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**Opportunity to Apply Recent Advances in Process Design to Bioenergy  
Systems: The Case of Sugarcane Processing in South Africa**

**A thesis submitted to the  
UNIVERSITY OF CAPE TOWN  
In fulfilment of the requirements for the Degree of  
MASTER OF SCIENCE IN ENGINEERING  
(CHEMICAL ENGINEERING)**

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## **Dedication**

*I would to dedicate this dissertation to my parents, Allen and Heather Botha, for their immeasurable support, commitment, and sacrifices for my academic pursuits.*

University of Cape Town

## **Acknowledgements**

I would like to thank everyone who gave me advice, support and information and aided me in any way throughout the duration of this dissertation.

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## Synopsis

Global environmental concerns have brought about a change in the way a design team tackles a new task. The field of process systems engineering has developed in response to these needs. In parallel, a modern 'bioenergy' industry has emerged in response to the same environmental pressures. The unsustainable modern industrial economy has led to global environmental concerns including global warming and human health effects. Bioenergy, or conversion of biomass to clean modern energy carriers and products, emerges as a response to these effects and draws strongly on process engineering.

The agricultural sector in South Africa can have an important role in meeting the renewable energy target proposed by the Department of Minerals and Energy. Such a medium term target is seen as a step in the right direction to achieving a truly sustainable future.

The dissertation investigates the role of conceptual design in aiding the development of a flowsheet for a selected bioenergy system. The main questions that guide the thesis are:

- *To what extent can the processing of crop residues into modern energy carriers contribute to meeting energy supply?*
- *What tools have been developed for generating various product and process options?*
- *What tools are available for assessing the various process and product options that could be generated?*
- *What tools are available for the screening of the product and process options generated?*

The questions are addressed with the aid of a literature study and two demonstrative case studies. The literature serves to inform the current state of process systems engineering and the advances that have taken place in the field over the last decade. The focus of the study resides in the conceptual engineering phase. This section of a design is a key focus area since the opportunities to explore benign alternatives is the greatest. The definition of this phase is critical for the study. The second part of the survey investigates the field of bioenergy and the contribution it can provide in the energy sector. Two case studies are used to provide answers to the key questions and validate the hypotheses.

The first case study compares the environmental dimension of current practices in sugar production against two alternatives, thus exploring the early stages of product development. The first, green electricity, is seen as the best method of achieving the renewable energy targets in South Africa. The second, producing ethanol from excess bagasse for the automotive industry as an octane enhancer, is thought to have a significant environmental benefit. The case reveals that both the green electricity system

and the bioethanol system outperform the base case, current sugar production, in all the life cycle assessment midpoint indicators chosen. Comparing proposed alternatives, the two bioenergy options outperform each other in three out of the six methods chosen. The overall indicator reveals the bioethanol to have the lower environmental impact.

The second case study employed heuristics conceived for waste minimization on an existing flowsheet to explore whether the perceived better processing route could be attained. The relevance and power of the available heuristics is evaluated. The first case dealt with an input/output level scenario, and case two therefore extended this to block flow and early PFD level.

The excess bagasse is used as the feedstock for ethanol production. The dilute acid hydrolysis of bagasse, as modeled by Kadam (2002), is used as the base process. Process systems engineering heuristics were then applied to the system to see what alternatives could be generated.

A biological conversion of the bagasse intuitively seemed to be the better option. The heuristics are used to see whether this would emerge as an option in the flowsheet. The study shows the usefulness of heuristics in revealing waste problems early in the design. In some instances the heuristics proved to be options generating, but they were not able to show the benefit of a biological process.

The case studies highlighted the usefulness of LCA in the conceptual design of a process, displaying strength and value as a screening tool. They also highlighted the power of hierarchical design and the potential to stimulate the designer to produce novel solutions to waste problems. The shortcomings in the field of heuristics with respect to bioenergy systems are exposed. One of the largest shortcomings of the heuristics is the inability to handle multi-product systems.

The biomass feedstock of choice, bagasse from the agricultural industry, has the potential to supply a large portion of the renewable energy target. The bagasse is best suited to a biological process for conversion. A combination of hierarchical approaches is needed to develop better flowsheet alternatives.

It is recommended to develop the biological conversion route of bagasse to ethanol so as to become commercially viable. Greater use of LCA and LCIA at all levels of a design is required. There is also a need to further expand the methods of structured thinking to include bioenergy systems and give more direct guidance to a design engineer working in this field.

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## Glossary of Terms Used

BFD – Block Flow Diagram

Biomass – Plant material

Bagasse – Fibrous material remaining after sugar extraction. 50% moisture

Conceptual Engineering – *“The goal of conceptual design is to find the best flowsheet (i.e. to select the process units and interconnections among these units) and estimate the optimum design conditions.”*  
(Douglas, 1988)

DME – Department of Minerals and Energy

Heuristics – Common engineering principles based on experience

LCA – Life Cycle Assessment

LCIA – Life Cycle Impact Assessment

LCPD – Life Cycle Product / Process Design

LR – Ligneous Residue, unconverted solid material of bagasse

P&ID – Process and Instrumentation Diagram

PFD – Process Flow Diagram

PSE – Process Systems Engineering

TEAM<sup>TM</sup> – Tools for Environmental Analysis and Management

WSSD – World Summit on Sustainable Development

# Chapter 1: Introduction

## 1.1 Background

The discipline of process systems engineering has developed rapidly over the past decade, to large extent in response to global environmental concerns. A major objective of academic work in this field has been to make such concerns become an integral part of process design methodologies.

In parallel to this work, a distinct industry -The Bioenergy Industry-, largely driven by the same environmental concerns and coupled with the unsustainable path of the modern industrial economy, has emerged. This industry is still relatively immature, with some established and some new technologies to exploit renewable biomass resources.

This new industry, occupied with the conversion of biomass into clean modern energy carriers, draws much more on the discipline of process engineering than its prominent renewable energy cousins (namely wind and solar energy).

### 1.1.1 Bioenergy

The increased utilisation of renewable resources is seen as a central element of sustainable development. Many countries have set targets for contributions of renewable energy to meeting their energy demand.

South Africa is no different, the Department of Minerals and Energy (DME-SA) has recognized the need to address the environmental issues regarding non-renewable resource use and is proposing medium term renewable energy targets, even though no international targets were set at WSSD 2002. (Department of Minerals and Energy (DME), 2002)

South Africa has the potential to produce a significant amount of renewable energy. The share which renewables have in the energy sector is set to increase as the replacement of fossil fuels becomes more urgent.

The conversion of wind to power (electricity) has developed as the global dominant form of renewable energy since the early 1990's. The second most

accepted form of renewable energy lies in photovoltaic (PV) cells. The development of PV's has remained limited to niche markets due to the high production costs of the cells. Biomass conversion technologies have shown great potential in completely replacing fossil fuels derived products. Bioenergy has recently emerged as a potential low cost and large scale renewable energy provider.

Biomass residues from industry can be used for this purpose. The residues from industries such as pulp and paper and agriculture are available for further processing. Another option is to produce crops for the sole purpose of conversion to an energy carrier, generally referred to as energy cropping.

A study conducted by Marrison and Larson, predicted that South Africa has the largest energy cropping potential in Africa. The study estimated that approximately 1350 PJ of biomass energy could be produced in South Africa in the year 2025, assuming only 10% of the available land is used for energy cropping. (Marrison and Larson, 1996)

Energy cropping has many social and environmental implications. There is a growing pressure for land coupled with the fact that world hunger remains an unresolved issue. Why should this land then be used for energy purposes? This unanswered question points, at least in the short term, to the use of industrial biomass wastes and residues for the purpose of renewable energy provision.

### **1.1.2 The South African Agricultural Industry and its Potential Contribution to Renewable Energy**

South Africa produces a wide variety of saleable crops. The largest of these crops is maize, which is the staple food of the nation. The current production figure for maize is estimated at 9 million tons per annum. (Mail and Guardian, 1999). These large volumes of crops are accompanied by large amounts of crop residues, which in the maize industry are mostly left on the field, returning nutrients to the soil.

The second biggest crop grown in South Africa is sugarcane used for the production of sugar. The saleable sugar amounts to 2 million tons per annum. The sugarcane that is harvested amounts to some 18 million tons. (South Africa Sugar Association, 2001) The crop residue, called bagasse, is currently used to for the process utility requirements on the plant. The energy efficiency of sugar mills

tends to be very poor due to the large amounts of the bagasse available. The potential to convert excess steam not required for process heat requirements into exportable electricity for export is good. (Beeharry, 1996)

This practice is employed in Mauritius where the largest crop is sugarcane, and the bagasse produced during farming, serves to supply the process needs for the mills as well as providing 8% of the country's grid electricity. (Beeharry, 1996)

However, it is well recognised that the current coal based electricity price in South Africa requires significant premiums to be placed on 'green electricity' in order for this use of bagasse to be economically attractive.

Alternatives to the combustion of biomass to produce process heat/steam and electricity have been raised and include:

- Gasification / Pyrolysis
- Cracking to yield feedstocks for the production of chemicals
- Hydrolysis to sugars followed by fermentation to produce chemicals and / or liquid fuels

Such, and other biomass conversion technologies to produce clean modern energy carriers (electricity, gas, or fuel) necessitates considerable process engineering. It stands to reason that new developments in process engineering will have the potential to improve biomass conversion technology.

### **1.1.3 Recent Advances in Process Systems Engineering (PSE)**

The discipline of PSE has seen several developments during the 1990's, the development of conceptual engineering as a distinct step of process design having been one of them.

The majority of the design work is fixed at the conceptual level (Yang and Shi, 2000). The opportunity to make changes during the design decreases as the project develops and becomes more constrained. This phase of the design is therefore pivotal in order to address environmental concerns before they are inherent in the process and can only be addressed by end-of-pipe solutions.

One of the biggest challenges was that of expanding the system boundaries during the conceptual design phase. This was largely brought about by the need to include environmental concerns within the design, with the ultimate aim being sustainability. The extending of system boundaries led to life cycle assessment (LCA) emerging as versatile tool to be used in the conceptual design phase.

The generation of flowsheet alternatives taking into account environmental objectives such as waste minimization and cleaner production has also enjoyed much development.

## **1.2 Problem Statement**

As mentioned above, technologies that convert biomass to energy are becoming more widespread. This, coupled with the need to replace non-renewable resource use, makes it quite clear that excess biomass can be put to good use. Current practice renders the residues waste rather than a potential energy feedstock.

Global competitiveness and growing environmental issues have brought new pressures to bear on the process industries, one of them being maximising products by utilising wastes.

Integration of new technologies into existing plants is a possible response. With such technologies becoming available, plants that utilise biomass have opportunities to maximise the gains from their residue. The sugarcane industry in South Africa has been using their crop residue to provide process heat requirements, albeit at a low efficiency, in order to satisfy process utility requirements. The option to convert the excess bagasse to other products is a very real opportunity that needs to be explored further.

With an increased shift towards wider and more efficient use of renewable resources, as well as set government targets for renewable energy, an opportunity has arisen to explore new product development in the sugar industry.

The problem or opportunity to be addressed by this thesis can thus be summarised as follows:

“Recent advances in conceptual design and in flowsheet development of process systems have created an opportunity for more systematic design also in the field of bioenergy. No work has been reported on the application of new process design tools in the field of bioenergy process design, specifically not in targeting the sugar cane processing industry in South Africa.”

### **1.3 Objectives**

The main objective of this dissertation is to first review and identify recent advances in process systems engineering, and secondly to evaluate their value, strengths and weaknesses with respect to the design of bioenergy systems by applying them to current or emerging opportunities in the sugar industry. It is envisaged that contributions to the bioenergy market in South Africa can be made by promoting the efficient and maximised use of crop residues.

The design stages to be investigated range from conceptual level design, where the opportunities to limit pollution are the greatest, to the feasibility stage, where flowsheets are fixed.

### **1.4 Key Questions**

The key questions to be answered in the dissertation are:

- *To what extent can the processing of crop residues into modern energy carriers contribute to meeting energy supply?*

Having identified the fact that crop residues in South Africa have the potential to provide a source of current or future energy carriers, the extent to which, and how, this can be achieved is to be evaluated.

- *What tools have been developed for generating various product and process options?*

In order to design processes utilising new and existing technologies to best effect, process systems design tools which generate many good and innovative

alternatives need to be applied. The identification of such tools is therefore necessary.

- *What tools are available for assessing the various process and product options that could be generated?*

Assessing whether any proposed flowsheet is indeed better than any other, raises the question of what exactly is a 'good' flowsheet? An evaluation method needs to be developed with the aid of modern assessment techniques. There are numerous tools and these need to be identified and the best selected for evaluating design options.

- *What tools are available for the screening of the product and process options generated?*

Having generated discreet flowsheets provides the designer with choices. Using a screening tool to eliminate some of the options helps to arrive faster at the best product or process option, avoiding the use of full assessments.

## **1.5 Hypothesis**

The hypothesis developed at the outset of this dissertation is:

- Selected recent advances in the process systems engineering sector applied to the design of bioenergy systems can aid the agricultural processing industry in maximising the value added by utilisation of crop residues, by enabling designers to create more efficient processes.

## **1.6 Methodology and Approach**

The first task therefore, is to present a review of the literature pertaining to process systems engineering (PSE), to reveal the recent advances in this field.

The second task is to review literature on biomass and biomass conversion to energy products / carriers. Advances in PSE and their applicability to the design of bioenergy conversion processes are also reviewed.

Thirdly, the development of an understanding of current sugar processing both locally and internationally is necessary in order to generate scenarios for crop residue utilisation in the bioenergy sector.

Application of selected advances in PSE to the sugar industry would then have to be demonstrated. This could either be achieved by the development of a generic argument, or through demonstration by means of case studies. The latter approach was chosen for this dissertation, with a two part-case study to be developed.

## **1.7 Dissertation Structure**

Having highlighted the opportunity and developed key questions to be addressed, a review of the literature used in this study follows. This is presented in two parts, where Chapter 2 reviews process systems engineering and the recent advances in the field and Chapter 3 reviews biomass and bioenergy. Once conclusions from the literature are drawn, the two-part case study is then presented in Chapters 4 and 5. Subsequently, conclusions are drawn and recommendations discussed in Chapter 6.

## **Chapter 2: Process Systems Engineering (PSE)**

### **Literature Review**

This chapter aims to review key features and advances of the recent development of process systems engineering. The chapter starts with a definition of the discipline, before moving on to the review of recent advances in process systems engineering and design. This will be followed by a review of the literature on a related new discipline known as 'Green Chemistry', and finally conclusions will be drawn.

#### **2.1 Introduction**

##### **2.1.1 Process Systems Engineering**

The creative design process occurs when ideas are generated and translated into processes and equipment for the production of new materials, or for significantly upgrading the value of existing materials. (Douglas, 1988). The discipline of process systems engineering uses qualitative approaches (e.g. rule-based heuristics), as well as quantitative approaches such as modeling, simulation and optimization, to design and improve processes. Process design should include all technical aspects. (Herder, 1999)

The term of interest is 'all technical aspects'. For a long time process designers did not include taking into account the interaction of the designed system with the environment. This, however, has changed due to the global recognition that the environment is an integral part of the design plane and so should be included as a technical aspect.

Process systems design will be discussed in more detail in sections 2.1.3 and 2.1.4.

##### **2.1.2 Key Questions for the Literature Review**

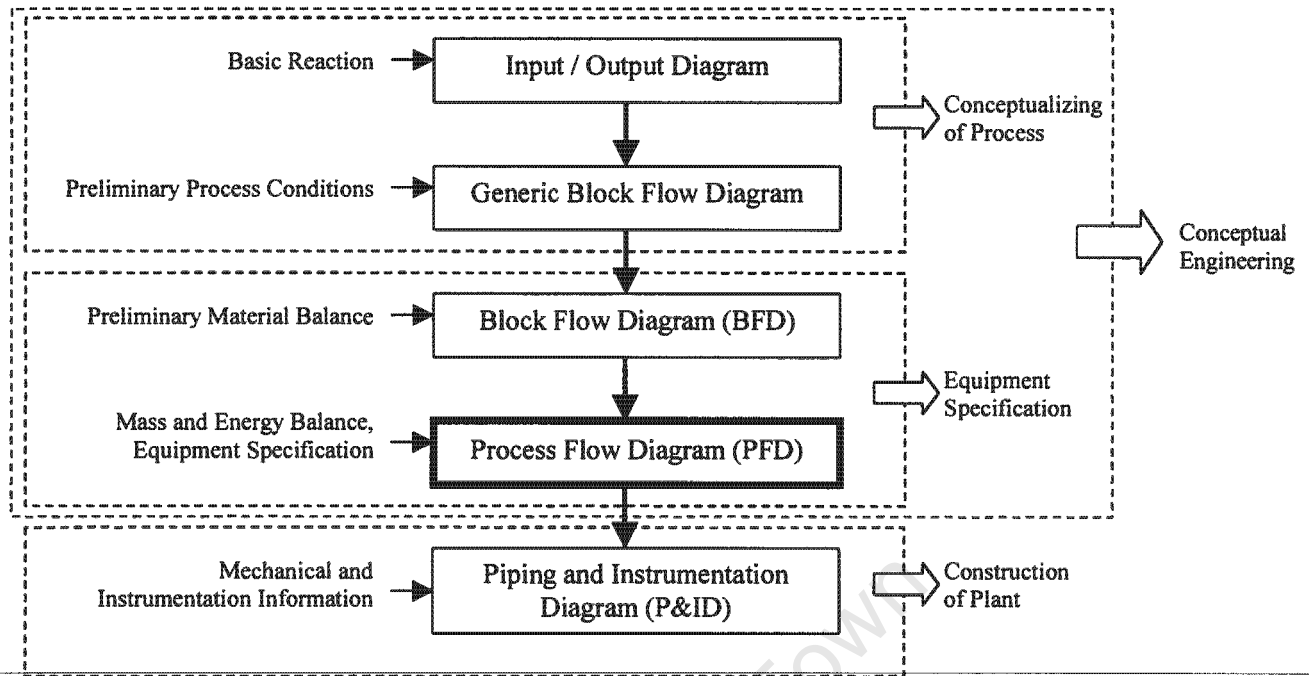
Key questions that need to be answered by the review of the process systems engineering literature have already been presented in Chapter 1. In some more detail, these questions are:

- What are the most important developments in this field over the past 10 years, with particular attention being paid to those concentrating on the environmental aspects of PSE?
- What new tools are available for generating various product and process options and how have existing tools been improved?
- What tools are available for assessing value-generating potential of the various process and product options?
- What tools are available for screening / assessing at the early design stage?

