

3.1 FORMAL DEFINITION OF THE SECUNDA COMPLEX

As already stated in Chapter 1, the motivation for this dissertation is to support the WRC project through identification and detailed analysis of integrated technology options which address issues contributing to salts and water related environmental sustainability problems in the Secunda complex. Given the emphasis on the development of an *integrated* technology intervention, a description of the Secunda Complex promotes understanding of how such an intervention might behave relative to other industries in the complex.

Remainder of this section is reproduced from a jointly written publication by the project group (Ras *et al.*, 2010b).

"The project team has defined the industrial complex located in the boundaries of the Highveld Coal field to consist of those industrial operations that are functionally linked and geographically close to the production of liquid fuels and chemicals, and electrical power generation from coal. Figure 6 shows the system within the boundaries of the industrial components of the complex.

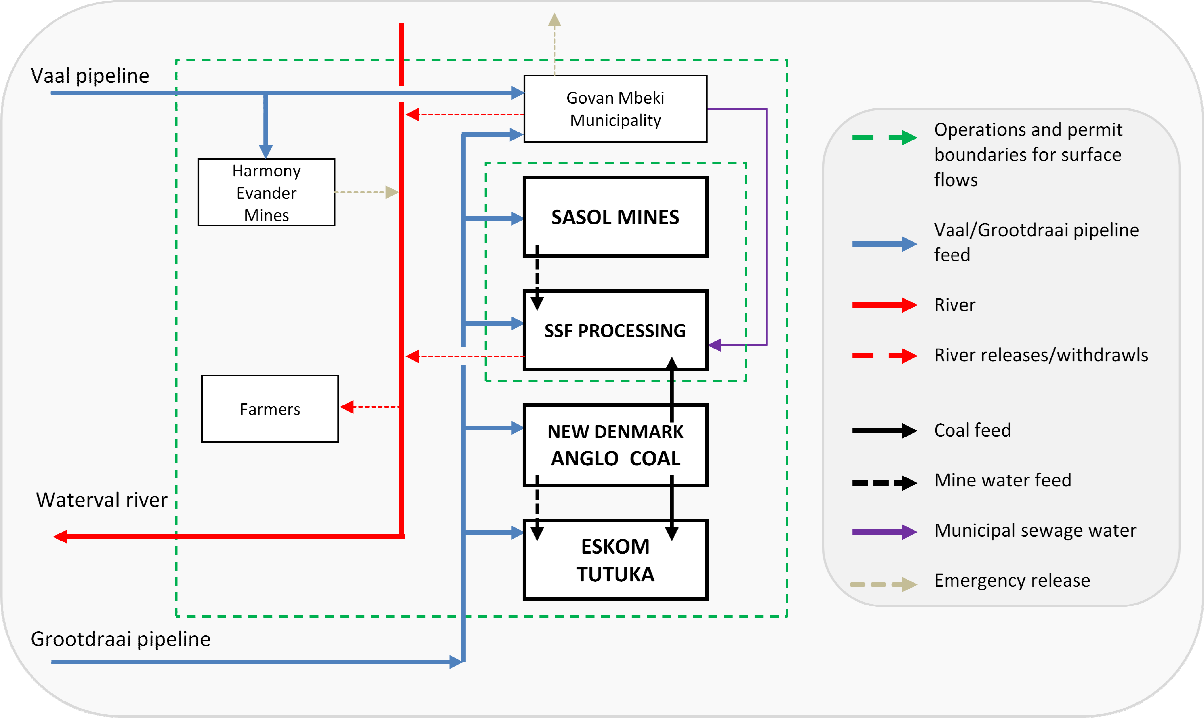

Figure 6: **Schematic summary of the Secunda Complex industries**

As demonstrated in Figure 7 below, locations of members of the complex are from top left, Harmony mine (yellow) with 3 shaft complexes (green), Sasol synthetic fuels, Sasol Mining (red), watershed Watervall and Grootdraai (dark yellow), Anglo Coal-New Denmark (purple), Eskom -Tutuka (bright yellow).

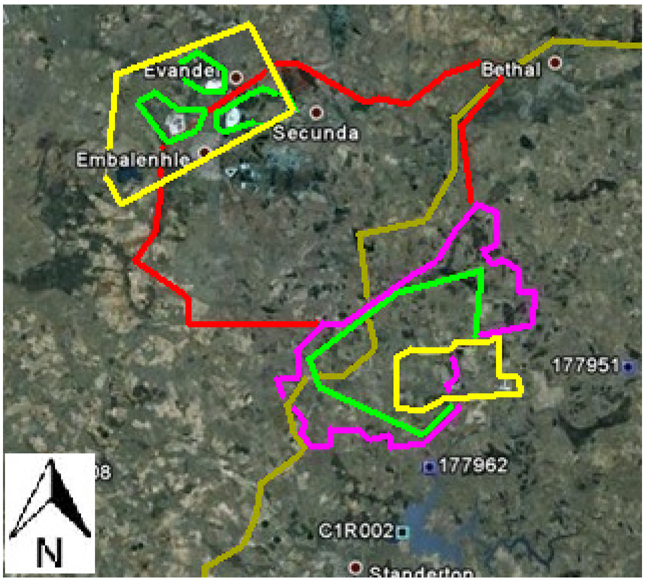

Figure 7: Boundaries of case study area, watershed and priority measurement location (Google^{TM}Earth image)

The Sasol Synfuels complex is at the North of the complex, and functionally links to the Sasol Mining coal mines supplying it. The Tutuka power station provides 900 MW of the Sasol Synthetic Fuels sub-complex continuous needs (Rogers and Ras, 2009). The Tutuka annual average supply to the grid has been around 8 962 GWh (ESKOM, 2001) and the Sasol Synfuels demand is therefore 18% of its total output. As a means to reduce dependence upon Eskom's unstable national supply system and to reduce the Sasol carbon footprint, Combined Cycle Gas Turbine with energy recovery is in the pipeline (Njobeni, 2010).

Also in geographic proximity, and sharing water resources, are the Govan Mbeki municipality, the Harmony gold mines at Evander, as well as commercial farming communities using irrigation along the Watervall River, and potable water supplied by the coal mines above the area where the water table has been removed by either extensive pumping, or collapsed aquifers. Fracturing of the rock strata above the working areas is the cause of discharge of the aquifers which would otherwise supply agriculture and rural communities which are located above underground mines (Hodgson, 1998)."

3.2 RESEARCH HYPOTHESES

The problem statement for this thesis identified the strong link between the economic health and prosperity of South Africa and the responsible management of fresh water. The literature review identified numerous isolated attempts by individual companies within the Secunda complex to reduce impacts of their operations on fresh water quality and availability with several failures. The literature review also identified the potential of collaborative approaches involving industrial symbioses at international case studies for addressing environmental problems associated with waste materials.

A first general hypothesis is formulated from these observations:

1. There are salts and water related violations of environmental sustainability principles in the Secunda Complex, but their severity can be reduced by integrated technology interventions that involve joint action by two or more industries in the complex.

The second hypothesis is based on the finding from the literature review, that by virtue of its positive feedback nature, chemicals-based ion exchange desalination technology at Sasol Synfuels is a factor contributing to the salts and water sustainability problem in the Secunda complex (see Chapter 2):

2. Implementation of a membranes-based water treatment technology for boiler feed water preparation will be associated with superior environmental performance in the complex to that of the current softening and ion exchange process at Sasol Synfuels. In particular, salts footprint associated with the use of power to desalinate water will not amount to significant burden-shifting of the large volumes of chemicals currently used for softening and ion exchange.

Subsequent subsections of this chapter develop a sequential procedure for testing the hypotheses.

3.3 OVERVIEW OF METHODOLOGY

The procedure undertaken in this dissertation for the achievement of objectives and testing of hypotheses is split into preliminary assessment and detailed assessment by Life Cycle Assessment (LCA). A summary of the procedure followed in subsequent chapters is presented in Figure 8.

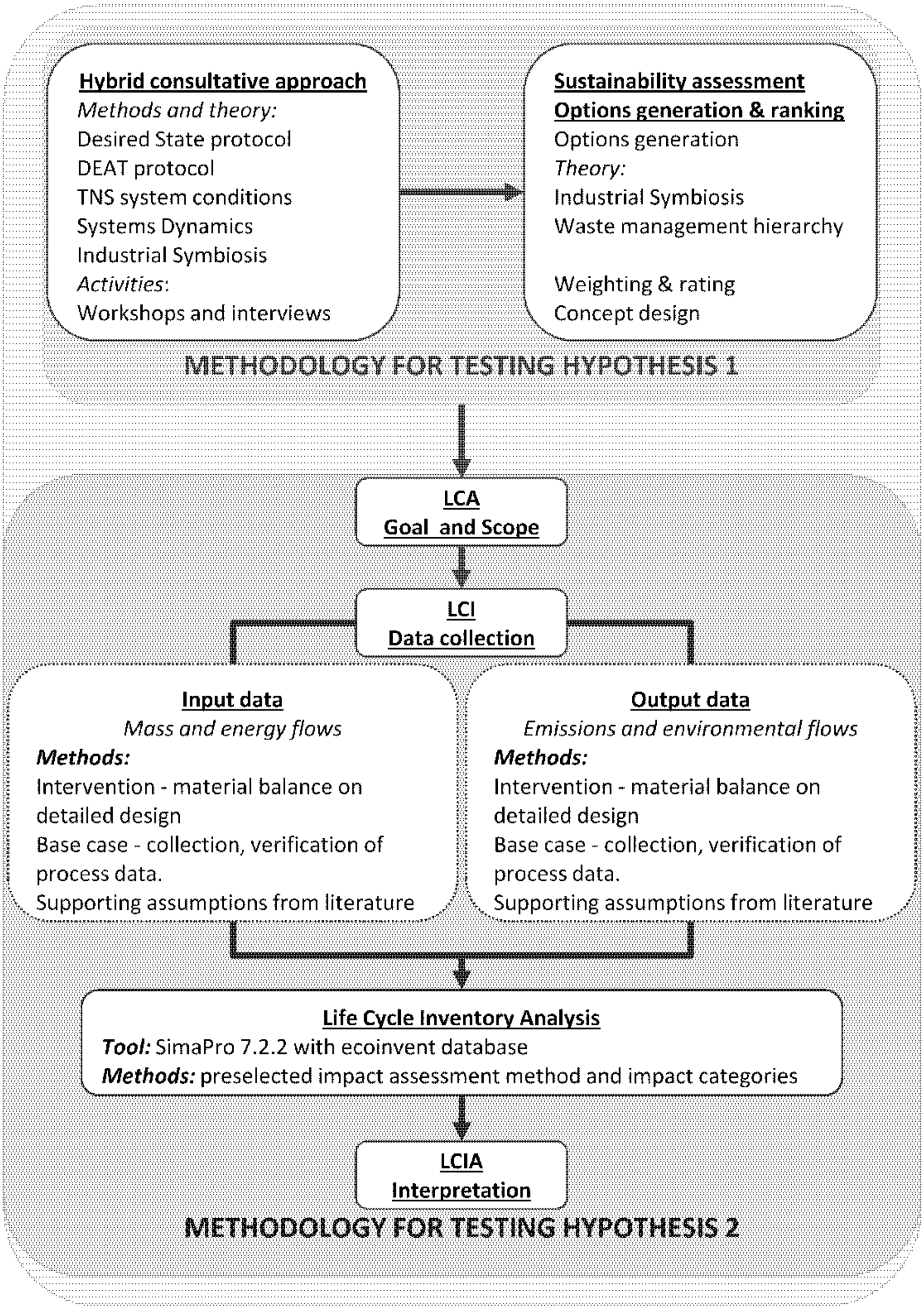

Figure 8: **Schematic summary of procedure employed for testing of hypotheses**

The first hypothesis of this thesis is tested by means of preliminary assessments which are informed by results from consultation with industries in the complex. The second hypothesis is tested by means of LCAs on the intervention selected for further study from the preliminary assessments and its base case. Process data gathered from ongoing consultation with industries is used to inform the compilation of the life cycle inventory (LCI) of the base case scenario whereas design data and literature on similar studies are used to inform the LCI for the proposed intervention.

3.4 PRELIMINARY ASSESSMENT AND DEVELOPMENT OF CONCEPT INTERVENTIONS

Formal consultative approaches such as the DEAT protocol (DEAT, 2008) and Desired State Protocol (Rogers and Bestbier, 1997) were adopted by project colleagues to achieve objectives relating to the investigation of Governance issues. With this platform available, a less formal, hybrid approach was adopted to obtain information on focussed issues relating to preparatory work for the technology assessment.

The consultation process was exercised during site visits, workshops, meetings and telephonic interviews with stakeholder industries. Relationships which manifested with stakeholder industries facilitated acquisition of process data and insight into complex industrial systems; discussions around IE type synergies and previous attempts at resolving salts and water related problems were held. The evaluation of potential, existing and abolished IE type synergies in Chapter 2 is informed by information made available by the stakeholders and supported by open literature sources on this topic in general.

With support of the larger project team, input and output flows of salts and water to the industrial network depicted in Figure 6 were compiled (Rogers *et al.*, 2009). This informed the formulation of proposals for the resolution of the complex environmental sustainability problem by prioritisation of key mass flows affecting sustainable development in the Complex and the identification of violations to elements of sustainable development as outlined by the Natural Step Framework (TNSF).

An industrial system can be said to be environmentally sustainable if its mobilisation of natural resources stays within the regenerative limits of its supporting ecological systems, and if its release of pollutants stays within the absorptive capacity of its ecological systems (Goodland and Daly, 1996).

Following The Natural Step Framework philosophy (Robèrt *et al.*, 2002) allows for identification of several practices in the complex that are classified as unsustainable in that they represent systematic increase in

i. *Concentrations of substances extracted from the Earth's crust*
ii. *Concentrations of substances produced by society*
iii. *Degradation by physical means*
iv. *Compromised fulfilment of human needs*

The focus of this study is on the first three principles while the last is addressed by project members working on Governance issues. The concept of "back casting" of TNSF (Robèrt *et al.*, 2002) is conceptually similar to that of a "desired future state" as in the Desired State Protocol (Rogers and Bestbier, 1997) employed by project colleagues working on the Governance aspects of this project.

To achieve sustainable development objectives or system conditions which address the first three criteria, interventions will be developed which deploy mechanisms of 'dematerialisation' (reduction of material flows) or 'substitution' (replacement of type/quality of flows and/or activities), (Robèrt *et al.*, 2002).

Proposals for integrated 'new technology' interventions which emanate from a combination of waste-management hierarchy and industrial ecology (IE) approaches will be used to generate a set of options, in an attempt at fulfilling Hypothesis 1.

In order to select an intervention "case study" for testing Hypothesis 2, screening criteria are applied to the generated interventions. Considerations for the final selection of interventions for further analysis include the following

i. Status of proposed technology
ii. Envisioned level of success of intervention at addressing ES problem
iii. Extent to which the intervention integrates IE synergy in complex
iv. Prevalence of other barriers (e.g. governance issues, trust problems, etc.)

The justification for these criteria is outlined next.

3.4.1 Evaluation criteria for options

A total of 20 points (an arbitrary total) is distributed amongst the selection criteria according to the deemed significance of each criterion. This is summarised for the 4 selection criteria listed in Table 4 below.

Table 4: Selection criteria for evaluation of technology options, weighting of criteria

	Selection criterion	Weighting (total of 20)
A	Technically feasible (established ‘off the shelf technology’ or innovative, new technology)	**8**
B	Sizable effect on salts problem in Complex	**6**
C	Level of cross-complex, multi-party engagement	**4**
D	Other barriers (incl. trust and governance issues)	**2**

Some existing technologies were identified in the complex with the potential for refurbishment or re-engineering (see Chapter 2). Innovative or “new” technologies such as eutectic freeze crystallisation are considered along with traditional, established technologies, but are viewed less favourable than established counterparts. Technical practicality and feasibility of an intervention are crucial, so **criterion A** is assigned with 8 points.

A major environmental problem is defined as the build up of Na and SO_4 ions in the complex. This is demonstrated in Chapter 4 where typical brines identified from the complex are characterised according to their ionic compositions. An important selection criterion is the impact that a technology option has on reducing the salts problem in the Complex. Accordingly, **criterion B** is allocated 6 points.

Given the complex-wide nature of the ES problem, in conjunction with criterion B, it is important that the technology options developed for further investigation will contribute to the notion of establishing IE across the complex. Preference is thus given to technology options that are applicable to several industries within the complex or that extend beyond the local, company-specific syntheses already present at some industries in the complex. This **criterion C** is awarded 4 points out of 20.

As identified during field trips to industries, there are several external issues/barriers that may prevent a particular technology option from being incorporated into the complex. Such issues include lack of trust amongst industries, governance problems, etc. While recognition of these problems is important, it is not considered crucial for this study and so **criterion D** is assigned 2 points.

The allocation of weighting of options was not done as part of an extensive, participative process in collaboration with the members of the greater project team. The limitations that this presents as a result of neglecting consideration of the performance of alternatives are acknowledged.

3.5 DETAILED ASSESSMENT THROUGH LCA

To assess the validity of Hypothesis 2, the environmental performance of the proposed intervention needs to be evaluated and compared to the base case by means of a comparative LCA. The framework underlying LCA practise is thoroughly covered in literature (Baumann and Tillman (2004), ISO guidelines, ISO 2006). The goal and scope for this LCA will form the first part of Chapter 5. It represents the methodology for the LCAs conducted in that chapter.

Simapro v7.2.4 software will be employed to perform impact assessment modelling, with the ecoinvent database used for background data and adjusted to local conditions where necessary.

3.6 CONCLUDING REMARKS ON THE METHODOLOGY

The methodology contained in this chapter was developed with the aim to facilitate the accomplishment of the research objectives of Chapter 1 and to address the relevant hypotheses developed in Section 3.2. The procedures summarised in Figure 8 are applied sequentially in Chapters 4 and 5 for the analysis of the results obtained.

The approach outlined in Section 3.4 is employed in Chapter 4 to identify and explore several technology interventions to address the salts and water related environmental sustainability problems in the complex; the points-allocation method described in Section 3.4.1 is applied to the set of options generated to select an intervention for further detailed analysis.

The approaches to modelling the material and energy balances and a method for impact assessment are described in the goal and scope in Chapters 5 to motivate the comparative investigation of environmental impacts associated with the two systems investigated.

CHAPTER 4

Generation of Technology Interventions

As discussed in Chapter 3, the approach adopted in this dissertation is to use qualitative techniques from the sustainability sciences to identify opportunities for intervention and to analyse their performance relative to the status quo through quantitative techniques.

Here, the results of the former approach, viz. generation, classification, short-listing and development of technological solutions for integration into the Secunda Complex to address salts-related environmental sustainability problems, are presented within the context of the methodology that was developed in Chapter 3. This needs to be done before a quantitative comparison can be made of the environmental performance of the current situation (base case) to intervention scenarios, which is the subject of Chapter 5.

