AN ASSESSMENT OF THE KEY FACTORS THAT INFLUENCE THE ENVIRONMENTAL SUSTAINABILITY OF A LARGE INLAND INDUSTRIAL COMPLEX

Volume III: Development and assessment of technological interventions for cleaner production at the scale of the complex

C Ras & H von Blottnitz

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by

Environmental & Process Systems Engineering Group
Chemical Engineering Department
University of Cape Town

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Water Research Commission
Private Bag X03
Gezina, 0031

orders@wrc.org.za or download from www.wrc.org.za

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This report is the third in a series of five reports.

Volume I: Inception report **(TT 544/12)**
Volume II: Inventory of inland salt production and key issues for integrated cleaner production for waste salt management at the Highveld mining and industrial complex **(TT 545/12)**
Volume III: Development and assessment of technological interventions for cleaner production at the scale of the complex **(TT 546/12)**
Volume IV: Governance assessment **(TT 547/12)**
Volume V: Linking technologies to governance **(TT 548/12)**

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Dr Suzan Oelofse	CSIR: Natural Resources and the Environment
Dr Ndeke Musee	CSIR: Natural Resources and the Environment
Prof Alan Brent	University of Stellenbosch
Prof Harro von Blottnitz	University of Cape Town
Mr Chris Brouckaert	University of KwaZulu-Natal
Ms Cornelia Ras	University of Cape Town (Student)
Ms Floor Hooijman	Technical University of Delft (Student)
Ms Thandeka Nene	University of KwaZulu-Natal (Student)
Ms Nirvana Reddy	University of KwaZulu-Natal (Student)
Ms Devi Naicker	University of KwaZulu-Natal (Student)
Ms Joshna Kampallal	University of KwaZulu-Natal (Student)
Mr Glen Jansen	University of Cape Town (Student)
Ms Dineo Kadi	Cape Peninsula University of Technology (Student)

EXECUTIVE SUMMARY

BACKGROUND

This report contributes an assessment of technological interventions to the project titled *An Assessment of the Key Factors that Influence the Environmental Sustainability of a Large Inland Industrial Complex*. The project focuses on the complex of mines and processing industries located around Sasol's fuels and chemicals production sites in Secunda. This report integrates the description of environmental sustainability problems of the complex, the literature review (from a first interim report), the development and approach to assessment of cleaner production options (described in a second interim report), and the results of the environmental assessment by means of a life cycle assessment.

RATIONALE

There are about 10 large industrial complexes in inland locations in South Africa. Typically centred around the exploitation of a particular geo-resource, they include large-scale metallurgical, energy, or chemical processing. Whilst many view them to be cornerstones of the South African economy, they also contribute significantly to overuse of resources (especially water and land) and to potentially catastrophic degradation of the environment. If environmentally unsustainable – they ultimately undermine the human and social development systems that they are meant to support and facilitate.

OBJECTIVES AND AIMS OF THIS REPORT

AIM 1

The first aim is to summarise and interpret the environmental assessments and inventories prepared by co-workers in tasks 2-4 of this project so as to define the nature of the environmental sustainability problem.

AIM 2

The second aim concerns efforts (to address salts and water problems) by industries and the DWA in the Highveld Complex and the challenges experienced or reasons for failure of these efforts.

AIM 3

The third aim is to review generic approaches to technological interventions to address the identified environmental sustainability problems. In particular, there is an interest in technologies available to address water and salts pollution, including the limitation of such technologies in the SA and international context.

AIM 4

The fourth aim is to develop a list of possible technological interventions, rooted in an industrial ecology approach and based on a good understanding of the environmental sustainability problem across the various industries making up the industrial complex.

AIM 5

The fifth aim is to set up a further assessment of the technological intervention selected for detailed study, i.e., the goal and scope for a life cycle assessment are described.

AIM 6

The sixth aim is to report on the findings of the life cycle assessment on a prioritized technological intervention, and to draw conclusions both for this and for other, similar types of interventions that rely on interactions between the various industries in the large industrial complex.

METHODOLOGY

The methodology for aims 1 & 2 consisted of a series of interviews with industry and project meetings with team members. These were carried out (mostly virtual) in cooperation with the data collection and analysis methodologies of the other research teams. Those methodologies provided environmental, governance assessments and records of resource use and emission inventories for all of the industries and sub-catchments in the complex. Aim 3 was addressed by means of a literature review of the SA and international work on Industrial Ecology.

These findings and observations made during ongoing field work in 2009 and 2010 formed a basis from which the development of ideas for intervention flowed (aim 4). Industry and Project Team discussions facilitated the identification of several potential technological options for integration into the Highveld Complex to address the salts-related environmental sustainability problem.

Standard life cycle assessment (LCA) methodology is followed in developing the 5^{th} aim of this report, by explicitly defining the goal for the LCA and specifying the scope so that the goal can be met.

The 6^{th} aim of the report is met by reporting on the compilation of the life cycle inventories, the ensuing life cycle impact assessment, as well as the interpretative discussion.

OUTCOMES AND DISCUSSION

Outcomes for Aim 1

The industrial complex was found to be environmentally unsustainable for the following reasons:

- It is responsible for large systematic fluxes of carbon and sulphur from the lithosphere to the ecosphere;
- There is no consensus that salts and brine disposal practices are relying on proven long term stability of storage of highly soluble salts in the complex. The possibility of ecologically and economically damaging releases is still undergoing research;
- Energy conversion efficiencies of several of the technologies implemented at large-scale in the complex are low, necessitating the dissipation of large quantities of low grade heat via evaporative cooling, which implies large water losses;
- Salts are inefficiently managed, including an amplification of the risk related to salts through the choice of ion-exchange technology for raw water treatment.

Outcomes for Aim 2

All mining and processing industries in the complex are challenged with the problems of sustainable salts management, the major symptom of the problem being unsustainable brine storage. The brine storage problem is discussed in detail in the Integration Report.

With the focus thus on the desalination technologies in the complex, it was found that, to address the failed subsequent design specification for "zero liquid discharge" (and the limited capacity on ash dumps and underground storage to retain saline water), several major and costly projects to reduce salts and water storage on sites have continuously been implemented. These installations include:

- a carbonation plant (for the production of Na_2 CO_3/$CaCO_3$),
- RO applications at several sites, for the desalination of clear ash effluent and Mine Water to supplement raw water intake),
- an evaporative crystalliser for recovery of salts from mine water RO retentate,
- RO (Project Landlord) for the desalination of cooling tower blow down.

However, significant quantities of raw water continue to be used once-through for dissipation in cooling towers, and salt storage problems persist. Mining saline solution storage is increasing annually and discharges increase with the area mined.

Challenges for the desalination technologies include the variability of mine water salt concentrations, the apparent loss of control over dosing by operators (for IEX) and in one case the incorrect scale up from pilot plants studies. Some existing applications, such as the Carbonation plant, pose potential for re-commissioning.

Outcomes for Aim 3

The main findings of the literature review are:

- Industrial ecology approaches can be useful for reducing environmental impacts of large industrial complexes and/or a number of industries in close proximity. The reductions in impacts resulting from industrial symbiosis type interventions must however be quantified to confirm that they are large relative to the total impacts of such industries. Quantitative assessments, especially Life Cycle Assessment, can also guide the identification and selection of meaningful industrial symbiosis projects. The status of application of industrial ecology approaches in South Africa has recently been described as immature.
- Approaches to process integration are important both for gaining an understanding of the structure of existing industrial systems, and for identification of designs to optimize technology interventions. Several recent examples exist of work where generation and optimisation of superstructures of process flow sheet options have been applied to water and salts process systems.
- Environmental life cycle assessments of water and waste water systems enable rigorous documentation and full comparison of alternative technical solutions. They have been applied in the South African and international contexts. Attention must be paid to important methodological choices in such LCAs. In the case of models for salinisation impacts at least 3 different approaches have been proposed and demonstrated.

Outcomes for Aim 4

Four possible integrated technology interventions to reduce environmental load were identified. They are

- Reduction in treatment chemical salt load of Ion Exchange (3 tonnes of salt waste generated per tonne of salt removed) by switch to Reverse Osmosis;
- Salt recovery from mine or brine water for sale in the industrial area or elsewhere on the Highveld in order to reduce imports of salts from outside of the region;
- Process water from SSF to Harmony Gold;
- Low grade (waste heat) from SSF to Harmony Gold, replacing electrical energy from Eskom Tutuka, lowering associated environmental burdens of the power station and coal mine.

They were rated against 4 criteria, each one weighted. In this way, an expected priority for the implementation could be established as shown.

Table ES1: Technology options ranking by MCDM

	Technology option	*Crit A*	*Crit B*	*Crit C*	*Crit D*	***Total score (10)***
1	Replace IX with membrane process (RO)	8	10	5	6	8.05
4a	Produce Na_2CO_3 from brine streams	8	9	6	2	7.2
4b	Produce Na_2SO_4 from brine streams	7	8	6	2	6.5
3	Use MW at Evander for slimes processing	3	8	5	7	5.9
2	SSF waste heat → Evander thermal needs	3	6	3	9	5.1

Not surprisingly, intervention 1 which is essentially a “reduction at source” option, was ranked higher than the other options which are essentially seeking to work with existing waste waters.

Outcomes for Aim 5

As a starting point for the life cycle assessment of the highest ranked option, the goal of the LCA was rigorously stated, and the scope defined.

The **goal definition** for the life cycle assessment of this intervention reads:
This consequential LCA is performed to determine how the environmental impacts of an existing ion exchange plant for the pre-treatment of boiler feed water from low salinity surface water within the SSF Complex compare with those of a proposed electrically operated (reverse osmosis) membrane process for the same purpose.

As part of the declaration of scope for the LCA, the functional unit for the LCA was was set as the production of 1 Mℓ of boiler feed water by either membrane or ion exchange technology, to the quality standards currently met. The functional unit corresponds to a reference flow to which all other modelled flows of the system are related.

Outcomes for Aim 6

Through the rigorous methodology of life cycle assessment, the environmental burdens associated with the operations of two distinct boiler feed water preparation technologies were investigated. In particular, the extent to which salinity burdens would merely be shifted from one industry in the Highveld Complex to another was addressed.

Inventory data were compiled through process analysis by means of the process flow diagram approach. These provided the input data for Life Cycle Impact Assessments, using the CML2000 method for mid-point indicators. 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 RO intervention would lower salt emissions related to boiler feed water preparation in the complex 4 to 5-fold, with only about 1% of the total new salts burden being shifted from Sasol Synfuels to Eskom Tutuka.
- 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 Highveld Complex, thus resulting in burden shifting.
- The RO intervention would lead to a poorer environmental performance (by about 20%) compared to IX in the impact categories of abiotic resource depletion and greenhouse gas emissions, which are both established problems in South Africa, unless its electricity would come from a non-fossil fuel source.
- When the IX technologies that make up the IX system were compared individually to RO, it was found that the ion-exchange demineralisation routes have significantly greater environmental burdens than RO, but that sodium softening (NaZ) is much less resource-demanding. Given that Sasol Synfuels operators change the ratio of sodium softening (NaZ) to demineralisation (D) product according to downstream requirements, the RO intervention becomes preferable from an environmental point of view for low sodium softening (NaZ) to demineralisation (D) product ratios.

CONCLUSIONS

This report on integrated technological interventions to address environmental sustainability problems of one large inland industrial complex has identified several reasons to be concerned. In some cases, the absorptive capacities of the ecosphere are routinely breached, in others a potential risk of a large breach of absorptive capacity is building up.

The literature review has identified a set of co-ordinated systemic approaches that can be used to develop integrated technological responses to these environmental sustainability risks and breaches. These responses are rooted in industrial ecology and in particular industrial symbiosis to understand the system and its possibilities, followed by rigorous approaches to conceiving of new process systems, followed by consequential life cycle assessments to ascertain the proposed technological interventions do not merely shift burdens.

An analysis of technological interventions to date has concluded that major industries in the complex have already implemented several large-scale projects to address environmental issues, of which some have failed and others succeeded. Some of the prior interventions have sought to create by-product or waste symbioses between two industries in the complex, but generally without a regard for system-wide effects.

By way of an example of an action that can be taken by one industry in the complex, but that has effects on others, an alternative production of water of boiler quality was assessed in more detail – asking the question whether actions to reduce salt burdens by one industry would result in a shift of salt burdens to another industry. Alternatively could these actions amplify environmental burdens in other compartments of the ecosphere?

The life cycle assessment carried out on this assessment showed that salt emissions related to boiler feed water preparation in the complex would be lowered 4 to 5-fold by switching from IX to RO technology, with only about 1% of the total new salts burden being shifted from Sasol Synfuels to Eskom Tutuka.

RECOMMENDATIONS

Four recommendations are made:

1) Life cycle assessments must not be carried out blindly: it is especially important to understand the methodological implications of choosing a consequential over an attributional approach. A suitable approach to the salinisation impact problem must also be chosen.
2) Ion-exchange based production of boiler feed water should be replaced with reverse osmosis methods, as these have now been shown by a life cycle assessment to significantly reduce salts-related sustainability risks, even if the electricity is generated at a power station where saline mine water is used.
3) The recovery of saleable salts from brines remaining after desalination of mine waters should be further explored, in part by developing technologies such as carbonation or eutectic freeze crystallisation, and assessing them by LCA as demonstrated here.
4) The critical literature on industrial symbiosis suggests that where such approaches are considered for reducing the identified environmental sustainability breaches and risks, care must be taken not to romanticise them as “silver bullets that solve all problems” – it is claimed that such approaches often reduce the existing problem only fractionally, whilst in a perverse way lending “green credibility” to the ongoing unsustainable practices. This should be borne in mind also for the outcomes of this study: even if the amplification of the salts burden arising from ion-exchange technology were removed, there would still remain large fluxes of water-

soluble salts in the Highveld Complex (currently from lithosphere to storage and not to the hydrosphere) – and these are only one of the environmental sustainability risks.

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LIST OF ABBREVIATIONS

ALCA	Attributional Life Cycle Assessment
BFW	Boiler Feed Water
CAE	Clear Ash Effluent
CLCA	Consequential Life Cycle Assessment
COD	Chemical Oxygen Demand
EFC	Eutectic Freeze Crystallisation
ESAPA	European Soda Ash Producers Association
IX	Ion Exchange
LCA	Life Cycle Assessment
MW	Mine Water
NaZ	Sodium softening plant at SSF
ND	New demineralisation plant at SSF
NF	Nano-Filtration
OD	Old demineralisation plant at SSF
R&D	Research and Development
RO	Reverse Osmosis
SRO	Spiral Reverse Osmosis
SSF	Sasol Synfuels Complex
MCDM	Multi Criteria Decision Method

1 INTRODUCTION AND OBJECTIVES

1.1 Background

This report forms part of a series of deliverables within the project titled AN ASSESSMENT OF THE KEY FACTORS THAT INFLUENCE THE ENVIRONMENTAL SUSTAINABILITY OF A LARGE INLAND INDUSTRIAL COMPLEX. The complex of industries surrounding the Sasol Synfuels facility in Secunda was selected for further study in the inception phase of the project.