### **2.1.3 Process Systems Design – a theoretical framework**

#### a) Hierarchy in Process Systems Design

Design in the process industry deals with all aspects of a project from definition to operation and sales and even to closure at the end of the project's life. Designs are most commonly undertaken in a series of stages, with each successive stage of the design having an increasing amount of requisite data. The progression from concept to final design can be represented in the form of the different diagrams needed at each level presented by Turton et al (1998), as shown in Figure 2.1.



**Figure 2- 1: Stages in Process Systems Design and the Associated Diagrams**

(Modified from Turton et al., 1998)

Figure 2-1 represents the design progression from early conceptualizing of a project to the construction of the plant, and the requisite data for the varying levels of detail and the diagrams needed to carry out the design task.

The figure was adopted from Turton et al (1998) Figure 0.1 and modified to show the stages which the various diagrams pertain to. Conceptual engineering as defined by Douglas (1988) is illustrated in red in Figure 2-1. Standard design texts (Seider et al., 1999; Biegler et al., 1999 ; Sinnott, 1999 ; Douglas, 1988) as well as various other sources (Basson and Petrie, 2001; Yang and Shi, 2000) have been consulted in order to clarify the term conceptual engineering as there is little unity in the definition. Figure 2-2 is therefore developed to show some difference of opinions as well as the definition of conceptual engineering applied to this study.

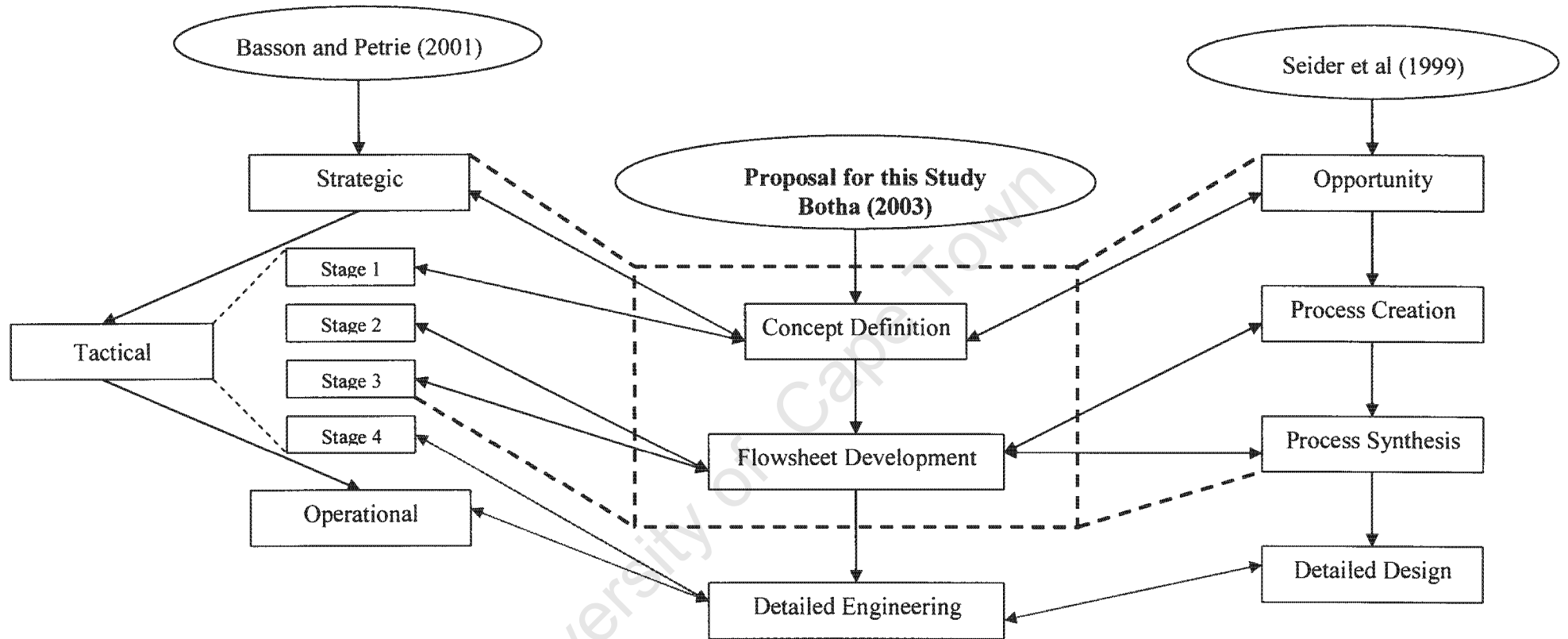


Figure 2- 2: Conceptual Engineering Definition and Relation to Other Sources

The definition of the term conceptual engineering is critical to place the work to be done in this study. The term, whilst commonly used in design text, takes no uniform definition. The term in this study therefore refers to Douglas (1988) definition:

*“The goal of conceptual design is to find the best flowsheet (i.e. to select the process units and interconnections among these units) and estimate the optimum design conditions.”* (Douglas, 1988)

Figure 2-2 represents the simplified levels of engineering detail, namely concept definition, flowsheeting, and detailed design. The concept definition is related to Basson and Petrie’s (2001) strategic design where decisions are made according to policies, plans, and programs. Relating the concept definition to Seider et al (1999) lies in the opportunity phase of a project.

The harder phase to define is flowsheeting. The discrepancy occurs, and few authors agree, where the boundary between concept and detailed engineering lies. In order to relate to other studies, the definition of flowsheeting again refers to Douglas (1988) where the designer is trying to find the best flowsheet and optimum operating conditions. The relevance for this study is therefore placed on detailed block flow diagrams (BFD’s) and early process flow diagrams (PFD’s). Turton et al (1998) recognize this as a very important section of design and the PFD is the single most important diagram for a chemical/process engineer. (Turton et al., 1998).

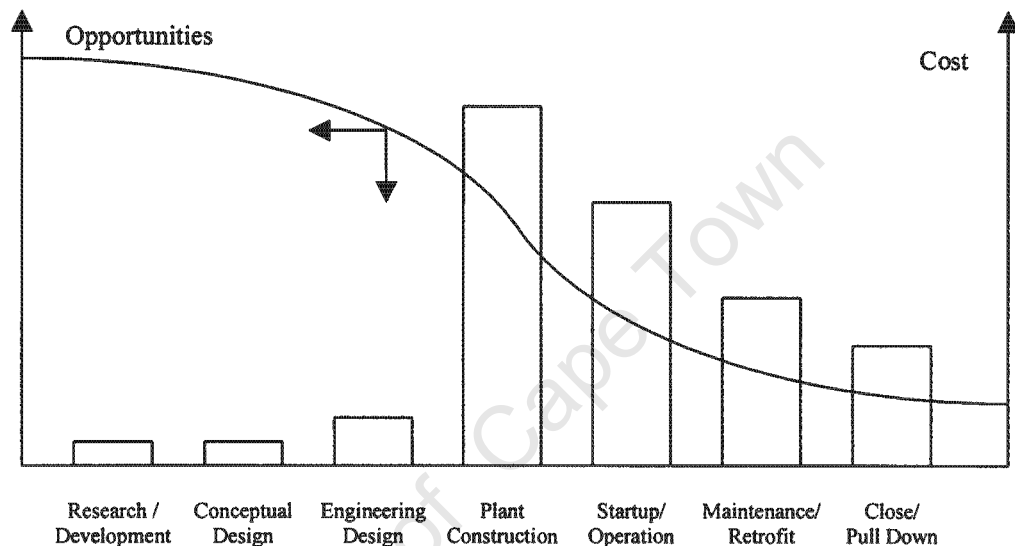
Basson and Petrie (2001) break their tactical design phase into four stages. The line drawn in this study, according to their definition, would lie at tactical design stage 3 (production of detailed BFD). The PFD falls into stage 4, but is lumped with detailed engineering and process and instrumentation diagrams (P&ID’s). This is not consistent with the definition adopted for this study.

Seider et al (1999) refer to process creation and process synthesis. Process creation involves preparing a flowsheet and applying process integration. Process synthesis involves first and second law analyses (material and energy balances) as well as heat and power integration. This remains within the bounds of the definition adopted.

Yang and Shi (2000) link research and development with conceptual design and state that it differs from engineering design. They feel that conceptual design is

the link between laboratory research and engineering design. While this definition may have merit, it does not sway the conceptual engineering definition used in this study.

Yang and Shi (2000), do however, correctly recognize the importance of this design phase, regardless of definition and provide a good account of the opportunities to make design changes and the costs involved. Figure 2 from Yang and Shi illustrates the narrowing of constraints and subsequent opportunity to make process changes at the expense of cost as a design progresses:

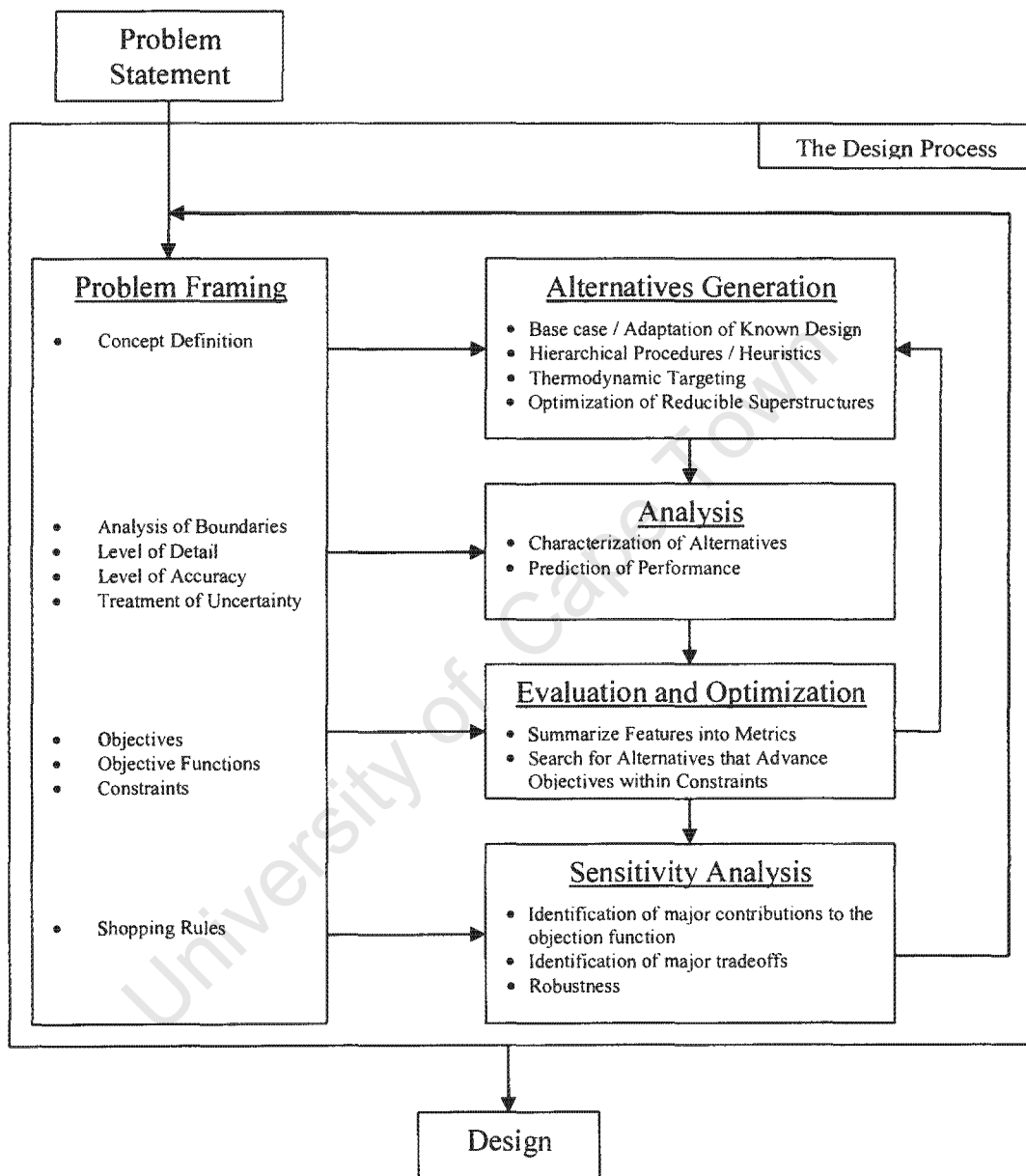


**Figure 2- 3: Opportunities of Environmental Impact Minimization Along Process Life Cycle**  
(Yang and Shi, 2000)

Conceptual engineering is a critical design phase as the majority of the design is fixed at this level. Nearly all major decisions are confirmed and the rest of the iterative design process serves to refine the design. (Herder, 1999) Figure 2-3 does not represent Herder's view sufficiently in this regard, as the slope of the opportunities line between the conceptual and engineering design phases would need to be steeper.

The value placed on this design phase is recognized and this study will focus on conceptual engineering, i.e. on the development of a flowsheet from input/output diagrams, and progress to detailed BFD's and early PFD's.

interrelation is shown in Figure 2-4, taken from the comprehensive review of environmentally conscious process design of Cano-Ruiz and McRae (1998).



\*(Cano-Ruiz and McRae, 1998)

Figure 2- 4: Components of the Design Process

## **2.2 Recent Advances in process systems design**

It is widely recognized that the scope of process systems design has expanded from a focus on reaction and separation only in the early 60's to including all facets of the manufacturing process in the 90's. According to Cano-Ruiz and McRae (1998), this first major step in the refinement of process systems engineering was the expanding of the system boundaries. Basson and Petrie (2001) as well as Yang and Shi (2000) recognize this as the biggest single change in PSE over the last few decades. This is a direct response to increased environmental pressures (Yang and Shi, 2000). The specific environmental pressures as seen by Basson and Petrie (2001) are:

- Waste Minimization
- Pollution Prevention
- Cleaner Production

The inclusions of more facets in the design lead to advances throughout the design process. The iterative methodology presented earlier in Figure 2-4 will now be discussed with reference to the advances in the field of PSE.

### **2.2.1 Advances in Problem Framing**

The first design phase addresses the issue of problem framing where all the decisions are made in order to formulate the optimization problem. In the review by Cano-Ruiz and McRae (1998) four advances in this phase of design are discussed:

- Inclusion of waste treatment infrastructure
- Material Integration
- The use of Life Cycle Assessment (LCA) to assess impacts “beyond the fence”
- Effluent concentration replaced by environmental impacts

#### **2.2.1.1 The Use of Life Cycle Assessment in the Dissertation**

While LCA as a field of study has developed significantly over the last decade, the individual advances in this study will not be presented. The focus on LCA and its varying applicability in the field of process design is evaluated. The life cycle

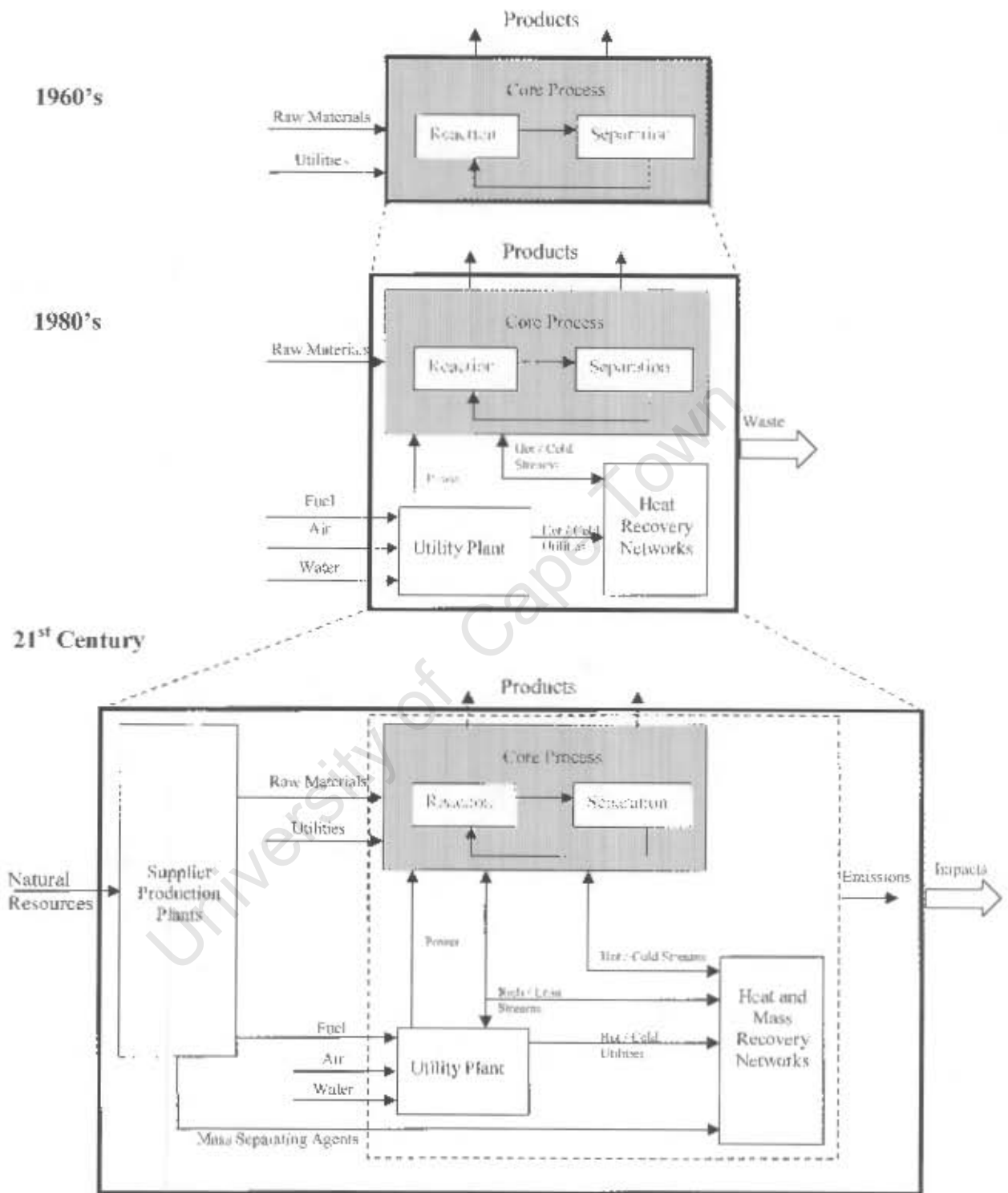
methodology used in this dissertation conforms to ISO 14000 standards. The details of each phase is well presented in these standards and so will not be discussed further. The broad headings used are:

- Goal and Scope Definition
- Life Cycle Inventory Analysis
- Life Cycle Impact Assessment (LCIA)

These phases of the LCA methodology will be used throughout the study and will be assumed to be understood.