The Natural Step Framework is applied in Section 4.1 to findings from the consultation process with industries. Several opportunities for dematerialisation and/or substitution are proposed to ease or counter the observed and deferred violations to environmental sustainability system conditions that are identified by this assessment. The principles of the waste-management hierarchy (Bosman, 2009) and industrial ecology (IE) are applied in Section 4.2 to generate specific intervention options expressing dematerialisation and substitution strategies broadly identified in Section 4.1. In Section 4.3, the criteria for the selection procedure outlined in Chapter 3 are applied to the generated options and an intervention for detailed further study is identified.

4.1 SUSTAINABILITY ASSESSMENT

Given the system conditions for sustainability prescribed by The Natural Step Framework (outlined in Chapter 3), examples of practices which represent observed and deferred violations of these conditions were identified along with potential options to address them. This is summarised in Table 5 below.

Table 5: Addressing system conditions violations for sustainability objectives

	Violations identified	Intervention prescription (Robèrt *et al.,* 2002)	Possible interventions
System condition 1			
Accumulation of substances extracted from Earth's crust in the ecosphere	***Observed violations*** Coal-based industry: systematic large-scale transfer of Carbon and Sulphur from the lithosphere into the atmosphere Mining techniques: problematic fissure mine water carries lithospheric elements into the hydrosphere Irrigation with brines resulting in soil degradation/salinisation was practiced historically, as allowed by permits, but is currently not practiced ***Deferred violation*** Transfer of soluble coal-bound salts from underground and "Indefinite" storage in surface and underground impoundments Transfer of soluble Sodium, Sulphur and Chlorine from remote mines via chemical production, amplifying the "indefinite" storage in surface and underground impoundments	Stop systematic increase in accumulation: Substitution/dematerialisation e.g. Produce less wastes, improve resource productivity, technology change, improved housekeeping, regulation of production volumes and characteristics Adjust quality of final deposits Recycling and other methods	***Substitutions:*** Replace coal with natural gas or with biomass, or use coal with lower levels of problematic ash constituents. Substitute ion exchange with a water treatment method which is not chemicals based Recovery of problematic salts from waste water to substitute chemicals produced from primary materials ***Dematerialisation*** Improved energy conversion Heat integration (regional and local)
System condition 2			
Accumulation of substances produced by society	FT synthesis generates a range of chemical compounds not found in nature but which do enter nature through air and possibly water emissions during production and/or at the end of life. Although this presents a possible violation, this concern over persistent organic pollutants is not pursued in this research.		Not pursued
System condition 3			
Degradation by physical means	***Observed violations*** Land-filling of ash on arable land Mining: destruction of natural ecosystems, resource depletion ***Deferred violation*** Overharvesting of water from surface water and ancient aquifers	Stop systematic physical degradation of nature through over-harvesting, introductions and other forms of modification. Draw resources only from well-managed eco-systems, systematically pursuing the most productive and efficient use both of those resources and land, and exercising caution in all kinds of modification of nature.	***Substitution*** Implement proactive, responsible raw material acquisition and waste management strategies; Utilisation or disposal in underground mines of solid wastes (ash) Utilisation of mine or waste water instead of raw water in other industries in the complex Dry cooling methods (technology change)

As detailed in Table 5 above, when evaluated according to TNS criteria for environmentally sustainable practise, the Secunda industrial complex, as defined in Chapter 3, is considered to be environmentally unsustainable[1]. The use of coal is identified as central to specific environmental sustainability problems that were identified in a separate report for the WRC project (see Ras *et al.,* 2010b). These findings are reproduced here:

In violation of **system condition 1** of TNSF, the coal-based nature of major industrial activities in the complex is inextricably linked to large and systematic fluxes of lithospheric materials into the ecosphere. This includes in particular the emission of carbon (in the form of carbon dioxide) and of sulphur (in the form of both hydrogen sulphide and sulphur dioxide) from gas stacks into the atmosphere. Substitution of fossil energy with renewables is proposed as a possible means for reducing the impacts of this unsustainable practice but, given the focus of this thesis on salts and water related issues in the complex, this not pursued further here.

Linked to this violation of system condition 1 for sustainability is the inherently inefficient nature of the conversion of coal-bound energy in the complex which results in vast quantities of waste low grade heat at both the Tutuka power station and the Sasol Synfuels facility, where coal is transformed into electricity and synthetic fuel products respectively. Integration of this energy source into local or regional synergies could result in dematerialisation and reduce the severity of several of the identified violations to system condition 1 of TNSF associated with the use of coal in this complex. Section 4.2 will propose a suitable waste heat synergy to address this.

System condition 3 is transgressed by overharvesting of surface and groundwater reserves to meet the needs of the industries in the complex and results in physical degradation of ecosystems through deprivation of water. Vast water losses are expressed in the evaporation of water through wet-cooling applications. This need for cooling is inextricably linked to the thermodynamics of the low efficiency coal to fuels and electricity conversion technologies at both the Sasol Synfuels and Tutuka power station. In order to meet this vast need for cooling, "fresh water is abstracted at rates beyond the regenerative capacity of the regional ecological systems, adding to an already stressed water situation in South Africa" (Ras *et al.*, 2010b)***.***

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[1] This is over and above the inequity in sharing of ecological burdens and financial returns which characterise the industrial practises in the Secunda complex. This is not pursued by this research; see Rogers *et al.* (2010) for further analysis

Although significant improvements on poor water-use efficiencies are “difficult to implement over the lifespan of the existing industrial facilities, the use of lower quality waste water sources for cooling presents a clear opportunity to reduce pressure on water resources” (Ras *et al*., 2010b). This will further address impacts associated with “indefinite” storage of mixed waste flows. Reuse of low-salinity waste water will present a more equitable distribution of water in the complex which is currently dominated by the large facilities. It can either be reused directly to substitute the use of under-valued fresh water (compared to cost of treatment and subsequent reuse of waste water), or its versatility for reuse could first be improved by treatment to remove major contaminants. This synergistic approach to the reuse of waste water by these large users represents a contributing factor towards sustainable water use in the complex.

“Indefinite” but ultimately limited storage of hyper-saline brines in surface dams and the associated fair-probability, high-impact risk thereof to the surrounding ecosystem represents a further violation to **system condition 1**, *viz.* the systematic transfers of large quantities of highly mobile salts (sodium chloride and sodium sulphate) from lithospheric mineral deposits into the ecosphere. Such hyper-saline mine fissure water cannot be released into surface or ground waters, so various industries in the complex desalinate it (see Chapter 2). This problem is exacerbated by inefficient and unsustainable operation of technologies for surface water treatment in the complex. Water treatment plants at several industries in the complex which incorporate (at least in part) ion exchange and softening (IX/S) processes present two-fold violations to system condition 1 of TNS.

Firstly, the desalination mechanisms of these processes rely on the use of chemicals which are produced from primary materials thus contributing to the systematic depletion of fossil reserves. Secondly, this additional transfer of highly soluble sodium, sulphur and chlorine (from remote deposits to the complex via chemical production) amplifies limited and “indefinite” storage problems in surface and underground impoundments (see Chapter 2). IX/S operation at Sasol Synfuels was identified in Chapter 2 as particularly problematic in this regard. The flux of highly-mobile salts from the lithosphere into surface storage spaces poses the risk of ecologically and economically damaging releases should the storage mechanisms fail or when brines are irrigated onto arable land. Section 4.2 will propose pathways for addressing the salts flux issues related to water treatment.

Mining practices violate two system conditions for sustainability according to TNSF. First, as described in Chapter 2, problematic fissure water is hauled up from underground for water recovery at various industries in the complex (see Chapter 2). This contributes to the flux of highly soluble salts from the lithosphere to the ecosphere with the associated risks described above. Second, mining destructs natural ecosystems. The associated systematic depletion of fossil resources is not an environmental, but a socio-economic sustainability concern.

4.2 GENERATION OF OPTIONS

To generate specific interventions from the discussion on Table 5 for possible further investigation, the principles of industrial ecology (IE) (see Chapter 2) and the Waste Management Hierarchy are applied next.

The Waste Act (DEA, 2010) adopts the **waste management hierarchy** (WMH) as a national approach to waste management. The well-known WMH seeks solutions that place first priority on attempts to avoid problems or reduce them at the source, then looks to reuse or recover problematic materials or recover energy from them, and finally it proposes treatment and final disposal of wastes if the first two steps are not appropriate. Substitution of the existing IX/S process at Sasol Synfuels with a membrane desalination mechanism (which is not associated with intensive use of salts/treatment chemicals in the use phase) represents "**reducing the (salts) accumulation/abstraction problem at source**". This case study includes potential **multi-partner effects** in that electricity from the Tutuka power station, which itself is associated with a high salts footprint (see Chapter 2), would be used to power high pressure pumps (see Chapter 5 for a detailed analysis of this effect).

Separation of waste water streams for recovery of water for reuse in local or regional synergies represents the "**reuse or recovery of problematic materials**" - tier of the WMH. The synergistic relationship between Harmony Gold Evander and Sasol Synfuels discussed in Chapter 2 is used as the case study for the direct reuse of waste water from one industry in another. This **multi-partner engagement** would support improvement of productivity (given additional water for slimes processing) at the gold mine while simultaneously addressing the positive water balance problems at Sasol Synfuels. The use of waste water or mine water for cooling applications represents a similar approach to waste minimisation but, considering the extensive work already done by the industries (see Chapter 2) this is not pursued further here.

As outlined in Chapter 2 and detailed in a further report to the WRC (Ras *et al.*, 2010a), full-scale calcium/sodium carbonate and sodium sulphate recovery technologies are installed at the Sasol Synfuels facility but are either decommissioned or do not operate as designed. In line with the "**reuse or recover problematic materials" -** tier of the WMH, it is proposed that novel brine management technologies (see Chapter 2) be reviewed along with these technologies for the recovery of sodium and sulphate salts (Na_2SO_4 and Na_2CO_3) from problematic concentrated brines that are found throughout the complex.

Interventions which substitute the use of coal-derived electricity for satisfying thermal energy needs by waste heat address integration represents the “**recover energy from waste”** - tier of the WMH. The *regional* synergy between Harmony Gold Evander and either Tutuka or Sasol Synfuels is selected as the case study option to represent the waste heat synergy scenarios for possible further study. Potential for *local* waste heat synergies with water treatment units of Sasol Synfuels or Tutuka were also identified during discussions with industrial partners but are not pursued.

The third tier of the WMH, to “**treat and finally dispose of wastes”** is not pursued by this research but may include opportunities for co-disposal of ash and brine as investigated by some of the industries in the complex (see Chapter 2), or storage of ash underground in excavated mine cavities.

The options generated above from WMH and IE for addressing the violations of sustainability system conditions are collected in Table 6 below.

Table 6: Options developed from waste management hierarchy and IE approaches

	Technology option
1	Substitute chemicals based softening and ion exchange with membrane process
2	Waste heat synergy of Sasol Synfuels waste heat and Evander thermal needs
3	Waste water synergy: recover waste water at Sasol Synfuels for slimes processing at Evander
4a	Produce Na_2CO_3 from waste water after volume reduction
4b	Produce Na_2SO_4 from waste water after volume reduction

It is understood that the potential for burden-shifting and dematerialisation associated with the interventions relative to their base cases would need to be verified by quantitative analysis (see Chapter 5).

For the selection of one intervention for detailed analysis, the procedure outlined in Chapter 3 is applied in the next section.

4.3 SELECTION OF OPTIONS

The interventions selected from the set of options generated are rated (out of a total of ten) according to each of the four criteria defined in Chapter 3, and given again in Table 7 below.

Table 7: Selection criteria for evaluation of technology options, and weighting of criteria

	Selection criterion	Weighting (total of 20)
A	Technical feasibility (innovative/new/established technology)	8
B	Sizable effect on salts problem in Complex	6
C	Level of cross-complex, multi-party engagement	4
D	Other barriers (incl. trust and governance issues)	2

Each score is then multiplied by the weighting factor of that criterion as recorded in Table 7. For example, technology option 1 is rated 10/10 for criterion A, 8/10 for criterion B *etc.*, whilst the overall importance of criterion A is weighted at 8/20, criterion B was 6/20 *etc.*

The total score (out of 10) for technology option 1 is thus calculated as follows:

$$10 \times \frac{8}{20} + 8 \times \frac{6}{20} + 5 \times \frac{4}{20} + 7 \times \frac{2}{20} = 8.1$$

This is procedure repeated for each of the technology options. Table 8 below summarises the scores for the individual criteria as well as the final total scores. Rationale for the allocations is relegated to Appendix 4.2.

Table 8: Technology options ranked according to selection criteria of Table 6

	Technology option	Criterion A	Criterion B	Criterion C	Criterion D	Total score (10)
1	Replace IX with membrane process	10	8	5	7	**8.3**
4a	Produce Na_2CO_3 from brine streams	9	8	6	4	**7.4**
3	Waste water synergy: use mine water at Evander for slimes processing	10	3	3	8	**6.8**
4b	Produce Na_2SO_4 from brine streams	8	7	6	4	**6.5**
2	Waste heat synergy: Sasol Synfuels waste heat → Evander thermal needs	6	3	3	9	**5.4**

From the *total score* column of Table 8 it is evident that, for the selection procedure followed above, technology options 1 and 4a score highest and are thus anticipated to be most useful for further study. Although Option 4a is not pursued in this dissertation, some further analysis is dedicated to it elsewhere (Ras *et al.*, 2010a).

4.4 CONCLUDING REMARKS

The assessment of environmental sustainability in the Secunda complex as presented in this chapter has identified several violations to the system conditions for sustainability suggested by The Natural Step Framework. The use of coal is central to the following specific environmental sustainability problems that were identified:

- Unsustainable abstraction and inefficient use of fossil resources and surface water results in the unsustainable flux of materials from the lithosphere to the ecosphere. This is coupled to the production of large volumes of problematic solid, fluid and gaseous wastes which penetrate several parts of the ecosphere and cause destruction of ecosystems by physical means.
- The undirected management of highly-mobile salts abstracted from fissure mine water and remote mineral deposits (for chemicals production) is coupled to a high risk of exposure to ecosystems.
- Coal mining results in large scale destruction of ecosystems by physical means.

Violations to conditions for environmental sustainability in this complex were found to be characterised by frequent transgressions of absorptive capacities of the ecosphere and the build up of potential risk of a breach of absorptive capacity. Furthermore, some technological systems in the complex were found to exacerbate these problems due to inefficiency.

In response to the violations identified, opportunities for substitution and dematerialisation which incorporate multi-party engagement or effects were generated from waste management hierarchy and IE approaches. Collaborative approaches have been shown to be successful in international case studies involving industrial symbioses (see Chapter 2) and thus this philosophy is anticipated to be an improvement on previous attempts by individual companies to reduce salts and water impacts of their operations in isolation.

Robèrt *et al.* (2002) suggest that to monitor the processes developed for achieving the desired system conditions, “tools and metrics that are designed from a total systems perspective” should be used to “indicate and audit progress towards sustainability”. The method selected in Chapter 3 for this purpose is a first order, comparative Life Cycle Assessment. Chapter 5 contains a comparative investigation into the environmental performance results obtained by applying this tool to the intervention selected for further analysis.

CHAPTER 5

Life Cycle Assessment of Water Treatment Scenarios

This chapter contains the comparative life cycle assessments (LCAs) of scenarios for boiler feed water preparation from low salinity surface water by two distinct desalination technologies: chemicals-based desalination by precipitation softening and ion exchange, and membranes-based desalination by ultrafiltration and reverse osmosis. This intervention was selected for further study in Chapter 4.

The goal and scope of the LCAs are defined in Section 5.1 while Section 5.2 contains a summary and discussion of each system's inventory data. Based on the impact categories selected in Section 5.1, the comparative study of impacts associated with the desalination technologies is presented in Section 5.3. The LCA interpretation and evaluation are documented in Section 5.4 and main conclusions to this chapter are drawn in Section 5.5.

The ISO standards are adhered to: the goal and scope are defined in Sections 5.1 and interpretation issues are addressed in Section 5.4; examination of this thesis by an external examiner is expected to satisfy the requirement for peer review.

5.1 GOAL AND SCOPE

The goal and scope definitions are returned to continuously throughout the study in order to ensure consistency in the LCA. While the goal definition sets out the intended audience and the purpose for performing the LCA, the scope definition explores the methodological choices, assumptions and limitations pertaining to the LCA (Goedkoop *et al.*, 2008).

5.1.1 Goal

The LCAs are conducted to model and compare the environmental consequences of low salinity raw water desalination for the production of boiler feed water (BFW) by either (a simplified version of) the chemicals-based process at Sasol Synfuels (base case) or the proposed intervention, a membranes-based process (as motivated in Chapter 4). The purpose of the study is to establish whether the latter system represents a better means for BFW preparation or whether it results in burden-shifting to other industries in the complex from which inputs would be drawn.

In line with the ISO guidelines, the findings of this study are compiled with an intended audience in mind. This may include but is not limited to

i. Project colleagues and the Water Research Commission
ii. Concept designers in water and wastewater management, technology and business decision makers at industries included in the life cycles studied
iii. Researchers with an interest in analysing large industrial complexes from an industrial ecology and/or life cycle perspective (with a particular interest in the role of water in the life cycle)
iv. Researchers with an interest in the application of a salinisation impact category for LCA in the South African context
v. Regulators, governance role-players, policymakers and strategists involved in shaping the future of water and brines management in water-stressed industrial hubs

The audience boundaries extend beyond that of internal sharing of data for the WRC project, as will be reflected by the style in which results are reported in later sections.

5.1.2 Scope

5.1.2.1 Functional unit

The functional unit is defined as the production of 1Ml of BFW from low salinity, surface raw water to the standard specified in Table 9 below by either the chemicals or membranes based technology. It will be used as the basis for data tabulation and calculations, thus all data will be reported on this basis.

Table 9: Raw water feed and boiler feed water quality required by Sasol Synfuels process steam boilers

Component	Raw water (mg/l)	Boiler feed water (mg/l)
Na dissolved	15.3	<1.5
Mg dissolved	11.3	<0.1
Ca dissolved	15.7	<0.1
Cl dissolved	11.7	<0.1
SO_4 dissolved	37.4	<2
Si dissolved	8.32	<0.5
Total hardness as $CaCO_3$	105.8	0
TDS	200	<10

5.1.2.2 LCIA method

In the attempt to adhere to ISO standards for LCA, an impact assessment method which meets the requirements of the ISO standard 14042 is selected. Such a method is supposed to clearly identify the following aspects: specific impact categories with distinction between the mid and end point categories (see Goedkoop *et al.,* 2008), the category indicator and characterisation model; and the allocation of LCI results to relevant impact categories and enable category indicator results to be obtained. **CML 2 baseline 2000 V2.04**, which satisfies these requirements and elaborates the problem-oriented (midpoint) approach, is used for the LCAs of both systems studied. This method, which replaces the preliminary version, is an “update from the CML 1992 method and is based on the spreadsheet version 3.2 as published on the CML web site” (Goedkoop *et al.,* 2008). The impact assessment procedure is packaged inside this readymade LCIA method which means that all in-depth calculation procedures for classification, characterisation *etc.* are performed by the LCA software, in this case SimaPro v7.2.4.