1.2 Rationale

The South African economy relies largely on the industrial activities of several large industrial growth centres that are located around mineral deposits and harbour sites. These complexes are typically simultaneously large consumers of water and located remote from the country's major river systems. This results in a disparity between the natural availability of water and its demand in around 90% of the South Africa's area. To service the needs of these water-intensive developmental nodes, extensive inter-basin transfers of raw and potable water have been developed.

The central role of these industrial hubs in country's economic growth necessitates the long-term sustainability of their wealth-generating activities. Accordingly, the implementation of a carefully integrated and sustainable relationship between the natural water supply and these water-intensive hubs (Brent et al., 2008) appears to be crucial for managing this precarious situation effectively.

However, this is not reflected in reality. It is believed that several factors have contributed to the environmental sustainability problems demonstrated in these regions. In particular, these problems are expressed by the long-term disposal/storage of large volumes of salts and brines in deep underground mines and the fast dwindling capacity of these mines. To date there appears to be no apparent techno-economic solution to the salts and water problems.

1.3 Objectives

The overall objective of this report is to develop and assess suitable technological interventions that could be retrofitted into the existing complex in order to reduce the risks resulting from environmentally non-sustainable practices. In particular, six objectives were set:

i) To interpret the environmental assessments and inventories generated in tasks 2-4 of this project so as to define the nature of the environmental sustainability problem;
ii) to review the literature on technological interventions that could be made to address the identified environmental sustainability problems, in particular, on technologies available to address water and salts issues;
iii) to review efforts in addressing salts and water problems by industrial partners in the Highveld Complex to date and the challenges experienced or reasons for failure of these efforts;
iv) to develop a list of possible technological interventions, rooted in an industrial ecology approach and based on a good understanding of the environmental sustainability problem across the various industries making up the industrial complex;
v) to set up a further assessment of the technological intervention selected for detailed study, stating the goal and describing the scope for a life cycle assessment;
vi) to report on the findings of the life cycle assessment on the proposed technological intervention, and to draw conclusion both for this and for other, similar type of interventions that rely on interactions between the various industries making up the complex.

2 DESCRIPTION OF THE ENVIRONMENTAL SUSTAINABILITY PROBLEM IN THE SECUNDA INDUSTRIAL COMPLEX

The project team has defined the industrial complex at Secunda to consist of those industrial operations that are functionally linked and geographically close to the production of liquid fuels and chemicals from coal. Figure 1 shows the system being studied. The Sasol Synfuels (SSF) plants are at the core of the complex, which functionally also includes the coal mines supplying it, the Tutuka power station which devotes the bulk of its electric output to powering SSF and the mines in the complex, as well as the coal mine supplying Tutuka, New Denmark. Also in geographic proximity, and sharing water resources, are the Govan Mbeki municipality, the Harmony gold mines at Evander, as well as commercial farmers along the Waterval River. It is acknowledged that all these water uses impacts on the water resource through return flows. However, for the purposes of this study, only the impacts from the industrial complex are considered.

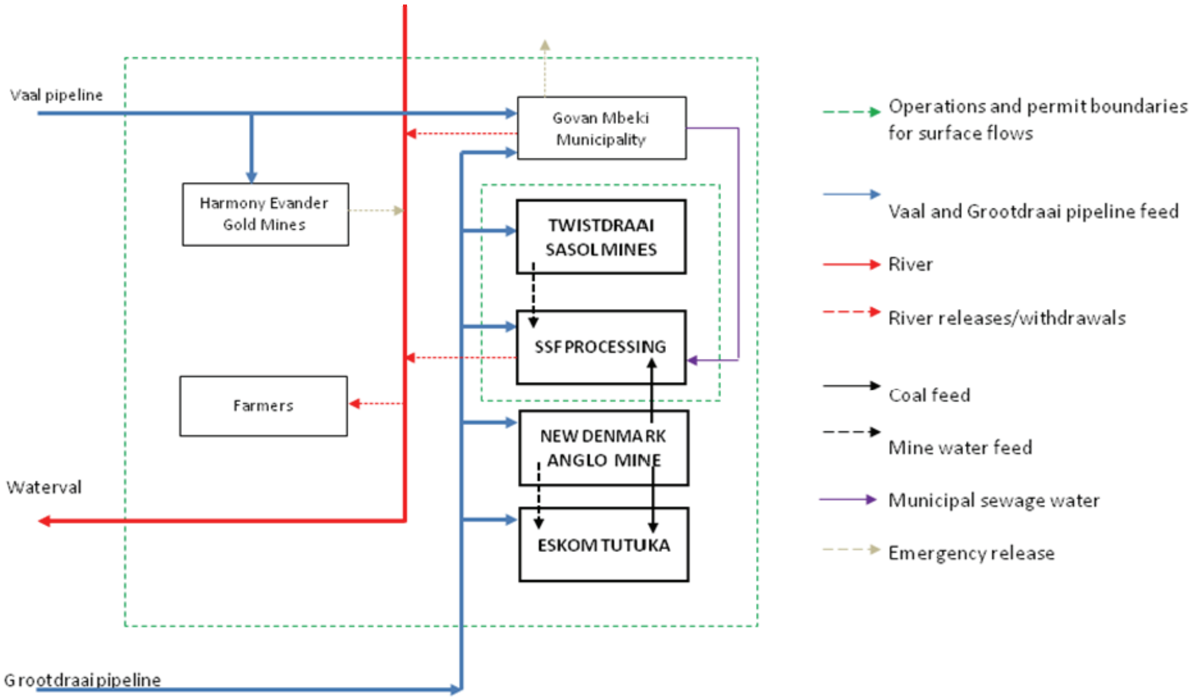

Figure 1: Schematic of the system under study

From the assessment of water quality, the assessment of governance in this system, and the compilation of water and salts inventories, the following key points emerge as to the environmental sustainability (or otherwise) of this industrial complex:

1) Surface water quality in the Waterval River has been improving slightly over the past 10 years.
2) The bulk of the water abstracted for use in this system is lost in evaporative cooling applications. Smaller amounts of this water are discharged, and a small but significant portion of highly saline waste water is stored either in surface impoundments, or in disused underground coal mines.
3) The bulk of water thus consumed in the industrial complex comes from the Vaal catchment, but some mine water (with a salinity of around 4 g/ℓ) is also used.
4) Salts, and especially highly soluble salts (sodium chloride, sodium sulphate) are accumulating in the industrial complex and its limited brine stores. Whilst the co-disposal of ash with brines is still being investigated, the practical experience seems to indicate that only less soluble salts can be permanently stored in the solid form.

5) The bulk of the accumulating salts have their origin either in mine waters or in coal ash, with only a small fraction being supplied with the fresh water. A significant aggravation of the salts burden is traced to the use of ion exchange technology, which generates further highly mobile salts due to the use of sulphuric acid, sodium chloride and sodium hydroxide for resin regeneration.

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). The Natural Step sustainability conditions stipulate separate assessments of i) materials extracted from the lithosphere and systematically released to the ecosphere, ii) materials synthesised in the technosphere and systematically released to the ecosphere, iii) systematic (bio-)physical destructions of components of the ecosphere, and iv) the system's efficiency and equitable sharing of resources and pollution burdens.

Against these criteria, the Secunda industrial complex as defined in this study is adjudged to be environmentally unsustainable on the following grounds:

1) There is a large and systematic transfer of lithospheric materials into the ecosphere, particularly of carbon (in the form of carbon dioxide) and of sulphur (in the form of both hydrogen sulphide and sulphur dioxide) into the atmosphere.
2) There is a fair-probability, high-impact risk of further systematic transfers of large quantities of lithospheric materials into the ecosphere, in the form of highly mobile salts (sodium chloride, sodium sulphate) into ground and surface waters, once the storage capacity for hyper-saline brines is reached, which is only a question of time. This risk may present itself in the form of upwells into the groundwater, and/or upsets in industrial systems that result in significant releases of saline effluent to surface waters.
3) Fresh water is not being abstracted at rates beyond the regenerative capacity of the regional ecological systems, but the general risk of water stress in South Africa is well understood, and the efficient usage of water by such a large user is therefore important. The large cooling requirements and consequent evaporative water losses are inextricably (thermodynamically) linked to the low efficiency of the coal conversion processes in both the SSF and in the electricity generation process. There is little that can be done over the lifespan of the existing industrial facilities to significantly improve these efficiencies, but the use of lower quality water sources for cooling presents a clear opportunity to reduce pressure on water resources.
4) The risk of salts releases into the ecosphere is being aggravated by inefficient technologies that amplify the salts burden.
5) The question of equitable access to water resources and to the sharing of pollution burdens is a complex one that is addressed in more detail in the governance report. Parts of the industrial complex are regarded to be of strategic national importance, implying that any sacrifices made in terms of access to water resources and/or sharing of pollution burdens is to be viewed to be for the greater public good. There is, however, a disturbing dimension to the situation in that private capital is a beneficiary of the ecologically detrimental and risky activities in the complex.

3 TECHNOLOGIES: PAST AND FUTURE

This section concerns itself with a brief review of efforts (to address the salts and water environmental sustainability problems expressed in the Highveld Complex) by industrial partners to date and the challenges experienced or reasons for failure of these efforts. It then proceeds to a brief review of other technological options currently in the research phase.

These findings and observations made during ongoing field work in 2009 formed a basis from which the development of ideas for intervention flowed.

The information, in particular regarding the sources of water and salts issues, was obtained through personal communication with plant personnel during onsite interviews at Sasol Synfuels Technology (SSF), Secunda (Roux 2009).

3.1 Sources of the major water and salts problems at SSF

Blowdown water has been identified by the industrial partner as the largest source of problematic waste water and second largest source of salts waste, while regeneration waste solutions from ion exchange water treatment is considered the largest salts waste and second largest problematic waste water source at SSF.

The major salts accumulation problem (approx 200 t/d), as identified by the industrial partner, arises due to the use of resin-regenerating chemicals in the chemical treatment (ion exchange) of municipal raw water and utility cooling water blowdown; salts content of water works regen-effluents is typically 3 to 4 fold that of raw water. The desalination of around 9 Mℓ of highly saline mine water (see Appendix A for composition) per day by spiral reverse osmosis (SRO) to supplement raw water intake is the second major source of salts waste. Together, these represent the largest salts issue on the plant and the second largest water balance problem on the SSF plant. Other salts sources such as salts liberated from ash exist. Clear ash effluent, the brine which drains off ash dumps is discussed in greater detail in Section 2 of this report.

The industrial partner deems that water balance problems result from various sources but in particular cooling tower and boiler water blowdown which is not desalinated for reuse and poor housekeeping (of clean, rain and storm water, water works regen-water, fire water (approximately 10-20 Mℓ/d) and boiler condensate). These water streams are indiscriminately mixed with more saline streams and disposed of to the ash system. Since the ash system is the final destination of several water streams and since it is constrained by the amount of water it can absorb, cooling towers run higher cooling cycles than design, resulting in higher TDS. The blowdown water represents the largest water balance issue on the plant and the second largest salts balance issue on the plant.

3.2 Endeavours by industrial partners to date and reasons for failure

Previous efforts by SSF to remove salts and recover water were revealed during field trip interviews. These efforts included installation of evaporative crystalliser unit for the treatment of mine water to supplement raw water and a carbonation plant intended to produce $CaCO_3$.

The carbonation plant is in disuse due to practical operational problems. It was designed to treat clear ash effluent (see Section 2) with a TDS of approximately 500-1000 mg/ℓ. Sand was fed to the Spiractor reactors (similar to cyclone) to act as seeding particles. Major operational problems that arose included:

1. Blockage of CO_2 feed-nozzle (this was fixed by R&D: softened water from the process was saturated with CO_2 and this was used to treat raw water instead of direct with gas treatment; this also lowered the scaling problem).
2. A very fine precipitation/product resulted. This resulted in entrainment of the precipitation due to design issues on up-flow process and the Spiractors themselves.

3. Softened water to plant tie-ins problems: specific softened water users were not serviced, recovered water was routed incorrectly and allowed to come into contact with thickener overflow which caused significant Ca precipitation due to a large pH difference between the two. In hindsight it is apparent that basic changes to piping were necessary to fix this problem. However, these changes were not made because the project was abandoned at this stage.

The carbonation plant was designed to produce a pure $CaCO_3$ product but was scaled up from pilot study without regard to the findings from the pilot study. The problems encountered in the full scale plant were mostly already identified in the pilot study.

Due to significant feed concentration variation, deviation from design specification and because design capacity is exceeded by the volume of brine to be treated, the evaporative crystalliser is not online continuously or to full capacity. Due to the variation in feed concentration, the composition of salts produced by the crystalliser is variable, not to specification of a potential purchaser and this reduces the marketability of the salts. As a result, brine solutions are presently disposed of together with ash produced by coal gasification on dams, instead of being upgraded to saleable product.

The SSF facility was designed to operate with zero liquid discharge but practically, it is considered to be cheaper to store water onsite than to treat and discharge it (Roux 2009).

Existing and potential industrial ecology opportunities were discussed. Na_2SO_4 recovered from mine water treated at Sasol's evaporative crystalliser has replaced imports for the vanadium industry. Also, the sale of $CaCO_3$ lime sludge (produced during utility cooling blowdown treatment, presently disposed of in the alkaline ash dam system) has been discussed with a company that produces potable water from mine water on the West Rand of Gauteng.

In the attempt to collectively address salts, brines and ash wastes problems, 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).

3.3 The future of 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 et al., 2010).

3.4 Contribution to development of ideas for intervention

It is understood that any 'new' raw water technology need would need to be flexible and effective toward variable raw water and mine water qualities as it is well known that mine water quality is generally not constant and it is known that the concentration of nitrates, phosphates and organic compounds in raw water have been reported to be increasing annually due to local population growth and water treatment practice by municipalities.

The availability of spare cold utility capacity within the complex that could potentially provide cooling to a eutectic freeze crystallisation (EFC) unit was deemed improbable by the industrial partner. The notion for potential recovery of salts by an EFC-type technology was thus not developed further, even though the availability of electric utility for this type of operation should not be a constraint.

The production of Na_2CO_3, soda ash, by the decommissioned carbonation unit is considered by SSF staff to be feasible and sound. Several highly saline brines and pure CO_2 is readily available on the plant as potential raw materials to this process.