### **2.2.1.2 Analysis of Advances in Problem Framing**

The list presented by Cano-Ruiz and McRae (1998) represents the key core advances with respect to system expansion. System expansion or larger system boundaries facilitates almost all of the advances presented. The design stages considered and their individual advances are a result of the underlying list above. This places a large emphasis on the problem framing section, and this fact is of critical importance and is recognized by Cano-Ruiz and McRae (1998).



\*(Cano-Ruiz and McRae, 1998)

Figure 2- 5: Evolution of Process Synthesis Problem Framing

Figure 2-5 illustrates the mindset change to incorporate wastes and impacts into problem framing. This has necessitated the expansion of the system boundaries to account for this developing design trend.

These sentiments are echoed by Yang and Shi (2000), who recognize the illustrative depiction of the change in conceptual design. Yang and Shi seem to be greatly influenced by the work of Cano-Ruiz and McRae, and regularly cite the article. (Yang and Shi, 2000 ; Cano-Ruiz and McRae, 1998) Yang and Shi extend Cano-Ruiz's process systems review and apply it to Environmental Impact Minimization (EIM).

This advance stems from designers realizing that waste minimization was a means and not an end. Measuring emissions of waste in terms of mass or concentration was not a fair reflection of environmental burden. (Cano-Ruiz and McRae, 1998) Replacing the consideration of wastes and emissions during design to an assessment of environmental impacts thus was a direct result of system boundary expansion.

The need to evaluate the impacts of a design prompted investigations of the usefulness of Life Cycle Assessment (LCA) during the conceptual design phase. (Azapagic, 1999)

Azapagic (1999) recognizes the fact that environmental pressures are steadily increasing and the shift towards the producer responsibility and zero emissions are becoming more common environmental design tenets. On the other hand, Yang and Shi (2000) dispute the applicability of LCA in conceptual design as the information available to a designer in this phase is limited and highly uncertain, rendering the results inaccurate.

Basson and Petrie (2001) agree with Yang and Shi (2000), in so far as there is large uncertainty in the early design stage, but argue that at the strategic (conceptual) level it is essential to consider all life cycle stages and impacts. Their reasoning agrees with that of Herder (1999): as the problem (design) becomes more constrained, opportunity for major changes in environmental performance become fewer, and the focus shifts to management of environmental degradation. This enforces the idea of the importance of conceptual level design having the largest scope to affect the environmental performance of a system, through early assessment and screening of design alternatives. Basson and Petrie (2001) also state that Life Cycle Impact Assessment (LCIA) is inappropriate at all levels due

to aggregated loading and estimated risks. Their proposal, therefore, is LCIA be used for comparative assessment at strategic levels and early design stages. (Basson and Petrie, 2001)

## 2.2.2 Advances in Generation of Alternatives

The generation of alternatives or options is the second step in the design process as identified by Cano-Ruiz and McRae (1998). Environmentally conscious alternatives generation need to include four key elements, namely:

- High economic potential
- High conversion of raw materials to desired products
- Energy efficiency
- Avoiding releases of hazardous substances to the environment

One of the most recent extensions of LCA, incorporating the above criteria, is its use in life cycle product or process design (LCPD). LCPD involves selecting a reference process and applying LCA throughout the design process. LCPD, therefore, offers the potential to employ technological innovation in the process concept and structure. This use of LCA can be seen as an options generating tool as well as utilizing innovative technologies where possible. (Azapagic, 1999)

Cano-Ruiz and McRae (1998) feel that attaining the four key elements lies in process integration. Yang and Shi (2000) as well as Rossiter (2001) agree that process integration is an invaluable part of the new design process.

Cano-Ruiz and McRae (1998) proposes six strategies for generating options in environmentally conscious process design:

1. The use of documented pollution prevention solutions as a source of design alternatives.
2. Design by case study
3. Hierarchical design approach – methods of structured thinking
4. Pinch Analysis and other targeting techniques
5. Mathematical programming
6. Expert systems and artificial intelligence

The use of documented pollution prevention strategies generates questions to specific processes and equipment changes. This strategy refers to databases,

journals, and government agency publications. This leads onto point two, or design by case study, where process models are used to simulate the performance of existing processes, or a base case. Process modifications are then made incrementally to see the changes. The third general design approach lies in hierarchical design, where methods of structured thinking are applied to a design to test its value and identify possible weaknesses.

The detailed design pollution prevention methodologies lie in options four to six. Pinch analysis and other targeting techniques have emerged over the last decade to use all streams in a system to exchange material and energy. The field has developed to include heat and energy (Heat Exchanger Network Systems) mass (Mass Exchanger Network Systems) and recently water integration (Water Pinch Technology).

Alongside this specific design aid, is mathematical programming where the advent of computer power has led to large multi variable systems being optimized rapidly and accurately. The development of multi objective optimization (MOO) is a result of more criteria being evaluated in conjunction with traditional economic objectives.

Expert systems and artificial intelligence is the newest field being explored by environmental designers, where computer prediction of changes occurs rapidly, and global optimization can be achieved by a computer program without evaluating each scenario provided by a design team.

These methodologies presented by Cano-Ruiz and McRae (1998) are presented under the heading generation of alternatives, but these design methodologies can be applied to many sections of the design process. MOO, for example, has great merit in the analysis and evaluation sections.

Rossiter (2001) proposes placing process integration methodologies under three headings:

- Pinch Technology
- Numerical Modeling
- Knowledge Based Approaches

This process integration strategy is covered by Cano-Ruiz and McRae (1998) points 4-6.

Yang and Shi (2000) feel that environmental impact minimization has progressed to include systematic methodologies such as hierarchical design approach, pinch technology, knowledge based systems, and numerical optimization. (Yang and Shi, 2000)

The true point to take from these strategies of various authors is the level of detail needed to carry out each step. From documented solutions to expert systems, the difference in the requisite level of detail is large. The information and time available in this study precludes the use of options 4,5 and 6. This does not place higher value on options 1-3 however, and the power of the design aids not explored are duly noted.

### **2.2.3 Review of Options Generating Methodologies Considered in the Dissertation**

The use of documented pollution prevention strategies is a very powerful and easy way to address environmental problems. The problem with such documents and databases is the constant updating and upgrading in order to stay abreast of developing trends. With regard to the application to the bioenergy field, there is very little literature in this regard.

Hierarchical design has been a fundamental design tenet for the last few decades. Structured thinking is very much a part of design. Douglas (1988) recognizes this fact, and has developed pollution prevention strategies in order to incorporate environmental concerns in a design.

Douglas (1992) targets elimination of pollution problems at the source, by using different process routes rather than end-of-pipe treatment and disposal, as a more efficient design strategy. The constant revision of the hierarchical decision procedure of Douglas (1988) reveals the change in attitude to environmentally conscious process design. Douglas (1992) proposes an 8 level decision strategy, with each subsequent level involving more detail.

**Table 2- 1: Hierarchical Procedure for Process Synthesis**

Level 1	Input information: type of problem
Level 2	Input-Output structure of the flowsheet
Level 3	Recycle structure of the flowsheet
Level 4	Specification of the separation system
Level 4a	General structure: phase splits
Level 4b	Vapor recovery system
Level 4c	Liquid recovery system
Level 4d	Solid recovery system
Level 5	Energy Integration
Level 6	Evaluation of alternatives
Level 7	Flexibility and control
Level 8	Safety

The major advance to this decision procedure lay in the classification of waste minimization problems according to the type of decisions that cause them as well as the level in which the problem arises. The use of the hierarchical procedure to identify waste minimization problems and process alternatives is simple, and therefore can be used to avoid these problems. (Douglas, 1992)

Rossiter (1993), who was influenced by Douglas' work, proposed a hierarchical process review for waste minimization. Rossiter (1993) proposed a 7 level approach for reducing emissions as a modification to Douglas (1992). The methodology is a specific problem eradication (waste minimization) approach whereas Douglas proposed a more general process synthesis procedure.

The 7 levels proposed by Rossiter (1993) are:

**Table 2- 2: Rossiter (1993) Hierarchy of Decisions**

Level 1	Processing mode: batch vs continuous
Level 2	Input/Output structure of flowsheet
Level 3	Recycle structure of the flowsheet
Level 4	Separation system
Level 5	Product Drying
Level 6	Energy Systems
Level 7	Equipment and pipework specifications

Fonyo et al (1994) also saw merit in the work of Douglas (1992) and provided a systematic waste reduction procedure. This four step procedure included:

1. Defining and tracking wastes
2. Data collection
3. Producing waste minimization alternatives
4. Technological and economic evaluation of alternatives

Retrofitting of pollution prevention strategies (end-of pipe solutions), although necessary, are not the ultimate answer. Design of systems that emit less pollution are far more efficient than making a problem, then solving it. The key to addressing potential environmental problems is early identification of waste streams. This can be achieved in the early design phase where constraints on the design are far less rigid than further down the design process. This was the fundamental design tenet of many authors. (Douglas, 1992 ; Douglas, 1995 ; Fonyo et al., 1994 ; Rossiter and Klee, 1993)

Pennington (2001) feels the Douglas (1988, 1992, and 1995) heuristics require minimal design knowledge. The base case developed is not intended to be final or detailed. The decisions made in the hierarchy will identify alternative process options. (Pennington, 2001)

At this point the number of alternatives is usually large, and flowsheet development is starting to take shape. The alternatives need to be evaluated in order to decrease the number of alternatives under consideration.

#### **2.2.4 Advances in the Analysis of Alternatives**

The subsequent design phase is referred to as analysis. Information is generated in order to evaluate the merit of a design. Historically, environmental information was not generated in the analysis step since economic concerns took precedence. Energy needs were quantified but the associated emissions were not included. (Cano-Ruiz and McRae, 1998)

This is seen as a negative in the context of an environmentally conscious design and again points to the usefulness of LCA in all phases of design where all associated emissions are considered. This fact is also a motivating factor to have larger system boundaries in order to gain a true insight into the environmental performance of a system.

Life cycle assessment has been used as a decision making tool in the fields of process selection, design and optimisation. The reason this methodology has found its way into PSE, is that LCA is based on thermodynamic and system analyses, which is central to the field. (Azapagic, 1999)

The current view of LCA is one of an environmental management tool which helps to provide insight into the interaction of systems with their surroundings. The two main objectives of LCA are therefore to quantify and evaluate the environmental performance of a product or process and aid the choice between alternatives, as well as assessing the potential improvements of a system's environmental performance. (Azapagic, 1999). These broad applications have continually been developed and now have made in-roads to sections such as:

- Strategic planning / environmental strategic development
- Product / process optimisation, design and innovation
- Identification of environmental improvements and innovation
- Environmental reporting and marketing
- Environmental audit framework creation

(Azapagic, 1999)

All these new aspects of LCA have led to key governmental policy making with broader life cycle thinking, and this has led to integration into the decision making process. An aspect that is fundamental to reaching sustainability targets.

The literature pertaining to LCA and its uses has been largely product focused. LCA used in the context of process selection highlight the need for expanded system boundaries, and reveals that the environmental consequences merely shift rather than become extinct with a narrow problem frame. The novel application of LCA emphasizes recovery of pollutants rather than destroying it. (Azapagic, 1999)

The main advances in this stage of the design process are:

- Environmental impacts considered and not species concentration
- Wider system boundaries

(Cano-Ruiz and McRae, 1998)

Analysis of alternatives provides the opportunity to screen some of the proposed options. The idea of screening alternatives at this stage can be divided into two categories: Qualitative and quantitative. Qualitative screening relies on the

designer's intuition. Some design alternatives produced will certainly not be viable and can therefore be removed. Designs where the choice is not obvious will need quantitative analysis where certain criteria must be met. LCA can be a powerful screening tool in this stage with regard environmental performance (Azapagic, 1999). Basson and Petrie (2001) propose three decision support tools for this screening, namely:

- Environmental Risk Assessment
- Life Cycle Assessment (LCA)
- Social Impact Assessment

Process simulators have developed to aid the process designer to model various flowsheets. Simultaneous optimization of flowsheets is normally inherent in the software package. Analysis of alternatives can be carried out by modeling a process and making various alterations to achieve numerous options which can be evaluated relative to each other. Cano-Ruiz and McRae (1998) feel the development of process simulators still have some way to go in order to handle trace elements in complex systems.

### **2.2.5 Advances in the Evaluation of Alternatives**

Having generated the information in the analysis phase, the next step is evaluation and optimization. The key question governing this aspect of the design is, how to balance environmental objectives with other objectives and is directly related to problem framing.

Human nature dictates that people place value on different issues and so trading off or ranking of alternatives is not site but person specific. These differences of opinions have led to little development in overall ranking methods and classification indicators (Yang and Shi, 2000). This fact does not preclude environmental concerns from the evaluation of alternatives. Cano-Ruiz and McRae highlight some of these growing trends:

- Environmental concerns as constraints on economic optimization  
This key development places higher value on environmental concerns and lessen the role of economic optimization which has a vital role in redressing the imbalances of design criteria. Design objectives have been skewed in favor of economics, but this is set to change. Multi-objective

optimization (MOO) can therefore be employed to trade of numerous, competing objectives in order to obtain the best solution.

- **Environmental constraints to economic objective functions**  
Mathematical programming and the development of computer power has lead to incorporating environmental constraints in the objective function.
- **Environmental concerns as objectives**  
The corollary to environmental constraints is the environmental objective which will be traded off against economic and other objectives. This is a major step in developing inherently cleaner processes. The use of MOO is the key advance, where competing objectives can be dealt with simultaneously.
- **Minimization of emissions of pollutants of concern**  
Early identification of potential hazards eliminates the need to apply end of pipe solutions once an environmental burden has been created. With the advent of multi-objective optimization and highly enhanced sensitivity analysis, pollutant concentrations can be measured and provide a constraint in the optimization problem, thereby limiting a certain species to a set concentration and trade off against various other design elements within the optimization problem.
- **Minimization of mass of waste generated**  
The shift away from measuring pollutant concentrations is a key step to assessing the true damage potential of a substance in the environment and is the link to environmental impact evaluation.
- **Minimization of contribution to specific environmental problems**  
The recognizing of local and global environmental problems has led designers to steer away from documented potential hazards. The increased complexity of process simulators to monitor trace elements in streams has led to the evaluation of alternatives far easier. Product and feedstock loss, as well as potential environmental hazards can be easily identified and alternatives evaluated against each other.

- **Minimization of overall indicators of environmental impact**  
Overall environmental indicators, while being useful, are not absolute and large input from the user is needed. This coupled with the subjectivity of these overall indicators has helped motivate designers to create more meaningful specific indicators that are of more value to a given situation.
- **Trading off environmental objectives with other design objectives**  
This point is the consequence of all the other points mentioned previously and is fundamental to a shift in designer attitude and environmentally conscious process design.

The development of process optimization away from being largely economically focused has led to LCA being used in this phase of a design. With environmental constraints employed up front in the design, environmental performance is a key optimization parameter. Numerous authors echo this idea. (Basson and Petrie, 2001; Cano-Ruiz and McRae, 1998)

The final stage of the iterative design process lies in sensitivity analysis, where the verification of the variables that affect the system significantly, is evaluated. The logical progression through the design influences the results of the analysis. The outcome of the analysis either leads to a finished design or returns to areas of weakness and so that improvements can be made.

## **2.3 The Emergence of Green Chemistry (GC<sup>h</sup>)**

Green chemistry is touted to provide novel heuristics regarding environmentally conscious product and process design. In this section, these heuristics are briefly reviewed, and the principles of green chemistry studied as they pertain to the design of process systems.

### **2.3.1 Green Chemistry Definition**

Green chemistry is a design mindset to aid the environmentally friendly manufacture of chemicals. Anastas (1997) defines green chemistry as:

*“... the use of chemistry techniques and methodologies that reduce or eliminate the use or generation of feedstocks, products, by-products, solvents, reagents, etc., that are hazardous to human health or the environment.”*

Green chemistry and designing for the environment are seen as the core to achieving sustainable development. Industrial ecology broadens the tenets of GC<sup>n</sup> with the aid of LCA and pollution prevention. (Anastas and Breen, 1997)

Green chemistry has been applied in situations from concept design through to end of pipe solutions.(Anastas and Breen, 1997) In contrast however, Pereira (1999) proposes that the immediate change should be for compliance but future changes will be health and safety related and including environmental concerns. (Pereira, 1999)

It is of interest to note that technical institutions are reportedly starting to offer design courses teaching the principles of green chemistry to undergraduate students. (Brennecke and Stadtherr, 2002)

### **2.3.2 Review of Green Chemistry Literature**

Proponents of green chemistry generally offer a set of principles to guide practice. Hjeresen (2002) and Anastas (2003) both propose 12 fundamentals of green chemistry.