Currently available impact methods and their categories are generally specific to geographies other than that of South Africa and are not representative for the South African context. Care is taken to select, where possible, impact categories and corresponding category indicators which represent the unique environmental sustainability problems in South Africa, and specifically the Secunda Complex (see Chapter 2, Section 2.1.1). Certain impact categories are neglected from the investigation on the grounds that they are not relevant to the system or that they do not represent comparably significant impacts. The omitted impact categories for the method used include Marine Aquatic ecotoxicity, Photochemical Oxidation, Ozone Depletion and Terrestrial Ecotoxicity.

The impact categories (and relevant category indicators) which were selected from the CML 2 baseline 2000 method for the study are listed below. Relevant background to the South African context was provided in Chapter 2.

Global warming potential: factors are expressed as Global Warming Potential for time horizon 100 years (GWP100), in kg carbon dioxide/kg emission.

Depletion of abiotic resources: the Abiotic Depletion Factor (ADF) is “determined for each extraction of minerals and fossil fuels (kg antimony equivalents/kg extraction) based on concentration reserves and rate of deaccumulation”. (Goedkoop *et al.*, 2008)

Acidification: The unit for acidification is kg SO_2 equivalents / kg emissions. The time frame is eternity and the geographical scale can range from local to continental.

Freshwater aquatic ecotoxicity: The unit for freshwater aquatic ecotoxicity is kg 1,4 DB equivalents / kg emissions.

Eutrophication: Nutrification potential is expressed as kg PO_4^{2-} equivalents / kg emission. The time frame is eternity and the geographical scale can range from local to continental.

Human toxicity: "Characterisation factors, expressed as Human Toxicity Potentials (HTP), are calculated with USES-LCA, describing fate, exposure and effects of toxic substances for an infinite time horizon. For each toxic substance HTP's are expressed as 1,4-dichlorobenzene equivalents/ kg emission." (Goedkoop *et al.*, 2008)

Salinisation impact category

In order to prevent over-emphasis of the "emissions-caused impacts" which the CML 2000 baseline method is focussed on, it is preferable to balance the analysis out with an assessment of "uncharacterised" inventory data which is available (Baumann and Tillman, 2004). Data relating to salts inputs to the BFW processes are available and relevant to the investigation. These data will be compared for the two processes on the inventory level and guided by the salinisation potential impact category developed by Feitz and Lundie (2002). Water-borne salty wastes and emissions which result from processes in the foreground system and are considered important and will be compiled and compared on the inventory level for the two systems compared here.

5.1.2.3 LCA type

As defined in Chapter 2, this comparative LCA study is classified as a consequential LCA as it models the effects of technology change to a process. The adherence to methodology choices pertinent to consequential LCAs, as far as possible, is demonstrated in the following sections.

5.1.2.4 System boundaries

Two distinct technologies, which produce BFW of comparable qualities, are investigated: a) softening and demineralisation/sodium softening, b) ultrafiltration and reverse osmosis

The two technologies that will be compared for the production of boiler feed water from raw water are described briefly next.

Water softening and ion exchange

As identified in Chapter 4, the problematic precipitation softening and ion exchange processes employed at Sasol Synfuels for BFW preparation represent the base case for this study.

The complicated water network at Sasol Synfuels shown in Figure 9 commences with clarification (coagulation and flocculation) of raw water for the removal of suspended solids. The product, clarified raw water, is used as makeup water for cooling and the production of boiler condensate make up water either directly after “New Demineralisation” (ND) or along a process sequence of “Hot Lime Softening” (HLS) and “Old Demineralisation” (OD) or “Sodium Softening” (NaZ), see Figure 10.

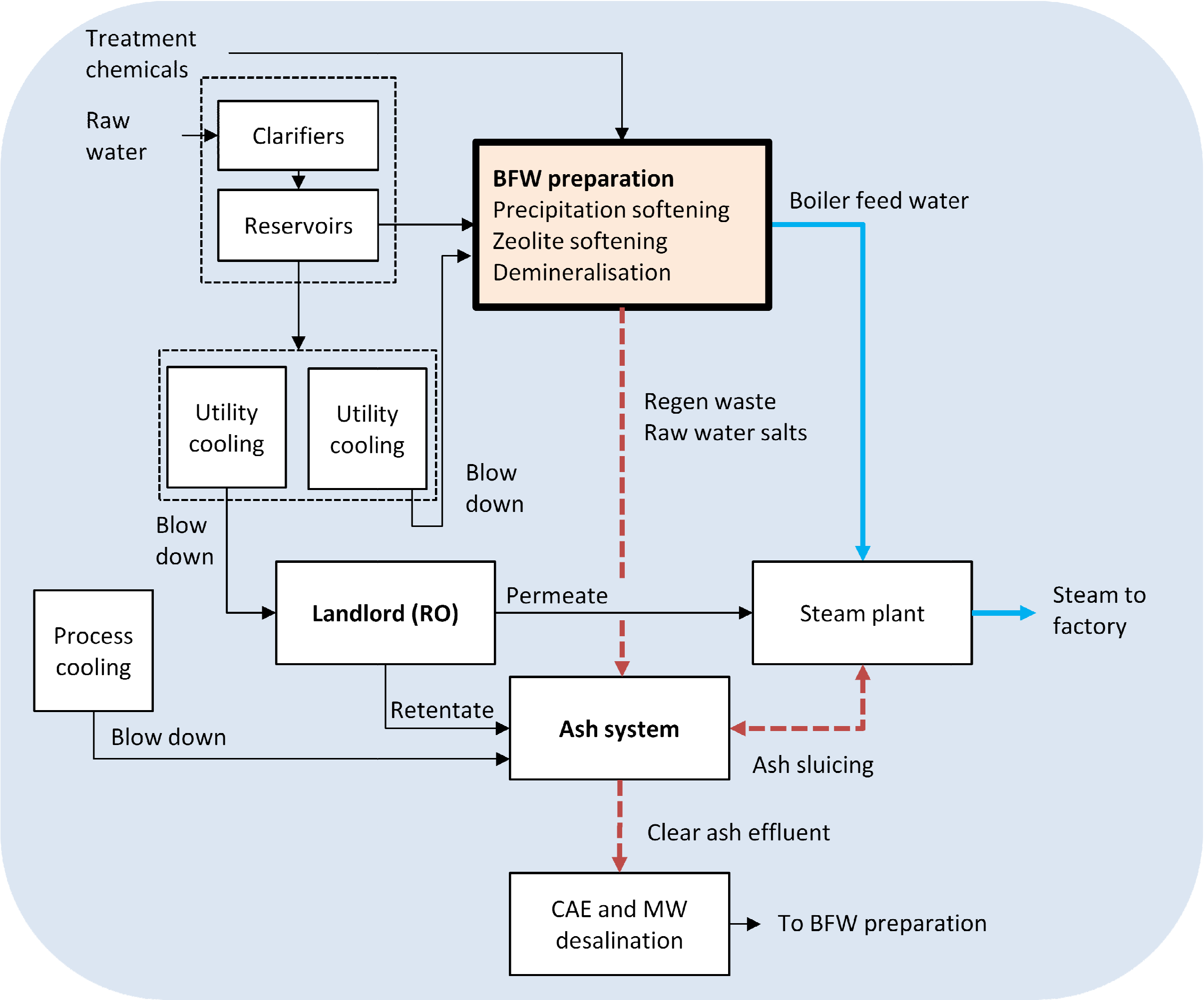

Figure 9: **Segment of the simplified water network at Sasol Synfuels. Highlighted is the IX/S unit for BFW production**

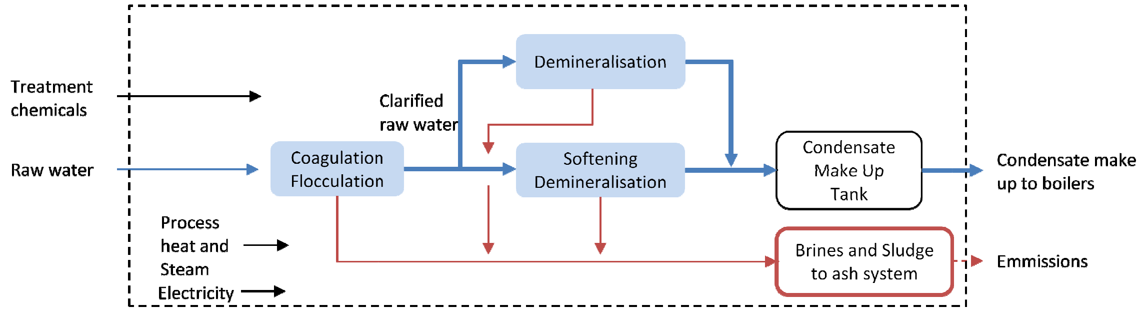

Figure 10: **Process flow diagram for the desalination of raw water by ion exchange and softening**

HLS employs low pressure steam and treatment chemicals to facilitate the precipitation of calcium and magnesium hardness and silica (see Section 5.2). The product is filtered by dolomite sand filters to remove floc, odour and pathogens before it is routed to NaZ and OD to produce water which of the desired quality for the boilers.

The mechanism for NaZ is the adsorption of dissolved Ca^{++} and Mg^{++} ions onto zeolite resin structure and the simultaneous release of the stoichiometric amount of 2 mol of Na^{+} off the resin. ND and OD operate similarly to NaZ but the presence of both strong and weak acid cation and strong and weak base anion exchanger resins allow for the adsorption of both cations and anions respectively with the subsequent release of stoichiometric amounts of H^{+} and OH^{-} respectively from the respective resins. For the ratio of ND, OD and NaZ products of 0.33:0.08:1, the collective product attains only calcium and magnesium quality requirements for condensate make up, as summarised in Table 9 and proven in Appendix 5.1. Since this is the ratio in which these products are feed to boilers at Sasol Synfuels it will be used in further calculations.

The quality of 68% of the OD product is further upgraded by mixed bed polishing to produce polished water. This is not included in the system boundaries. The resources inputs, wastes and emissions associated with OD will be averaged for the 32% or 3.84Ml/d that OD product contributes to condensate make up water (MU).

To maintain their functionality, resins which become loaded with ions removed from water, require frequent daily regenerations daily with regenerating chemicals and this results in the production of a concentrated saline waste stream. At Sasol Synfuels, ND (cationic and anionic) resins are regenerated 5 times daily while OD (cationic and anionic) and NaZ resins undergo 4.8 and 4.6 regens daily respectively. This procedure also requires washing cycles which rinse off treatment chemicals and or raw water salts.

Resins are replaced as their performance diminishes due to fouling and other aspects. Resin regeneration chemicals and resin replacement are considered to be process flows and are included in the system boundary of the background system (see Section 5.2). Based on process data provided by Sasol Synfuels, estimates for resin replacement are captured in Appendix 5.2.

Ample excess waste heat is available for heating and low pressure steam generation so the associated environmental impacts are neglected from the system boundaries.

Membrane processes

The intervention proposed in Chapter 4 is that of membrane desalination to replace the process described above in the desalination of raw water, as illustrated in Figure 11 below. Pretreatment protects units downstream of feed water pumps. Cartridge filters protect pumps and membranes by retaining large particulate matter; chemicals are dosed to mitigate bioactivity in supply lines, prevent mineral scale formation in RO unit and protect membranes from attack by residual free chlorine (see Section 5.2).

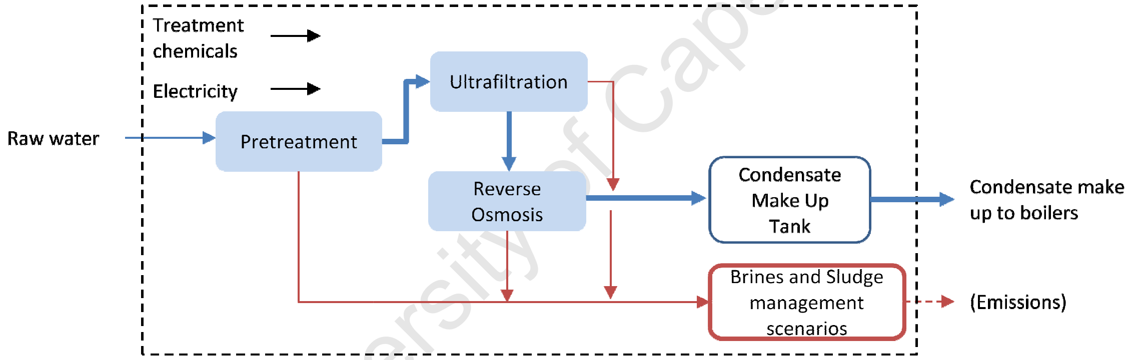

Figure 11: **Process flow diagram for the desalination of raw water by integrated membrane system**

The porous membranes of an Ultrafiltration system represent a physical barrier which retains macro molecules and suspended solids but allow dissolved salts to pass.

Brackish water reverse osmosis membranes reject dissolved solids with a water recovery in excess of 95%. Around 99% of salts are rejected by the membranes which results in a BFW stream of adequate quality (see Appendix 5.1) as well as a concentrate stream which requires disposal and/or treatment.

The performance of membranes is restored when foulants are removed from membrane surfaces during daily chemically enhanced backwash (CEB) and biannual cleaning in place (CIP). These chemicals and the membrane replaced once every 8 years are considered to be process flows and are included in the system boundary (Wilf *et al.*, 2007).

Included in the foreground system of this process is the production of electricity by the Tutuka power station in the complex for the high pressure pump unit of the RO process. As described in Chapter 2, as far as possible, marginal data should be used to populate the foreground systems. Thus, the use of Tutuka inventory data for electricity production is not strictly compliant with the consequential approach because Tutuka is one of 27 existing power stations and has been supplying electricity to the grid for over 25 years (see Chapter 2). The use of data relating to a renewable energy or new power stations, *e.g.* Medupi which will allegedly feature "super critical boilers with higher thermal energies than current plants" (Eskom, 2007) would be more appropriate as marginal data for the consequential analysis (Eskom, 2008). However, in line with the objectives of this thesis, the choice of Tutuka as the supplier of electricity is made in order to demonstratively evaluate burden-shifting at the level of the complex, and is also expected to be a worst-case, as Tutuka is the power generation unit with the highest salinity impacts on the national grid (see Chapters 2, 3 and 4).

The processes and environmental burdens associated with the extraction of raw water from the Spruit and the processes beyond the collection of condensate make up water in the tank are identical for both systems and thus excluded from the system boundaries, as demonstrated in Figure 12. The methodology for impact assessment of water extraction from nature in LCA is poorly developed and this is particularly true for the South African context (see Chapter 2). Thus, while the two systems have different percentage water recoveries (~99% for IX and ~95% for RO) and so require different amounts of raw water from the Spruit, the possibility that the difference in raw water intake (between 10 and 20%, see inventories below) will translate into significantly increased environmental burdens will not be pursued.

Ample excess waste heat is available for heating and low pressure steam generation so the associated environmental impacts are neglected from the system boundaries.

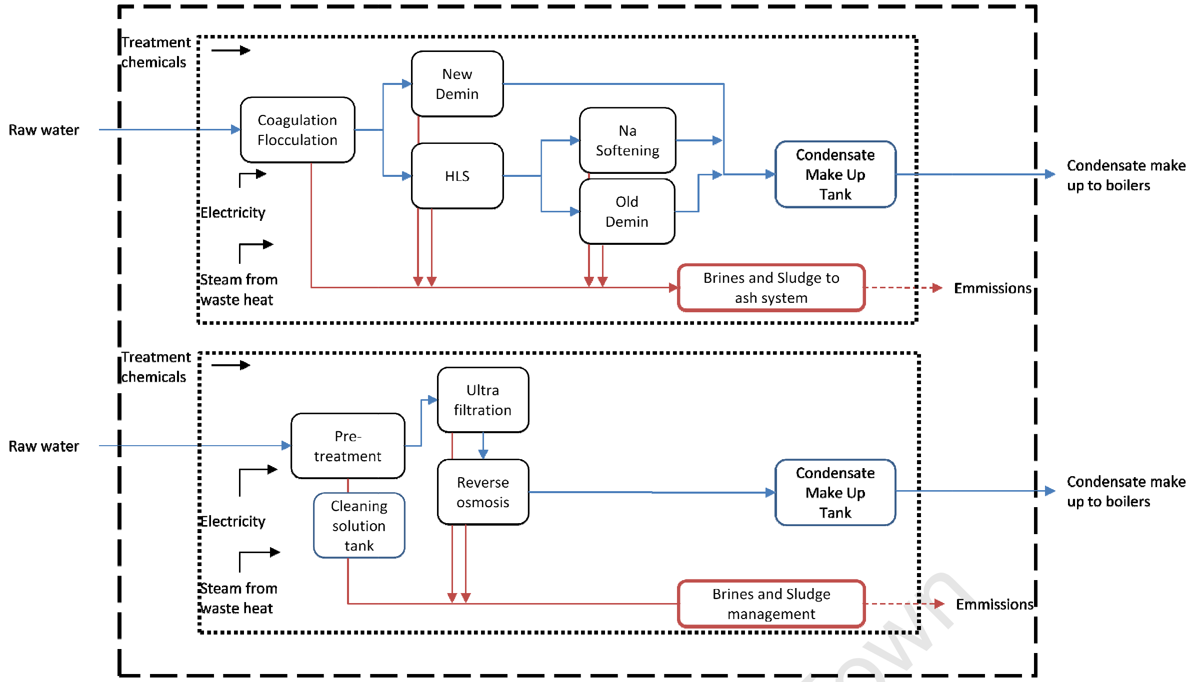

Figure 12: **System boundary for the life cycle study**

Maintenance of the water treatment equipment (*viz.* resin regeneration and membrane performance restoration) and the replacement of parts (*viz.* membranes and resins) are associated with significant resource use and wastes production. These process flows will be included in the scope of the LCAs but other maintenance activities, such as work on pumps and pipes will be excluded.

Treatment chemicals, replacement resins and membranes are taken to be transported from the greater Johannesburg region (~200km from the Complex). Impacts associated with the shipment of exotic materials (resins and membranes) acquired from international producers are considered to be negligible when compared to the rail and or truck transportation required for final delivery to complex industries.

5.1.2.5 Level of detail

First order input/output material and energy balances, simplifications of reality, were used to compile the data for the IX system LCI. The processes do not operate at “steady state” and so to account for the effect of such fluctuations over time, further scenarios would have to be modelled.

A simplified procedure was followed in the design of the RO process to establish its resources and emissions inventory. Oversight resulting from this may be corrected by a more detailed design.

The systems studied by LCA are tailored to meet the BFW quality required at Sasol Synfuels. Other industries in the complex (power stations in particular) require higher quality water by virtue of operating at different temperatures and pressures. The BFW qualities would thus need to be revised should this LCA be used as a comparison for industries.

5.1.2.6 Data categories and qualities

As per the ISO standard, different aspects of data quality are categorised into three components, *Relevance, Reliability and Accessibility* (ISO 14041, 1998).

Relevance

Time and geographical relevance are easily addressed. Current process data is available from complex industries and will be used in the inventory for the IX/S process. Design data for the RO process was obtained from a modern RO design procedure which includes the use of current trends in this field. The relevance of data with respect to time is thus considered to be good. A geographic aspect of data quality is addressed through consideration of the electricity supply associated with process inputs. For the background system, the South African power mix will be used while the foreground system will make use of electricity from the Tutuka power station.