The potential for industrial symbiosis type interventions in the way of waste water and excess energy exchanges between SSF and other industries became apparent and lead to the development of some interventions that consider this.

Quantitative data obtained during field work has been summarised to characterise the brines at SSF and to determine which salts could be recovered. The plots shown in Figure 1 indicate that the recovery of Sodium and Sulphate- containing products would reduce the present build-up of Sodium and Sulphate ions.

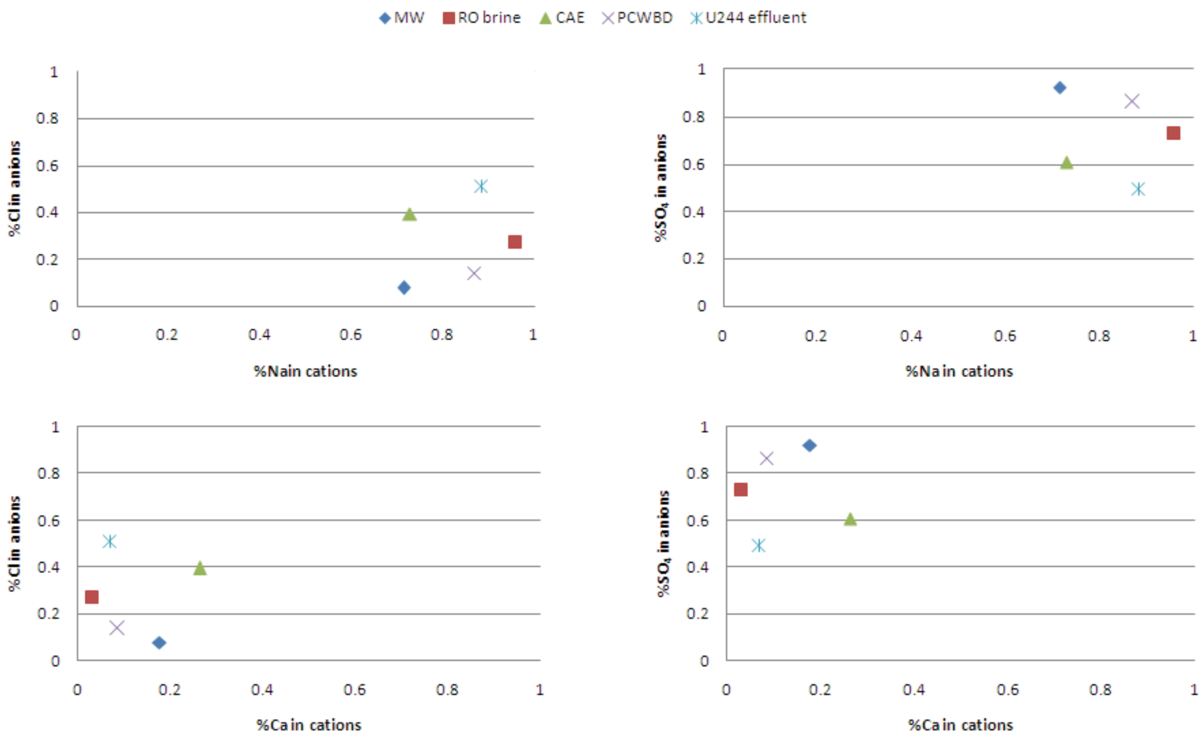

Figure 2: Characterisation of some significant SSF brines according to ionic compositions

4 LITERATURE REVIEW

Against this assessment of environmental sustainability breaches and risks, a literature review was carried out to determine what technological interventions could be conceived to address the identified problems.

4.1 INDUSTRIAL ECOLOGY

The development of industrial ecology during 1970's to late 1990's is summarised 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 following section will look at three recent publications on case studies at, in particular, large-scale industrial complexes similar to the Secunda industrial complex.

Brent et al. (2008) recently conducted a survey of industrial ecology efforts in South Africa in which applications/examples 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 is influenced by successful case studies at foreign locations. Future advancements of industrial ecology concepts in South Africa were recommended to be driven by the application of industrial symbiosis type strategies both at local and regional level.

Jacobsen (2006) provides an improved, quantitative account of the well-known industrial ecology example, Kalundborg. Unlike the oft cited paper by Ehrenfeld and Gertler (1997), Jacobsen (2006) addresses several important aspects such the market sensitivity of and 'threat' of advancement in technology in such industrial ecology 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. Jacobsen (2006) raises the question of whether industrial symbioses actually represent a “comprehensive strategy for environmental improvements” and recommends that a life cycle assessment 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 it may introduce unintended complications to further optimisation opportunities is considered.

Van Beers et al. (2007) 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. 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 industrial ecology 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 industrial ecology-type synergies can be identified through a step-by-step methodology based on the cleaner production approach. This is supported by a resource and process flow database, and opportunity identification workshops with industries. 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 the well-known international examples of regional synergy development such as Kalundborg.

On a smaller scale, Hart et al. (2005) illustrated by means of a case study on office paper that life cycle assessments may be useful in uncovering viable opportunities for industrial ecology. They conclude that this “more imaginative approach to managing end-of-life materials and products could lead to the development of peri-urban ‘ecoparks’, located around a [material and energy recovery facility]” that could handle a range of products and materials.

4.2 CONCEPTUAL PROCESS SYNTHESIS

The environmental impacts of process industry plants arise in large part from the methods that were used to conceive and design them. Improvements to existing process plants similarly start with a conceptual design phase. In order to address the environmental sustainability problems identified in section 2 above, it is thus essential that key features of process synthesis be understood.

Several review articles have been published on the development and advancement in conceptual process synthesis (Westerberg 2004; Daichendt and Grossmann 1996 & 1997; Saif et al. 2009; Li and Kraslawski 2004). Generally, two main branches of conceptual process synthesis are identified, viz. optimisation-based methods, and knowledge-based methods.

4.2.1 Knowledge-based approach

Knowledge-based design techniques are centred on the use of heuristics to solving design problems. The design philosophy of Douglas (1988), “Hierarchy of Decisions”, represents a well-known example of this approach, which can be summarised into the steps shown in Table 2 below.

Table 2: Hierarchy of decisions (adapted from Douglas 1988)

1.	Selection between batch *vs.* continuous process
2.	Development of the input-output system to the process
3.	Development of the recycle system to the process
4.	Design of general structure of the separation system
5.	Heat exchanger network design

As illustrated by a case study on the synthesis for the hydrodealkylation of toluene (HDA process), this technique makes use of decomposition and screening, while heuristic rules are applied at different design levels to generate flowsheet alternatives (Douglas 1988). The detail of this approach and modifications to it are well documented in the literature, some of the useful sources include Douglas (1988), Gadewar, Daichendt and Grossmann (1997). The detail of the approach is thus not presented as part of this literature review but it is critiqued instead.

Critique levelled against the competence of this technique is prevalent in the literature: the procedure is sequential and does not account for interactions between subsystems (Daichendt and Grossman 1996); process alternatives are not evaluated simultaneously (Saif et al., 2009), thus eliminating the opportunity for significant improvement (Daichendt and Grossmann 1996); multiple design objectives cannot be accommodated the way sophisticated modern optimisation techniques can (Saif et al., 2009, Westerberg 2004); and lastly, the hierarchical heuristic method offers no guarantee of finding the "best possible design" (Li and Kraslawski, 2004).

Typical of design techniques developed prior to 1990 (Li and Kraslawski, 2004), the Hierarchy of Decisions (Douglas 1988) gives no consideration to environmental-degrading aspects of the process it develops. While heat and mass recovery through steps 3 and 5 of Table 1 may represent "environmentally friendly" material and energy savings, the real driver for their inclusion is the implied economic cost savings instead. As Li and Kraslawski (2004) illustrate, the potential for making decisions that reduce the environmental impact of a process is known to be highest at the early design stage. An out-dated design technique such as that of Douglas (1988) should thus be used with caution in modern conceptual process synthesis.

The fourth edition of the Chemical Engineering Design handbook (Sinnott 2002) displays a similar disregard for environmental considerations. Aside from a brief discussion on Environmental Impact Assessment, the importance of integrating environment protecting aspects into the design procedure is not discussed. Instead, the guidelines given represent a dated way of thinking about environmental responsibility: end-of-pipe clean up strategies.

4.2.2 Optimisation-based approach – options superstructures

Superstructures represent a multitude of different arrangements of design variables (such as technology choices and process operating conditions) to arrive at a large number of alternative process configurations. A subsystem to a superstructure can be defined loosely as a single flowsheet defined by a route from the inputs to the superstructure to the final desired output via any unique combination of intermediate steps. Intermediate steps and products are typically common to several subsystems.

Establishment of a superstructure is subject to practical considerations and assumptions surrounding the inclusion of certain variables and how they are interlinked. At an abstract level, known targets (e.g. minimum energy requirements determined from heat integration analysis), 'common sense' or practical limitations and the use of heuristics enable sensible reduction in the magnitude of sub-optimal or improbable alternatives (Westerberg 2004). However, this preliminary procedure has been considered insufficiently rigorous and even fallible by Daichendt and Grossman (1996) who instead recommend an approach which combines "preliminary screening" and mixed-integer nonlinear programming with the objective "not only to reduce the size of the problem, but to reduce it in such a way that the best (global optimal) solution remains embedded in the superstructure" (Daichendt and Grossman 1996).

As defined by Li and Kraslawski (2004), "the main idea of [this] optimisation-based approach is to formulate a synthesis of a flowsheet in the form of an optimisation problem. It requires an explicit or implicit representation of a superstructure of process flowsheets from among which the optimal solution is selected". As described by Daichendt and Grossmann (1996), "a superstructure [collects] alternative processing units [or technologies] and interconnections [which] are modelled as discrete, binary variables (O-l) to depict the existence (1) or nonexistence (0) of that unit". The model that these variables belong to is the formal, mathematical representation of the design problem (Li and Kraslawski 2004), and it is subsequently optimised to obtain the optimal subsystem (Saif et al., 2009).

Saif et al. (2009) claim that the use of superstructures overcomes many of the problems of the heuristics based process synthesis technique while creating the opportunity for improved designs due to the wealth of alternatives considered in the method; different parts of a flowsheet can be integrated and optimised simultaneously.

Daichendt and Grossmann (1996) attribute the strength of an options superstructure approach to it "providing a systematic framework for modelling and simultaneous optimization, and providing automated capabilities for synthesis problems". Li and Kraslawski (2004) share this opinion, adding that it presents opportunities for "the more rigorous analysis of features such as structure interactions and capital costs".

Li and Kraslawski (2004) and Daichendt and Grossmann (1996) also discuss the disadvantages of this technique: superstructures cannot be generated automatically; the large computational efforts involved create difficulties in solving large-scale problems; a model must be developed to be robust to avoid 'getting trapped' in sub-optimal solutions. Li and Kraslawski (2004) further state that "this approach encounters great difficulties when dealing with the optimisation of under-defined design problems and uncertainties that result from the multi-objective requirements of the design problem".

The level of detail in the representation can be low (a global view of different processes whose own inherent/inevitable details that are not shown), as exemplified by Figure 3a, or high (specialised options for aligning functional units within a particular unit operation) as shown in Figure 3b.

Figure 3a illustrates a minimally detailed superstructure developed by Mathiolakis et al. (2006) for the transformation of renewable energy sources to supply power to a multitude of desalination technologies to meet the demand for fresh water on the other end without committing to specific layouts for any of the technologies. . Figure 3b illustrates a combined power cycle coupled to thermal desalination plants to determine the optimal configuration and design of a dual purpose plant (Mussati et al. 2005).

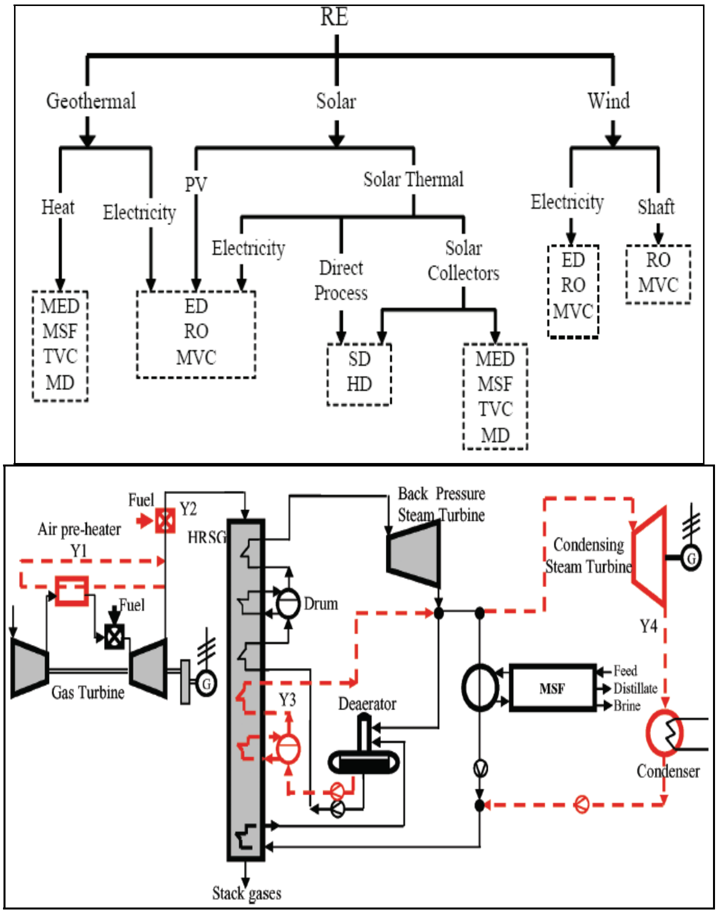

Figure 3: a) Technological combinations superstructure of renewable energy and desalination methods (Mathiolakis et al. 2006) b) Combined power cycle coupled to thermal desalination plants (Mussati et al. 2005)

<u>Objectives for using superstructures in water-treatment applications</u>

Despite its limitations, the optimisation-based superstructure approach for process synthesis is adopted in recent research, and in particular in the field of desalination networking. Following is a review of the objectives that have been identified from recent literature relevant to the proposed research for the use of superstructures.

In a series of ongoing research, Mussati et al. (2008) have recognised the potential for dual-purpose power desalination plants. The objective of their study was to obtain an optimal configuration and process operating conditions of a combined power cycle coupled to thermal desalination plants (multi-effect distillation and multi-stage flash technologies) at minimum, levelled cost. This was done by the optimisation of a superstructure of alternative configurations. The superstructure was modelled by a novel mathematical model based on generalised disjunctive programming.