<b>Hjersen et al (2002)</b>	<b>Anastas and Zimmerman (2003)</b>
<b>1 It is better to prevent waste than treat or clean up waste after it is formed</b>	1. Designers need to strive to ensure that all material and energy inputs and outputs are as inherently non-hazardous as possible.
2 Synthetic methodologies should be designed to maximize the incorporation of all materials used in the process into the final product.	<b>2. It is better to prevent waste than to treat or clean up waste after it is formed.</b>
3 Wherever practicable, synthetic methodologies should be designed to use and generate substances that possess little or no toxicity to human health and the environment.	<b>3. Separation and purification operations should be designed to minimize energy consumption and materials use.</b>
4 Chemical products should be designed to achieve efficacy of function while reducing toxicity.	4. Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency.
5 The use of auxiliary substances (e.g. solvents, separation agents etc.) should be made unnecessary wherever possible and, innocuous when used.	5. Products, processes, and systems should be 'output pulled' rather than 'input pushed' through the use of energy and materials.
<b>6 Energy requirements should be recognized for their environmental and economic impacts and should be minimized. Synthetic methods should be conducted at ambient temperature and pressure.</b>	6. Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition.
7 A raw material or feedstock should be renewable rather than depleting wherever technically and economically practicable.	<b>7. Targeted durability, not immortality, should be a design goal.</b>
8 Unnecessary derivatization (e.g. blocking group, protection/deprotection, temporary modification of physical/chemical properties) should be avoided.	8. Design for the unnecessary capacity or capability (e.g. 'one size fits all') solutions should be considered a design flaw.
9 Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.	9. Material diversity in multicomponent products should be minimized to promote disassembly and value retention.
<b>10 Chemical products should be designed so that at the end of their function they do not persist in the environment and break down into innocuous degradation products.</b>	10. Design of products, processes, and systems must include integration and interconnectivity with available energy and materials flows.
11 Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.	11. Products, processes and systems should be designed for performance in a commercial 'afterlife'.
12 Substances and the form of a substance used in a chemical process should be chosen so as to minimize the potential for chemical accidents, including releases, explosions, and fires.	<b>12. Material and energy inputs should be renewable rather than depleting.</b>

Figure 2- 6: The Differences in the 12 Principles of Green Chemistry

Figure 2-6 illustrates the 12 principles of Green Chemistry as seen by these two authors. (Hjeresen et al., 2002) ; (Anastas and Zimmerman, 2003) The one identical principle that is common to both is Hjersen et al (2002) point 1 and Anastas and Zimmerman (2003) point 2. There are three other principles common to both and are highlighted in Figure 2-4.

The fact that the fundamental tenets underlying green chemistry are not same inhibits the development of this design methodology from becoming more widespread. The rift comes about to due a split in focus of the definition. Some authors tend to treat pure chemistry and catalysis as the focal point (Pereira, 1999), while others expand green chemistry into industrial practice, linking it with environmental and economic constraints (Hjeresen et al., 2002) or even sustainable development and industrial ecology. (Anastas and Breen, 1997) Yang and Shi (2000) see green chemistry as fundamental to reaction path synthesis, which has for a long time been a core consideration in process design.

Further work in this field by Anastas (2003), reveals a life cycle thinking approach associated with the development of green chemistry. The problems with green chemistry are highlighted by the general and broad principles laid out by Anastas. These principles are intended to guide a design process, but unlike the process design heuristics of Douglas (1992) and Rossiter (1993) they lack definitive rules to help the designer in specific situations. (Anastas and Zimmerman, 2003)

From the above, it is concluded that the definition of green chemistry is not sufficiently clear. The concept seems to differ according to the context in which it is written. The broad definition is usually given with guideline principles, which are not common to all published works. In terms of process design, it appears that the more recently proposed design heuristics reviewed above, especially in the area of reaction path synthesis, should adequately cover the ambitions of “green chemistry”.

## **2.4 Conclusions**

In this chapter, process systems engineering has been defined, and the literature pertaining to recent advances of process systems design has been reviewed, especially with respect to environmental demands. The conclusions that can be drawn are:

### Attitude changes in design methodology gave rise to a decade of advances in PSE

Cano-Ruiz and McRae's review of design literature serves as testament to the task of designers to not only recognize the environmental implications of a design but eliminate the problem in advance. (Cano-Ruiz and McRae, 1998)

A call for a change in attitude is made and the development of PSE over time shows the field is in a state of flux in response to this call. Forward thinking and beyond compliance are very real and attainable goals. (Brennecke and Stadtherr, 2002 ; Basson and Petrie, 2001) Education of prospective design engineers is vital in this regard and is now duly recognized by academic institutions.

### Response to environmental pressures brought about expanded system boundaries

The most important developments in PSE over the last 10 years stem from problem framing where not only is the reaction/separation system considered but rather all major sections of a flowsheet, and indeed the role of design choices for a flowsheet within its industrial life cycle.

### Assessing environmental burden using impact indicators

The shift away from using concentration and mass of wastes was a major development. The use of mass of wastes is sensitive to various issues such as location and climatic conditions. Aggregating all mitigating factors of a particular pollutant in a specific area and producing a potential impact score gives a more precise reflection of environmental performance of a system.

### Life Cycle Assessment can be used as a screening tool in the early design phase

LCA has been shown to be a valuable screening tool in the concept or early design phase. A frequent use is to rank alternatives with regard to environmental performance.

### LCIA best suited for use in comparative assessment

Life Cycle Impact Assessment (LCIA) cannot be used at all levels of the design process due to data aggregation and assignment of estimated risks. LCIA should be used for comparative assessment at strategic levels and early design stages where data sensitivity is not a key issue.

Multi-objective optimisation can play a role in trading off environmental as well as economic objectives

Computer power has enabled a designer to use large multi-variable systems to trade off many objectives simultaneously. The emergence of complex mathematical programming and multi-objective optimisation, where the design objectives have increased in complexity, can be evaluated in conjunction with many differing and competing objectives rapidly and accurately. Economic objectives, while still a major driver, are being traded off against other objectives, specifically environmental objectives.

Green Chemistry is not sufficiently developed as a design methodology

Green chemistry as a design tool falls somewhat short, as the fundamental principles underlying the definition have not been widely accepted by all in the field. The design principles described by various authors, and the principles that lie behind this new environmental thrust, are too broad to apply directly to process systems design. Future revision in the field will lead to more definite process heuristics to aid the design of green processes and systems.

## **Chapter 3: Conversion of biomass to energy: Opportunities and technology**

The previous chapter has shown that there have been significant advances in the field of process systems design over the last decade, particularly with respect to environmentally conscious design. Chapter 2 has thus elaborated on the term “selected recent advances in the process engineering sector” used in the formulation of the hypothesis guiding this dissertation.

It is the central objective of this thesis to investigate to what extent these recent advances in PSE can be harnessed to improve industrial processes which convert biomass to modern energy carriers. To gain a better understanding of this opportunity, the following chapter will review the current energetic use of biomass, both globally and locally, before focusing specifically on residue in the sugarcane processing industry, which was selected to provide case studies for this dissertation. The advances revealed in Chapter 2 are then discussed for application to process design to better utilize the chosen biomass resource.

### **3.1 Biomass and Bioenergy**

The global demand for energy is steadily increasing while the rate of discovery of oil and gas reserves is decreasing. This has brought renewable energy to the forefront of much research and development work.

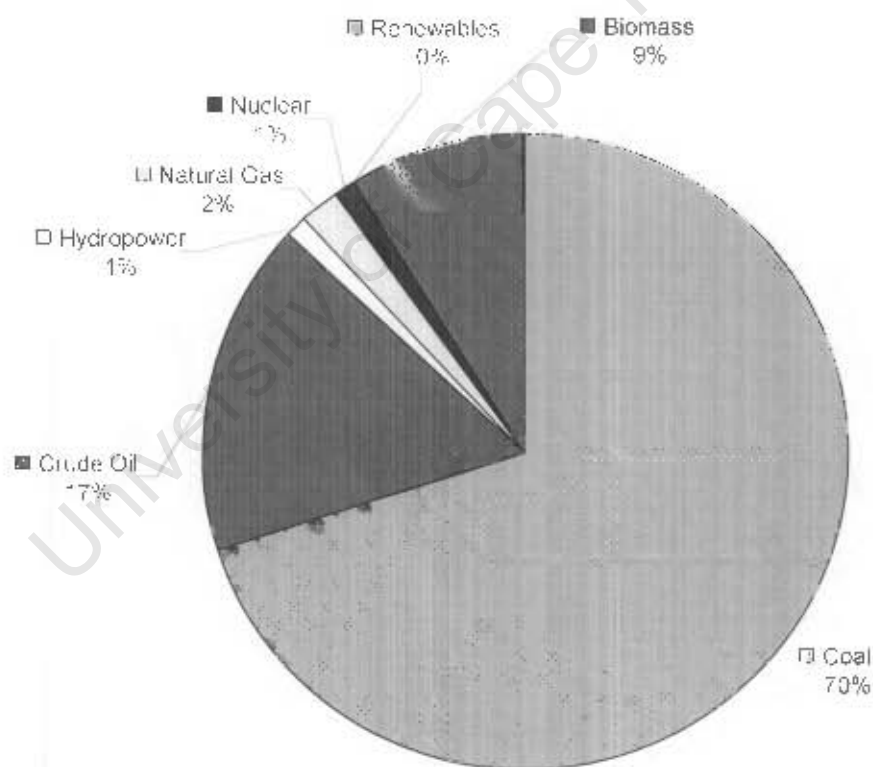
As stated in Chapter 1, the answer to large scale renewable energy production has for some time been thought to lie in harnessing solar and wind power. These still remain attractive options but recent developments have shown the field of biomass conversion has large scope in completely replacing fossil fuels. Technically, all products derived from coal, oil and gas can be produced from biomass (renewable) feedstocks. (Sims, 2001) This agrees with Marrison and Larson’s (1996) prediction that renewable energy sources (particularly biomass) can play a critical role in replacing fossil fuels.

The current technologies place the biomass industry in an unfavorable position. The high production costs and the relatively low fossil fuel prices render these proposed new fuels too expensive. Their viability lies in subsidies and technology improvements. The improvements are ongoing and biomass to high quality energy

carriers (electricity and liquid fuels) is starting to bridge the economic divide between renewables and non-renewables. (Marrison and Larson, 1996)

The attractiveness of renewable energy lies in the replacement of non-renewable carbon sources. Developing countries, which do not rely as heavily on fossil energies, have the opportunity to produce renewable energy and trade the saved carbon emissions as credits to the developed world.

The current contribution of bioenergy to the world energy demand has been estimated to be 10-13%. (UN Development Programme, 0000, Sims, 2001) This is a large portion of the total but the reality is that this number is inflated due to inefficient use of wood for heating and cooking requirements in developing countries. South Africa's energy breakdown shows a similar reliance on biomass, as can be seen in Figure 3-1.



(Department of Minerals and Energy (SA), 2001)

**Figure 3- 1: Fuel Contribution to South Africa's Primary Energy Demand**

The biomass (firewood) percentage is high at 9%. The contribution of other renewables is very low. The large majority of energy is derived from coal since the

reserves in South are large. This notwithstanding, the Department of Minerals and Energy (DME-SA) has resolved to increase the contribution of renewable energy to 10000 GWh of final energy in South Africa by 2012. The main contributors, as seen by the DME are biomass, wind, solar and small-scale hydroelectric energy. (Department of Minerals and Energy (DME), 2002) The final energy demand in South Africa can be seen in Figure 3-2.

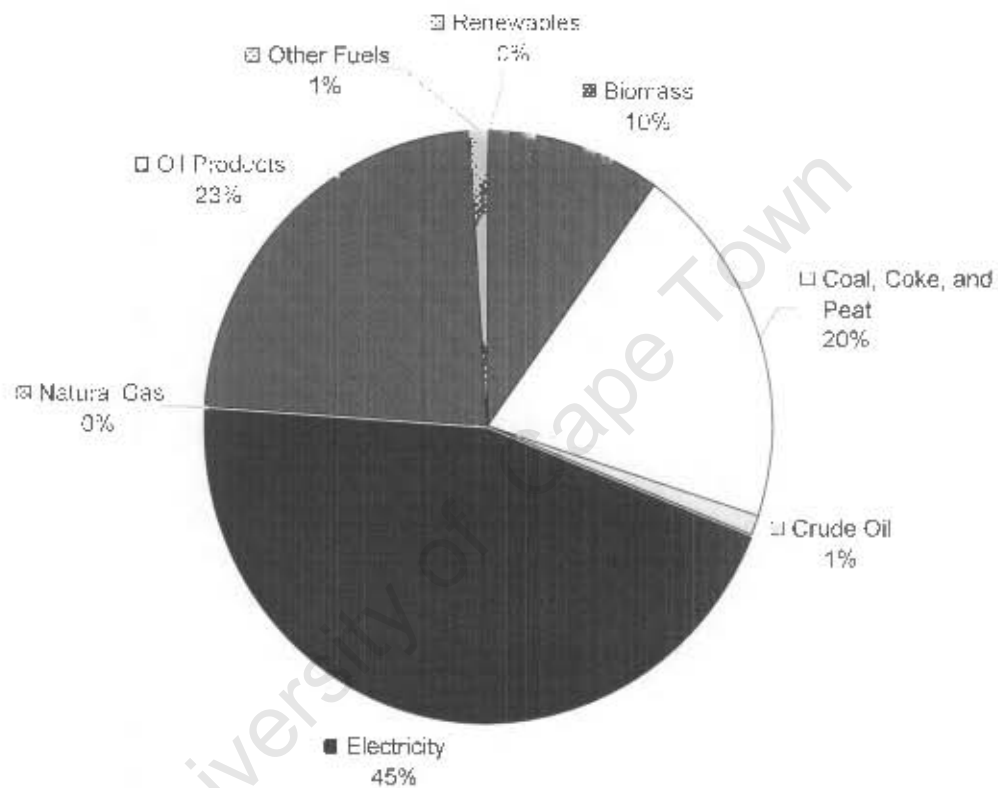


Figure 3- 2: Final Energy Demand in South Africa 2001

Eskom's electricity generation (coal contribution of 89%) was 300000 GWh or 1.1EJ for 2001. (Eskom, 2001) The entire energy demand in South Africa in 2001 is, therefore, 670000GWh or 2.7EJ. To put these very large numbers into perspective, the world's global fossil fuel use was 302EJ in 1994. (Marrison and Larson, 1996)

The renewable target set by the DME, 1.5% of final energy demand derived from renewable resources by 2012, is quite modest. While the target should be attained

rather easily, the change from non-renewable resources is fundamental to reaching the ultimate goal of sustainable development, and so any targets, however modest, are seen as an improvement.

The proportion of primary energy supplied by biomass is set to increase despite the continual progression of photo voltaic and wind technologies. (Sims, 2001) The carbon credits gained from the use of renewable energy will play an important role in the development of the bioenergy sector.

The development of the biomass derived bioenergy sector depends on the source of the feedstock. The destruction of the natural vegetation throughout the world has lead to constraints being placed on the source of the biomass. The answer to the problem lies in using excess biomass, such as agricultural residues, where the non-usable (for the agricultural sector) portion of the biomass is sold or given away for further processing. Another option is energy cropping.

### **3.1.1 Energy Cropping**

This term refers to producing a crop for the purpose of producing an energy product. A study conducted by Marrison and Larson (1996) showed that Africa has great potential to produce a significant amount of renewable energy from energy cropping. The study investigates the effect of harnessing 10% of the land that is not used as cropland, forest areas, or wilderness. The projection was for the year 2025 where Africa would be able to produce 18EJ biomass energy per year. South Africa showed the greatest potential with 1.3EJ per year. (Marrison and Larson, 1996)

An example of energy cropping can be seen in the Brazilian alcohol program.(Moreira and Goldemberg, 1999). When the world experienced the oil crisis in the early 70's necessity, rather than willingness produced a search for alternate fuels, and today they still have a highly developed and well regulated bioethanol transport industry. The Brazilian sugar industry produced 273Mt of cane in 1996, 59% of which was used for ethanol production and the rest for sugar. (de Carvalho Macedo, 1998) This was a result of a global need to find alternate fuels. The increased population and growing world hunger are further crises that have developed over the few decades and has rendered the need to search for alternate forms of energy without compromising the effort to alleviate

the afore mentioned social issues and strengthens the claim to use agricultural residues as a source of biomass.

The problems associated with energy cropping are both of an environmental and social nature. The growing pressure for land and food are unresolved issues and using the land purely for energy purposes will need serious consideration of possible impacts.

The current conversion of biomass to bioenergy lies mainly in the use of agricultural residues, as energy cropping has not overcome the social implications. This study will therefore concentrate on the use of agricultural residues as the main source of biomass feedstocks.

### **3.1.2 Sugar Processing Residues for Bioenergy**

The agriculture industry is well established worldwide. A large amount of crop residue is produced, from corn husks to fibrous bagasse, most of which is used as fertilizer for the fields or cattle feed (ref). This practice whilst beneficial to the agro-industry may not represent the best use of biomass.