Adequate technology coverage is determined by technology type, and the use of site-specific or average data, marginal or average data. For both systems studied, datasets which are specific to the technologies investigated in the foreground will be used, thus satisfying this aspect of technology coverage.

It is not possible to use *site specific* technology data for all inputs to the foreground system that emanate from the background system. Hence, averages from datasets and literature and most common production techniques which have been compiled for Europe will be used to populate the background system inventories for both systems studied here. Where information is available, technology types and production data for the South African production mix of specific inputs will be used. While the development of formal datasets specific to the South African context is in progress (Ecoinvent, 2011), this approach is deemed satisfactory for *relevance of data*.

While this LCA is not concerned with studying the effects of producing an increase in direct product (BFW) from the foreground systems, the nature of the desalination mechanism employed by Reverse Osmosis implies that the technology change from IX to RO will be associated with an increase in the direct electricity usage by the foreground system compared to its base case (see the inventories in Section 5.2 below). Given the presently limited reserve margin on the Eskom grid, the methodology for consequential LCAs dictates that it would be preferable that the foreground system makes use of *marginal electricity data* instead of average data (see Chapter 2). However, consideration of the following issues is used to justify that the average inventory for electricity production at Tutuka will be used as an input to the foreground system instead of marginal data:

- Uncertainty around marginal electricity supply for South Africa;
- Existing power purchase relationship between Sasol Synfuels and Tutuka;
- Rationale behind the definition of the complex (see Chapter 2 and 3).

Furthermore, the use of average data from the Tutuka power station is in line with the main objective of this research, which is to investigate potential for burden-shifting of salts due to a technology change. As described in Chapter 2, the recovery of mine water at the Tutuka power station increases its salts footprint well above that of all Eskom's other facilities. Together with the considerations listed above, this makes for an ideal worst case scenario analysis with regard to salts impacts associated with the life cycle of BFW produced from a technology which relies on coal-based electricity.

Data for the foreground systems is considered to be *complete* and emissions associated with the foreground system are recorded at the inventory level. Given the reliance on process data and realistic design data, the data used is considered to be *representative* of the actual processes modelling the systems analysed.

Reliability

Reliability of data is assessed by considering *precision and consistency*. As far as possible, process data was confirmed with industrial partners and checked for errors. Given the small inventories of these two systems, the potential for a numerical error is reduced.

Accessibility

Accessibility is assessed by means of *reproducibility and consistency*. All data is recorded in the appendices and this should enhance reproducibility of the results. As far as possible, the data used in this study was obtained from technically competent personnel at the relevant industries. Dubious data was checked and omitted or replaced by own estimates based on literature data. Given the confidentiality guarantees associated with this project, it is anticipated that the data supplied by the industries is as correct as possible. Further credibility is lent to the data for the IX/S process as most of it was taken from an independent study of the larger total water system at Sasol Synfuels.

5.2 INVENTORY ANALYSIS

The goal and scope for the LCA have identified the processes evaluated in the study, and the system boundaries. In this section, inventories of resource usage and wastes and emissions are compiled.

Process analysis is the traditional approach of life cycle inventory (LCI) compilation (Rowley *et al.*, 2009). The popular “process flow diagram approach” (Suh and Huppes, 2005) will be adopted here in favour of the matrix inversion approach by Heijungs (1994).

Data for the IX/S process is compiled from industry data collected and verified, in part, by means of engineering principles. These processes do not operate at “steady state” and so to account for the effect of such fluctuations over time, further scenarios would have to be modelled.

Inventory data for the resources and emissions associated with the membrane intervention is compiled from a preliminary design and verified by literature sources on similar systems. The simplified design procedure which was followed in the design may have resulted in oversights which could be corrected by a more detailed design, as will be considered in the sensitivity analysis of Section 5.4.

This section provides an overview of the procedures followed for compilation of the data relating to the production of 1Ml of BFW from either technology. A summary of major components to the mass and energy balance concludes this section.

5.2.1 Softening and ion exchange process

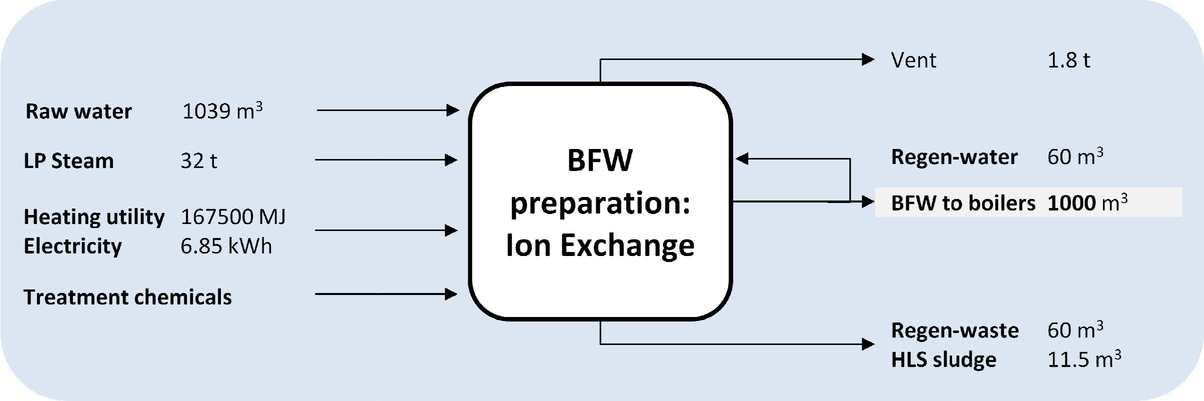

Figure 13: **Selected flows for the Ion Exchange process**

Table 10: **Water balance on ion exchange BFW preparation system**

Water flowrate in (m^3)		Water flowrate out (m^3)	
Raw water	1039	Boiler feed water	1000
Steam (ton)	32	Water vapour (ton)	1.8
		Regen-waste	58
		HLS sludge water	11.5
Total	**1071**	**Total**	**1071**

Table 11: **Salts balance on ion exchange BFW preparation system**

Salts flowrate in (kg)		Salts flowrate out (kg)		Ions eluted from resin (kg)	
Raw water salts	***104***	***Boiler feed water salts***	***4.3***		
Treatment chemicals	***643***	***Regen-waste***	***465***		
NaOH	109	Raw water salts	99		
H_2SO_4	198	Na^+ from NaOH	63	OH^-	46
NaCl	182	SO_4^{-2} from H_2SO_4	193	H^+	4
Alum coagulant	50	Cl^- from NaCl	110	Na^+	72
MgO	19				
$Ca(OH)_2$	67	***HLS sludge***	***154***		
Na_2CO_3	19	Alum coagulant	50		
		MgO	19		
		$Ca(OH)_2$	67		
		Na_2CO_3	19		
Total	**747**	**Total**	**624**	**Total**	**123**

The desalination mechanism of this system based on the adsorption of dissolved inorganic ions from the feed solution onto resin material in the units. This is accompanied by the simultaneous release of stoichiometric amounts of H^+ and OH^- (demineralisation units) or Na^+ ions (Sodium softening) into the solution. The resins are regenerated daily with acid and base (demineralisation units) or NaCl ions (Sodium softening) to restore desalination performance.

The inventory for 1Ml BFW from this system is based on the process data available for 67.44Ml/d production from the combined NaZ, OD and ND system (Roux 2009).

Flocculation and clarification

Upon dosing with coagulant, feed water (see Table 9) is vigorously mixed to ensure contact with a coagulant (ferric chloride or ferric sulphate) to destabilise colloidal particles. During flocculation, particles are brought together by gentle mixing to agglomeration. The larger particles which result from this settle out and are removed as a sludge or thickener underflow which is disposed of in the ash system, and clarified raw water results.

An alum coagulant (aluminium sulphate powder) is dosed at 50ppm, of 50kg for the production of 1Ml of BFW by the system. This value is estimated from Gagnon *et al.* (1997) since no process value was available.

The units require electrical energy to drive motors for rapid mixing and flocculation. Approximately 6.8 kWh is required per 1Ml of BFW produced by the system (see Appendix 5.3 for detailed calculations) (Harding, 2008).

Hot lime softening, dolomite filtration

Hot lime softening coupled with the dolomite sand filters reduces the total hardness of clarified feedwater from 105.8 mg/l (as $CaCO_3$) to 50 mg/l (Steenkamp, 2010).

Lime, $Ca(OH)_2$, magnesium oxide, MgO and soda ash, Na_2CO_3, are dosed for precipitation of hardness. An average production of 51.84 Ml/d by this unit (excludes water for polished product) requires approximately 1.3 t/d of MgO, 1.3 t/d of Na_2CO_3 and 4.5 t/d Lime; or 19, 19 and 67 kg/Ml BFW from the overall IX/S system respectively.

To favour precipitation, the temperature of the feed is raised from between 10 – 25°C to 60°C by heat exchange prior to HLS with power station waste heat circuit, which is associated with zero burden (see Appendix 5.4). To heat 1Ml of water, for a heat capacity of 4.187 kJ/kg.K, this requires approximately 167 500 MJ.

In addition, low pressure saturated steam (at 35 kPa_{gauge}, 2690kJ/kg) is used to regulate temperature and pressure in the unit. This steam is generated by the power station waste heat system. For the average daily production of 51.84Ml/d by the HLS unit (excludes water for polished product), steam is fed at a rate of 90.7t/hr or 32t/Ml BFW from the IX system. A vent of approximately 1.8t water vapour is released per Ml BFW from the HLS unit.
A sludge 1.5% of feed water or 11.5 t sludge per Ml BFW from the IX system, BFW from the IX/S system) consisting of Ca and Mg carbonates and Mg silicate is routed to the Clarification unit where it is removed as thickener underflow.

Demineralisation

There are two demineralisation units, as shown in Figure 10 above. The “New demin” (ND) treats clarified raw water directly, while the “Old demin” (OD) treats water which has been softened in HLS. These units have 100% water recovery.

For an average condensate make up (MU) production of 15.6 Ml/d by the ND, regeneration of resins requires approximately 2.8 Ml rinse-water and 6.1 t NaOH, 11.6 t H_2SO_4 daily or 0.04 Ml, 91 kg and 172 kg per Ml/d BFW produced by the IX system respectively.

Averaged for the portion of OD product which contributes to condensate MU (3.8Ml/d or 32% of total OD product), regeneration of resins requires 0.3Ml rinse-water and 1.20t NaOH, 1.76t H_2SO_4 daily or 0.004Ml, 17.8kg and 26kg per Ml/d BFW produced by the IX system respectively.

A regeneration waste stream approximately equivalent in volume to regeneration rinse-water and loaded with feed water salts and regeneration chemicals is produced by demineralisation units.

Sodium softening

This unit treats HLS product and has 100% water recovery.

An average production 48Ml/d requires approximately 0.8Ml rinse-water and 12.3t NaCl for regeneration of zeolite resins. This translates to 0.01Ml and 182kg NaCl per Ml BFW produced by the IX system.

A regeneration waste stream approximately equivalent in volume to regeneration rinse-water and loaded with feed water salts and regeneration chemicals is produced by sodium softening units.

5.2.2 Membrane processes

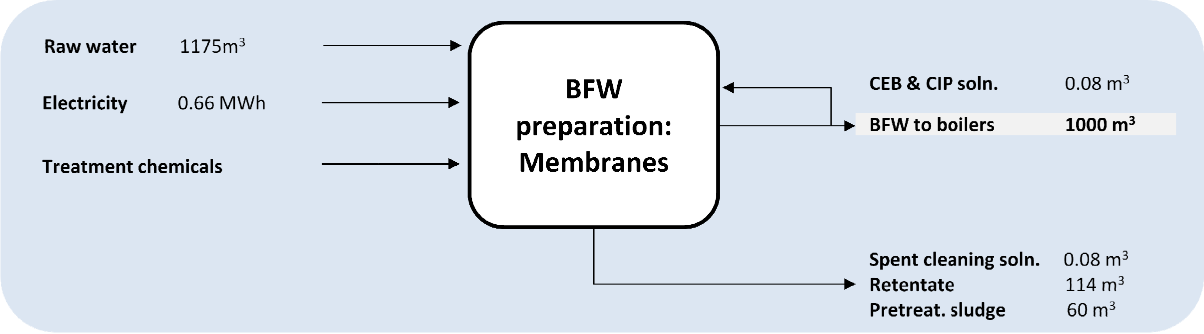

Figure 14: **Selected flows for the Reverse Osmosis intervention**

Table 12: **Water balance on membranes based BFW preparation system**

Flowrate in (m^3)	
Raw water	1175
Total	**1175**

Flowrate out (m^3)	
Boiler feed water	1000
Retentate	114
UF pretreatment sludge	60
Spent cleaning solution	0.08
Total	**1175**

Table 13: **Salts balance on Membranes based BFW preparation system**

Salts flowrate in (kg)	
Raw water salts	***117***
Treatment chemicals	***25***
HCl	24
$NaHSO_3$	0.43
NaOH	0.02
Citric acid	0.22
Cl_2	0.14
Total	**142**

Salts flowrate out (kg)	
Boiler feed water salts	***4.3***
RO retentate	***131***
Raw water salts	107
HCl	24
Cl_2	0.14
UF pretreatment sludge(RW salts)	5.9
Spent CIP/CEB soln.	***0.68***
Citric acid	0.2
$NaHSO_3$	0.4
NaOH	0.02
Total	**142**

Pretreatment

Feed water is dosed at 5ppm with chlorine gas (0.15kg/Ml BFW), and Sodium Bisulphate (0.012kg/Ml BFW) to inhibit bio-fouling and prevent membrane damage by free residual Chlorine (see Hydronautics, 2008).

Acid is dosed at 20ppm or 25.74kg/Ml BFW as an anti-scalant mechanism. Hydrochloric acid is preferred to sulfuric acid, as the latter can increase sulphate scaling potential (Tate, 2008).

Ultrafiltration

At a specific power consumption of 0.1 – 0.2 kWh/m^3, this unit requires 0.1 – 0.2 MWh per 1 Ml product from the UF system (Wilf *et al.*, 2007) (Harding, 2008).

Chemically enhanced backwash (see Appendix 5.5) is performed once daily with a cleaning solution of around 3.8m^3 or 0.056m^3/Ml BFW produced by the system. Treatment chemicals NaOH and NaOCl are dosed at 10ppm which translates to 0.01kg of each chemical per Ml BFW produced by the process.

Reverse osmosis

At a specific power consumption of around 0.4 – 0.5 kWh/m^3, this unit requires 0.4 to 0.5 MWh per 1 Ml BFW produced by the system (Wilf *et al.,* 2007) (Harding, 2008).

Biannual membrane restoration procedure (see Appendix 5.5) requires a cleaning solution of 760m^3 for high and low pH treatment with 2% NaOH and 2% citric acid respectively. This translates to 0.023Ml cleaning solution, 0.61kg citric acid and 0.61kg NaOH as well a negligible amount of surfactant per Ml BFW produced by the system.

5.3 COMPARISON OF BFW PREPARATION OPTIONS

As outlined in Section 5.1, the impact categories with problem-oriented/mid-point indicators selected for the rigorous account and analysis of environmental impacts associated with the inventories of two treatment options were Abiotic Depletion, Acidification, Eutrophication, Human toxicity, Freshwater aquatic ecotoxicity, Global Warming Potential.

The software used to execute the LCA was SimaPro version 7.2.4 and the impact method selected specifically for the elaboration of the problem oriented approach was CML 2 baseline 2000.

Although an impact category for salinisation has not yet been formalised, it describes an important environmental problem in the complex and is central to the meaningful comparison of the intervention with the base case (see Chapter 2 and 4). Salinity impacts are compared at the inventory level.

To determine the strength of the results obtained from this section undergo Interpretation and Evaluation in Section 5.4.

5.3.1 Comparing results within impact categories

In this section, the inventories compiled in Section 5.2 are assessed and analysed relative to the impact categories described in Section 5.1.2.2. In particular, contributing sub-processes associated with each impact category are compared for the boiler feed water preparation technologies described in Section 5.2.

Figure 15 shows a comparison of characterisation results for the production of BFW from either of the two desalination technologies.

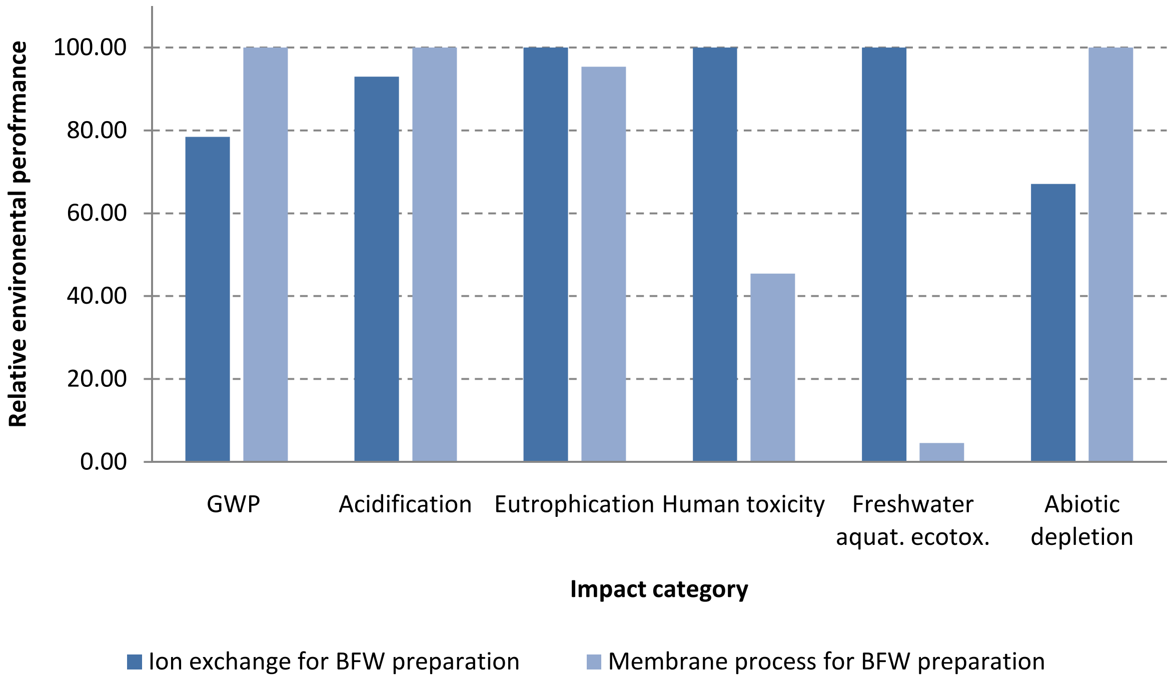

Figure 15: **Comparison of characterisation results for the production of 1Ml BFW by either technology**

In the following subsections, each impact category will be analysed to determine the cause of dominance displayed by either technology, as shown in Figure 15 above.

This data will be compared by means of a contribution analysis (Baumann and Tillman, 2004).

5.3.1.1 Global warming

As is evident from Figure 15 and Table 14, emissions contributing to greenhouse gases (GHGs) for RO are greater than those of the IX process by a factor of about 1.3.