De Faria et al. (2009) performed a preliminary analysis on the industrial waste water system of a petrochemical refinery. A nonlinear programming model was configured and illustrated schematically as a network superstructure. The objectives of the study were to obtain from the superstructure a water network which minimises the consumption of freshwater through a wastewater reuse and/or recycling strategy, and to investigate the potential for reducing operating costs.

In a publication by Mathiolakis et al. (2007), a superstructure of technology options for the conversion of renewable energy sources into thermally or electromechanically driven desalination technologies is developed. By means of a review and state-of-the-art account of these technologies, the objective of the study was to highlight the advantages and technically mature status of desalination by means of renewable energy sources; in particular the socio-economic issue of service delivery: providing electricity supply and freshwater to low-density populations typically located remote from municipal infrastructure.

Sustainability and LCA used in conjunction with process synthesis and optimisation

Azepagic and Clift (1995) have shown that linear programming can be combined with the environmental impact assessment tool, life cycle assessment (LCA), to aid process selection, design and optimisation. This method aims to determine an environmentally optimal design and can be used to identify improvements in the environmental performance of the developed process during the Improvement Assessment phase of LCA. The authors argue that a linear programming setup is in particular suitable to LCA, which makes use of "linear relationships between activities and environmental burdens" (Azapagic and Clift, 1995). The approach is shown to be useful for traditionally problematic areas of the LCA procedural framework: co-product burden allocation, the allocation of environmental impacts in the impact assessment and the improvement assessment.

In related work, Azapagic and Clift (1999) have developed strategies for multi-objective optimisation of a process to arrive at a range of designs that optimise both economics as well as environmental aspects of the design. Social aspects were considered too by means of a Pareto analysis.

In more recent work, Azapagic et al. (2006) have developed a method that "enables identification of relevant sustainability criteria and indicators, comparison of alternatives, sustainability assessment of the overall design and identification of 'hot spots' in the life cycle of the system". The approach is illustrated by means of a simplified design case study of the production of vinyl chloride monomer (VCM).

4.3 TECHNOLOGICAL OPTIONS FOR DESALINATION

It might be expected that a project of this nature should include a detailed review of potentially applicable water treatment and desalination technologies. A number of review papers exist and can be directly considered in the eventual selection of technologies (WRC Project K5/1669//3 2008, Mathiolakis et al., 2007). An investigation into the potential to retrofit the multitude of existing technologies within the system boundary is deemed relevant, and novel technologies (such as eutectic freeze crystallisation) will be of particular interest for the superior benefits they have shown in comparison with other technologies in the South African context (WRC Project K5/1669//3 2008).

4.4 LIFE CYCLE ASSESSMENT

Responding to increasing pressures to reduce their environmental impacts, industries have moved from implementing end-of-pipe or clean-up technologies to an integrated and sophisticated approach of cleaner production strategies (Clift, 2009). Life Cycle assessment (LCA) continues to evolve as a useful tool to assess the environmental performances product or process systems, as well as proposed changes to such systems (Baumann and Tillman, 2004).

Despite its popularity however, LCA is a tool that is still undergoing development and this is particularly true for water applications (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 1, 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).

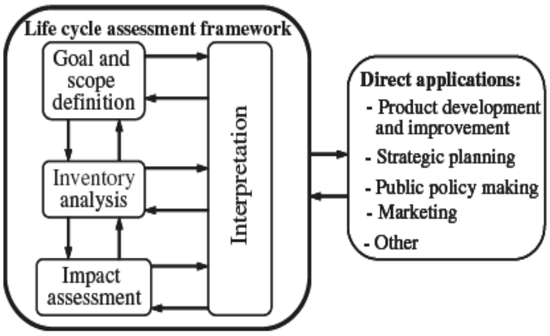

Figure 4: LCA Procedure (ISO 2006)

Since the framework underlying LCA practise is thoroughly covered in literature, it will not be presented in detail here and the reader is referred to the textbook by Baumann and Tillman (2004) as well as the ISO guidelines (ISO, 2006). 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 proposed research. In particular, the review will focus on the methodology used in these studies. This section ends with a summary of the key aspects identified in literature that are of relevance and need to be borne in mind for the proposed study.

4.4.1 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 a crucial to the success of the LCA (Baumann and Tillman, 2004).

LCAs are further categorised as either ‘product assessments’, that study impacts of a certain product or process, or ‘technology assessments’, that identify the impacts of implementing a particular technology or process (Sanden and Kalstrom, 2007).

Attributional 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 LCA

Consequential LCA are also described as change-oriented, effect-oriented, comparative, or 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 system (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, the 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 are used for product development and in public policy making (Weidema 2003).

Table 2 summarises the main differences between ALCA and CLCA. Weidema (2003) and 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 et al. (2008), a trend of seemingly "[choosing] one methodology independent of research question" is a common problem in the literature on applied studies of LCA.

Table 3: Characteristics of accounting type and change-oriented LCI models (Tillman 2000)

	Type of LCA	
Characteristic	**Accounting**	**Change-oriented**
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

4.4.2 Recent LCA applications to water systems and desalination

In light of widespread local, regional and global current and projected 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. Case studies similar to the research proposed later on in this document are encouraged to help develop a rigorous LCA methodology for water applications (Koehler 2008) in particular for the South African setting (Brent and Landu, 2007).

Some local and international case studies of LCAs performed on wastewater treatment systems and desalination plants have been isolated from the literature to inform the proposed research. These are summarised in Table 3 and discussed in the following sections. Section 3.4.2.1 describes the objectives for using LCA in these studies and Section 3.4.2.2 discusses the methods and types of

LCA contained in these studies. Section 3.4.2.3 describes an impact category for salinisation that has been developed by recent research. Lastly, key findings of this literature are summarised in Section 3.4.3.

Objectives for performing LCA on water systems

The study by Brent and Landu (2007) was aimed at addressing limitations of the available, ready-made LCIA methodologies in the South African context, especially with respect to the LCI 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.

Table 4: 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

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.

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.

Methods used in selected literature on water systems

As explained previously, classification of LCA type and the impact assessment methods used in a study are important to the understanding of both the LCA practitioner as well as the intended audience of the study. The following subsection identifies methodologies that were employed in the case studies on water treatment summarised in Table 3.

a) Types of LCA used in the selected literature

Brent and Landu (2007) studied the environmental impacts associated with water supply to a specific industrial in the Tshwane 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.

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.

b) Methods of LCIA used and impact categories investigated

The life cycle impact assessment (LCIA) phase of the life cycle assessment 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 (SimaPro7 Manual). 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; SimaPro7 Manual).

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 SimPro7 Manual, the use of endpoints typically simplifies the interpretation of results for decisions makers and clients not conversant 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), whilst in 2009 ReCiPe was introduced. 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 (SimaPro7), emphasising the iterative process described by Figure 3.

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 Tshwane, Brent and Landu (2007) used the Resource Impact Indicator (RII) calculation procedure using the South African LICA framework to calculate impacts. 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 of the LCIA profile 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.

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 life cycle impact assessments 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 was developed in the research includes consideration of aquatic eco-toxicity effects, damage to man-made environment, loss of agriculture production, aesthetic effects and effects to fauna and flora. Total salinity potentials are determined based on emissions into the various initial release compartments: 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). As outlined in Section 1 of this document, the salts problem at the Highveld Complex is of particular concern and hence this salination impact category is particularly relevant for the proposed research.

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).

Hansen et al., 2006 point out that the activities of primary industries result in the production of large volumes of solid waste (ash and salts). Environmental impacts resulting from management of these solid wastes are deemed important in LCA studies on these processes and the inclusion of these impacts is considered to be a major improvement over current LCA methodologies. For the impact assessment phase, Hansen et al. (2006) proposed the use of an impacted land footprint (ILF), based on 1st order hydrological modelling.

4.4.3 Key findings from selected literature on water systems LCA

ALCA and CLCA are altogether different approaches in LCA. It is important to distinguish clearly between ALCA and CLCA upfront to reach a higher degree of transparency; LCA experts have encouraged practitioners of different research areas to perform case studies to address differences between ALCA and CLCA (Thomassen et al., 2008). LCA goal and scope are continuously drawn from during the LCA procedure; thus it is important that these are clearly defined upfront and adapted iteratively where necessary as the LCA proceeds (Baumann and Tillman, 2004).

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.

LCA methodology and databases for water issues is regarded as underdeveloped and several critical issues regarding resource classification, life cycle inventory modelling and life cycle impact assessment 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 standardisation of impact categories and the categorisation of 'new' impact categories such as soil salinity, desiccation, and erosion is presently debated in the LCA community (Reap, 2008). In particular, the inclusion of a salinisation impact category is deemed crucial to the relevance of environmental life cycle impact assessments performed in the South African context. The indicators developed by Leske (2003), Feitz and Lundie (2002) and Hansen et al. (2006) are envisaged to be useful for the proposed study.

5 GENERATION OF IDEAS FOR TECHNOLOGICAL INTERVENTIONS

Following on from the identification of environmental sustainability problems (section 2), the review of approaches discussed in the literature (section 3), and the review of efforts in the Secunda industrial complex to date to address environmental issues, efforts in the project were then focused to generate, classify, further develop and shortlist technological solutions for integration into the complex, especially to address salts-related environmental sustainability problems, primarily by means of an industrial ecology approach.

5.1 Technology options identified

Through the field work and in discussions held with project team members, several potential options have become apparent. These include:

1. *Replacement of ion exchange (IX) with membrane process (RO):* an operational ion exchange plant at SSF is responsible for the final treatment of boiler water. This unit is known to be amplifying the salts problem: approximately 100 t/d of chemicals (NaOH, H_2SO_4, lime, etc.) is used for regeneration and ends up as dissolved salts in effluents. RO technology, especially with energy recovery, is known to be more energy efficient than traditional desalination technologies (Thomson 2005). However, it is recognised that power generation in the Complex is associated with salts problems, thus the salt load for producing electricity required by the membrane process needs to be considered and compared to the present salts burden associated with the poorly operating IX technology.
2. *Provide for Evander boiler thermal needs with waste heat available in the Complex*: Evander Gold presently makes use of electrical elution boilers in the recovery of gold. Considering the vast excess "waste heat" available in the vicinity (at SSF), this energy requirement could be serviced by means of an energy recovery at SSF.
3. *Use mine water (MW) for slimes processing at Evander*: a need for additional water for the processing of slimes dams has been identified. Mine water represents a potential supplement to or substitute for raw water.

4. *Recovery of Na_2SO_4 and Na_2CO_3 from brine streams:* water quality data (see Appendix A) indicates that Na^+ and SO_4^{--} ions predominate. It is anticipated that removal of Na containing ions from water bodies stored in dumps above ground will reduce the leakage of soluble sodium salts. Also, presently soda ash is imported from Botswana into this already salts-stressed region of South Africa, of which the complex forms part. Producing soda ash from local "wastes" to replace these exports is in line with the objective to establish industrial ecology opportunities in the Complex.
5. *Integrate the use MW for cooling and pre-concentration* into the above options. Mine water contains ions that can be recovered by technology option 4. Also, mine water represents a potential supplement to or substitute for the customary use of raw water for cooling.

5.2 Evaluation criteria for options

The options listed above are filtered according to the objectives of the project. A total of 20 points (arbitrary total) is distributed amongst the selection criteria according to how important each is deemed. This is summarised for the 4 selection criteria listed in Table 1 below.

Table 5: Selection criteria for evaluation of technology options, and weighting of criteria

	Selection criterion	*Weighting (total of 20)*
A	Sizable effect on salts problem in Complex	**6**
B	Technically feasible (off the shelf technology to innovative)	**8**
C	Other barriers (incl. governance issues)	**3**
D	Cross-complex, multi-party engagement are preferred to internal solutions	**3**

The environmental problem is defined as the build-up of Na and SO_4 ions in the complex. This is demonstrated in Appendix A which characterises typical brines identified from the Complex according to their ionic compositions. Thus, an important selection criterion is the impact that a technology option may have on the salts problem in the Complex. Accordingly, this criterion is assigned 6 points.

Some existing technologies were identified in the complex with the potential for refurbishment or re-engineering. Innovative or "new" technologies such as eutectic freeze crystallisation will be considered along with traditional, established technologies, but will be rated less favourably than established technologies. This criterion is assigned with 8 points.

As identified during field trips to the plants, there are several external issues/barriers that may prevent the technology option from being incorporated into the complex. Such issues include lack of trust amongst industries, governance problems, *etc*. This criterion is assigned 3 points.

Lastly, in conjunction with criterion 1, it is important that the technology options developed for further investigation will contribute to the notion of establishing industrial ecology across the Complex. Preference is thus given to technology options that extend beyond the local, company-specific syntheses already present at some industries in the Complex.

5.3 Selection of options

The technology options of Section 1 can each be ranked (out of a total of ten) according to the four criteria defined in Section 2 above.

This score is then multiplied by the factor of that criterion as defined in Table 1 above. For example, technology option 1 was ranked 8/10 for criterion A, 10/10 for criterion B *etc*., and correspondingly the overall importance of criterion A was ranked 6/20, criterion B was 8/20 *etc*.

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

$$8\times\frac{6}{20}+10\times\frac{8}{20}+5\times\frac{3}{20}+6\times\frac{3}{20}=8.05$$

This is repeated for each of the technology options. Table 2 below summarises the scores for the individual criteria as well as the final total scores.

Table 6: Technology options ranked according to selection criteria of Table 1

	Technology option	*Crit A*	*Crit B*	*Crit C*	*Crit D*	***Total score (10)***
1	Replace IX with membrane process (RO)	8	10	5	6	**8.05**
4a	Produce Na_2CO_3 from brine streams	8	9	6	2	**7.2**
4b	Produce Na_2SO_4 from brine streams	7	8	6	2	**6.5**
3	Use MW at Evander for slimes processing	3	8	5	7	**5.9**
2	SSF waste heat → Evander thermal needs	3	6	3	9	**5.1**

From the *total score* column of Table 2 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.

5.4 Development of shortlisted technology options

The focus has been on further investigating technology options 1 and 4a since, as indicated in Table 2, they have shown to be most favourable with respect to the criteria defined above. Life cycle assessments will eventually be conducted on these technology options to compare their effects on the salts-related environmental sustainability problem in the complex.

To develop option 1 further, preliminary flow sheets have been set up to determine (by means of Excel calculations) material and energy balances of potential reverse osmosis and existing ion exchange desalination technologies.

A flow sheet based on the Solvay process (ESAPA, 2004), the dominating process globally (Wesnoes and Weidema 2006), has been modified for technology option 4a, the production of soda ash from Complex brine and CO_2. Material and energy balances were determined by Excel and Aspen modelling.