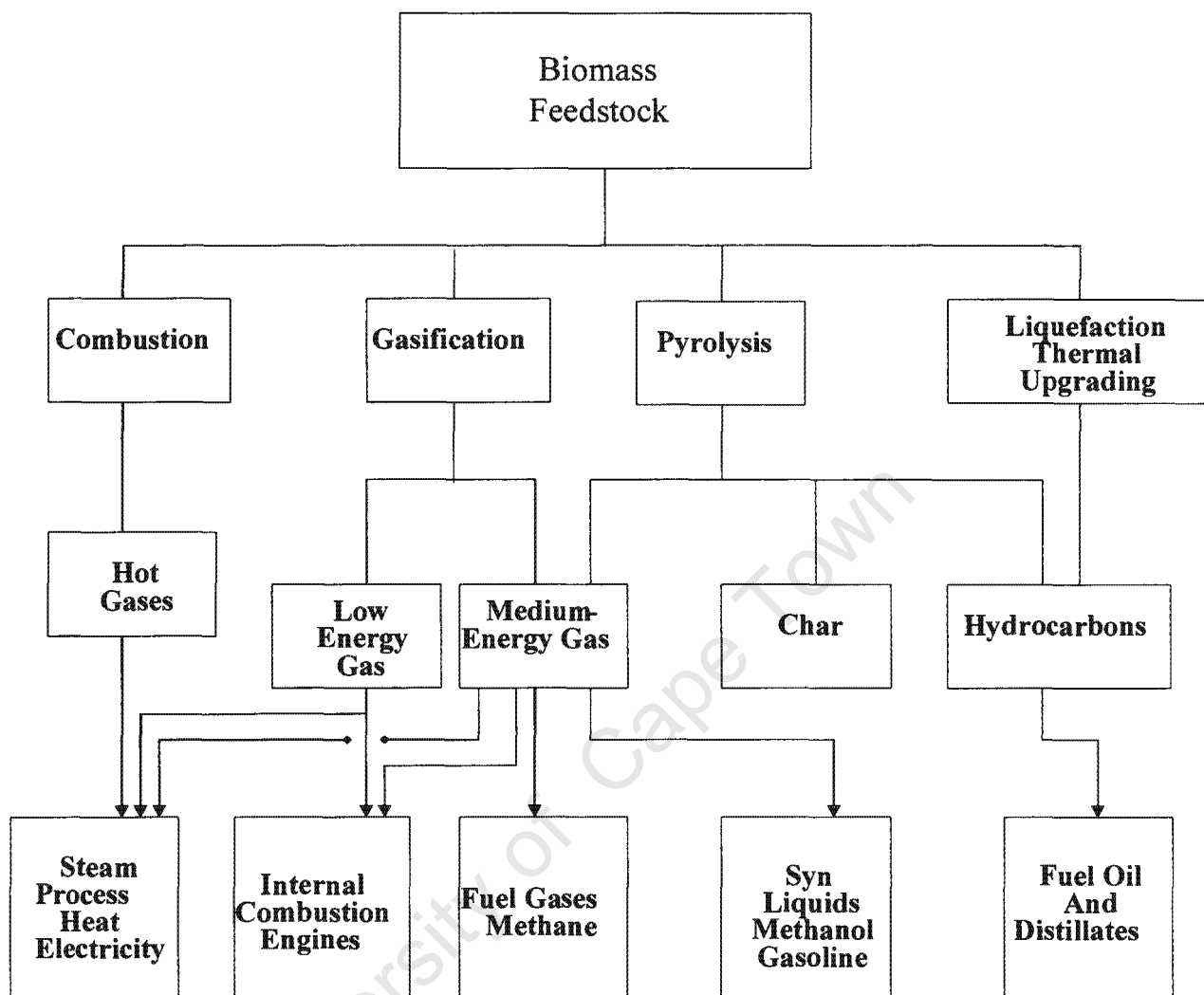
The potential to use of this feedstock for the energy market is on the rise. This is not to say that energy products have not and are not being used for this very purpose, the Mauritian sugar industry is a large contributor to the country's electricity production. (Beeharry, 1996) The growing of sugarcane and production of electricity from the agricultural residues has become a symbiotic relationship.

### **3.2 Biomass to Energy Conversion Technologies**

The field of biomass conversion and the technologies available are developing rapidly. The conversion and yields obtained from such processes are ever increasing and many of the technologies have graduated from laboratory research to full scale industrial production.

Bioenergy systems rely on the conversion of biomass to a specific energy carrier. Growing environmental concerns associated with the rapid and burdensome use of fossil fuels lends itself to reevaluating the energy demands we place on processes within industry.

Figure 3-2 illustrates the various ways of converting biomass to energy within this broad heading of bioenergy.



(McKendry, 2002)

Figure 3- 3: Biomass Conversion Technologies

McKendry (2002) proposes many options for the thermochemical conversion of biomass to energy products but does not explore the biological process routes. The number of thermochemical options validates the claim of Sims (2001) that technically all products derived from fossil fuels can be produced from a biomass feedstock.

The current conversion of biomass (bagasse) in the sugar industry is combustion. The associated efficiency with this technique ranges from 20-40%. Gasification, or partial oxidation of the biomass at high temperatures, is used to obtain higher efficiencies (40-50%). (McKendry, 2002) This relatively new process is still in the demonstration stage, but could have far-reaching consequences for the future.

The field of bioprocessing, while newer than thermochemical conversion techniques, is expanding rapidly. The fact that McKendry (2002) does not acknowledge the biochemical routes is seen as a weakness in the review in the production of energy from biomass. Szczodrak and Fiedurek (1996) propose a more comprehensive review of biomass conversion routes. The focus is placed on biological conversion but physicochemical conversions are noted as well and can be seen in figure 3-3.

McKendry (2002) states that high moisture content biomass sources are better suited to biological processes. Bagasse would fall into this category having a moisture content of 50% on average. (Mohee and Beeharry, 1999)

The commercial application of biological processes is becoming more widespread. Corporations such as Iogen and Arkenol are the first to employ the biological route to convert cellulosic material to liquid fuels. (Reith et al., 2001)

Lynd (1996) proposes that the emerging field of biotechnology be projected to mature technology in order to compare against the already mature fossil energy sector in order to gain a fair comparison.

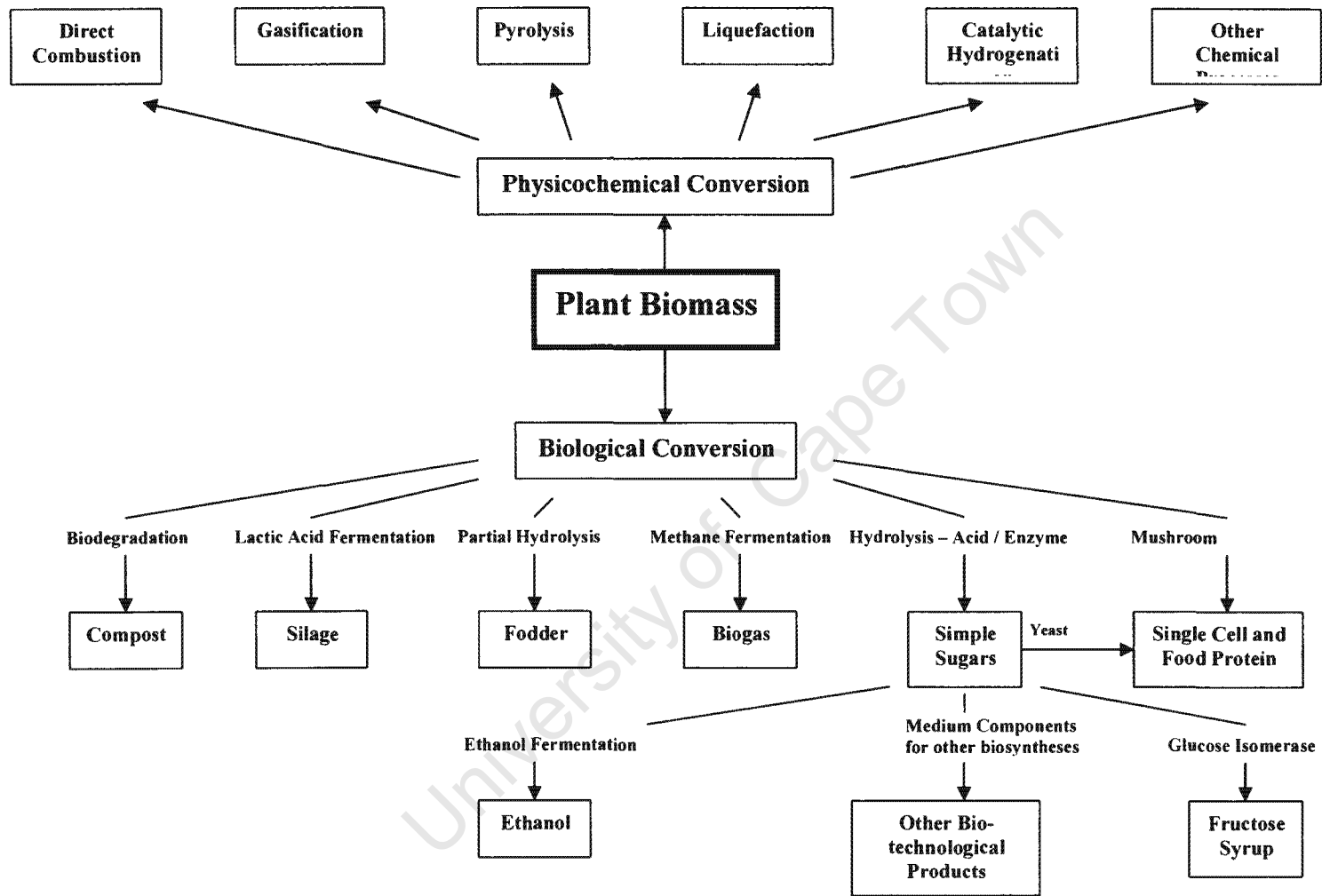


Figure 3- 4: Biomass Utilization Pathways

(Szczodrak and Fiedurek, 1996)

Maximizing resources within processes is now more than an added bonus, it has become an aggressive edge in an ever increasing competitive market. The notion of one process plant producing one output is now replaced by recovering wastes to extract usable and often saleable products that were previously dumped, causing large scale environmental problems.

The fact that environmental laws are getting ever more stringent as well as fluctuating markets reveals quite clearly the need for a process to be flexible. When the price of a commodity falls, the process should be able to shift and produce another, sometimes value added, product to help smooth the impact of the changes. This links to the incorporation of multi-objective optimization in the tools of a process designer.

### **3.3 Potential for Bioenergy in the South African Sugar Industry**

#### **3.3.1 The South African Sugar Industry**

Sugar production in South Africa is second only to maize production. The sugar industry produces 21 Mt of cane per annum (South Africa Sugar Association, 2001) at 15 mills throughout South Africa producing 2 Mt of sugar and 0.8 Mt of molasses.

These primary products produced by the sugar industry are sold as such, and some of the molasses is currently used in a distillery where it is fermented to produce potable alcohol.

#### **3.3.2 Current Production Statistics**

The sugar industry generates a significant amount of bagasse, the fibrous residue weight, 6.4Mt. This figure is quoted to include the moisture content which is, on average, 50%. The lower heating value, LHV, of the fuel is 8MJ / kg.

Table 3-1 compares the calorific value of some common fuels.

**Table 3- 1: Calorific Value of Fuels**

<b>Fuel</b>	<b>Calorific Value (MJ/kg)</b>
Coal	27
Methane	55
Bagasse (wet)	8

(Department of Trade and Industry - UK, 2001 ; Engineering Tool Box, 2003 ; Beeharry, 1998)

The available heat, derived from the potential bagasse available and the calorific value, is 51PJ. Conversion to electricity, assuming an efficiency of 40% (Technical Consultant, 2002), is 20.4 PJ. This would constitute 1.7% of South Africa's electricity production. (See Appendix 1)

The current use of the bagasse is as a boiler fuel to raise steam and electricity to satisfy mill utility requirements. The surplus bagasse remains very little to none after satisfying the mill requirements. This is due to the inefficient boilers and the need to 'get rid' of all the bagasse. The opportunity to exploit the bagasse has become apparent.

### **3.3.3 Current Practice in the Sugar Industry**

Energy integration has long been the industry norm, due to the availability of a 'free' boiler fuel and hence process heat requirements have always been provided for on site. This is therefore seen as plant optimization and efficient resource utilization.

The misperception of true optimization is leading to resource waste. Having identified bagasse as a possible source of value added chemicals leaves the door open a review of current processing of sugar. This in conjunction with (if not eliminating of bagasse for heating) further processing of bagasse has lead to this opportunity of applying recent advances in process synthesis.

This view of having long been an efficient operation is a generally accepted notion. The company consulted does not have a dedicated research and

development team. They rather rely on the SASI (South African Sugar Institute). This, however, is still somewhat lacking due to the fact that there is no initiative from the institute side but rather inspired by ideas from the industry. Another source of research is based at the University of Natal, but not linked to the company. This again is driven by ideas derived from the various mills and sent to the labs for testing and the like.

A suggestion was to form a dedicated research and development team, which was met with some surprise by the company. They felt (again) that what they were doing was better than industry standard and therefore enough.

A senior mechanical engineer that has been in the sugar industry for many years was surprised at the versatility of the feedstock (sugarcane). Highlighting to him the different products that could be obtained from sugarcane, and more specifically bagasse, proved enlightening as well as emphasizing the fact that the current sugar industry is not in a state of flux and does not wish to be either. (Technical Consultant, 2002)

Illustrating the need for a dedicated R&D (research and development) team the attitude towards business as usual was seriously questioned.

Out of this conversation coupled with a visit to a semi-independent mill that specializes in different products from bagasse the term value added products was introduced. This too sparked conversation and thought. The natural progression from here was to revealing the worth of these 'new' products could have. This again can only be gained with resource optimization something, which in the past has not been a key concern as bagasse in excess was used to raise more steam which would be let down in order to obtain a steam 'balance' that neatly provided for all the steam and heating requirements on the plant.

The fact that competitive companies need to diversify operations has been seen as an area of concern for the local sugar industry. The fact that single input multiple output systems are seen to be the step towards resource optimization is recognized but not fully understood. Embracing new technologies is also underrated. The fact that some industry standard practices in foreign markets are not employed locally is a cause for concern.

Senior technicians in the sugar industry seem to be unaware of the changing tide and are preoccupied with the *status quo*. Incorporating all people involved in the

sugar industry can only bring about the shift to a more dynamic process operation.

According to a project engineer at a local sugar company there is a designated structure to project engineering. Whilst the generation of new ideas is seen as a route for improvement a detailed front end package (FEP) is produced for each new project. This is a detailed document containing all the relevant details of a proposed project. This document is only submitted when final approval for the project is required. This is usually done at top level.

The ideas are generated at mill level. If a mill is meeting the target sugar production and has an idea to either increase production or propose a modification then a base document of the proposal is submitted, should this meet head office approval, the FEP is produced and put to the board. Mill level generation of ideas is not seen to be an optimum source of development. The primary task is to produce sugar, anything else is secondary. (Technical Consultant, 2002)

The ideas presented for the diversity in the sugar industry are presented in figure 3-3.