Table 14: Process contributions to GWP for the two processes

GWP (kg CO_2 equivalent per Ml BFW produced)		
	IX	RO
Total of all processes	**534**	**681**
Hard coal burned in power plant/ZA – Tutuka	344	639
Quicklime in pieces, at plant/ZA	51.2	0.25
Transport, lorry	23.2	1.06
Magnesium oxide, at plant/ZA	18.5	-
Hard coal, at mine/ZA	14.0	26.0

Electrical energy to power the high pressure pumps for the RO process is sourced from the coal-fired Tutuka power station situated in the complex. The greenhouse gas emissions associated with this thermally inefficient means of electricity generation account for the only significant source (94%) of GHG emissions for the RO intervention.

The major component of the IX process' contribution to GWP is indirectly attributed to the use of **Sodium Hydroxide** in demineralisation units for resin regeneration (described above in Section 5.2 above). Greenhouse gas emissions associated with electricity input for electrolysis of NaCl brine to produce NaOH account for around 64% of the total GWP impact of this desalination process (344 kg CO_2 equivalent out of a total of 534 kg CO_2 equivalent per Ml BFW produced).

Hot lime softening treatment chemicals, quicklime and magnesium oxide, respectively contribute 51.2 and 18.5 kg CO_2 equivalent per Ml BFW produced or 10% and 3% of the total GWP impact of this process. GHG emitting processes associated with the production of **lime** include energy intensive crushing of limestone, carbon dioxide releasing calcination and electricity for pre-heating of heavy fuel oil used in heavy machinery.

Magnesium oxide is produced by crushing rock for the liberation of minerals. As stated by the data compilers for the ecoinvent database (from which the background data for MgO was sourced), "*large uncertainty exists around the process data* [for MgO] *due to weak data on the production process. The data is approximated from energy intensive iron mining and beneficiation as well as lime crushing and milling*". The uncertainty around this does not affect the overall result significantly.

A further contributor to GWP by both technologies is the combustion gases of transport fuels for the **transportation of chemicals** from the greater Johannesburg region to the Secunda Complex. The transport distance estimated in Section 5.2 was 200 km. Transportation in LCA is typically measured in terms of distance travelled multiplied by the weight transported. As illustrated in Section 5.2, the chemicals for the IX process are approximately 24 times more by mass than that of the RO process, which explains the 24 fold discrepancy in the emissions due to transportation for the two processes, as reflected in Table 14.

From a life cycle perspective, environmental impacts associated with the production of electricity from coal are linked to those of **coal mining operations**. Coal mining contributes to GWP through the release of carbon dioxide from the lithosphere as well as the fossil-fuels based energy requirements of mining operations (crude oil and coal). This is reflected in Table 14 by "**Hard coal at Mine**", which is a sub-process to electricity generation.

As described in Chapter 2 and Section 5.1.2.2, GHG emissions in the Secunda complex are at a disproportionally high level and although this impact category does not directly address the central issue of this thesis (salts and water related sustainability problems), it remains a very relevant factor in the discussion of overall environmental sustainability of a new intervention.

The characterisation method behind this impact category has been extensively elaborated and improved which lends credibility to the results here. It can thus conclusively be said that for this impact category the IX out-performs the RO intervention as regards emissions of green house gases.

This finding was subject to two major assumptions

i. That a large amount of waste heat is available for the softening units of the IX/S system and that this aspect of the current water preparation system therefore carries zero environmental burdens; and

ii. That marginal power capacity in South Africa is coal-based and not derived from renewables.

5.3.1.2 Acidification

As explained in Section 5.1.2.2, this impact category relates the environmental impacts that result when acidifying gaseous emissions such as Ammonia, SOx and NOx become trapped in rain and are deposited onto water and soil bodies.

Despite the impacts for electricity use (associated with NaOH production as explained above) being lower for the IX process compared to RO, emissions of particularly sulphur dioxide associated with the production of sulphuric acid (for resin regeneration) results in the IX/S process surpassing the RO process for this impact category by 0.38 kg SO_2 equivalent per Ml BFW produced, 5%.

SO_2 emissions from the collection of processes which culminate in the production of Sulphuric Acid contribute 21% (1.72 kg SO_2 eq per Ml BFW produced) towards total acidification impacts of the IX process. The major sub-process for this is “Hard coal burned in power plant”, as illustrated in Table 15.

Electricity-related SO_2 emissions for the aggregated production processes of Sodium Hydroxide contribute 49% (4.03 kg SO_2 eq per Ml BFW produced) towards total acidification impacts of the IX/S process. The major sub-processes are “Secondary Sulphur at refinery” and “Sulphuric Acid at plant”, as illustrated in Table 15.

Table 15: Process contributions to Acidification for the two processes

Acidification (kg SO_2 equivalent per Ml BFW produced)	IX	RO
Total of all processes	**8.16**	**7.78**
Hard coal burned in power plant, ZA – Tutuka	4.03	7.49
Secondary Sulphur at refinery/ZA	1.83	7.45E-03
Sulphuric acid, at plant, liquid/ZA	1.72	7.00E-03

As described in Section 5.1.2.2, acidification is a particularly problematic environmental problem in the Mpumalanga and this, based on the results above, might suggest that the RO process is preferable in this instance. However, it must be noted that there is only a small difference in results for the two desalination systems for this impact category, and that the switching from using HCl acid to H_2SO_4 acid for the RO process would reverse the ranking. Within the bounds of data and technical uncertainty it should thus be concluded that no distinction can be made between the two options in this impact category.

5.3.1.3 Human toxicity

Figure 15 and Table 16 illustrate that emissions resulting from the IX process which contribute to human toxicity are more than double those of the RO process.

Table 16: Process contributions to Human Toxicity for the two processes

Human toxicity (kg 1,4 -BD equivalent per Ml BFW produced)		
	IX	RO
Total of all processes	**51.1**	**23.2**
Disposal, red mud from bauxite digestion/CH	9.63	0.120
Hard coal burned in power plant/ZA - Tutuka	7.75	14.4
Monoethanolamine at plant	4.43	3.41E-05

For the RO process, 62% of total emissions contributing to HT are accounted for by the collection of processes that culminate in the **coal-based generation of electricity** (to power high pressure pumps). The only other major contributor of this process to HT is the production of Monoethanolamine for hydrochloric acid production representing a further 9% of total emissions.

Red mud is a problematic solid waste “by-product” which is produced at a rate of 2 ton per ton of alumina during **bauxite digestion**, a component in the conversion of bauxite to alumina (Tan and Khoo, 2003). This ultimately forms part of the production of **Aluminium Sulphate** (New Zealand Institute of Chemistry, 2006). This waste is disposed of in landfills with the potential for leakage or spillage of a range of heavy metal contaminants from the landfill facility into groundwater and river systems (Tan and Khoo, 2003). Toxic metals such as Arsenic, Cadmium, Chromium IV, Antimony, Cobalt, Nickel, Vanadium and Selenium are thus potentially available for direct ingestion by aquatic ecosystems and direct or indirect exposure of human populations. A recent disaster of this nature in Hungary reflects the potential danger inherent with the storage of such a waste material and the calamitous effects associated with its contact with nature.

Whilst the focus of this study is primarily to investigate salinity effects within the local Secunda complex, the life cycle approach has identified that the use of this seemingly mild treatment chemical results in human toxicity impacts that extend beyond the boundaries of the Secunda complex to affect communities where Bauxite is mined and processed (Australia, Jamaica, Guinea or Brazil).

5.3.1.4 Abiotic depletion

Figure 15 and Table 17 illustrate that overall emissions which contribute to depletion of abiotic resource bodies follow a similar pattern to those for GWP, as described in Section 5.3.1.1.

Table 17: Process contributions to Abiotic Depletion for the two processes

Abiotic depletion (kg Sb equivalent per Ml BFW produced)	IX	RO
Total of all processes	**3.87**	**5.77**
Hard coal at mine/ZA	3.05	5.67
Crude oil production, onshore/RAF	0.150	7.40E-03

For both desalination options investigated, the extraction of "**Hard coal in ground**" (to generate electricity for high pressure pumps of the RO or to produce NaOH for IX) accounts for the most significant contribution to abiotic depletion: 98% or 5.67 kg Sb equivalent per Ml BFW produced by RO and 79% or 3.05 kg 1,4-BD equivalent per Ml BFW produced by IX/S.

This finding was subject to two major assumptions

i. That a large amount of waste heat is available for the softening units of the IX/S system and that this aspect of the current water preparation system therefore carries zero environmental burdens; and

ii. That marginal power capacity in South Africa is coal-based and not derived from renewables.

The second largest but in comparison insignificant contributing process is the crude oil used for transportation of chemicals to the Secunda industries as described previously (see discussion on GWP).

Although this impact category does not directly address the central issue of this thesis (salts and water related sustainability problems), it remains a relevant factor in the discussion of overall environmental sustainability of a new intervention compared to the base case. As described in Section 5.1.2.2, depletion of abiotic reserves for inefficient production of thermal energy is particularly problematic when considering that South Africa has vast renewable energy potential. This will be discussed in the Evaluation.

5.3.1.5 Eutrophication

Figure 15 and Table 18 illustrate that overall emissions which contribute to nutrification of water bodies are quite similar for the two desalination technologies investigated.

Table 18: Process contributions to Eutrophication for the two processes

Eutrophication (kg PO_4^{2-} equivalent per Ml BFW produced)		
	IX	RO
Total of all processes	**0.30**	**0.33**
Hard coal burned in power plant/ZA - Tutuka	0.15	0.27
Sodium carbonate	0.029	-
Blasting	0.025	0.044

For both desalination options investigated, the collection of processes that culminate in the **coal-based generation of electricity** (to power high pressure pumps for RO or produce NaOH for IX/S) accounts for the most significant contribution to eutrophication: 82% or 0.27 kg PO_4^{2-} equivalent per Ml BFW produced for RO and 50% or 0.15 kg PO_4^{2-} equivalent per Ml BFW produced for IX/S. The major sub-process for both these technologies is “Hard coal burned in power plant”, as illustrated in Table 18.

Sub-processes related to the production of treatment chemicals contribute the remaining 0.15 kg PO_4^{2-} equivalent per Ml BFW produced for IX/S. Notably, rock blasting with explosives releases Nitrogen Oxides.

The life cycle inventories indicate that the major substance responsible for eutrophication in both cases is the emission of Nitrogen Oxides to air which affects low-population density areas: 0.141 kg PO_4^{2-} equivalent per Ml BFW produced for IX/S and 0.243 kg PO_4^{2-} equivalent per Ml BFW produced for RO.

While eutrophication of surface water in major river systems (as consequence of the industrial activities found in the Secunda complex) represents adverse implications for aquatic ecosystem health and the health of human users of water that should give rise to concern (see Section 5.1.2.2), the two systems analysed here perform similarly and this will not be discussed further in the Evaluation.

5.3.1.6 Freshwater aquatic ecotoxicity

The results for this subcategory of the aquatic toxicity are governed by the leaching of heavy metals from solids waste product landfill facilities (red mud and coal ash). Since these impacts mimic those of Human Toxicity discussed above, they are not discussed again here.

Table 19: Process contributions to Freshwater Aquatic ecotoxicity for the two processes

Freshwater aquatic ecotoxicity (kg 1,4 -BD equivalent per Ml BFW produced)		
	IX	RO
Total of all processes	**37.40**	**1.69**
Disposal, red mud from bauxite digestion/CH	22.40	0.28
Magnesium oxide, at plant/ZA	9.64	-
Disposal, hard coal ash/PL	0.26	0.42

5.3.2 Salts footprint analysis

Given that characterisation indicators for ions in the life cycle inventories of the BFW systems compared here are not well developed (see Chapter 2), the implications of these emissions are reported on the inventory level and will be analysed qualitatively next. This is done in order to determine whether the intervention proposed in Chapter 4 is associated with burden-shifting of salts within the complex.

First, the salts footprint associated with the desalination of mine water at the Tutuka power station is determined in order to compare the electricity-based RO process to the chemicals intensive IX process. The main cations that will be compared are calcium, magnesium, sodium, while the main anions that will be compared are chloride and sulphate. The sources of dissolved salts that are included in the comparison are raw water, treatment chemicals and the salts associated with mine water desalination at the Tutuka power station.

5.3.2.1 Electricity from Tutuka power station

Salts and water balance problems associated with the production of electricity at the Tutuka power station were described qualitatively in Chapter 2. Figure 16 and Table 20 summarise the raw water, mine water, treatment chemicals and total ions input associated with the production of 1 MWh at the power station. Appendix 5.6 contains the calculations supporting these results.

Raw water ions represent a minor contributor for all ions while mine water represents the main contributor to sodium, chloride and sulphate ions. Treatment chemicals contribute 0.15 kg calcium ion and 0.98 kg sulphate ion per MWh produced as a result of the addition of hydrated lime ($Ca(OH)_2$) for cold lime treatment of cooling water and sulphuric acid (H_2SO_4) for ion exchange resin treatment.

Desalination of raw and mine water is performed by membranes processes, thus not incurring further major treatment chemicals, as reflected in Table 20.

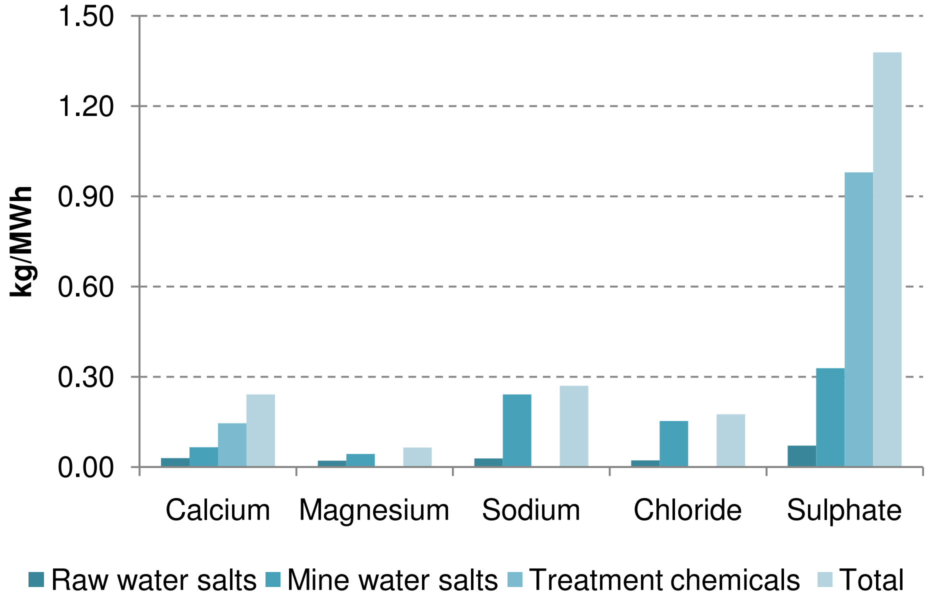

Figure 16: **Salts footprint associated the electricity production at Tutuka**

Table 20: **Summary of Tutuka salts burden**

ESKOM TUTUKA (kg/MWh)				
	Raw water ions	Mine water ions	Treatment ions	**Total ions**
Calcium	0.03	0.07	0.15	**0.24**
Magnesium	0.02	0.04	-	**0.07**
Sodium	0.03	0.24	-	**0.27**
Chloride	0.02	0.15	-	**0.18**
Sulphate	0.07	0.33	0.98	**1.38**

5.3.2.2 Boiler feed water from the Reverse Osmosis intervention

As indicated in Figure 17 and detailed in Table 21, dissolved salts in the raw water generally accounts for all the ions associated with the production of boiler feed water by reverse osmosis.

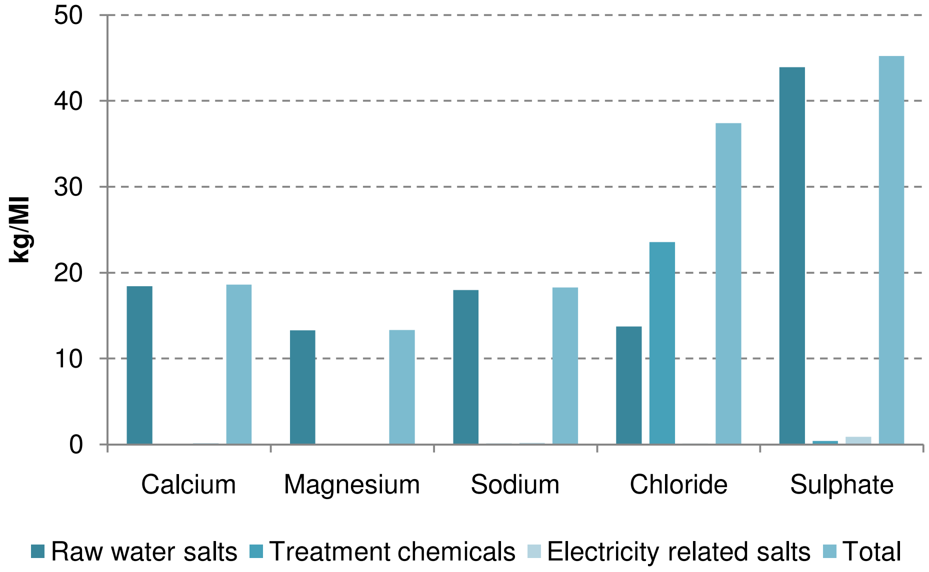

Figure 17: **Salts footprint associated with the reverse osmosis intervention**

Table 21: **Summary of salts balance associated with the RO intervention**

REVERSE OSMOSIS PROCESS (kg/Ml BFW produced)				
	Raw water salts	Electricity-related salts	Treatment chemicals	**Total**
Calcium	18.44	0.16	-	**18.60**
Magnesium	13.27	0.04	-	**13.32**
Sodium	17.97	0.18	0.11	**18.25**
Chloride	13.74	0.11	23.54	**37.40**
Sulphate	43.93	0.90	0	**45.22**

As demonstrated in the inventory analysis of Section 5.2.2, the only significant treatment chemicals associated with this technology are HCl for anti-scaling and Cl_2 gas for bio-fouling control. This accounts for the major contribution by treatment chemicals to chlorine input associated with this technology.

5.3.2.3 Boiler feed water from the ion exchange process at Sasol Synfuels

Salts balance problems associated with the ion exchange process at Sasol Synfuels are described qualitatively in Chapter 2 and are illustrated in part by Figure 18 and Table 22: the use of treatment chemicals (described in Section 5.2.1) contributes more than 80% of total sodium, chloride and sulphate inputs to this process.