6 PROCESS SYNTHESIS OF TECHNOLOGICAL INTERVENTIONS

As a starting point for the life cycle assessments to follow, in this section, flowsheets are developed for the two technological solutions selected by the MCDM.

6.1 Intervention 1: replacing ion exchange with membrane process

This intervention concerns itself with an attempt to reduce the current unsustainable build-up of salts resulting from the preparation of boiler feed water at Sasol SynFuels, Secunda (SSF).

Raw water obtained from the Bossiesspruit Dam is clarified and stored for direct use as cooling water in utility cooling tower, U205, and indirect use as boiler water after desalination. Desalination of raw water is performed by ion exchange while cooling water blowdown from the utility cooling towers, U05 and U205, is desalinated separately by ion exchange and reverse osmosis (RO). An RO unit, the "Landlord", is responsible for the desalination and recovery of U05 blowdown whereas U205 blowdown undergoes hot lime softening, ion exchange, sodium softening, deaeration and polishing. Water treatment and regeneration chemicals required by the system include Lime, NaOH, H_2SO_4, MgO and NaCl.

Water recovered from the "Landlord" and chemical treatment processes is feed water to boiler systems and gasification whereas raw water salts and regen waste are disposed of to the ash system, as shown below.

The "inside ash system" (U03 and 203) concerns itself with the removal and classification of coarse and fine ash into movable states. The "outside ash handling system" (U303) concerns itself with the storage of coarse and fine ash, and clear ash effluent (CAE). The interlinking processes are illustrated in Figure 5 below.

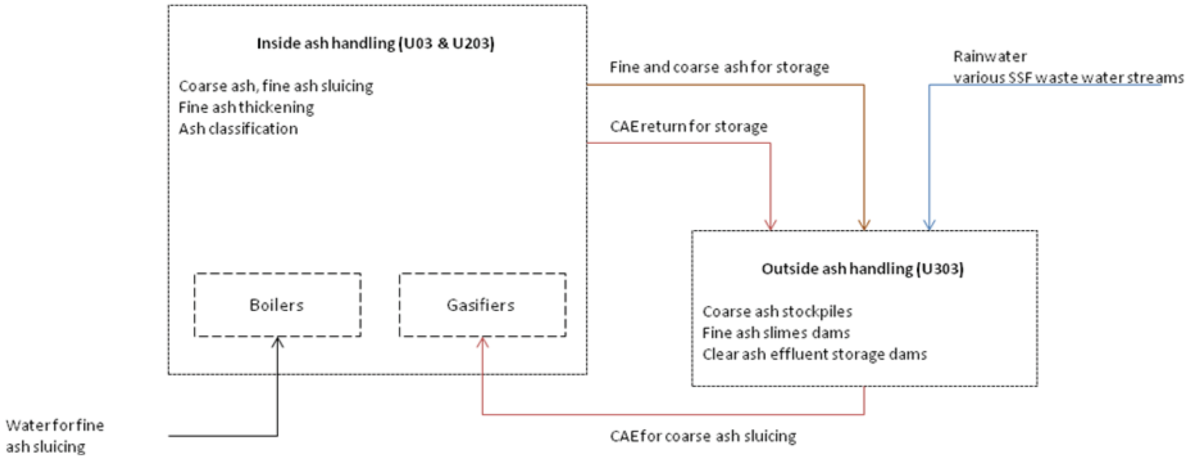

Figure 5: Simplified representation of the ash and clear ash effluent handling systems at SSF (adapted from Roux 2008)

CAE is a hyper-saline brine stream that results from the liberation of ash-bound salts into rain and wastewater disposed of at the ash system. It is collected from ash dams, stored and returned to the SSF factory where it is used to sluice coarse ash from gasifiers. Vibrating screens and rake classifiers remove coarse ash onto conveyor belts which in turn route it to outside ash handling where it is stockpiled. Fine ash is sluiced from the steam plant with water and thickened with thickeners to form a slurry stream which is pumped to slimes dams at outside ash handling.

In addition to ash sluicing, CAE is periodically desalinated in units U66/7/8/9 (evaporator, SRO/TRO, TRO) to supplement boiler feed water.

The approximate composition of CAE is summarised in Appendix A.

Figure 6 below shows a generalised flowchart for the currently installed units at SSF responsible for the treatment of raw water and blowdown from U205.

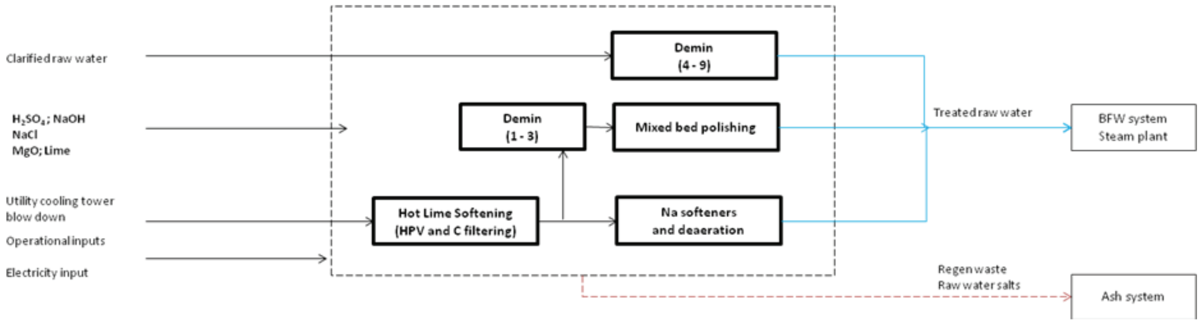

Figure 6: General flowchart for base-case to technology intervention 1

Boiler feed water is treated to the specifications contained in Appendix A.

Treated raw water (permeate) serves as boiler feed water to boiler systems and gasification whereas raw water and blowdown salts (retentate) are removed by NF and RO which are disposed to the ash system. An important feature in modern RO plants is work recovery from the retentate stream, so as to reduce the electrical energy required to keep the whole operation at 70 bar (Greenlee et al. 2009). To achieve this, an energy recovery device is included in the system. According to Greenlee et al. (2009) "energy recovery devices have been developed to help recover some of the energy typically lost from the pumps and membrane system. The primary objective is to recover much of the energy held in the pressurised RO concentrate stream (retentate). Before continuing to disposal or treatment, the concentrate is sent through an energy recovery device, and the recovered energy is used to partially power the pumps."

Figure 7 below shows a generalised flowchart for technology intervention 1, membrane processes for the treatment of raw water and blowdown from U205.

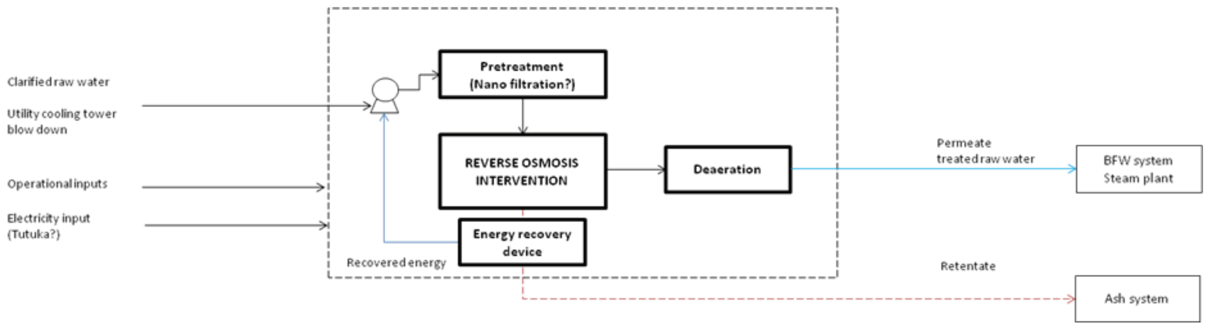

Figure 7: Block flow diagram for technology intervention 1

6.2 Intervention 4a: soda ash production from brine and CO_2

This intervention concerns itself with an attempt to produce soda ash from sodium rich effluents and waste carbon dioxide at SSF, replacing the mining and transport of Soda Ash from Botswana into the already salts-sensitive Highveld region of South Africa.

Figure 8 is a schematic of the supporting processes for the import of Soda Ash to South Africa. Also shown is the current disposal of Sodium-rich brine to ash and CO_2 emissions related to the fuels-synthesis process at SSF Secunda.

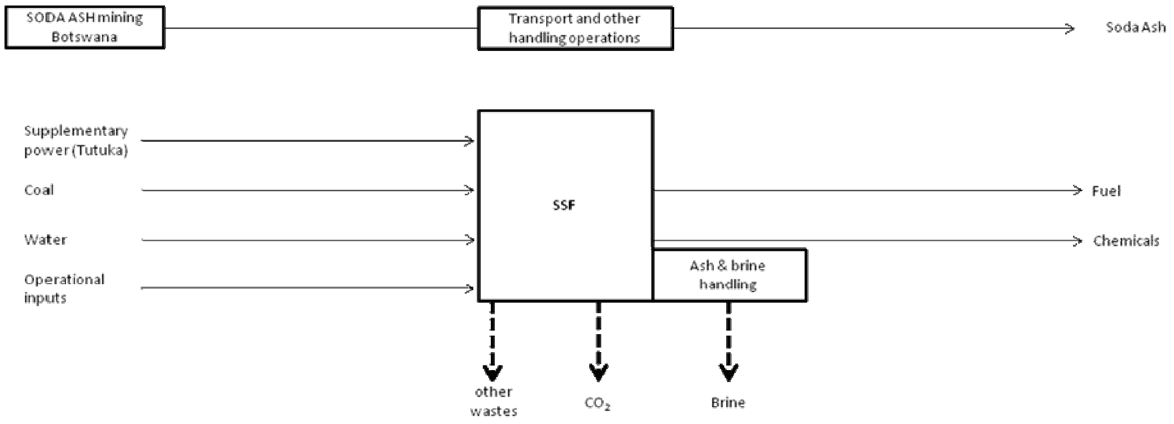

Figure 8: Block flow diagram for base case to technology intervention 4a

It is proposed here that the traditional Solvay process for producing Soda Ash from NaCl brine and limestone (ESAPA 2004) could be modified to accommodate SSF brine and CO_2 (purified at the SSF factory) as alternative raw materials. This is shown along with the necessary inputs to the Solvay process in Figure 9 below.

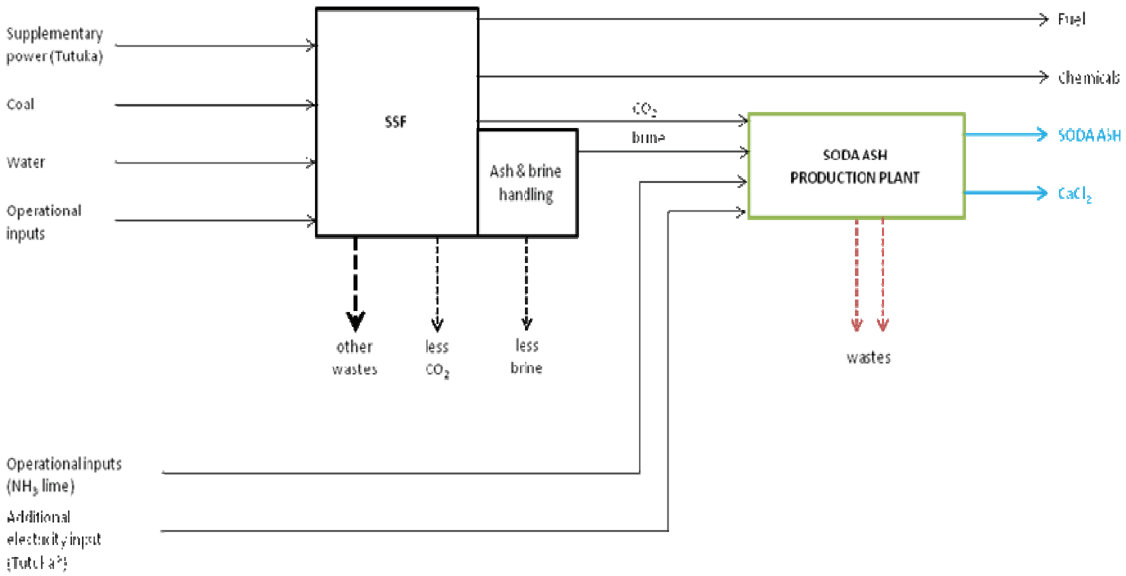

Figure 9: Solvay process for the production of Soda Ash from alternative raw materials, SSF brine and CO_2

As is explained in system boundaries definitions to the above two flow sheets (see Section 2.2), the SSF complex with its inputs and outputs is common to intervention 4a and its base case and will thus be omitted from the life cycle inventory analysis.

7 GOAL AND SCOPE FOR LIFE CYCLE ASSESSMENTS OF THE PREFERRED TECHNOLOGY INTERVENTION

As illustrated by the double arrows of Figure 10, 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).

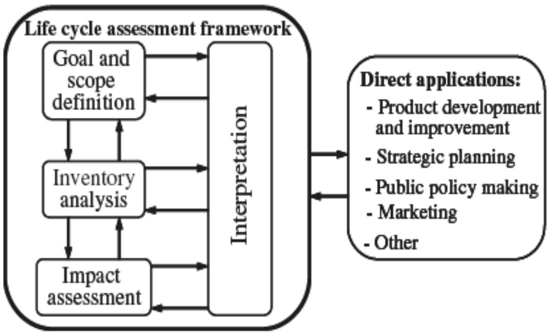

Figure 10: LCA Procedure (ISO 2006)

Since the framework underlying LCA practise is thoroughly covered in literature it will not be presented in detail here and the reader is referred to the textbook by Baumann and Tillman (2004) as well as the ISO guidelines (ISO 2006). In this report, the goal and scope will be presented in this section 7, and the inventory analysis, impact assessment and interpretation will make up section 8.

7.1 Technology intervention 1: replacing ion exchange with membrane process

In this LCA, the environmental benefits of a reduced treatment chemicals used in ion exchange (and disposed of to ash) will be compared to the environmental impact of increased coal-fired power usage by the membrane processes. Ion exchange units are employed at several of the industries in the Complex and so the study is assumed to be of some relevance beyond the SSF boundary.

7.2 Type 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 is evident: the type of LCA is inextricably linked to the goal and scope definition of a study (see Figure 10), 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 a crucial to the success of the LCA (Baumann and Tillman 2004). LCA 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 (Sandén and Kalström 2007).

Since the LCA here is aimed at “describing the consequences of changes” to an existing water treatment technology, it is classified as a “change oriented, prospective or consequential” technology LCA, for which “the [..] perspective is assumed to be forward-looking” (Sandén and Kalström 2007).