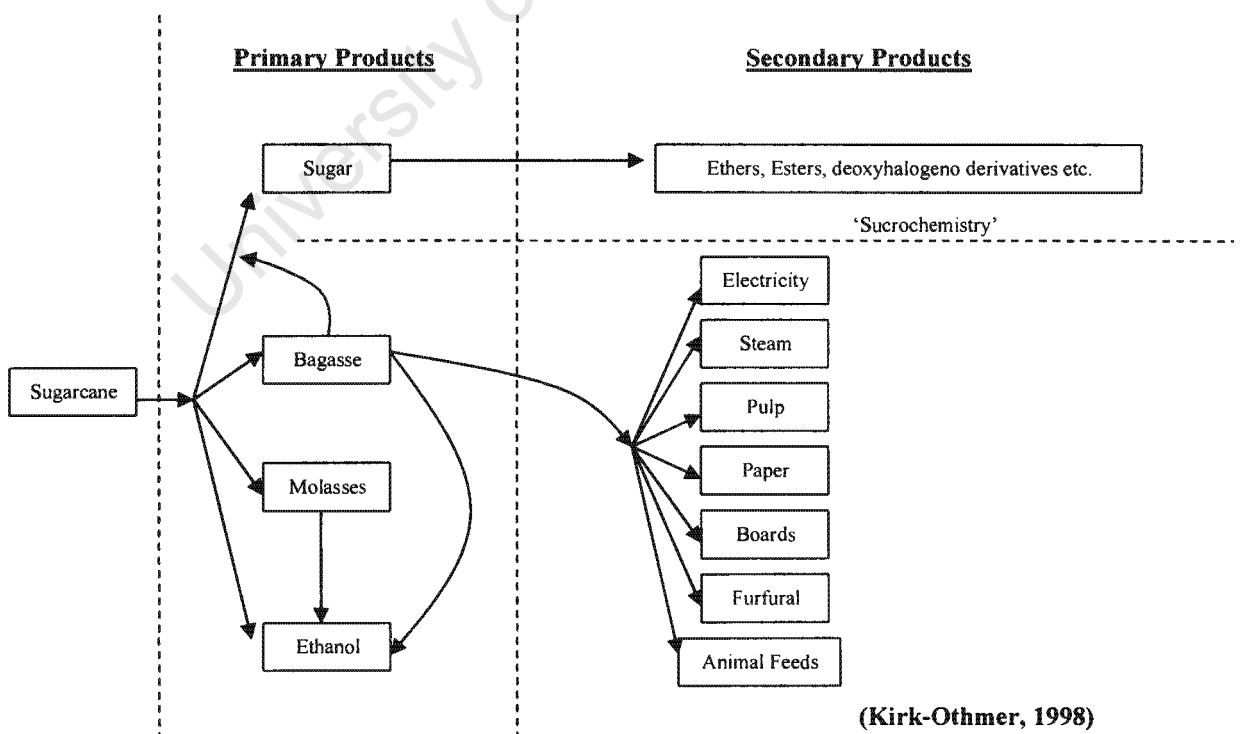


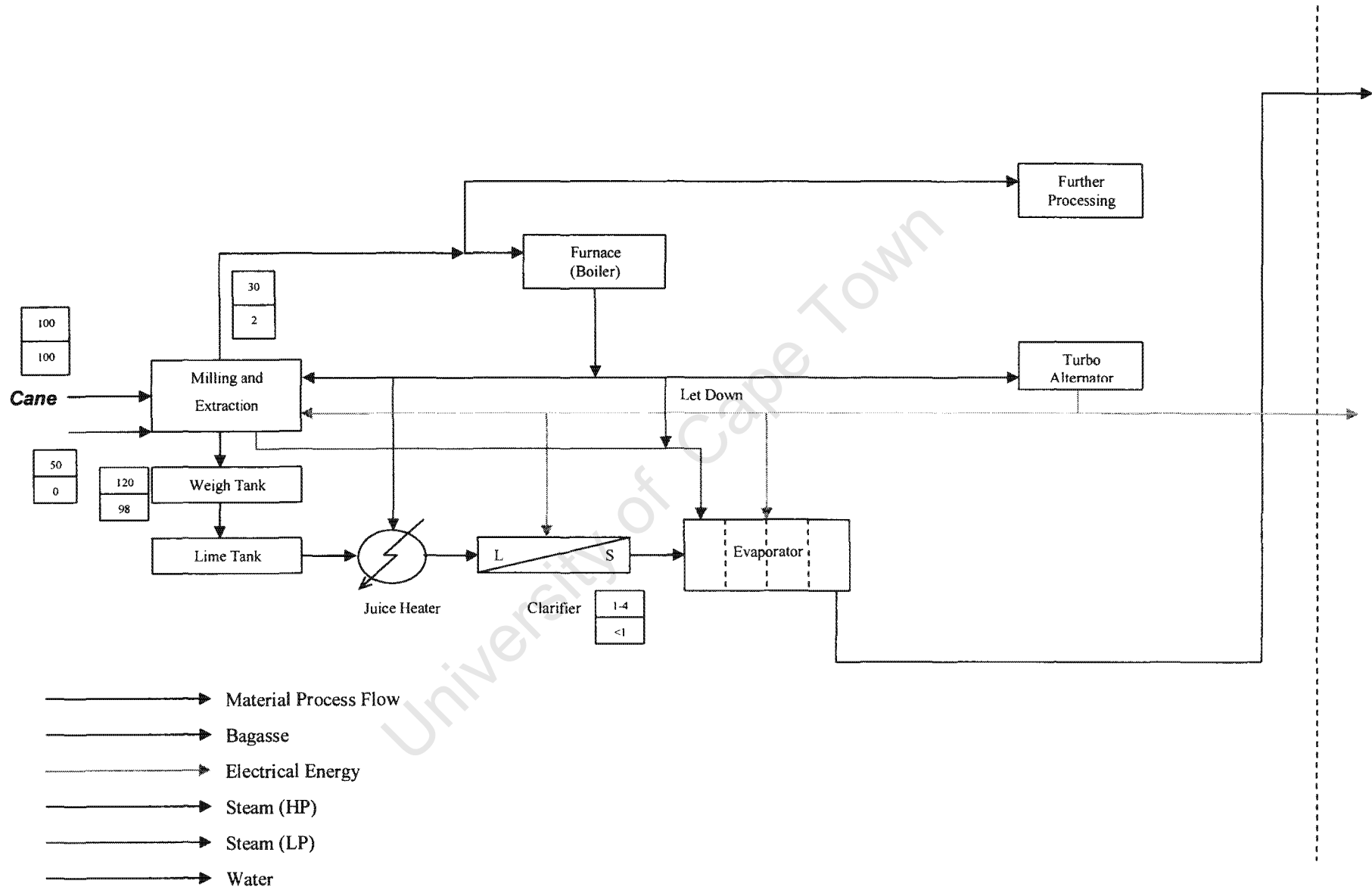
Figure 3- 5: Downstream Process Options

These options illustrated in this diagram are not exclusive. There are more products that could possibly be derived from sugarcane but the options shown are seen to be the most popular.

The distinction between the sucrochemistry products and the rest comes from the fact that sugar is easily transportable and so these specific products would be made off site at individual laboratories. The rest of the primary and secondary product options available are seen to be best suited to on site processing.

Processing the options is generally seen to be possible only after the sugar has been extracted from the cane. All downstream processes are only applicable with the aid of sugar production. The various associated policy issues surrounding the seemingly 'untouchable' sugar process are discussed above.

The mill visit served to inform, in more detail, how the production of sugar is carried out. A standard Fletcher-Smith mill is used for the production of raw sugar and molasses. The mill layout can be seen in Figure 3-6. The numbered streams indicate a basis of 100t of cane processed as well as the associated sugar balance.



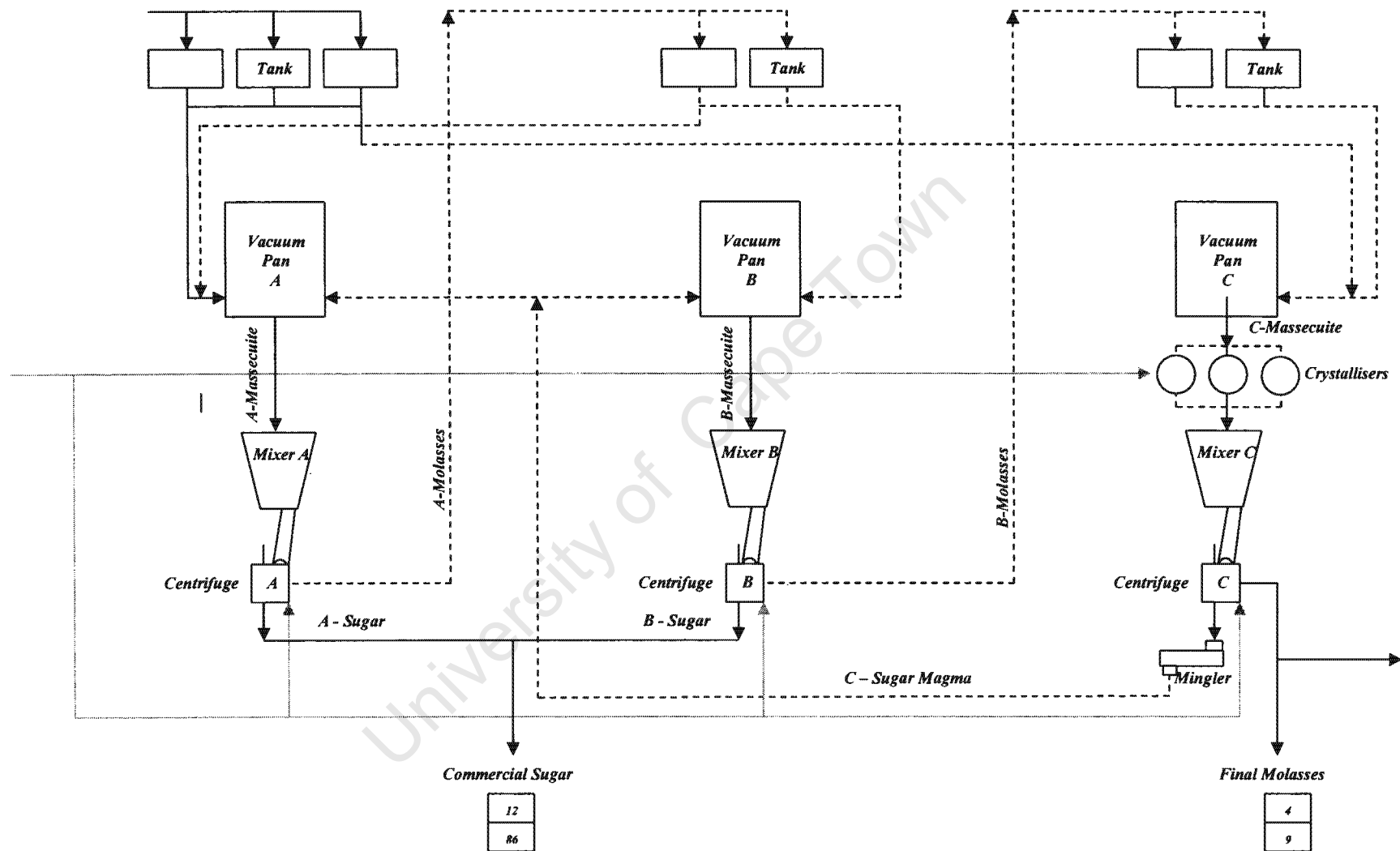


Figure 3- 6: Fletcher Smith Mill as Employed by a Local Sugar Company

Bagasse from the sugar production is seen to be the best feedstock for further processes. The current practice of using it as boiler fuel is seen as a primary requirement for heat integration, but this study aims to prove, high value low commodity as well as high volume low value products can be readily attained from the bagasse. The associated environmental consequences of this fact are to be investigated.

### **3.4 Energetic utilization of bagasse**

Whilst the use of bagasse for the purpose of producing electricity is well-established, the production of ethanol is as yet untested with no plants in operation. That notwithstanding, at least one published study has engaged with the environmental dimension of this opportunity.

The study presented by Kadam (2002) considers utilizing the excess bagasse in the Indian sugar industry. The bagasse would be converted to ethanol for use in the transport sector as an octane enhancer. The study shows the excess bagasse, after meeting milling requirements, is in the region of 15-25%. Kadam (2002) does state this figure could be higher with technological improvements, which echoes the sentiments of Beeharry (1996) where the excess bagasse could be as high as 53%. A French company operating in Zimbabwe predicts 65% of the bagasse could be used for electricity export, based on performance data. (Mbohwa and Fukuda, 2003)

The current excess bagasse in India is allowed to decompose and used as fertilizer on the fields. Mohee and Beeharry (1999) showed the sugarcane yield can increase as a result of placing this excess, as well as unused tops and trash, on the field as fertilizer. (Mohee and Beeharry, 1999)

The two systems which Kadam (2002) compared are the base case where the cane is burnt (for utility requirements) expanded to include the current use of fossil fuel derived gasoline, and the alternative of converting bagasse to ethanol, via two methods, to use as a 10% blend in gasoline. This study places high value on the transport sector and the avoided emissions from the motor vehicles.

Both methods of bagasse conversion would produce significant environmental improvements to the current situation. There would be a net decrease in carbon

monoxide, hydrocarbons, sulfur dioxide, nitrous oxides, particulate matter, carbon dioxide and methane emissions. There would also be a significant reduction in fossil energy consumption. (Kadam, 2002)

The potential benefits for using the bagasse to produce ethanol were clear, and the method of ethanol production was significant. (Kadam, 2002) Lynd (1996) states that for a bio-refinery (conversion of biomass to a liquid fuel) to be competitive, technical maturity needs to be reached. Ethanol from biomass at maturity would be comparable to a fossil fuel refinery of today. This substantiates Kadam's findings, where process options play a significant role in the overall performance. Mature technology indicates a standard production method with only a few differences present. There are presently numerous routes for the conversion of cellulosic materials to ethanol with varying degrees of efficiency.

Lynd (1996) proposes an analytical methodology for conversion to ethanol, namely:

- Pre-treatment (including milling and handling)
- Biological conversion
  - Cellulase production
  - Cellulose hydrolysis
  - Hexose and xylose fermentation
- Distillation
- Power Cycle

The main process: Pre-treatment, Biological Conversion, and Fermentation; presented by Lynd (1996) is covered by numerous authors in sufficient detail. (Graf and Koehler, 2000 ; Sun and Cheng, 2002) The adopting of a conversion process of cellulose to ethanol is the next step in the development of the field. The current work is restricted to process models and research and development work. The options available, particularly in the pre-treatment phase, are broad and no industry standard has become apparent. The economic factor, producing a liquid fuel of comparable price to fossil fuel derived source, has not been overcome and hence re-enforces Lynd's (1996) call to evaluate the technologies on a projected basis. (Reith et al., 2001)

### **3.5 Application of PSE to Bioenergy Systems**

Having identified the opportunity to exploit agricultural residues to add value to an existing process, the task is to determine the best use of the resource. The ideas presented in chapter 1 were the production of a biofuel, namely bioethanol for the use in the automotive industry as an octane enhancer. This system is to be compared against the DME of South Africa's proposal of 'green' electricity constituting the renewable energy target.

The task at hand is to assess what value can process systems engineering literature guide the design of this process.

Heuristics employed blindly due to previous knowledge of a common process was common place but, these rules of thumb, while many that are based on sound engineering principles and are therefore still valid, are not the only tools available to a project engineer any more. New processes that have evolved, such as those in the bio-technology field, have no dedicated heuristics due to the field's sudden rapid growth. The aim therefore, is to evaluate whether the old heuristics are still applicable to new systems and whether any heuristics have changed to include environmental considerations.

#### **3.5.1 Applicable Methodologies for this Study**

As identified in Chapter 2, Cano-Ruiz and McRae (1998) put forward 6 methodologies to generate and screen various process options. These methodologies highlighted were:

1. The use of documented pollution prevention solutions as a source of design alternatives.
2. Design by case study
3. Hierarchical design approach – methods of structured thinking
4. Pinch Analysis and other targeting techniques
5. Mathematical programming
6. Expert systems and artificial intelligence

This study makes use of options 1-3 in order to generate flowsheet alternatives. Options 4-6 while very powerful tools are more detailed design aids, and the

requisite data needed to establish true alternatives was deemed too great. The application of the tools focuses on the early flowsheeting of alternatives where the data may not even exist at concept level. Tools 1-3 are considered ideal for new, emerging technologies. The case studies set out to validate this claim that environmentally conscious conceptual design is applicable to bioenergy systems. These systems, while becoming more and more popular, still remain data limited.

### **3.6 Conclusions**

The review of literature in this chapter has shown the current state of biomass and bioenergy, both locally and abroad. The conversion technologies were presented and the possible products derived from biomass sources discussed. The current situation in the sugar industry was presented and finally the role that process systems engineering can play in its development was investigated. The conclusions that can be drawn are:

The contribution of renewable energy to total energy provision is small

The renewables contribution to the final energy demand remains low. The largest use of biomass is for inefficient cooking and heating purposes in the developing world.

Biomass derived energy products display environmental benefits

The fact that carbon is sequestered from the atmosphere during the production of biomass potentially renders the carbon balance zero when the fuel is burnt. Bioenergy systems are therefore 'cleaner' than fossil based systems.

Local recognition of the inherent benefits of biomass

The South African Department of Minerals and Energy (DME-SA) has set medium term renewable energy targets. These targets are modest but show a forward thinking approach to reaching sustainable development targets.

Technology advances in the biotech field have increased dramatically

The range of biomass-derived products is on a par with those derived from fossil fuel based feedstocks due to the rapidly expanding research and development in the biotechnology field.

Energy cropping has not overcome social pressures

Producing crops to produce an energy product places burdens on the land that could be used for other purposes, such as housing and food production.

The agricultural sector in South Africa can provide biomass feedstocks

The agricultural sector in South Africa is well regulated and well managed. This coupled with large volumes of crops places the use of agricultural residues as the best source of bioenergy feedstocks.

The current South African sugar industry has potential to deliver value added products

The sugar industry in South Africa has been using the agricultural residue to provide heat and power for the production of sugar. The potential to generate excess electricity, or further processing to a liquid fuel, is great.

Bagasse Conversion to Further Products is Suited to Biological Processes

The high moisture content of bagasse is more suited to biological conversion rather than the more traditional combustion, or the emerging gasification process routes.

There is no PSE literature pertaining to the development of bioenergy systems

Currently there is no literature on PSE and methods of structured thinking specifically geared towards the development of bioenergy system flowsheets. The applicability of old PSE literature needs to be investigated.

In closing, and to give more guidance to the following two chapters, in which case studies will be presented to demonstrate how recent PSE developments can be utilized in bioenergy process design, the hypothesis stated in chapter 1 will now be revisited. This hypothesis stated that:

- *Selected recent advances in the process systems engineering sector applied to the design of bioenergy systems can aid the agricultural processing industry in maximising the value added by utilisation of crop residues, by enabling designers to create more efficient processes.*

Based on the literature pertaining to bioenergy systems as well as process systems engineering literature the hypothesis is now refocused to two particular process

systems design tools in the context of better bagasse utilization in the South African sugar industry:

- Application of Life Cycle Assessment at a Concept Design stage will show that producing a liquid fuel from biomass residue, namely ethanol via hydrolysis of bagasse to sugars followed by fermentation, represents an energetically and environmentally superior utilisation of this crop residue than conversion via heat and steam to electricity.

Further,

- The application of recently developed process design heuristics for environmentally conscious design to an ethanol from bagasse flowsheet will identify opportunities for more efficient processing, thus generating more value to the sugar industry.

These two hypotheses will now be examined by means of the case studies presented in chapters 4 and 5.

# **Chapter 4: The Use of Life Cycle Analysis in Conceptual Design of Bioenergy Systems**

## **4.1 Introduction**

Having set the objective to investigate the potential of Life Cycle Assessment (LCA) as an evaluation tool in the early or conceptual design stage of a bioenergy project, it was decided to design and execute a demonstrative case study, which would yield insights into the value, strengths and weaknesses of LCA in such a situation. The case study was positioned within the thematic field of a better utilization of current arisings of waste biomass in agricultural production in South Africa.

The objectives of the case study and its topic are described in section 4.2, the case itself is presented in section 4.3, and an evaluation of the case study follows in section 4.4.

## **4.2 Case Study Objectives and Definition**

### **4.2.1 Case Study Objectives**

The broad objectives of developing and presenting this case study at this point are to yield insights into the value, strengths and weaknesses of LCA when applied to process design in the field of bioenergy, as well as to add to the existing bioenergy literature in South Africa by illustrating alternative energetic routes of utilising agricultural residues, specifically bagasse in the sugar cane processing industry.

Specific objectives for this case study were to:

- Test the value of LCA at conceptual level design with respect to its potential as a screening tool to various process options
- Verify the ability of conceptual LCA to provide early assessment of potential environmental impacts of a product or process.

- Assess whether the results generated by the LCA are reliable enough to make an informed decision regarding the future of a project.
- Evaluate the sensitivity of LCA to data quality
- Gain insight into the value of taking a life cycle perspective in the bioenergy sector, specifically in terms of the carbon balance.

These objectives will be revisited in the evaluation of the case study in section 4.4.

#### **4.2.2 Case Study Topic: Which Bagasse Derived Bioenergy Product?**

As identified in chapter 1, the increased utilisation of renewable resources is regarded as an essential component of sustainable development, both for reasons of resource availability in the long term, and of the more pressing environmental unsustainability of the unidirectional transformation of large volumes of materials. In terms of energy, South Africa has the potential to generate a significant amount of its needs from renewable resources, with biomass identified as the largest potential contributor. (Sims, 2001; Department of Minerals and Energy (DME), 2002)

The South African sugar industry produces approximately 21 Mt of cane per annum, second amongst agricultural products only to maize production. The 15 sugar mills throughout South Africa produce about 2 Mt of sugar as the primary product from this resource. A secondary product, molasses, is processed off-site to ethanol by some operators in the industry, destined for beverage and industrial markets. Fuel ethanol production was ceased in the 1970's.