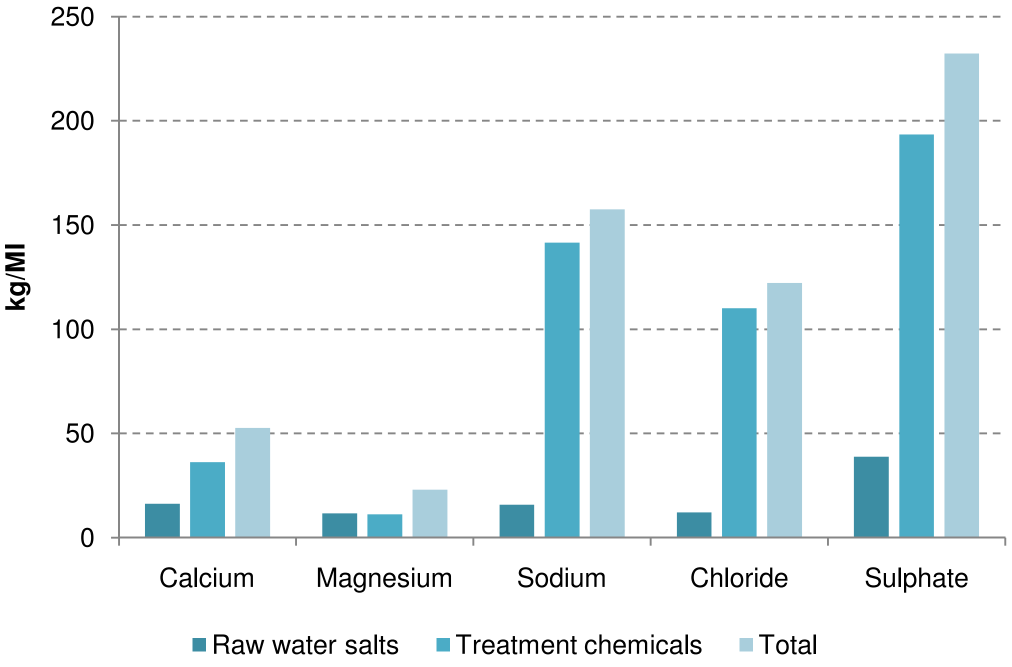

Figure 18: **Salts footprint associated with the ion exchange process at Sasol Synfuels**

Table 22: **Summary of salts balance associated with the IX intervention**

ION EXCHANGE PROCESS (kg/Ml BFW produced)			
	Raw water salts	Treatment chemicals	**Total**
Calcium	16	36	**53**
Magnesium	12	11	**23**
Sodium	16	142	**158**
Chloride	12	110	**122**
Sulphate	39	193	**232**

5.3.2.4 Comparison of boiler feed water preparation technologies

Figure 19 shows a final comparison of the salts footprints associated with the two options for producing boiler feed water at Sasol Synfuels considered here.

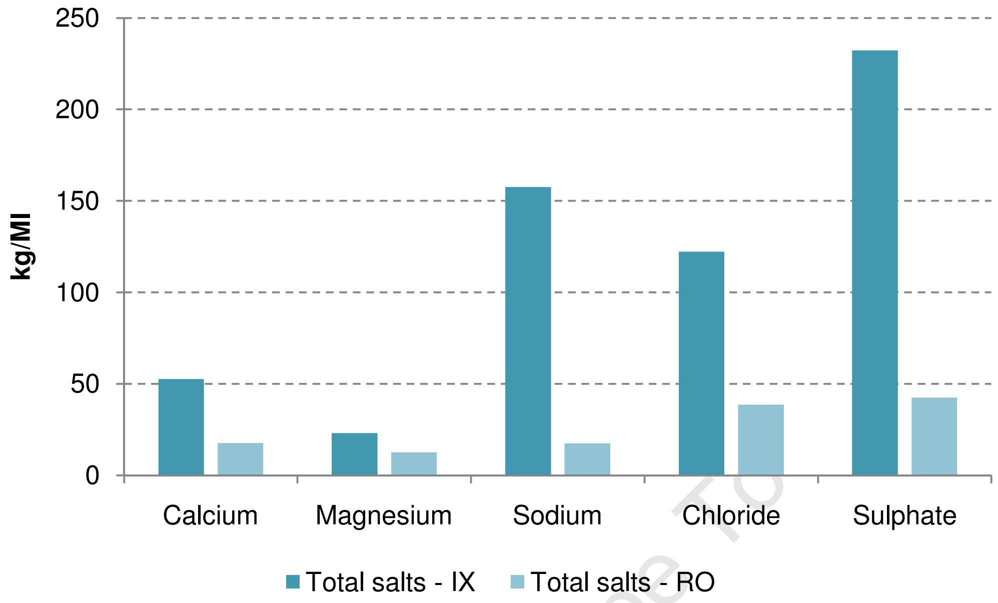

Figure 19: Comparison of the salts footprint of the two technologies studied

Despite the desalination of hyper-saline mine water at the power station on which the Reverse Osmosis intervention relies for its power supply, this method of BFW production would introduce almost 5 times less salty cations and 4.4 times fewer salty anions into problematic indefinite storage in the complex, thus not contributing towards the salinity problem described in Chapter 2 as much as the IX process does. This is true in particular for problematic sodium, chloride and sulphate ions (see Chapter 2 and 4).

5.4 LCA INTERPRETATION

As per the ISO standard definition, this last phase of the LCA is concerned with establishing whether “the findings from either the inventory analysis or the impact assessment or both are combined consistent with the defined goal and scope in order to reach conclusions and recommendations”, (ISO 14040 1997). This allows for drawing meaningful conclusions from the LCA and is done through a process of screening raw results, identification of critical data and the assessment of the importance of missing or inferred data.

This section ends with an evaluation of the robustness of these conclusions and variation analyses to explore the effects of alternative scenarios and life cycle models.

5.4.1 Identification of significant issues

Given the focus of this thesis on environmental sustainability problems relating to salts and water issues, the finding that implementation of the RO intervention does not result in shifting of the salts burden is significant. This result is especially meaningful in light of the inclusion for RO of the worst case scenario for electricity with regard to salts footprint (see Section 5.1.2.6).

For all other impact categories used in the study, the environmental performance of the RO system is dominated by effects relating to the use of electricity from thermal power plants. For the IX process, on the other hand, a number of other chemicals production processes contribute to the environmental burdens, and as a result, the IX/S option also fares worse than the RO option in terms of toxic emissions.

Although not analysed further in the variation analyses of Section 5.4, it is obvious that substituting electricity from coal-fired power stations for renewable (MacColl, 2009) or even nuclear based alternatives would improve the performance of the RO system for all impact categories including Salinisation and especially Depletion of Abiotic Resources (coal) and Global Warming Potential. The impact assessment for this, as contained in Appendix 5.7, illustrates that, for 100% substitution of fossil-derived electricity, the impacts are markedly reduced across all impact categories.

The IX/S process yielded unexpected results for Human toxicity and Freshwater Aquatic Ecotoxicity categories. It was found that the use of seemingly benign aluminium sulphate coagulant is associated with adverse environmental impacts due to heavy metal contamination from solid waste landfills associated with bauxite processing.

5.4.2 Evaluation

Sufficient data were available to complete all phases of the LCA and thus the goal and scope of this study are deemed adequately met (see Section 5.1.2.6).

The investigation of some potential alternative situations or scenarios included in the results adds to the robustness of results and the conclusions drawn from them.

5.4.2.1 Variation analysis

Given the identification that the use phase of the technologies studied are associated with the most significant impacts, **variation analyses** on inputs to this phase could be interesting. A variation analyses is performed on the IX technology mix for BFW production.

Ion exchange processes comparison

As described in Sections 5.1 and 5.2, the ion exchange process at Sasol Synfuels is comprised of demineralisation and sodium softening technologies which collectively produce boiler feed water. Figure 20 below shows the environmental impacts associated with the system collectively producing 1 Ml of BFW for the configuration 6% OD product, 23%ND product, 71% NaZ product by volume.

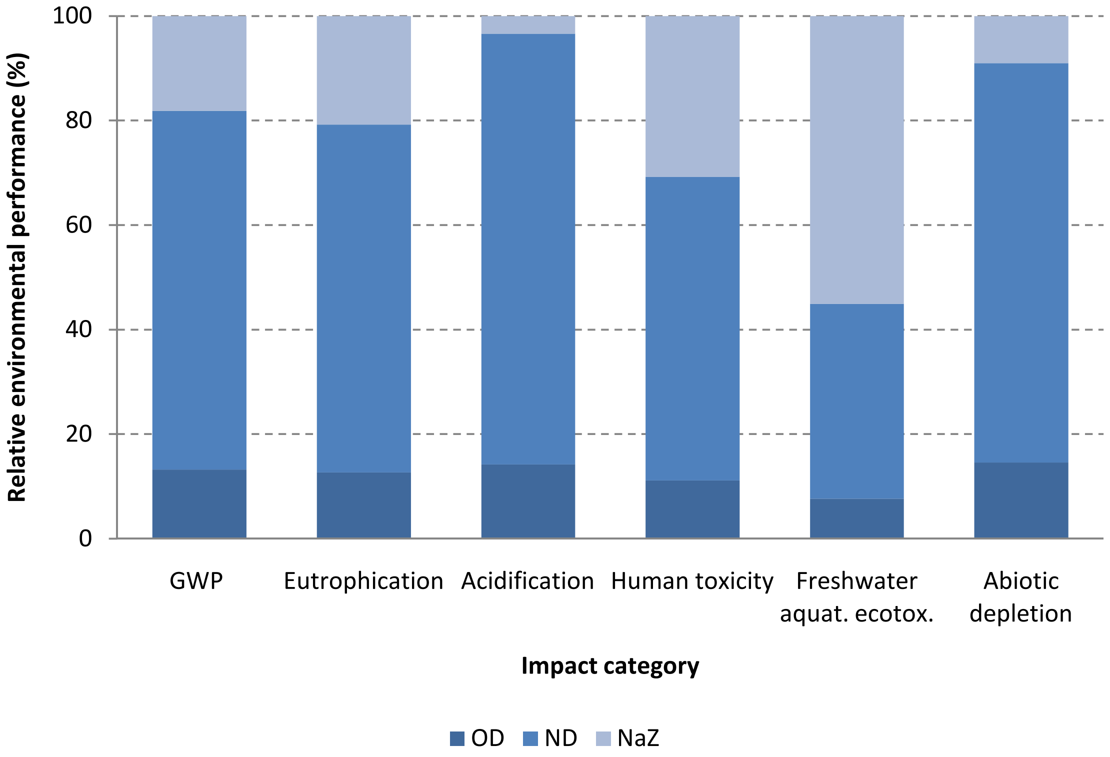

Figure 20: **Collective contribution of IX technologies to environmental performance of IX system for the production of 1Ml of BFW (6% OD product, 23%ND product, 71% NaZ)**

New Demineralisation only contributes 23% of the 1 Ml produced by the system, yet it accounts for more than half the environmental impact for all impact categories excluding freshwater aquatic ecotoxicity.

Figure 21 shows the comparison of ion exchange and reverse osmosis processes for the production of 1 Ml of BFW from each.

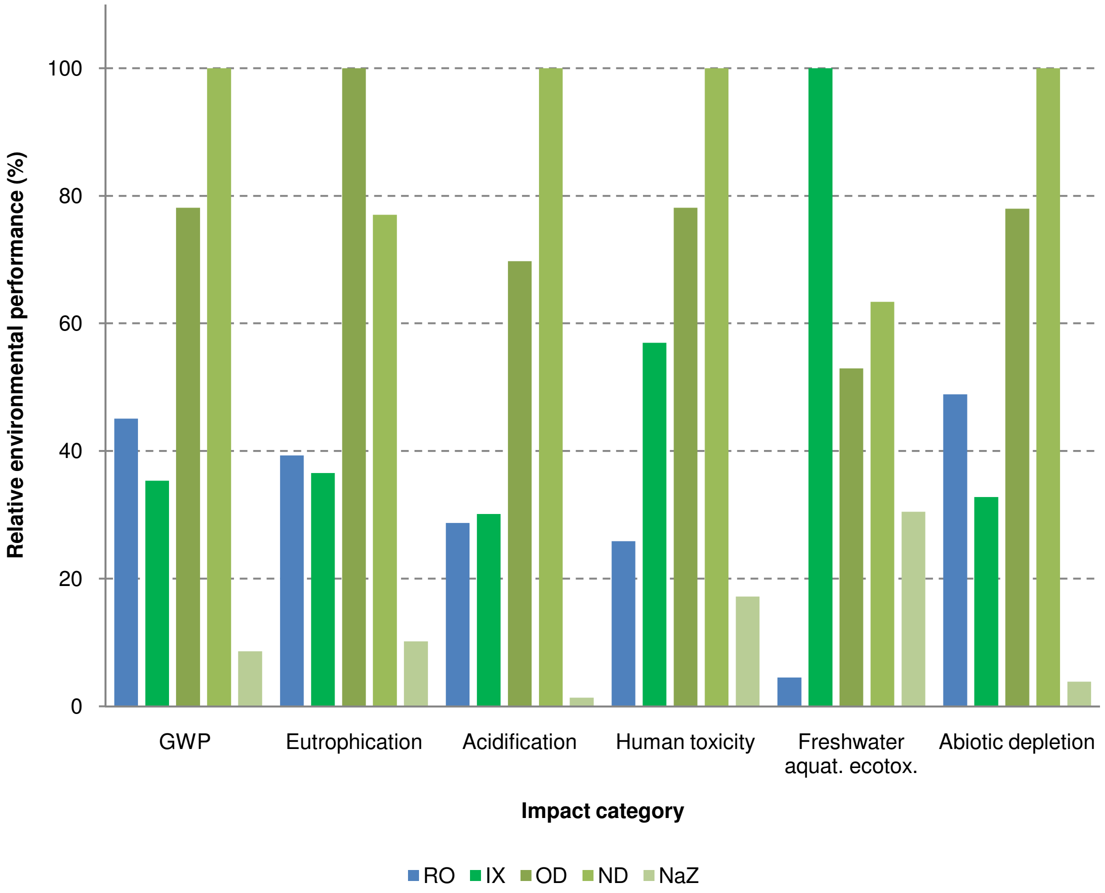

Figure 21: **Production of 1Ml of BFW from individual IX technologies is compared to RO**

The environmental impact of the combined IX system (6% OD product, 23%ND product, 71% NaZ product by volume) is reduced by the low percentage of OD product (which has a larger impact compared to RO for 1 Ml produced) and a larger portion of poorer quality NaZ product (which has a reduced impact compared to RO for 1 Ml produced).

This comparison illustrates that, for the production of one mega litre of boiler feed water, New and Old Demineralisation units have more detrimental overall effects on the environment compared to the electricity usage of the RO process.

5.5 CONCLUDING COMMENTS

Through the rigorous methodology of LCA, the purpose of this chapter was to analyse the environmental burdens associated with the operations of two distinct the boiler feed water preparation technologies, and in particular to evaluate to what extent salinity burdens would merely be shifted from one industry in the complex to another.

Goal and scope definitions proposed the approach and problem statement for the investigation and defined the system boundaries for the systems for which inventories were compiled from material and energy balances on the processes. Inventory data were compiled through process analysis by means of the process flow diagram approach in Section 5.2. Section 5.3 contains the results of the Life Cycle Impact Assessments (LCIA) for the impact categories defined to be relevant to the objectives of this study. In order to prevent over-emphasis of the "emissions-caused impacts" which this method is focussed on, it was deemed necessary to balance the analysis out with an assessment of "uncharacterised" salts/ions inventory data which was available.

Significant findings from the LCAs include:

- The use of Aluminium Sulphate coagulant results in adverse impacts on human toxicity and freshwater aquatic ecotoxicity in geographies outside of the borders of the Secunda complex, thus resulting in burden-shifting.

- Especially for impact categories relating to abiotic resource depletion and greenhouse gas emissions, which are both established problems in South Africa, the RO intervention is associated with a poorer environmental performance compared to IX, unless its electricity would come from a non-fossil fuel source.

- The RO intervention does not result in burden-shifting of salts problems.

- When the IX technologies that make up the IX system were compared individually to RO, it was found that ND and OD products have significantly greater environmental burdens than RO. Given that Sasol Synfuels operators change the ratio of NaZ to OD&ND product according to downstream requirements, the RO intervention becomes preferable from an environmental point of view for low NaZ to OD&ND product ratios.

The next chapter of this dissertation will combine the significance of these results with those from the other chapters, to address the key objectives of this thesis.

CHAPTER 6

Conclusions and Recommendations

This chapter will revisit objectives and hypotheses that led this thesis and, upon reflection on the results obtained in the previous chapters, the subsections of this chapter will establish whether these were adequately met.

Section 6.1 first revisits the objectives of this work and establishes how the procedures followed in this thesis were used to address these objectives systematically. The second part of Section 6.1 captures the major findings from the literature review, sustainability assessment, options generation and life cycle assessments. Section 6.2 reflects on these findings to determine the validity of the research hypotheses that were formulated in Chapter 3. Following this, Section 6.3 finally concludes this thesis with key recommendations for further research and for the industries within the Secunda complex.

6.1 OBJECTIVES AND MAJOR FINDINGS

As described in Chapter 1, the purpose of this research was to address the following objectives:

i. To identify salts and water related environmental sustainability issues in the complex
ii. To develop appropriate technological interventions to address these issues
iii. To compare in detail the environmental performance of one such intervention to its base case by means of LCA.

These objectives were addressed through a sequence of steps outlined in detail in Chapter 3. As part of the literature review to this IE dissertation, sources of salts and water related environmental sustainability problems in the complex were investigated and in light of this, endeavours by the industrial partners to address these problems were reviewed.

The first objective was addressed by means of an assessment of industrial practices which result in transgressions of environmental sustainability in the complex as detailed in Chapter 4. This assessment was guided by the philosophy of The Natural Step Framework and from this several industrial symbiosis interventions which aim to address the identified transgressions by substitution or dematerialisation options were established. The generation of options in Chapter 4 was informed by the principles of the waste-management hierarchy and IE, and accomplished the second objective of this research.

In fulfilment of the final objective, complete and detailed comparative life cycle assessments of the selected intervention and its base case were performed in Chapter 5 to ascertain whether the proposed intervention would genuinely reduce environmental burdens, or merely shift them.

Following is a brief account of the most significant findings from the literature study, sustainability assessment and the LCAs.

6.1.1 Conclusions drawn from literature

The literature review provided the following guiding themes for the research.

A brief recount of the broad **environmental sustainability problems** in the Secunda Complex and South Africa highlighted the need for caution when making use of “ready-made” impact assessment methods that were developed for foreign geographies. In particular, the inclusion of a salinisation impact category was deemed decisive for meaningful comparison of technology interventions with the base case.

A review of **endeavours by industries to address salts and water balance problems** (installation of several expensive and elaborate desalination and brine handling technologies) revealed that although water balance problems were generally alleviated by these endeavours, frequently these have not been matched with proportionate alleviation of the salts balance problems. In general, it was found that, the salts recovery technologies failed or at best deferred the salts problem to indefinite storage.

While **industrial ecology** was found to be an as yet immature approach in the South African context, the relevance of this approach to attempts similar to this research at reducing environmental impacts of large industrial complexes and/or a number of industries in close proximity was demonstrated by means of a review of international case studies.

The methodology for **life cycle assessment applied to water systems** was found to be an evolving application of LCA. A case study review revealed that this systemic approach has been applied to a variety of water and waste water systems including the South African context.

6.1.2 Assessment of sustainability violations

The assessment of the environmental sustainability in the Secunda complex identified several violations to the system conditions for sustainability suggested by TNSF. The use of coal was found to be central to the following specific environmental sustainability problems that were identified:

- Unsustainable abstraction and inefficient use of fossil resources and surface water results in the unsustainable flux of materials from the lithosphere to the ecosphere. This is coupled to the production of large volumes of problematic solid, fluid and gaseous wastes which penetrate several parts of the ecosphere and cause destruction of ecosystems by physical means.
- The undirected management of highly-mobile salts abstracted from fissure mine water and remote mineral deposits (for chemicals production) is coupled to a high risk of exposure to ecosystems.
- Coal mining results in large scale destruction of ecosystems by physical means.