7.3 Goal definition

LCA goal and scope are continuously drawn from during the LCA procedure (see Figure 10); thus it is important that these are clearly defined upfront and adapted iteratively where necessary as the LCA proceeds (Baumann and Tillman 2004). According to the ISO standard (ISO 14041 1998), the goal definition “shall unambiguously state the intended application, the reasoning for carrying out the study and the intended audience”.

The **goal definition** for the life cycle assessment on this intervention sets the context for the study and was phrased as follows:

This LCA is performed to determine how the environmental impacts of an ion exchange plant for the pre-treatment of boiler feed water (BFW) within the Highveld Complex compare to those relating to the use of an electrically operated reverse osmosis plant for the same purpose. The results will be used to determine whether the implementation of such an intervention will reduce the impacts of the salts generating ion exchange technology or whether burden-shifting occurs; that is, by improving existing water treatment technologies in the Complex, the salts-related environmental sustainability problems in the Complex are addressed without unavoidably creating other environmental sustainability problems.

7.4 Statement of scope

The purpose of the life cycle assessment study on the water treatment methods is to evaluate the implementation of RO as a solution to an environmental sustainability problem identified in the Secunda industrial complex and to determine whether burden shifting occurs. This approach and methodology aims to present the industries in the complex with a useful tool for assessing sustainability concerns. The findings from the study are not intended to be generalised to all systems that involve ion exchange.

The IX plant is a major source of Sodium in the waste water system at SSF. As is illustrated in Figure 11, the proposed Soda Ash production intervention is fed by a brine stream which results from upstream processing at SSF and does not affect the raw water treatment process. However, Soda Ash plant requires a brine stream which is highly concentrated in NaCl (ESAPA 2004), such as IX regen waste. Since RO depends on mechanical and not chemical removal of dissolved salts, implementation of the RO intervention results in an anticipated reduction or abolition of the Sodium rich regen waste stream (indicated by the red dotted stream) normally an important input to the Soda Ash plant. The scope of the LCA on the water treatment intervention proposed here is thus defined in the absence of the conceptual implementation of the Soda Ash plant intervention.

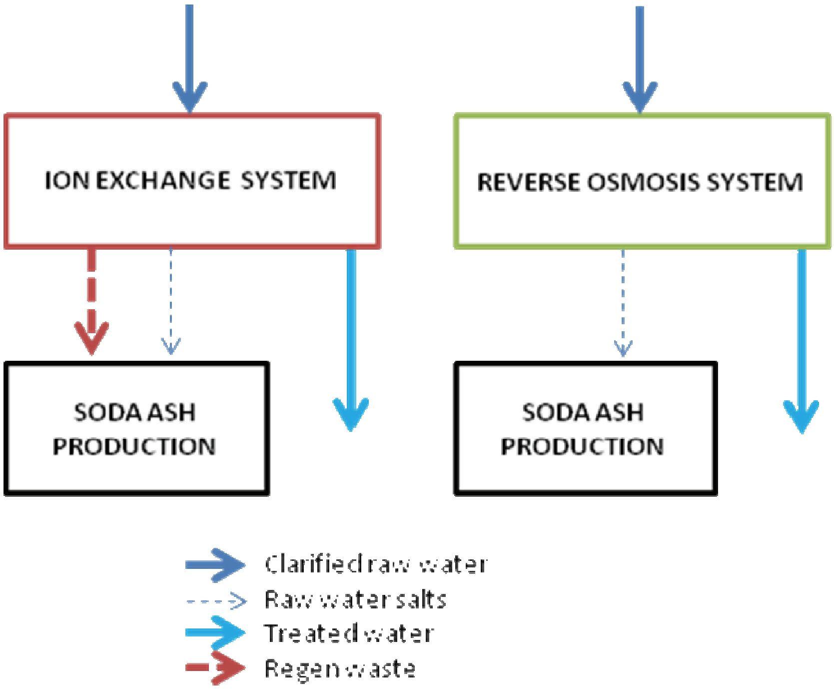

Figure 11: RO permeate and IX regen waste as potential feeds to the Solvay, Soda Ash process

7.4.1 Feasibility of options to be modelled

Čuda et al. (2006) have investigated the use of RO for boiler feed water preparation and have shown that RO is "very promising" in this regard. "When the feed water has medium or high mineralization and the capacity of the water treatment plant is planned to be large, then *[compared to ion exchange]* it is advantageous to install RO technology" (Čuda et al. 2006).

SSF performs RO in blowdown (Landlord) and uses the recovered water as boiler feed water. Reverse osmosis and ion exchange are considered to be technically comparable in the preparation of boiler feed water. Ion exchange, Landlord and boiler feed water qualities are being obtained from SSF staff at present and will be used as guidelines to verify this assumption in coming work.

7.4.2 Working definition of the functional unit

The functional unit will provisionally be defined as the production of 1 Ml of water of boiler feed quality by either technology (RO and IX) to the quality standard specified in Appendix A.

The functional unit is not defined as the full amount of water to be treated by a specific IX plant in the Complex. The generic functional unit can be scaled up to give results for the individual IX plants in the Complex for which capacities are known.

7.4.3 System boundary and process description for base-case

As illustrated in Figure 13 below, the system boundary for this LCA is defined to include as the **foreground system** the treatment of clarified raw water and utility cooling tower blow down by a combination of demineralisation (ion exchange), hot lime and Sodium softening, and polishing; and as the **background system** the provision of treatment chemicals and further operational input requirements relating to the operation of these units. Outputs from the system boundary are treated raw water which is used as boiler feed water, while salts removed from the raw water and blowdown, lime sludge and regen waste are disposed of in the ash system.

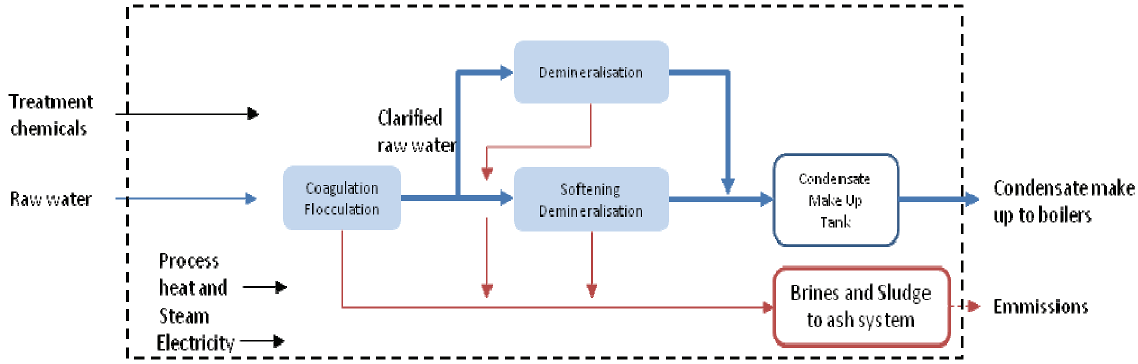

Figure 12: System boundary definition for LCA on the base-case for producing boiler feed water

7.4.4 System boundary and process description for intervention

As illustrated in Figure 13 below, the system boundary for this LCA is defined to include as the **foreground system** the treatment of clarified raw water and utility cooling tower blow down by nano-filtration pretreatment (to prevent fouling of RO membranes by suspended solids), subsequent reverse osmosis to remove dissolved salts and deaeration to remove oxygen and other corrosive gases; and as the **background system** the provision of electricity and other operational input requirements (such as new membranes) relating to the operation of the foreground units. Outputs from the system boundary are treated raw water (permeate) which is used as boiler feed water, while salts removed from the raw water and blowdown (retentate) are disposed of in the ash system (see Figure 5 above).

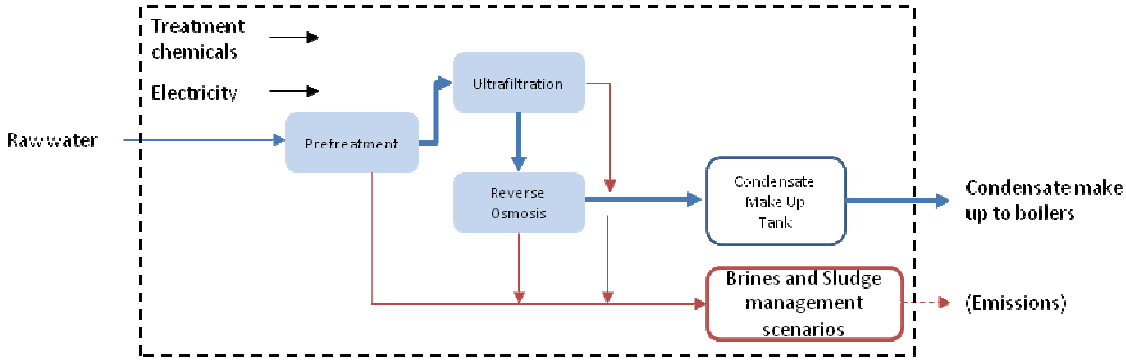

Figure 13: System boundary definition for LCA on technology intervention

8 RESULTS OF THE LIFE CYCLE ASSESSMENT

8.1 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) was adopted here rather than the matrix inversion approach by Heijungs (1994).

Data for the IX process was compiled from industry data collected and verified by mass balance calculations. 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, as will be considered in the sensitivity analysis of Section 8.3.

Inventory data for the resources and emissions associated with the membrane intervention were 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 8.3.

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

8.1.1 Softening and ion exchange process

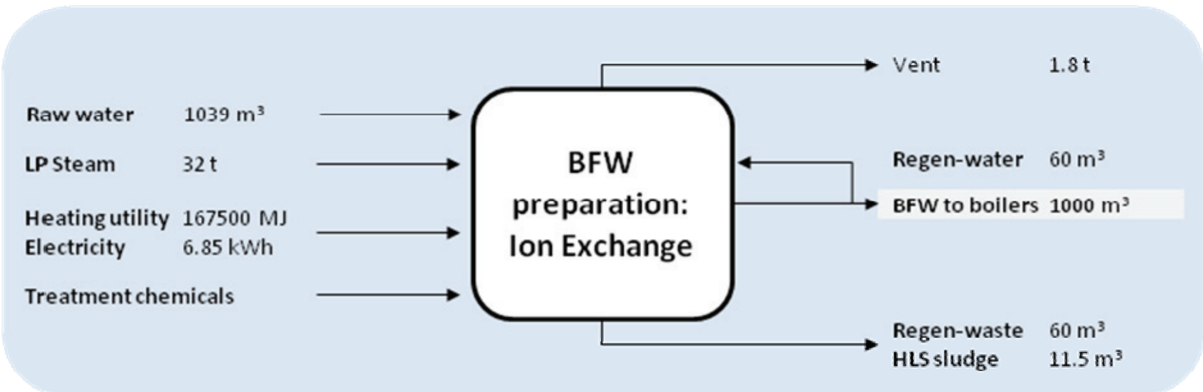

Figure 14: Selected flows for the Ion Exchange process

Table 7: 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 8: Salts balance on ion exchange BFW preparation system

Salts flowrate in (kg)		Salts flow rate 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 1 Mℓ BFW from this system is based on the process data available for 67.44 Mℓ/d production (Roux 2009).

Flocculation and clarification

Upon dosing with coagulant, feed water (TDS 200 mg/ℓ) 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 50 ppm, of 50 kg for the production of 1 Mℓ 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 1 Mℓ of BFW produced by the system (see the third Appendix to this chapter for detailed calculations).

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 ppm (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 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 (see fourth Appendix to this chapter). To heat 1 Mℓ 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 kPagauge, 2690 kJ/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 51.84 Mℓ/d by the HLS unit (excludes water for polished product), steam is fed at a rate of 90.7 t/hr or 32 t/Mℓ BFW from the IX system. A vent of approximately 1.8 t 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 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 6 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 93% water recovery and produce water that is of condensate MU quality.

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.

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

Sodium softening

This unit treats HLS product and has 98% water recovery. Its product is of condensate MU quality.

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

8.1.2 Membrane processes

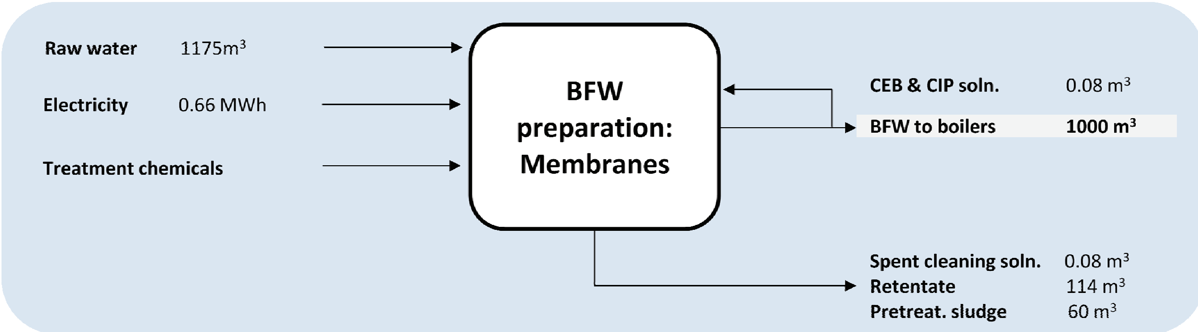

Figure 15: Selected flows for the Reverse Osmosis intervention

Table 9: Water balance on membranes based BFW preparation system

Flowrate in (m^3)		Flowrate out (m^3)	
Raw water	1175	Boiler feed water	1000
		Retentate	114
		UF pretreat. sludge	60
		Spent cleaning soln	0.08
Total	**1175**	**Total**	**1175**

<u>Pretreatment</u>

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

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

Table 10: Salts balance on Membranes based BFW preparation system

Salts flowrate in (kg)		Salts flowrate out (kg)	
Raw water salts	***117***	***Boiler feed water salts***	***4.3***
Treatment chemicals	***25***	***RO retentate***	***131***
HCl	24	Raw water salts	107
$NaHSO_3$	0.43	HCl	24
NaOH	0.02	Cl_2	0.14
Citric acid	0.22		
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**	**Total**	**142**

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. 2004).

Chemically enhanced backwash is performed once daily with a cleaning solution of around 3.8 m^3 or 0.056 m^3/Mℓ BFW produced by the system. Treatment chemicals NaOH and NaOCl are dosed at 10 ppm which translates to 0.01 kg 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 0.4-0.5 MWh per 1 Mℓ BFW produced by the system (Wilf et al. 2004).
Biannual membrane restoration procedure requires a cleaning solution of 760 m^3 for high and low pH treatment with 2% NaOH and 2% citric acid respectively. This translates to 0.023 Mℓ cleaning solution, 0.61 kg citric acid and 0.61 kg NaOH as well a negligible amount of surfactant SDBS per Mℓ BFW produced by the system.