Under-utilized bagasse is generally regarded as the best feedstock for further value-addition. On site processing of the bagasse can yield a large number of products (both high and low value). With some modifications to existing mills to improve energy efficiency, the amount of bagasse available for downstream processing could be greatly enhanced.

The options chosen for comparison in this case study represent uses of bagasse that are deemed to be most applicable for bioenergy provision under current South African conditions. The case study will compare currently employed operations (base case), the most likely envisaged alternative ('green' electricity from excess bagasse after implementation of energy efficiency measures), and an alternative

energetic utilisation (fuel ethanol through the processing of the cellulosic components of excess bagasse).

The 'green' electricity option, while only an extension of current use of bagasse, assumes a change in the status of bagasse from that of a waste to that of a resource. In the past, bagasse was regarded a large volume waste and was used to serve the energy requirements of the mills. This is no longer the case, and bagasse is now increasingly discussed as a resource from which value can be added. With modifications to the steam economy on the mills, this resource could provide surplus 'green' electricity to export to the national grid. The consequent replacement of coal-based electricity (most likely through avoiding or delaying new investments into coal-based generation) is the main driver behind national policy on this matter (Department of Minerals and Energy (DME), 2002), potentially resulting in a range of related environmental spin-offs (including reduced carbon emissions) .

The alternative use of bagasse considered in this study, production of bio-ethanol, relies on the same starting premise where bagasse is further utilised to add value. Fuel ethanol produced from bagasse could replace lead additives as the octane enhancer in gasoline. The transportation sector is still responsible for the emission of large amounts of airborne lead, which is widely regarded to have serious environmental and health consequences. The addition of an ethanol blend to gasoline, it is postulated, would serve to alleviate this problem. A secondary outcome of the use of an ethanol blend would be savings of non-renewable resources (crude oil, coal and natural gas) due to a fraction (of the order of 10%) of the gasoline being replaced by the bio-ethanol.

These two potential bioenergy provision systems will now be evaluated from the perspective of improved product and process efficiency against the base case of current sugar production, with respect to environmental performance.

## **4.3 Life Cycle Assessment to Evaluate the Concept Design Alternatives**

### **4.3.1 Goal and Scope Definition**

#### **4.3.1.1 Goal**

The goal of the study is to analyze the environmental performance of two bagasse-derived bioenergy products with each other, and with current practice, with a view to ranking them at the conceptual stage of a new business development process.

The target audience for this study consists of a) the key decision makers in the sugar processing industry, in order to reveal the implications of generating various products other than current practices; b) researchers in LCA uses at different design stages; c) policy makers at the national level concerned with increased biomass usage in South Africa. (Department of Minerals and Energy (DME), 2002)

#### **4.3.1.2 Scope**

##### **a) Level of Detail**

In order to evaluate the selected options at the concept design stage, an input/output mass and energy analysis needs to be available. In the next phase of the design each would be expanded to the level of a process flow diagram (PFD) incorporating all major pieces of equipment.

##### **b) System Boundaries**

As stated above, the study aims to compare three different processing routes for the utilisation of a biomass resource.

The benchmark for the better utilisation of biomass is represented by the base case system. This is the current production of sugarcane in South Africa, where bagasse is used internally for process heat requirements. The bagasse is fired in a boiler to raise high pressure steam. All the bagasse is consumed in this step. The

sugar mill's primary product is raw sugar, with molasses as a secondary product. The molasses is further processed to ethanol at an off site distillery.

The proposed option, for more efficient use of the biomass usage, is reducing the amount bagasse needed for sugar processing and using the excess steam generated to produce electricity. This option, touted commonly as 'green' electricity, is deemed the best way to meet current renewable energy targets in South Africa. (Department of Minerals and Energy (DME), 2002) The green electricity produced will replace the respective amount of coal based electricity. The reduced environmental consequences are the benefit of this process option.

The validity of claim that green electricity is the "best" biomass derived energy product is to be investigated. Technology is being developed which would allow the production of a liquid fuel from this biomass. The comparison of these two process options can therefore prove or disprove this claim.

The alternative process option is to produce bioethanol, or ethanol derived from biomass, which would be added to gasoline as an octane enhancer. The ethanol additive would be used as a substitute for lead in gasoline. The system therefore aims to show the avoided impacts of producing the equivalent amount of gasoline as well as the impact of removing harmful airborne lead.

#### c) Functional Unit

The functional unit for the systems under consideration is the products that could be derived from 1 hectare of land under current sugarcane farming. This farmed land in use in South Africa, produces on average 64.5 tons of wet sugarcane which provides the feedstock to all systems and is therefore the reference flow. Each system is measured in terms of the sugar output (which is kept constant), the amount of 'green' electricity produced in kilowatt hours, and the distance traveled on an ethanol fuel blend.

The associated farming, transport and processing of the agricultural products, therefore forms its life cycle. Included are flows to and from the environment from raw material extraction to delivered product. The systems analysis is a cradle to gate and is consistent with the tactical design phase. (Basson and Petrie, 2001)

#### d) Data Categories included

The inputs to the systems have been modeled as elemental flows where possible. The systems boundaries do not include the return of the materials to elementary

flows. The expanded systems chosen render the end of life of the products equivalent, and are therefore excluded from the life cycle analysis.

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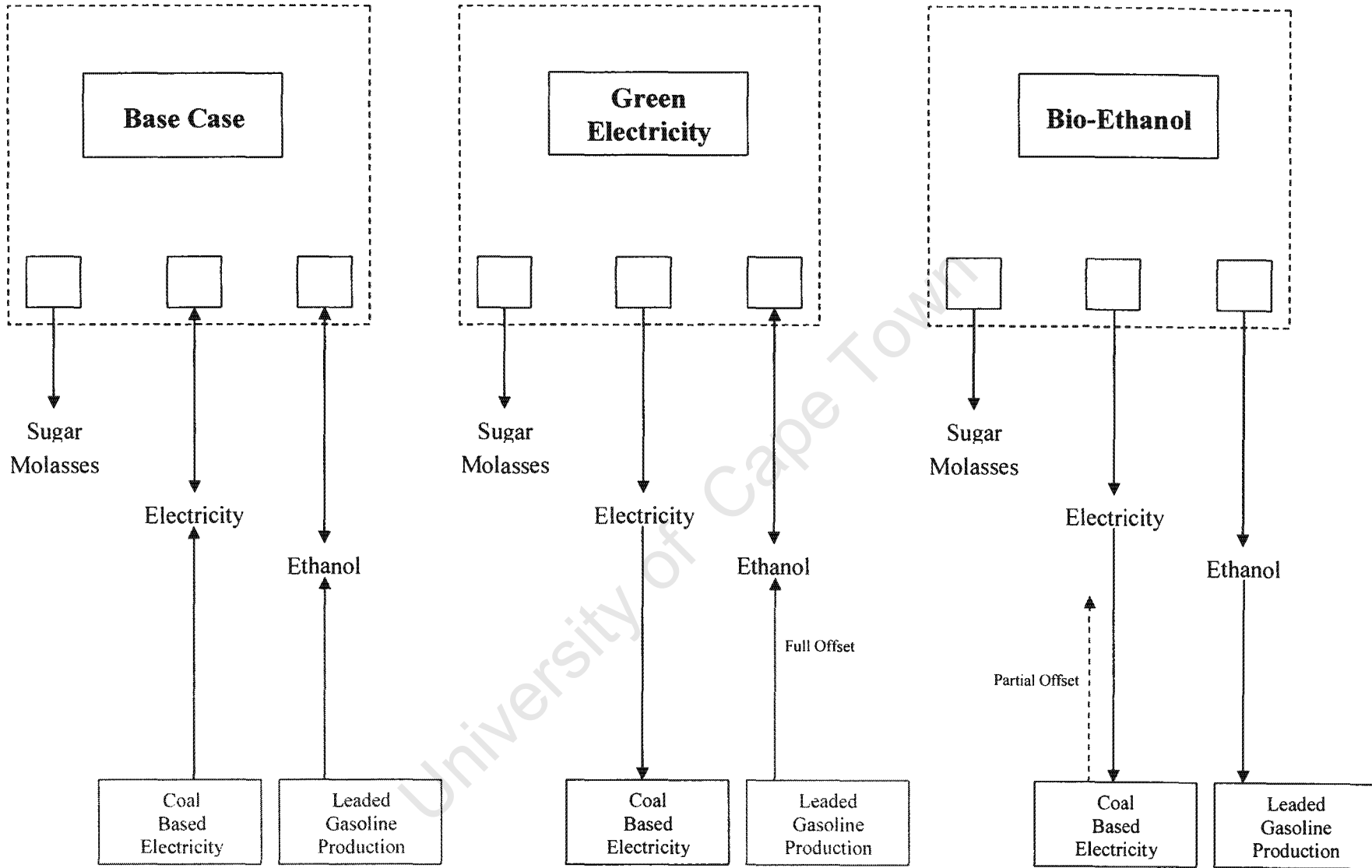


Figure 4 - 1: System Equivalence Diagram

Figure 4-1 addresses the issue of system equivalence. The Green electricity system produces electricity that would offset the equivalent amount of coal based electricity. This is therefore the benchmark for the other two systems. The bioenergy system produces some green electricity (less than that of the green electricity option) and therefore only receives a partial offset and base case receives no offset. The bioenergy system produces ethanol and this would replace the equivalent amount of crude oil derived gasoline. Neither of the other two systems replace gasoline and hence receive no offset. The offsets represent the potential environmental benefits from switching to a renewable resource. The system setup would thus render some flows in the inventory negative.

In order to produce a comparative LCA, the systems need to be comparable on all levels. The expanded systems chosen render the end of life equal, and the upstream processes therefore need to be equal as well. The processes preceding the sugar mill are identical and therefore no allocation of burdens to certain flows or modules is necessary, hence the systems considered use no allocation factors.

The functional unit chosen represents current and future practice. The land under sugarcane cultivation is not in a state of flux and well documented statistics of production are widely available, thereby providing the functional unit of study. Downstream modifications will need to show a direct benefit in order to be viable. All environmental burdens would need to be considered, against the base case, of equal foundation. This can only be achieved if all burdens are accountable to the entire system and not only certain flows or modules, hence the exclusion of allocation factors.

The emissions from the three systems have been inclusive where possible. The process blocks that have not been expressly modeled, are limited to air emission spectra only. While this is a crude estimate of environmental performance, further detailed engineering on the systems will yield the requisite data for more detailed emission inventories.

The emissions associated with each system contribute to the environmental impact. These impacts need to be quantified and compared against each other in order to determine the 'best' alternative, if indeed there is a best. The base case will provide the zero line, and each system needs to perform better than the base case in order to be a viable substitute.

Burning of fuels has the most implications with respect to environmental concerns. The systems under consideration are dominated by boiler emissions.

The main concerns are carbon dioxide, sulphur dioxide, and nitrogen oxides. Relevant impact categories are chosen to best characterize the full impact of each system. For this reason the following impact categories are investigated: global warming potential, air acidification, terrestrial eco-toxicity, and eutrophication.

Resource use, particularly non renewable resource use, can be curbed with the use of renewable resources. The effect of the bioenergy systems on resource use will thus also be shown.

The overall performance can be measured by taking into account all impact categories studied, and applying weightings to each individual category. This phase of the study aims to show environmental trends only, and so an aggregated indicator (eco-indicator 95) is used to verify the trends attained.

The individual categories chosen were selected to show trends in the overall performance of the systems. The trends displayed by the various methods are seen as more important for the level of detail modeled. Further iterations and more detailed modeling would consequently require a more systematic selection of impact categories.

Where different methods were available to measure certain environmental burdens, a comparative method was employed to verify results and trends. This accounts for the inclusion of double methods.

#### e) Completeness

There were no obvious life cycle stage omissions. The systems boundaries were restricted to incorporate raw material extraction and processing to produce a defined product. The product use is not included in the study as the goal is to compare the use of a natural resource, rather than evaluate the performance of using certain biomass derived products.

#### f) Peer review

The life cycle assessment presented in this case study has been checked by the research supervisor. A paper on this case study has been presented at a national conference (Botha and von Blottnitz, 2003). It is anticipated that the external examiner will comment on the life cycle methodology employed in this case study, and that specific comments in this regard will be included with the published dissertation in Appendix 5.

g) System descriptions

The systems under consideration in this comparative LCA study are the base case, current sugar production in South Africa, 'green' electricity production from excess bagasse, and thirdly bioethanol produced via dilute acid hydrolysis of the surplus bagasse. Life cycle diagrams of the three systems follow.

The unit processes involved can be seen in Figure 3, 4 and 5. The current sugar production system is illustrated in Figure 3.

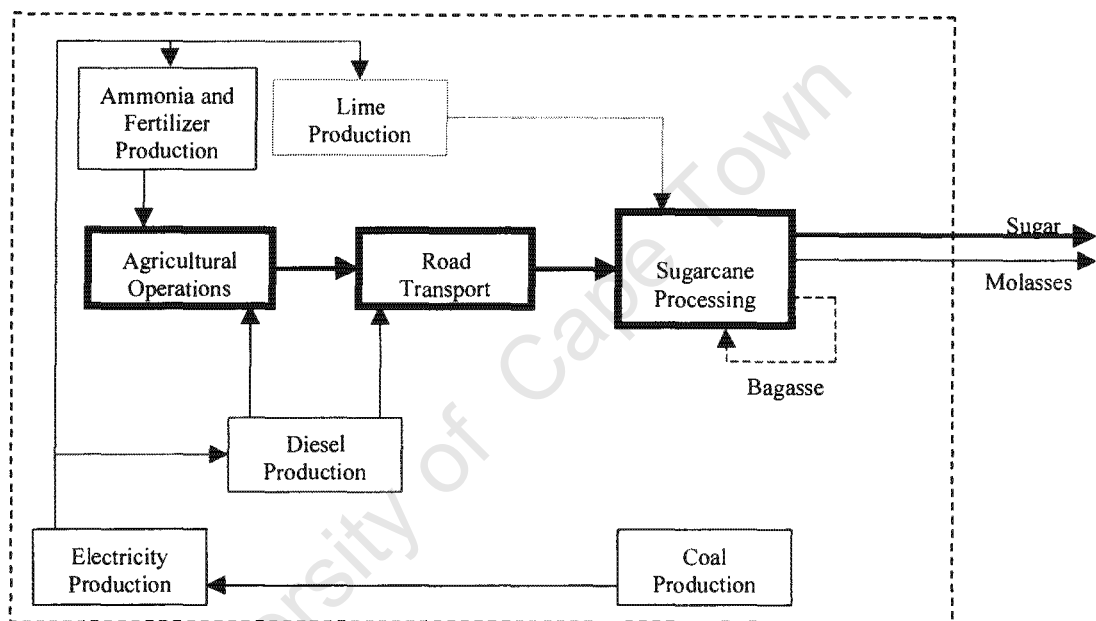


Figure 4 - 2: Life Cycle Diagram illustrating Base Case (Current Sugar Production)

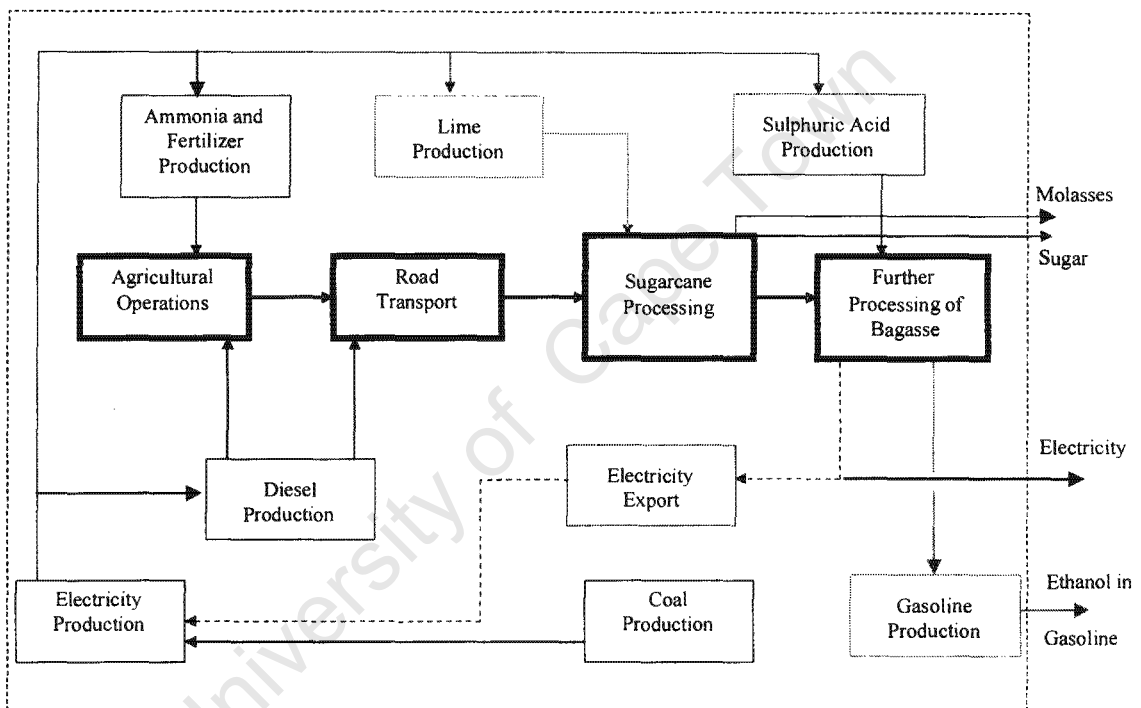
The base case system produces raw sugar as a primary product, with molasses as a secondary product that is sold for further processing. Bagasse is consumed internally for process heat requirements. The sugarcane processing block, amongst others, is common to all three systems. The mill is based on a conventional Fletcher Smith mill (Idea, 2003), using steam to drive the cane knives and shredders. The steam is raised using bagasse as a feedstock only, no coal is supplemented other than for start up purposes.