6.1.3 Options generation

The principles of IE and the waste-management hierarchy were applied to the findings from the sustainability assessment for the generation of possible interventions for further investigation. These interventions incorporated consideration for multi-party engagements or effects. They are summarised in Table 23 below.

Table 23: Options generated for intervention

	Technology option
1	Substitute chemicals based softening and ion exchange with membrane process
2	Waste heat synergy of Sasol Synfuels waste heat and Evander thermal needs
3	Waste water synergy: recover waste water at Sasol Synfuels for slimes processing at Evander
4a	Produce Na_2CO_3 from waste water after volume reduction
4b	Produce Na_2SO_4 from waste water after volume reduction

Option 1 was selected through a process of ranking and rating as the subject for further investigation.

Substitution of the existing IX/S process at Sasol Synfuels with a membrane desalination mechanism addressed "**reduction at source**" of the salts accumulation/abstraction problem. This case study incorporated potential **multi-partner effects** in that electricity from the Tutuka power station, which itself is associated with a high salts footprint, was included in the model for powering high pressure pumps.

The *regional* synergy between Harmony Gold Evander and either Tutuka or Sasol Synfuels was selected as the case study option to represent "**recover energy from waste"** approach of the WMH. Potential for *local* waste heat synergies with water treatment units of Sasol Synfuels or Tutuka were identified but not pursued.

A multi-partner engagement between Harmony Evander and Sasol Synfuels for the exchange of water for the reuse in local/regional synergies represented the intent to "**reuse or recovery of problematic materials"**. The use of waste water or mine water for cooling applications represented a similar approach to waste minimisation but extensive work has already been done by the industries so it was not pursued as an option further.

For the "**reuse or recover problematic materials"** approach of the WMH, it was proposed that novel brine management technologies be reviewed along with the installed technologies at Sasol Synfuels for the recovery of sodium salts (Na_2SO_4 and Na_2CO_3) from problematic concentrated brines that are found throughout the complex.

6.1.4 Environmental viability of generated options

A comparative LCA was performed on the ion exchange and softening process at Sasol Synfuels to establish its environmental performance in impact categories deemed relevant to the existing problems in South Africa and specifically the Secunda complex. This was then compared to the findings from a similar analysis on the proposed membranes process intervention.

Significant findings from these LCAs include

1. The RO intervention would not result in shifting of salts problems from one place to another. The IX/S process releases approximately 460% (by mass) the amount of problematic salty ions that the RO process does.

2. For impact categories relating to abiotic resource depletion and greenhouse gas emissions, which are both established problems in South Africa, the RO intervention is associated with a 22% poorer environmental performance compared to IX.

This 2nd finding was subject to two major assumptions

i. That a large amount of waste heat is available for the softening units of the IX/S system and that this aspect of the current water preparation system therefore carries zero environmental burdens; and

ii. That marginal power capacity in South Africa is coal-based and not derived from renewables.

3. The use of Aluminium Sulphate coagulant by IX/S, an apparently harmless chemical, results in adverse impacts on human toxicity and freshwater aquatic ecotoxicity in geographies outside of the borders of the Secunda complex, thus resulting in burden-shifting.

4. A variation analysis showed that, when the IX technologies that make up the IX system are compared individually to RO, products from demineralisation units have significantly greater environmental burdens than RO. Given that Sasol Synfuels operators change the ratio of sodium softening to demineralisation units' product according to downstream requirements, the RO intervention becomes preferable from an environmental point of view for low sodium softening to demineralisation product ratios.

6.2 OVERALL CONCLUSIONS AND EVALUATION OF HYPOTHESES

A general first hypothesis was formulated in Chapter 3 in light of the strong link between the economic health and prosperity of South Africa and the responsible management of fresh water (Rogers *et al.,* 2008):

1. *There are salts and water related violations of environmental sustainability principles in the Secunda Complex, but their severity can be reduced by integrated technology interventions that involve joint action by two or more industries in the complex.*

As summarised in Section 6.1.2, several ES violations were identified through application of TNSF principles to findings from the consultative approach. Various integrated technologies and waste exchanges that incorporate concepts of industrial symbioses and result in a reduced environmental load were developed by means of the WMH as outlined in Section 6.1.3.

Thus, the notion that there are salt-related ES problems in the complex and that IE-type interventions to address them exist was confirmed.

The second hypothesis pertaining to the work of this thesis was based on the finding from the literature review that, by virtue of its positive feedback nature, chemicals-based ion exchange desalination technology at Sasol Synfuels is a factor contributing significantly to the salts and water sustainability problem in the Secunda complex. This finding was confirmed in the sustainability assessment.

2. *Implementation of a membranes-based water treatment technology for boiler feed water preparation will be associated with superior environmental performance in the complex to that of the current softening and ion exchange process at* Sasol Synfuels*. In particular, salts footprint associated with the use of power to desalinate water will not amount to significant burden-shifting of the large volumes of chemicals currently used for softening and ion exchange.*

The major results of the LCA which investigated the validity of this hypothesis are contained in Section 6.1.4. Since the RO process represents a significant reduction in the **salts burden**, in light of the major focus of this study, the RO process has a better environmental performance than the IX/S process. While environmental impacts relating to the use of coal-fired electricity appeared to be worse for the RO intervention, this was subject assumptions which relate to product ratio for IX/S technologies, waste heat availability to the IX process and the nature of marginal electricity supply to the South African grid.

6.3 RECOMMENDATIONS

Based on the conclusions drawn from the analyses presented in this dissertation and in light of the context of this research, recommendations are made for further research as well as for the industries in the complex.

6.3.1 Recommendations for further research

1. Other interventions that were developed in Chapter 4 are recommended as the subjects of further research.
    a) The **recovery of carbonate salts** from the installed but abandoned carbonation plant at Sasol Synfuels presents an opportunity for further research. Aspects relating to the disuse of this unit were studied in its pilot-study and were shown to be rectifiable. The availability of a pure CO_2 stream was identified as a product from the Benfield process at Sasol Synfuels and the requirement for alkalinity could be met by a study on abundant ash wastes.

b) Investigations into the potential dematerialisation associated with the **reuse of waste water and waste heat** at Harmony Evander from Sasol Synfuels is put forward for further analyses. This is reinforced by the appetite already expressed by both these industries for this type of exchange.

c) An assessment into the implementation of a novel brine technology such as **Eutectic Freeze Crystallisation** for the extraction of pure salts and water as a final step in water reclamation initiatives.

2. The allocation of weighting of options was not done as part of an extensive, participative process in collaboration with the members of the greater project team. The robustness of the results may be enhanced by consideration of the performance of alternatives.

3. Detailed **further analysis into the assumptions** that were cause for ambiguity in the Life Cycle Impact Assessment (LCIA) results could be verified by further analyses. The potential for utilisation of **renewable energy** to power the energy requirements of the membranes based desalination process is proposed for further study. Also, detailed analysis into the waste heat situation at Sasol Synfuels is proposed to determine the viability of the assumption regarding **waste heat availability** for hot lime softening in the IX/S system.

6.3.2 Recommendations to Secunda complex industries

The ES problems embodied in the Secunda complex were identified to be characteristic of a complex system with multiple interactions and effects. Development of meaningful interventions thus requires an understanding of the governing phenomena of such systems and necessitates consideration of multi-party effects and engagements. It is suggested that the principles used for the sustainability assessment and options development in this thesis could represent an alternative vantage point for engaging with the challenges relating to transcendence of water and salts related environmental sustainability problems in the Secunda complex.

The membranes-based intervention for boiler feed water preparation has been shown to represent a preferable option to chemicals based desalination in the Secunda complex under certain conditions and in particular in relation to salts burdens. It is recommended that the findings which underlie this assertion be pursued further in a feasibility study for replacing chemicals based desalination with a membranes process for the preparation of boiler feed water.

An awareness of the life cycles of chemical products enables selection of environmentally preferable options. For example

- An alternative to Sodium Hydroxide for the regeneration of resins could be investigated to reduce the hidden carbon footprint of the ion exchange units that this represents;
- An investigation into an alternative to the Aluminium Sulphate coagulant is recommended to reduce environmental burdens incurred in locations remote from the Sasol Synfuels facility.

Industrial activities in the Secunda complex have almost exclusively negative connotations with regard to environmental impact. Informed technology use for water treatment and the recycling/reuse of water and salts waste products should be viewed beyond potential economic gains and rather explored for the strides towards sustainable resource use that these may represent.

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APPENDICES

APPENDIX 2.1 SOUTH AFRICAN LICA FRAMEWORK TO CALCULATE IMPACTS

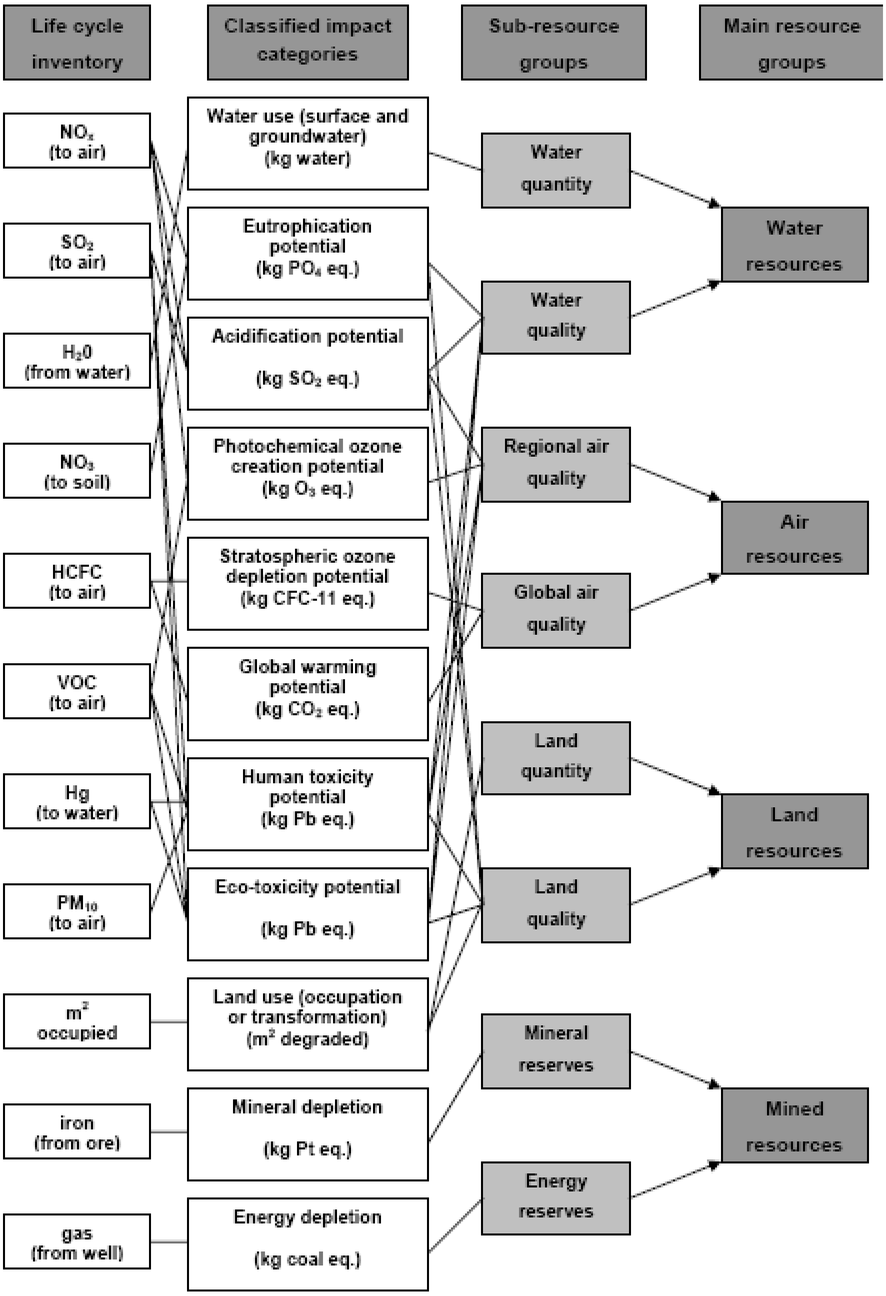


Figure 22: Framework of the South African LCIA procedure (Brent and Landu, 2007)

APPENDIX 4.1 CHARACTERISATION OF BRINES

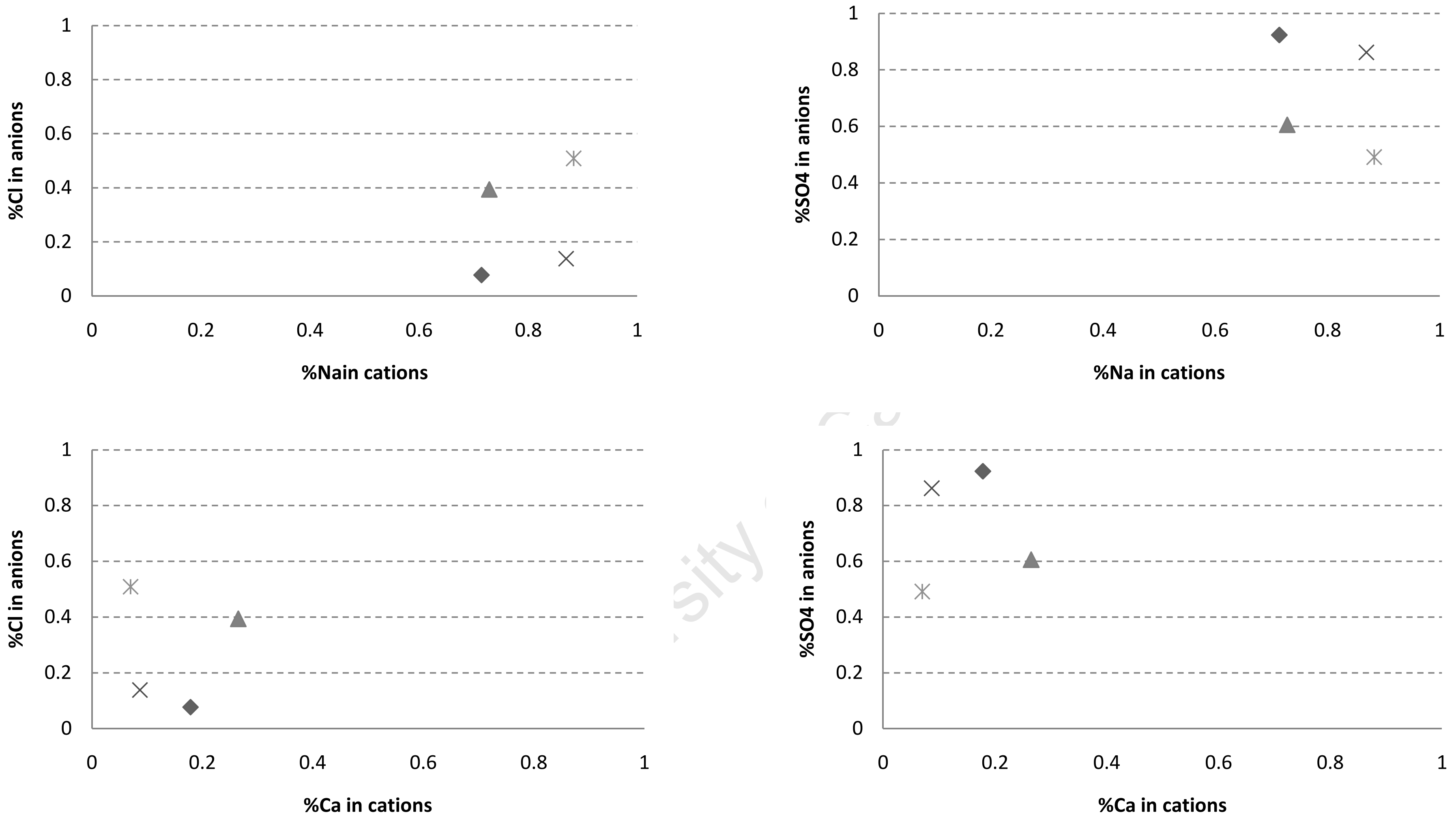


Figure 23: **Characterisation of Sasol Synfuels brines by ionic compositions**

◆MW: mine water, ▲CAE: clear ash effluent, X PCWBD: process cooling water blow down, ✳Ion exchange resin regeneration waste

APPENDIX 4.2 JUSTIFICATION FOR POINTS ALLOCATION

Weightings for technology options relative to selection criteria

	Selection criterion	Weighting (total of 20)
A	Technical feasibility (innovative/new or established “off the shelf” technology)	8
B	Sizable effect on salts problem in Complex	6
C	Level of cross-complex, multi-party engagement	4
D	Other barriers (incl. trust and governance issues)	2

	Technology option	Criterion A	Criterion B	Criterion C	Criterion D	Total score (10)
1	Replace IX with membrane process	10	8	7	5	**8.3**
4a	Produce Na_2CO_3 from brine streams	9	8	4	6	**7.4**
3	Waste water synergy: use mine water at Evander for slimes processing	10	3	8	3	**6.8**
4b	Produce Na_2SO_4 from brine streams	8	7	4	6	**6.5**
2	Waste heat synergy: Sasol Synfuels waste heat → Evander thermal needs	6	3	9	3	**5.4**

Technology option 1: replace IX/S with RO

Criterion A: Reverse osmosis technology is well established; recent improvements have made this technology especially attractive compared to others, (Greenlee *et al.*, 2009, see literature review in Section 4.5). This technology is awarded 10 points for criterion A.

Criterion B: Recovery of “waste water” is a crucial aspect identified in Table 4.1 of Chapter 4 for establishing sustainability, since it relates directly to achieving all three system conditions. However this must be conducted without exacerbating existing salts-related environmental problems. As is shown in (Appendix 4.1), this is not the case: all brines resulting from wastewater recovery by desalination practices (Mine water, PCWBD and CAE which are directly or indirectly treated by ion exchange) are major contributors to the accumulation of Na and SO_4 due to the addition of Na, SO_4 intensive treatment chemicals (NaCl, NaOH, H_2SO_4) for the regeneration of IX resins. This intervention is awarded 8 points for criterion B, since substituting IX with a membranes process will reduce the amount of treatment chemicals introduced into the complex.

An assessment of burden-shifting associated with the use of electricity from Tutuka, which itself uses IX/S and desalinates Mine Water, is done in Chapter 5 and 6.

Criterion C: Although this intervention does not require significant multi-party engagement (as is required to score high on criterion D), it has cross-complex appeal in that several industries within the complex make use of IX/S. It scores 7 for criterion D.

Criterion D: Given the company-specific nature of this intervention, it is to be constrained in terms of criterion C by company specific issues which are unknown. For criterion C this intervention scores a neutral 5 out of 10.

Given these ratings, this intervention scores 8.3 out of 10 overall.