8.2 Comparison of BFW preparation options

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, and 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. Salinity impacts were compared at the inventory level.

The robustness of the results presented in this section is evaluation further in Section 8.3.

8.2.1 Comparing results within impact categories

In this section, the inventories compiled in Section 8.1 are assessed and analysed relative to each of the selected impact categories. In particular, contributing sub-processes associated with each impact category are compared for the boiler feed water preparation technologies described in Section 8.1.

Figure 16 shows a comparison of characterisation results for the production of BFW from the two desalination technologies.

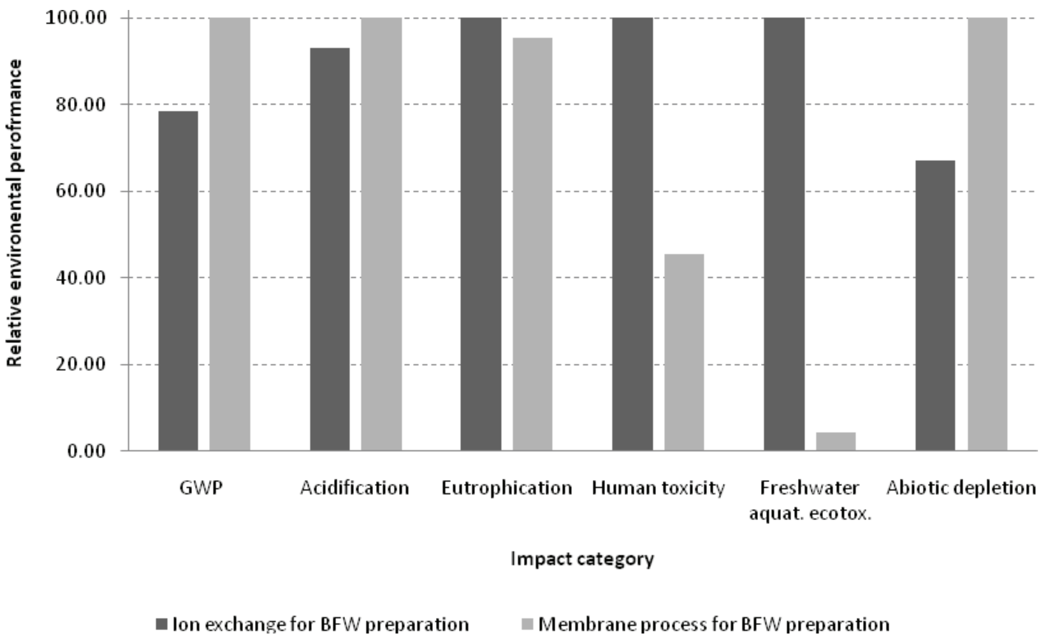

Figure 16: Comparison of characterisation results for the production of 1 Ml BFW produced by ion exchange and reverse osmosis

In the following subsections, each impact category will be analysed to determine the cause of dominance. The results will be compared by means of a “contribution analysis” (Baumann and Tillman 2004).

<u>Global warming</u>

As is evident from Figure 16 and Table 11, emissions contributing to greenhouse gases (GHGs) for RO are greater than those of the IX process by a factor of about 1.3.

Table 11: Process contributions to GWP for the two BFW preparation processes analysed

GWP (kg CO_2 equivalent)		
	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	26

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 8.1 above). Greenhouse gas emissions associated 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).

Hot lime softening treatment chemicals, hydrated lime and magnesium-oxide, respectively contribute 60.7 and 19.3 kg CO_2 equivalent or 11% and 4% 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 preheating 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 combustions gases of transport fuels for the **transportation of chemicals** from the greater Johannesburg region to the Highveld Complex. The transport distance estimated in Section 8.1 was 200 km. Transportation in life cycle assessment is typically measured in terms of distance travelled multiplied by the weight transported. As illustrated in Section 8.1, 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 11.

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 11 by "**Hard coal at Mine**", which is a sub-process to electricity generation.

GHG emissions in the Highveld Complex are at a disproportionally high level and although this impact category does not directly address the central issue of this investigation (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 greenhouse 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.

Acidification

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 process surpassing the RO process for this impact category by 0.38 kg SO_2 equivalent, 5%.

SO_2 emissions from the collection of processes which culminate in the production of Sulphuric Acid contribute 45% (3.69 kg SO_2 eq) 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 12.

Electricity-related SO_2 emissions for the aggregated production processes of Sodium Hydroxide contribute 50% (4.07 kg SO_2 eq) towards total acidification impacts of the IX process. The major sub-processes are “Secondary Sulphur at refinery” and “Sulphuric Acid at plant”, as illustrated in Table 12.

Table 12: Process contributions to Acidification for the two processes analysed

Acidification (kg SO_2 equivalent)		
	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

Acidification is a particularly problematic environmental problem in 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.

Human toxicity

Figure 16 and Table 13 illustrate that emissions resulting from the IX process which contribute to human toxicity are more than double those of the RO process.

Table 13: Process contributions to Human Toxicity for the two processes analysed

Human toxicity (kg 1,4 -BD equivalent)		
	IX	RO
Total of all processes	**51.10**	**23.20**
Disposal, red mud from bauxite digestion/CH	9.63	0.12
Hard coal burned in power plant/ZA – Tutuka	7.75	14.40
Monoethanolamine at plant	4.43	3.41E-05

For the RO process, 89% 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 Hydrochloric acid 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). 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 Highveld 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 Highveld Complex to affect communities where Bauxite is mined and processed (Australia, Jamaica, Guinea or Brazil).

Abiotic depletion

Figure 16 and Table 14 illustrate that overall resource usages which contribute to depletion of abiotic resource bodies follow a similar pattern to those for GWP, as described in Section 8.2.1.1.

Table 14: Process contributions to Abiotic Depletion for the two processes analysed

Abiotic depletion (kg Sb equivalent)		
	IX	RO
Total of all processes	**3.87**	**5.77**
Hard coal at mine/ZA	3.05	5.67
Crude oil production, onshore/RAF	0.15	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 $Sb_{eq.}$ for RO and 80% or 3.05 kg $Sb_{eq.}$ for IX.

This finding was subject to two major assumptions

iii. 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

iv. 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 study (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. The 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.

Eutrophication

Figure 16 and Table 15 illustrate that overall emissions which contribute to eutrophication of water bodies are quite similar for the two desalination technologies investigated.

Table 15: Process contributions to Eutrophication for the two processes analysed

Eutrophication (kg PO_4^{2-} equivalent)		
	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) accounts for the most significant contribution to eutrophication: 85% or 0.269 kg PO_4^{2-} equivalent for RO and 48% or 0.147 kg PO_4^{2-} equivalent for IX. The major sub-process for both these technologies is "Hard coal burned in power plant", as illustrated in Table 15.

Sub-processes related to the production of treatment chemicals contribute the remaining 0.15 kg PO_4^{2-} equivalent for IX. 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 for IX and 0.243 kg PO_4^{2-} equivalent for RO.

While eutrophication of surface water in major river systems (as consequence of the industrial activities found in the Highveld Complex) represents adverse implications for aquatic ecosystem health, the two systems analysed here perform similarly and this will not be discussed further in the Evaluation.

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 16: Process contributions to Freshwater Aquatic ecotoxicity for the two processes analysed

Freshwater aquatic ecotoxicity (kg 1,4 -BD equivalent)		
	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

8.2.2 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 section 4.4), 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 proposed intervention 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.

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 section 3. Figure 17 and Table 17 summarise the raw water, mine water, treatment chemicals and total ions input associated with the production of 1 MWh at the power station. Appendix B 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 most to Calcium ion input as a result of lime used for cooling water treatment.

Desalination of raw and mine water is performed by membranes processes, thus not incurring further major treatment chemicals, as reflected in Table 12.

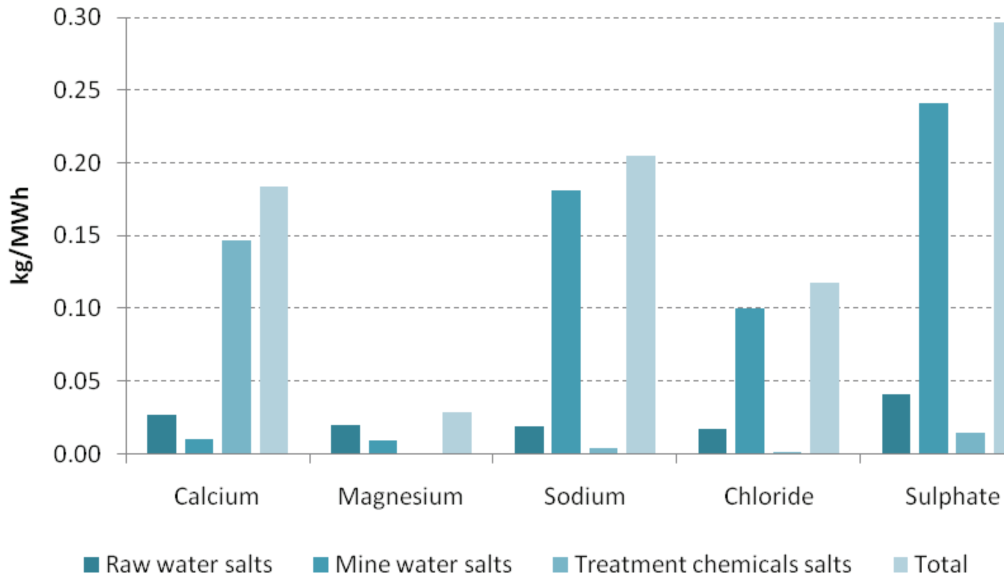

Figure 17: Salts footprint associated the electricity production at Tutuka

Table 17: Summary of Tutuka salts burden

ESKOM TUTUKA (kg/MWh)	Raw water ions	Mine water ions	Treatment ions	**Total ions**
Calcium	0.03	0.01	0.15	**0.18**
Magnesium	0.02	0.01	-	**0.03**
Sodium	0.02	0.18	0.00	**0.20**
Chloride	0.02	0.10	0.00	**0.12**
Sulphate	0.04	0.24	0.01	**0.30**

<u>Boiler feed water from the Reverse Osmosis intervention</u>

As indicated in Figure 18 and detailed in Table 18, dissolved salts in the raw water would generally accounts for all the ions associated with the production of boiler feed water at Sasol Synfuels, if this were done by reverse osmosis.

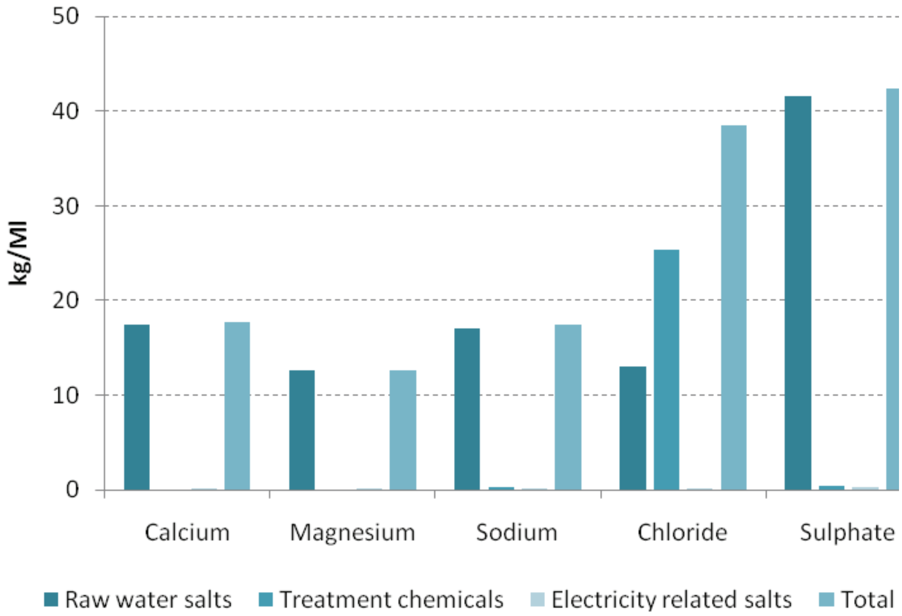

Figure 18: Salts footprint associated with the reverse osmosis intervention

Table 18: Summary of salts balance associated with the RO intervention

REVERSE OSMOSIS PROCESS (kg/Ml BFW)				
	Raw water salts	Electricity-related salts	Treatment chemicals	**Total**
Calcium	17.47	0.20	-	**17.67**
Magnesium	12.57	0.03	-	**12.60**
Sodium	17.02	0.23	0.23	**17.48**
Chloride	13.02	0.13	25.38	**38.53**
Sulphate	41.61	0.33	0	**42.36**

As demonstrated in the inventory analysis of Section 8.1.2, 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.

Boiler feed water from the ion exchange process at Sasol Synfuels

Salts balance problems associated with the ion exchange process at Sasol Synfuels were described qualitatively in section 3 and are illustrated in part by Figure 19 and Table 19: the use of treatment chemicals (described in Section 8.1.1) contributes more than 80% of total Sodium, Chloride and Sulphate inputs to this process.

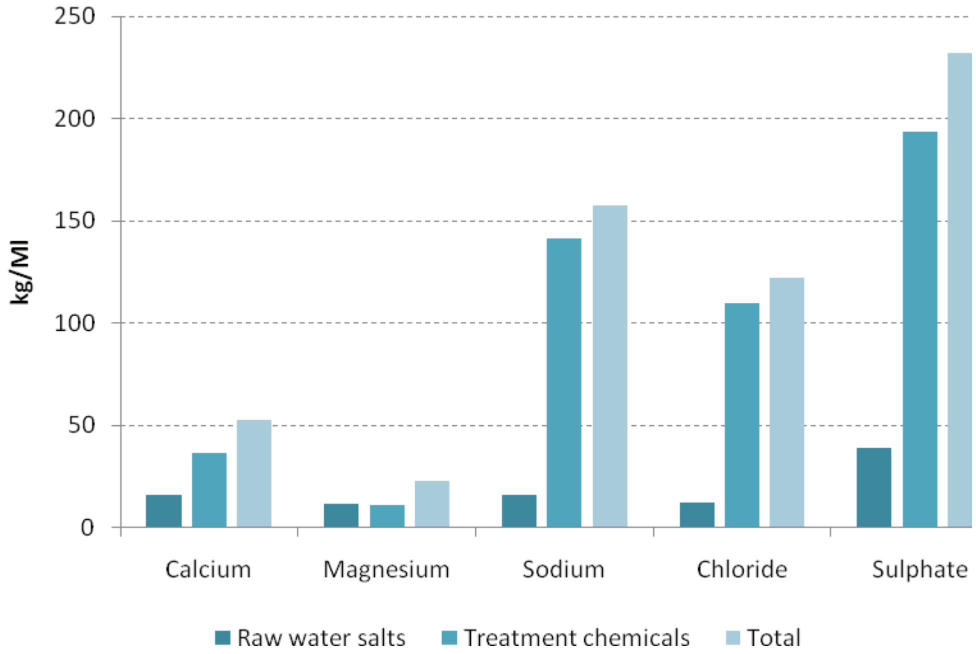

Figure 19: Salts footprint associated with the ion exchange process at Sasol Synfuels

Table 19: Summary of salts balance associated with the IX intervention

ION EXCHANGE PROCESS (kg/Ml BFW)			
	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**

<u>Comparison of boiler feed water preparation technologies</u>

Figure 20 shows a final comparison of the salts footprints associated with the two options for producing boiler feed water at Sasol Synfuels considered here.

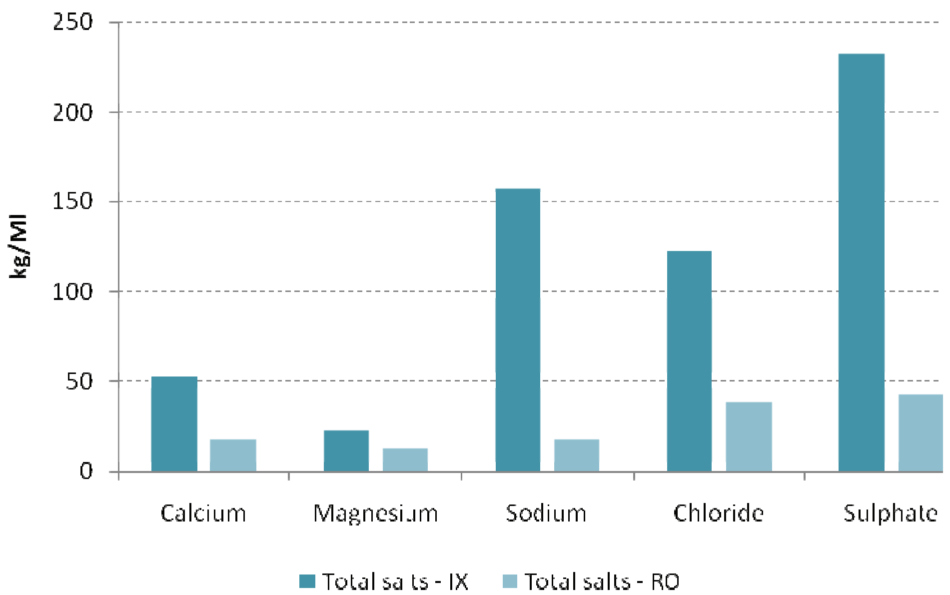

Figure 20: Comparison of the salts footprint of the two technologies studied

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 cations and 4.4 times anions (by weight) into problematic indefinite storage in the complex, thus not contributing towards the salinity problem described in section 3 as much as the IX process does. This is true in particular for problematic sodium, chloride and sulphate ions.

8.3 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.

8.3.1 Identification of significant issues

Given the central interest in this investigation on environmental sustainability problems relating to salts and water issues, the finding that implementation of the RO intervention would 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.

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 option also fares worse than the RO option in terms of toxic emissions.

Although not analysed further in the variation analyses of Section 8.3.2, it is obvious that substituting electricity from coal-fired power stations with renewable 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 IX 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.

8.3.2 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.

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.

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

The ion exchange process at Sasol Synfuels is comprised of demineralisation and sodium softening technologies which collectively produce boiler feed water. Figure 21 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.

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

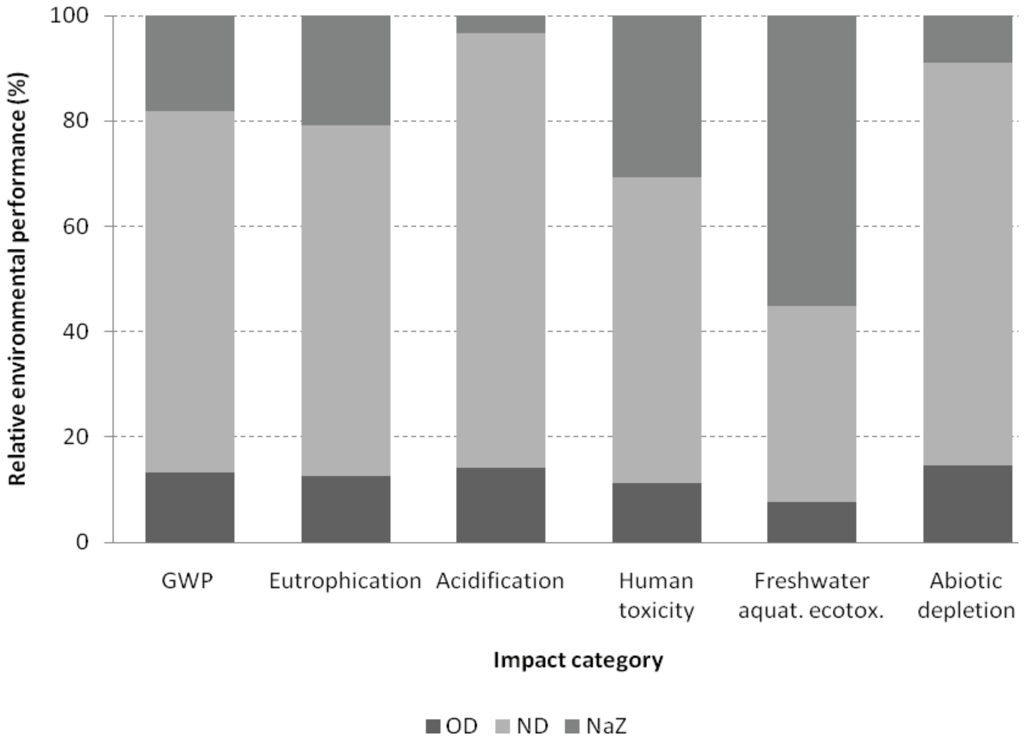

Figure 21: Collective contribution of IX technologies to environmental performance of IX system for the production of 1 Mℓ of BFW (6% OD product, 23%ND product, 71% NaZ product by volume)

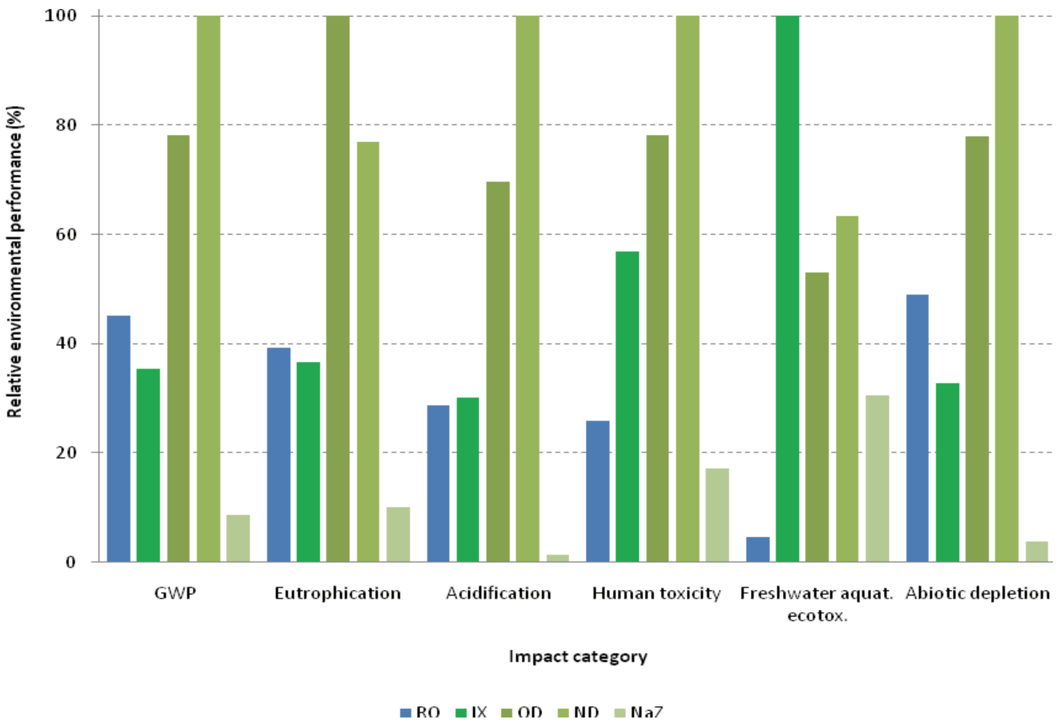

Figure 22: Production of 1 Ml of BFW from each individual IX technology is compared to RO

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.

8.4 Concluding comments

Through the rigorous methodology of life cycle assessment, the environmental burdens associated with the operations of two distinct boiler feed water preparation technologies have been investigated. In particular, the extent to which salinity burdens would merely be shifted from one industry in the Highveld Complex to another has been addressed.

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 8.1.

Section 8.2 contains the results of the LCIAs 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 RO intervention would lower salt emissions in the complex 4 to 5-fold, with only about 1% of the total new salts burden being shifted from Sasol Synfuels to Eskom Tutuka.
- 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 Highveld 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 (by about 20%) compared to IX, unless its electricity would come from a non-fossil fuel source.
- 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 downstream water requirements dictate the ratio of NaZ to OD&ND product, the RO intervention becomes preferable from an environmental point of view for low NaZ to OD&ND product ratios.

9 CONCLUSIONS

This report on the environmental sustainability of one large inland industrial complex has identified 5 reasons to be concerned. In some cases, the absorptive capacities of the ecosphere are routinely breached, in others a potential risk of a large breach of absorptive capacity is building up. The technological systems used are also known to be energy- and carbon-inefficient.

The literature review has identified that a set of co-ordinated systemic approaches exists that can be used to develop integrated technological responses to these environmental sustainability risks and breaches. These responses are rooted in industrial ecology; in particular industrial symbiosis is proposed to understand the system and its possibilities, followed by rigorous approaches to conceiving new process systems, followed by consequential life cycle assessments to ascertain that the proposed interventions do not merely shift burdens.

Previous efforts by the industrial partners to address the environmental sustainability problem have been reviewed. Several water reclamation projects have proven successful, but salts management projects have either failed or have relied on indefinite storage.

Based on the completed analyses, several industrial ecology type project ideas were generated and ranked. Unsurprisingly, an option that would seek to minimise the salts problem rather than deal with it was ranked as the preferred idea. In order to evaluate whether it would really be a waste minimisation option at the scale of the complex, not just one industry, a life cycle assessment was set up.

The results of the life cycle assessment show that the RO intervention would lower salt emissions in the complex 4 to 5-fold, with only about 1% of the total new salts burden being shifted from Sasol Synfuels to Eskom Tutuka. Environmental burdens in some other impact categories would however increase, notably for depletion of abiotic resources (coal) and greenhouse gas emissions, by around 20%, unless the power source for the RO process were to be a renewable or nuclear one.

10 RECOMMENDATIONS

Four recommendations are made:

1) Life cycle assessments must not be carried out blindly: it is especially important to understand the methodological implications of choosing a consequential over an attributional approach. A suitable approach to the salinisation impact problem must also be chosen.
2) Ion-exchange based production of boiler feed water should be replaced with reverse osmosis methods, as these have now been shown by a life cycle assessment to significantly reduce salts-related sustainability risks, even if the electricity is generated at a power station where saline mine water is used.
3) The recovery of saleable salts from brines remaining after desalination of mine waters should be further explored, by further developing technologies such as carbonation of eutectic freeze crystallisation and assessing them by LCA as demonstrated here.
4) The critical literature on industrial symbiosis suggests that where such approaches are considered for reducing the identified environmental sustainability breaches and risks, care must be taken not to romanticise them as “silver bullets that solve all problems” – it is claimed that such approaches often reduce the existing problem only fractionally, whilst in a perverse way lending “green credibility” to the ongoing unsustainable practices. This should be borne in mind also for the outcomes of this study: even if the amplification of the salts burden arising from ion-exchange technology were removed, there would still remain large fluxes of water-soluble salts in the Highveld Complex – and these are only one of the environmental sustainability risks.

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Appendix A: Water qualities at SSF

Table A-1: Water qualities of a selection of brines at SSF (from Roux, 2000; 2009)

	Contaminated Storm Water	*Process Cooling Water Blow Down*	*Clear Ash Effluent*	*Mine Water*	*Raw water*	*TRO Brine (U67/9)*	*U44 effluent*	*U244 effluent*	*U544 effluent*	*U544 retentate*	*Firewater to ash (EAST)*	*Firewater to ash (WEST)*
Ca [mg/l]		30	400	255	4.16	707	368	368	197	7	5	6
Mg [mg/l]		15	10	160	3.01	208	245	245	131	7	3	4
Na [mg/l]	120	300	1100	1170	4.04	21149	4641	4641	1254	1319	79	73
Cl [mg/l]	200	400	1300	265	3.10	11135	4364	4364	1826	530	60	71
TSO_4 [mg/l]	950	2500	2000	3260	9.91	29920	4218	4218	138	2377	519	498
COD [mg/l]	900	1 600	250	30	3.18							
TDS [mg/l]		5 000	4 000	4 000			15056	15056	3599	4783		
Cond.	3 200	7 500	6 000	6 500		68000					2323	2324
SS [mg/l]	300	2 000	130	130					15003	0	431	384
F [mg/l]	150	400	30	2	0.05							

All values expressed as mg/l, except pH and conductivity (µs/cm).

Table A-2: Typical steam qualities at SSF (from Grant, 2006)

COMPONENT	UNITS	HP SUP STEAM	LP STEAM	CONDENSATE	POLISHED WATER
Conductivity	µS/cm	< 10	< 20	< 10	< 0.8
pH		6.9-7.0	9.0-10.0	8.8-9.4	7.0-7.5
Total dissolved solids	mg/l	< 0.1	**12**	< 7	**13**
Dissolved oxygen	ppb	< 5	< 10	< 5	**14**
TOC	mg/l	< 0.1	< 10	< 2	**15**
Sodium	ppb	< 10	< 10	< 10	< 10
Calcium	ppb		< 1	< 300	< 10
Chlorides	ppb	< 10	< 10	< 300	< 50
Silicates	ppb	< 20	< 20	< 700	< 50
Iron	ppb	< 50	< 10	< 50	< 10
Total sulphates	mg/l	< 5	< 10	< 5	< 0.5

Appendix B 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 B1: 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 B2: 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 B3: 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