Technology options 4a and 4b: recover $NaSO_4$, $NaCO_3$ from brines

Criterion A: A well established process for Soda Ash production is the Solvay process (Steinhauser, 2008). Existing technologies were identified in the Sasol Synfuels complex for salts recovery. In particular, a carbonation plant is available (Ras *et al.*, 2010a), which justifies the higher rating for intervention 4a.

Criterion B: Similar to technology option 1, the recovery of Na and SO_4 rich salts from desalination brines will “eliminate: these components from the complex. As is shown in Appendix 4.1, all brines resulting from desalination practices (Mine water, PCWBD and CAE which are directly or indirectly treated by ion exchange) are major contributors to the accumulation of Na and SO_4 due to the addition of Na, SO_4 intensive treatment chemicals (NaCl, NaOH, H_2SO_4) for the regeneration of IX resins. Given that removal of SO_4 is more advantageous in terms of Criterion B, intervention 4a is awarded 8 points as opposed to the 7 awarded to intervention 4b.

Criterion C: As for intervention 1, although this salts-recovery does not require multi-party engagement (as is required to score high on criterion D), it has cross-complex appeal in that brines are available for salts recovery at several industries within the complex. It scores 4 for criterion D.

Criterion D: Considering the oversupply of these chemicals on world markets, this intervention is awarded with a low score of 6 for criterion C). The quality of salts resulting from these interventions would need to be upgraded to improve the marketable values.

Intervention 4a scores 7.4 out of 10 overall while Intervention 4b scores 6.5 out of 10 overall.

Technology option 3: Multiparty waste water synergies

Criterion A: Several water desalination methods are commercially available. This intervention scores 10 for criterion A.

Criterion B: Recovery of "waste water" is a crucial aspect identified in Table 4.1 of Chapter 4 for establishing sustainability. It is allocated with 3 points for criterion B, given the indirect nature in which it influences salts problems in the complex.

Criterion C: Given the dependence on cross-complex engagement for the success of this intervention, it scores high for criterion D – 8 points are allocated.

Criterion D: Given the multiparty engagement of this intervention, it is anticipated that geographical location and trust issues may limit its success relative to Criterion C. It is thus awarded with 3 points for this criterion.

This intervention scores 6.8 out of 10 overall.

Technology option 2: Multiparty waste heat synergies

Criterion A: Heat recovery technologies are well established but proximity requirement may be limiting. 6 points are allocated.

Criterion B: recovery of waste heat is an important aspect identified in Table 4.1 of Chapter 4 for establishing sustainability, since it relates indirectly to achieving all three system conditions. In particular, it is useful for substituting heat requirements within the complex that are electricity-dependant with waste heat from industrial processes at Sasol Synfuels.

This substitution reduces not only the cooling water and electricity requirements of the associated processes, but in particular it eradicates treatment chemicals and salts associated with cooling water and mine water desalination at the complex power station (Tutuka). 3 points are allocated to the indirect nature in which this technology contributes to criterion A.

Criterion C: Given the dependence on cross-complex engagement for the success of this intervention, it scores high for criterion D – 9 points are allocated.

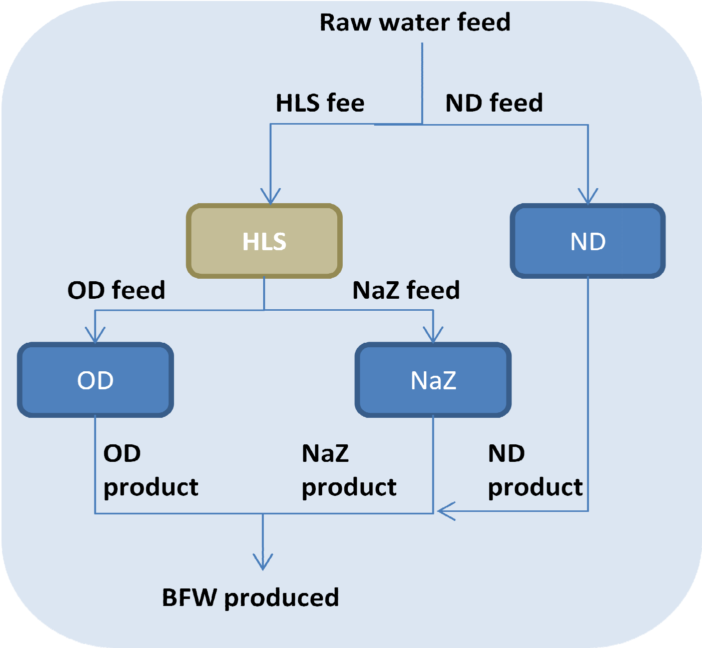
Criterion D: Given the multiparty engagement of this intervention, it is anticipated that geographical location and trust issues may limit its success relative to Criterion C. It is thus awarded with only 3 points for this criterion.

This intervention scores 5.4 out of 10 overall.

APPENDIX 5.1 BOILER FEED WATER QUALITY CHECKS

Table 24: Quality comparison: BFW produced by RO vs. required by Sasol Synfuels

	Raw water salts	Removed by UF (5%)	Removed by RO (99.7%)	Salts in BFW feed	BFW quality produced	BFW quality required	Quality check
	(kg/Ml)	(kg/Ml)	(kg/Ml)	(kg/Ml)	(mg/l)	(mg/l)	
Calcium	18.44	0.92	17.47	0.05	0.05	1.5	TRUE
Magnesium	13.27	0.66	12.57	0.04	0.04	0.1	TRUE
Sodium	17.97	0.90	17.02	0.05	0.05	0.1	TRUE
Chloride	13.74	0.69	13.02	0.04	0.04	0.1	TRUE
Sulphate	43.93	2.20	41.61	0.13	0.13	2	TRUE



<u>This comparison is subject to the following estimates/assumptions</u>

- HLS and dolomite filters remove 95% of Ca and Mg, 30% of all other ions in feed
- Demineralisation units remove 99.8% of all ions in feed
- NaZ removes 99.8% of Ca and Mg from feed with the release of stoichiometric equivalent amount of Na released off resin, no other ions are removed from feed

Table 25: Quality comparison: BFW produced by IX vs. required by Sasol Synfuels

	Total raw feed	ND feed	ND product	HLS feed	HLS product	OD feed	OD product	NaZ feed	NaZ product	Total	BFW quality produced	BFW quality required	Quality check
Flowrate (Ml/d)	**1.000**	0.231	0.231	*0.769*	*0.769*	0.057	0.057	0.712	0.712	**1.000**	(mg/l)	(mg/l)	
Na dissolved (kg)	15.3	3.54	7.E-03	*11.76*	*8.23*	0.61	1.E-03	7.62	9.03	9.04	9.04	1.50	FALSE
Mg dissolved (kg)	11.3	2.61	5.E-03	*8.69*	*0.43*	0.03	6.E-05	0.40	8.E-04	0.01	0.01	0.10	TRUE
Ca dissolved (kg)	15.7	3.63	7.E-03	*12.07*	*0.60*	0.04	9.E-05	0.56	1.E-03	0.01	0.01	0.10	TRUE
Cl dissolved (kg)	11.7	2.71	5.E-03	*8.99*	*6.30*	0.47	9.E-04	5.83	5.83	5.84	5.84	0.10	FALSE
SO_4 dissolved (kg)	37.4	8.65	2.E-02	*28.75*	*20.12*	1.49	3.E-03	18.63	18.63	18.65	18.65	2.00	FALSE

Table 26: **Ions balance on NaZ unit**

	NaZ feed	Na eluted off resin	NaZ product
Na dissolved (kg)	7.62	-	9.03
Na eluted off resin (kg)	-	1.41	-
Mg dissolved (kg)	0.40	-	8.E-04
Ca dissolved (kg)	0.56	-	1.E-03
Cl dissolved (kg)	5.83	-	5.83
SO_4 dissolved (kg)	18.63	-	18.63

APPENDIX 5.2 RESIN REPLACEMENT AT SASOL SYNFUELS

Sodium Softening

Amberjet 1200 Na - SAC exchanger		
Specific annual replacement for SYSTEM	0.53	kg/Ml

Old Demineralisation

Amberjet 1500 H - SAC exchanger		
Specific annual replacement for SYSTEM	0.24	kg/Ml

Amberjet 4400 Cl - SBA exchanger		
Specific annual replacement for SYSTEM	0.41	kg/Ml

New Demineralisation

Amberjet 1500 H - SAC exchanger		
Specific annual replacement for SYSTEM	0.10	kg/Ml

AMBERLITE™IRA458RF Cl - SBA exchanger		
Specific annual replacement for SYSTEM	0.08	kg/Ml

AMBERLITE™ IRC86 - WA exchanger		
Specific annual replacement for SYSTEM	0.08	kg/Ml

AMBERLITE™ IRA96RF - WBA exchanger		
Specific annual replacement for SYSTEM	0.12	kg/Ml

APPENDIX 5.3 COAGULATION/FLOCCULATION POWER ESTIMATION

Power for Coagulation and Flocculation

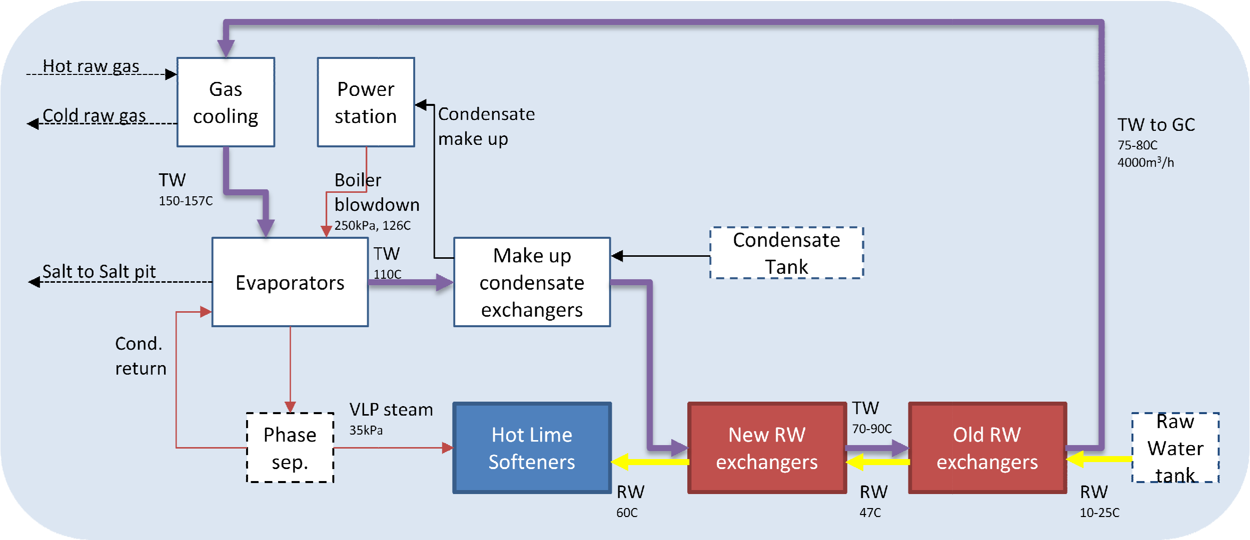
Rapid mix tank - Coagulation

	m^3/hr	m^3/s
Q_{HLS}	2500	0.69
Q_{ND}	650	0.18
V = Q x t =	8.75	m^3
Mixer power	11.19	kW
@80% efficiency	8.95	kW
G	1000	s^{-1}
Reqd mixing vol	8.50	m^3
Number of tanks	2	tanks
Vol of each tank	4.38	m^3
So power for 24hr operation		
	430	kWhr
	6.37	kWhr/Ml

Flocculation tank

	m^3/hr	m^3/s	
Q_{HLS}	2500	0.69	
Q_{ND}	650	0.18	
20 min allowed for flocculation			
V = Q x t =	1050	m^3	
V_{comp} =	350	m^3	3 compartments for tapered mixing
Axial flow flocculators for constant G			
G_{av} =	30	s^{-1}	
Reqd mixing vol	8971	m^3	
P_{comp1}	0.59	kW	
$P_{comp1\ (motor)}$	**0.74**	**kW**	
P_{comp2}	0.33	kW	
$P_{comp2\ (motor)}$	**0.41**	**kW**	
P_{comp3}	0.15	kW	
$P_{comp3\ (motor)}$	**0.18**	**kW**	
So power for 24hr operation			
	32	kWhr	
	0.48	kWhr/Ml	

APPENDIX 5.4 HLS RAW WATER HEAT EXCHANGE - TEMPERED WATER CIRCUIT



Tempered water circuit at SSF

Old RW/TW exchanger			New RW/TW exchanger		
Temp of RW feed	20	°C	TRWin	47	°C
Temp of RW out	47	°C	TRWout	60	°C
Mass flow of RW	1000000	kg/d	mRW	1000000	kg/d
Specific heat (C_p)	4.187	kJ/kg.K	Specific heat (C_p)	4.187	kJ/kg.K
$H_{exchanged}$	1.1E+08	kJ	$H_{exchanged}$	5.4E+07	kJ
	113049	**MJ**		**54431**	**MJ**
Total					
$H_{exchanged}$				**1.7E+05**	**MJ**

APPENDIX 5.5 CLEANING CHEMICALS FOR MEMBRANES PROCESS

PERMEATE QUANTITY FOR ANNUAL CLEANING OPERATION		
System permeate recovery	69388	m^3/d
RO unit configuration	49.20	m^3/d/element
	1411	elements
	7	elements per PV
	202	PV
	120	PV per train
	2	trains
Cleaning procedure configuration		
Train segmt size for a single cleaning	60	PV
Annual cleaning frequency	2	per yr
Cleaning procedure		low pH cleaning high pH cleaning
Fixed Equipment Volume (FEV)		
Free vol of PV	10.50	m^3
Vol of manifolds (10% of PV)	1.05	m^3
Vol of connecting piping (50% of PV)	5.25	m^3
total FEV	***16.80***	***m^3 per segmt per train***
Soln circulation flowrate	8	m^3/hr/PV
Soln. circulation time	3	min
total PV circulation soln.	***24***	***m^3 per segmt per train***
PV-CS. + FEV	40.80	m^3
Total cleaning soln for low pH	**274.72**	**m^3/yr**
Total cleaning soln for high pH	**274.72**	**m^3/yr**

CHEMICAL QUANTITY FOR ANNUAL CLEANING OPERATION		
Solution 1 - Citric acid		
2% citric acid	5.49	t/yr
	0.22	*kg/Ml*
Solution 2 - NaOH & SDBS		
0.2% NaOH	0.55	t/yr
	0.02	*kg/Ml*
0.2% SDBS	0.55	t/yr
	0.02	*kg/Ml*

APPENDIX 5.6 TUTUKA SALTS FOOTPRINT ESTIMATIONS

Tutuka's 2001 capacity of 3510 MW and a load factor of 65% (Eskom, 2010) are used to approximate 55 GWh sent out daily

$$3510MW \times \frac{24h}{day} \times 65\%\ load = 54.8MWh\ or\ 55GWh$$

Data for "Mine Water Ions" are calculated from the mine feedwater quality and quantity desalinated as provided by Buhrmann *et al.* (1999).

Table 27: Tutuka mine water

GWh sent out daily **55** **GWh**
Mine water desalin. **12** **Ml/d**

	Mine water quality (mg/l)	**Mine water ions (t/d)**	**Mine water ions (kg/MWh)**
Calcium	300	3.6	0.07
Magnesium	200	2.4	0.04
Sodium	1100	13.2	0.24
Chloride	700	8.4	0.15
Sulphate	1500	18	0.33

Raw water ions are estimated from raw water quality data and the specific raw water consumption reported for Eskom at 2000 levels, 1.9 l/kWh (Eskom, 2000).

Table 28: Tutuka raw water

GWh sent out daily 55 GWh
Raw water usage 1.9 l/kWh

	Raw water quality (mg/l)	**Raw water ions (t/d)**	**Raw water ions (kg/MWh)**
Calcium	16	1.6	0.03
Magnesium	11	1.2	0.02
Sodium	15	1.6	0.03
Chloride	12	1.3	0.02
Sulphate	37	3.9	0.07

Main treatment chemicals are sulphuric acid estimated for the ion exchange resin regeneration process and hydrated lime for softening of cooling water (Pather, 2004).

The amounts of these chemicals used are estimated at 0.5 - 1 t/d H_2SO_4 and 10 - 15 t/d lime. The upper limits are used in the calculations.

Table 29: **Tutuka treatment chemicals**

GWh sent out daily	55	GWh
H_2SO_4 usage	1	t/d
Hydrated lime usage	15	t/d

	Treatment chemicals used (t/d)	Treatment chemicals ions (kg/MWh)
Calcium	8.00	0.15
Sulphate	0.98	0.98

APPENDIX 5.7 IMPACT ASSESSMENT FOR DIFFERENT RO ENERGY OPTIONS

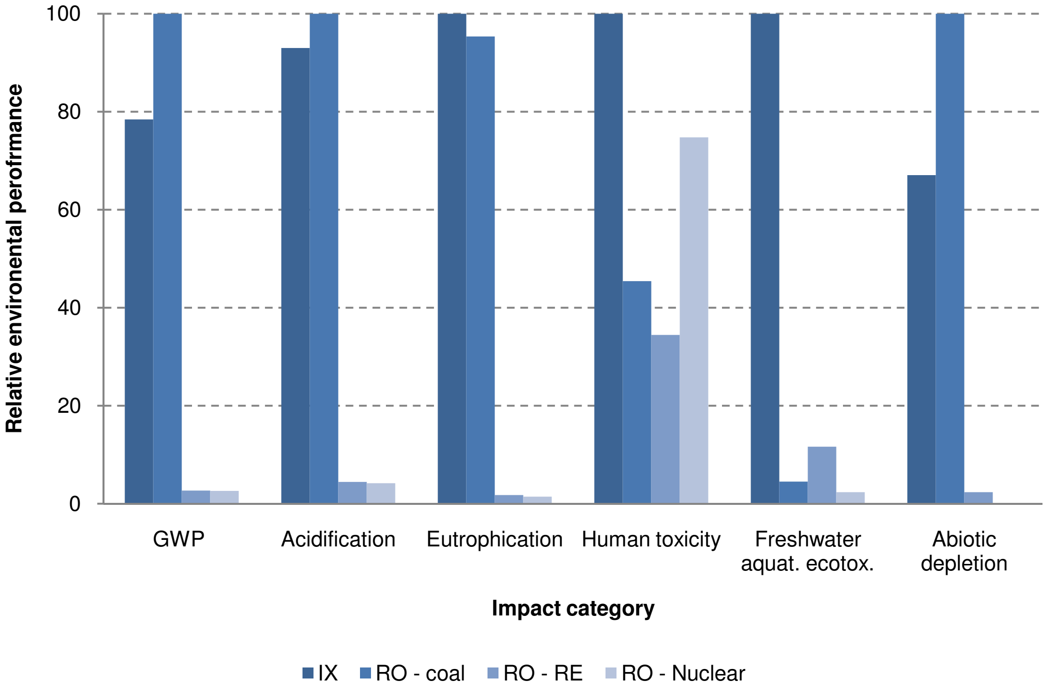


Figure 24: **Comparison of IX and diverse energy sources to power RO high pressure pumps**