The fertilizer being used is assumed to be calcium ammonium nitrate (CAN), for the purposes of this first assessment in the conceptual design phase. The amount of fertilizer required is based on similar production statistics that were available. (Brentrup et al., 2001)



The practice of firing the boiler with bagasse remains standard; the efficiency at which the bagasse is used is now optimized to free the resource for further processing which shifts the main objective of the mill. The bagasse derived using a rigorous steam economy is not currently employed on the mill.

Utility requirements on site are decreased in order to produce as much excess electricity as possible in order to export to the national grid. This form of electricity is commonly referred to as 'green' electricity as no non renewable resources are used in its production.



**Figure 4 - 4: Life Cycle Diagram illustrating Bioethanol Process Option**

The main process blocks for the bioethanol system are the sugarcane processing and the integrated bio refinery. The function of the sugar cane processing block, within the defined system is, again, to produce excess bagasse for further processing in the IBR. This system again shifts the focus of the mill to attaining a rigorous steam economy.

The integrated bio refinery is supplied with bagasse from the sugar processing plant. This process is not currently employed in South Africa, and so data was not readily available even at a conceptual level. The predicted values are taken from various literature sources. (Kadam, 2002 ; Lynd et al., 1996) The process model is

based on the Kadam model, utilizing dilute acid hydrolysis to separate the hemi cellulose component of bagasse, and to ferment this portion to ethanol.

This process yields ligneous residue (LR) as a by-product which can be used in a bagasse type boiler to supply the energy requirements. The LR produced is enough to satisfy steam and heat requirements as well as some excess, which can therefore be used for electricity export.

#### h) Data Quality

The goal of the study is to show the applicability of LCA at a conceptual level of design. The value, therefore, placed on data and data categories are not as strict as if a more detailed assessment was to be carried out. This illustrates the varied uses of LCA during this critical design phase, highlighting areas of concern within a chosen system. Where data were sourced from literature not specific to South African industrial conditions, they were adapted for local conditions where possible.

The individual data categories were evaluated with the aid of a pedigree matrix. (Weidema and Wesnaes, 1996)

**Table 4 - 1: Data Quality Indicators**

Base Case Process	Score				
	Reliability	Completeness	Temporal	Geographical	Technological
Agricultural Operations	5	4	1	1	3
Fertilizer (Ammonia) Production	1	2	2	5	3
Transport	1	2	2	5	3
Diesel Production	1	2	2	5	3
Lime Production	1	2	2	5	3
Sugar Processing	3	4	1	1	1
Sulphuric Acid Production	1	2	2	5	3
Electricity Production	1	2	3	1	1

<b>Bio-ethanol</b>	<b>Score</b>				
Process	Reliability	Completeness	Temporal	Geographical	Technological
Agricultural Operations	5	4	1	1	3
Fertilizer (Ammonia) Production	1	2	2	5	3
Transport	1	2	2	5	2
Diesel Production	1	2	2	5	3
Lime Production	1	2	2	5	3
Sugar Processing	3	4	1	1	1
Sulphuric Acid Production	1	2	2	5	3
Integrated Bio Refinery	3	4	1	3	2
Gasoline Production	1	2	2	5	3
Electricity Production	1	2	3	1	1
<b>Green Electricity</b>	<b>Score</b>				
Process	Reliability	Completeness	Temporal	Geographical	Technological
Agricultural Operations	5	4	1	1	3
Fertilizer (Ammonia) Production	1	2	2	5	3
Transport	1	2	2	5	2
Diesel Prod.	1	2	2	5	3
Lime Production	1	2	2	5	3
Sugar Processing	3	4	1	1	1
Sulphuric Acid Prod.	1	2	2	5	3
Electricity Production	1	2	3	1	1

The lower the category scores the better the data. This matrix highlights the areas of concern. This matrix should not be taken as absolute, reliability and completeness scores are most important. Temporal, geographical, and technological scores should be treated relative to the processes involved. Table 4-1 thus reveals possible areas of concern.

The score of 5 for all geographical categories results from no information given in the TEAM modules used in calculation. The software is designed by a French company (Ecobilan<sup>®</sup>), and the assumption there are geographical concerns for the various modules used to represent process blocks, seems fair. The matrix calls for a poor score where no knowledge of the data is known. This fact, coupled with the inventory yielding high values of natural gas used in some processes indicates European standards. South Africa, on the other hand, makes very little use of natural gas. This is seen as a limitation on the inventory. Further iterations will need to adjust the energy use in the form of natural gas to local coal based utilities. The associated emissions will alter the performance of the systems affected.

Due to the current level of detail in this phase of the LCA study renders the quantification of fugitive emissions impossible. Further iterations will serve to rectify this omission.

Data quality, as with all life cycle assessment studies, is of major importance in order to present accurate and meaningful results. This study is no different, hence the best possible data was acquired, and where no data was present literature pertaining to the subject was consulted. Various unit processes had data pertaining to it from live sources. All data of poor quality has been highlighted for further iterations as discussed in the pedigree matrix.

The technology related data was confined to current and near future technologies only. The reason for this requirement was due to the comparative study being carried out; all systems therefore compete within a small time frame and on an equal basis.

Literature sources provided a portion of the necessary data, hence some conversions to localize the data were required in order to account for geographical concerns. The range of literature sources was mutually inclusive to represent as broad a spectrum as possible to ensure completeness and representitiveness. The sources consulted were journals of various fields, books, articles, proceedings and government papers.

The large majority of modules have been restricted to South African conditions. Modules that do not fall into this category are deemed to be uncertainties and reserved for review in subsequent iterations. The full listing of all flows in the inventory can be seen in Appendix 3A-C.

### **4.3.2 Inventory Analysis**

The data used were collected from numerous sources. Sugarcane processing data were obtained from a local milling company (Reid, 2002). Studies of the same nature were consulted for input to the various processes where no local data could be found. While this is not entirely accurate, it provides a good first estimate as well as providing scope for further modeling of the systems. All systems modeled from literature sources were checked for numerous consistencies as well as adjusting, where possible, for local conditions.

The assessment was completed using common process knowledge combined with various literature sources. Block flow analysis was applied to all major unit processes. This included first order mass and energy balances. Where no data or literature sources were available assumptions were made in order to complete the investigation. These assumptions have been documented (see Appendix) and will be discussed. All assumptions have been verified and refined. Ratification of the assumptions consisted of various consistency checks (mass and energy balance, carbon balance) as well as sensitivity analyses in order to verify the effect of all major assumptions.

Utilities required that are not expressly revealed in the life cycle inventory (see Appendix 1) have been included as reminders within the relevant modules. These reminders were calculated in the TEAM model automatically for all inherent modules, and using mass and energy balances in derived modules. The energy requirements for processing to the various products are illustrated in Table 4–2. These flows are consumed internally and are therefore not expressly shown in the inventory.

**Table 4 - 2: Internal Energy Flows**

<b>Internal Energy Required for Key Process Blocks</b>				
<b>Feedstock</b>	<b>Electricity Production</b>	<b>Diesel Production</b>	<b>Sugar Production</b>	<b>IBR</b>
NR Energy	68 MJ	9000 MJ	0 MJ	0 MJ
Bagasse	0 MJ	0 MJ	72000 MJ	0 MJ
Ligneous Residue	0 MJ	0 MJ	0 MJ	31000MJ

Table 4–2 reveals the fact that bioenergy systems can approach a net carbon balance of zero. Almost all energy utilized in the production of the products stem from renewable resources.

**Table 4 - 3: Pertinent Reference flows within the 3 systems**

		<b>Base Case</b>	<b>Bio - Ethanol</b>	<b>Green Electricity</b>
Bagasse	t	0	5.2	5.2
Sugar	t	7.8	7.8	7.8
Molasses	t	2.6	2.6	2.6
Ethanol	kl	0	1.2	0
Electricity	MWh	0	2.1	6.9
<b>Reference Flow</b>		<b>65t wet cane</b>		
<b>Functional Unit</b>		<b>Utilisation of resources from 1 ha cultivated land</b>		

Table 4-3 highlights the various key reference flows in the various systems. All systems produce 7.8 tons of sugar and 2.6 tons of molasses per 65 tons of harvested cane. Currently, these are the only significant outputs. The view that more could be made of agricultural residues is represented by systems 2 and 3. These are seen as value added products.

A carbon balance was done on each system from which the carbon closure was calculated for each system. These are illustrated in Figure 4-5.

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Base Case			Green Electricity			BioEthanol		
	In	Out		In	Out		In	Out
<b>Renewable</b>			<b>Renewable</b>			<b>Renewable</b>		
Field Uptake - Growing Cane	8.36 t		Field Uptake - Growing Cane	8.36 t		Field Uptake - Growing Cane	8.36 t	
Sugar (7.8 t)		3.27 t	Sugar (7.8 t)		3.27 t	Sugar (7.8 t)		3.27 t
Molasses (2.6 t)		0.49 t	Molasses (2.6 t)		0.49 t	Molasses (2.6 t)		0.49 t
CO <sub>2</sub> (bagasse burning)		4.55 t	CO <sub>2</sub> (bagasse burning)		4.55 t	CO <sub>2</sub> (LR & Bagasse burning + Ferm.)		4.01 t
	<u>8.36 t</u>	<u>8.31 t</u>		<u>8.36 t</u>	<u>8.31 t</u>	Ethanol		0.50 t
						Biogas Methane		0.06 t
							<u>8.36 t</u>	<u>8.33 t</u>
<b>Fossil</b>			<b>Fossil</b>			<b>Fossil</b>		
Oil	0.180		Oil	0.180		Oil	0.198	
Coal	0.004		Coal	0.004		Coal	0.006	
Lime Stone	0.012		Lime Stone	0.012		Lime Stone	0.024	
Diesel Production		0.016 t	Diesel Production		0.016 t	Diesel Production		0.018 t
Electricity Production		0.002 t	Electricity Production		0.002 t	Electricity Production		0.004 t
Ammonia Production		0.039 t	Ammonia Production		0.039 t	Ammonia Production		0.039 t
Lime Production		0.017 t	Lime Production		0.017 t	Lime Production		0.034 t
Transport		0.119 t	Transport		0.119 t	Transport		0.119 t
	<u>0.196 t</u>	<u>0.193 t</u>		<u>0.196 t</u>	<u>0.193 t</u>	Sulphuric Acid Production		0.004 t
							<u>0.228 t</u>	<u>0.217 t</u>
<b>Credits</b>			<b>Credits</b>			<b>Credits</b>		
Oil		0.000 t	Oil		0.009 t	Oil		0.559 t
Coal		0.000 t	Coal		2.200 t	Coal		0.667 t
		<u>0.000 t</u>			<u>2.209 t</u>			<u>1.226 t</u>
								<u>-1.009 t</u>
		<u>0.193 t</u>			<u>-2.017 t</u>			
Carbon Closure		98%			124%			112%

Figure 4 - 5: Carbon Accounting of the three Bioenergy Systems

The carbon closure is a ratio to indicate the degree of renewability of energy systems. The ratio is defined as:

$$CC_{\%} = 100 \cdot \left( 1 - \left( \frac{fC_{in}}{rC_{in}} \right) \right) \quad (\text{Mann and Spath (1997)})$$

Where:  $fC_{in}$  is the fossil carbon entering the system and,  
 $rC_{in}$  is the renewable carbon entering the system.

Table 4-4 represents the relative carbon closure for the three systems.

**Table 4 - 4 Relative Carbon Closure for the three systems**

System	Carbon Closure
Base	98 %
Green Electricity	124%
Bio-Ethanol	112 %

Both the green electricity and bio-ethanol systems exhibit carbon closures of greater than unity. This is a result of the fossil carbon savings for the two systems in the form of coal and crude oil. The base case exhibits a high carbon closure due to very little fossil carbon utilized for the production of sugar. The bioethanol system has a higher fossil carbon use compared to green electricity. This occurs due to the extra processing step required to convert the bagasse to ethanol.

### 4.3.3 Life Cycle Impact Assessment (LCIA)

An LCIA may be carried out within an LCA, in order to obtain insights into the environmental problems which result from the resource uses and emissions compiled in the inventory stage. In this case study, it was decided to calculate so-called "midpoint" indicators for a number of impact categories, in order to gain insight into the relative environmental performance of the three systems.

#### 4.3.3.1 Calculation

Impact category midpoint indicators were calculated with the aid of the life cycle software (TEAM) as approved by the ISO 14040 standards. All the fundamental flows needed for the various methods employed are inherent in the calculation

procedure. All missing flows were verified to be absent from the systems and were not needed contribute to the score of the indicator.

#### **4.3.3.2 Limitations**

The indicator methods employed in the TEAM software are calculated using standard procedures. Certain defined variables (e.g. Particulates PM10) have not been included in the impact assessment and this is seen as a limitation. The exclusion of such defined variables arises from the impact methods using specific key flows to determine the environmental score. These defined variables in the study, such as PM10, are therefore excluded in the calculation. Inclusion of these variables is therefore a key to refinement. A sensitivity analysis of these omissions yielded less than 1% difference in the impact scores.

#### **4.3.3.3 Results**

The results of the impact assessment illustrate the environmental 'score' of each system. The comparative results for the systems are seen as indicators of performance not absolute results. The relative scores indicate the projected performance for further and more detailed design criteria.

The category indicators were chosen to represent a fair and relevant comparison for environmental performance of the bioenergy systems. Where more than one method is offered for impact assessment, the robustness of the results was checked by comparing their results.. These indicators were applied to the base case to provide a reference point. Case 1 used the following indicators:

- i. Greenhouse Effect, 20 years (IPCC – Inter-governmental Panel on Climate Change) – This method is set out by the inter-continental panel for climate change. The 20 year estimate is seen as a direct impact and uses scale factors to portion chemicals relative to carbon dioxide. Major contributors include CO<sub>2</sub>, methane CH<sub>4</sub>, and nitrous oxide (N<sub>2</sub>O). All of these major contributors are present in the three systems and therefore need to be monitored.
- ii. In order to reveal the potential of bioenergy systems to reduce the burden on natural or non-renewable resources, two methods were chosen to measure the resource consumption. These methods are: Depletion of non renewable resources (CML – Centre of Environmental Science, University of Leiden)

and Depletion of non renewable resources (EB(r) – Ecobilan Group). These methods apply scale factors to resources, dependant on their respective scarcities.

- iii. Burning of fuels to produce energy yields oxidized sulphur compounds in the exhaust gases. The potential of these substances to convert to sulphuric acid in the air significantly contribute to acid rain. Other components with the same potential to lead to acidification are scaled accordingly. Production of energy from all the systems is a result of burning bagasse. The monitoring of air acidification needs to be measured, even though the sulphur content of bagasse is relatively low (0.1%) The two methods chosen are: Air Acidification (CML) and Air Acidification (ETH – Swiss Federal Institute of Technology, Zurich).
- iv. The use of lead based petroleum has significant implications when the fuel is burnt as the lead is released to the air. The associated effects on both land and people need to be investigated. In order to measure the potential savings of airborne lead in ethanol enhanced petroleum fuels was carried out by the methods of Human Toxicity (CML) and Terrestrial Eco-toxicity (CML).
- v. The overall performance of the systems can be assessed via the methods already described, that take into account the flows pertaining to the systems and producing a score to weigh against each other. In order to validate the trends displayed, an aggregate method, Eco Indicator 95, was used. The major contributors to the impacts methods chosen can be seen in Table 4-5. All negative flows in the table are a result of the credit system employed (electricity production and crude oil refining).

**Table 4 - 5: Summary Inventory Table**

	Flow	Units	Base Case	Green Electricity	Bio-Ethanol
<b>Inputs:</b>	(r) Coal (in ground)	kg	6.846	-3858	-1167
	(r) Lignite (in ground)	kg	0.03	0.0263	-0.02
	(r) Limestone (CaCO <sub>3</sub> , in ground)	kg	98.81	-541.0	6.025
	(r) Natural Gas (in ground)	kg	63.22	-2.93	5.83
	(r) Oil (in ground)	kg	212.1	200.9	-422.9
	Water Used (total)	litre	1641	-6556	-3331

<b>Outputs:</b>	(a) Carbon Dioxide (CO <sub>2</sub> , fossil)	t	0.71	-5.65	-1.50
	(a) Carbon Dioxide (CO <sub>2</sub> , green)	t	16.70	16.70	14.70
	(a) Hydrocarbons (except methane)	g	2021	917	-2394
	(a) Lead (Pb)	g	0.085	-5.149	-334.4
	(a) Methane (CH <sub>4</sub> )	g	2247	-20705	-8286
	(a) Nitrogen Oxides (NO <sub>x</sub> as NO <sub>2</sub> )	g	68273	53585	63056
	(a) Nitrous Oxide (N <sub>2</sub> O)	g	61.91	-10.65	38.05
	(a) Particulate Emissions	kg	5.98	2.79	7.99
	(a) Sulphur Oxides (SO <sub>x</sub> as SO <sub>2</sub> )	g	19809	-12786	9956
	(w) COD (Chemical Oxygen Demand)	g	31.44	30.10	-63.07
	(w) Lead (Pb <sup>++</sup> , Pb <sup>4+</sup> )	g	0.04	-0.20	-0.06
	(w) Nitrates (NO <sub>3</sub> <sup>-</sup> )	g	31.27	29.66	25.29
	(s) Calcium (Ca)	g	0.90	0.86	-0.76
	(s) Carbon (C)	g	0.67	0.64	-0.57
	(s) Chromium (Cr III, Cr VI)	g	0.0011	0.0011	-0.0010
	(s) Iron (Fe)	g	0.45	0.43	-0.38
	(s) Sulphur (S)	g	0.13	0.13	-0.11
	Waste (hazardous)	kg	0.21	-0.21	-0.65
	Waste (total)	kg	4.18	-2116	-644
	Waste: Radioactive	kg	0.02	0.02	0.00
<b>Products:</b>	Molasses	t	2.59	2.59	2.59
	Sugar	t	7.76	7.76	7.76

These key inventory species (amongst others) were then used to calculate the various impact methods highlighted.

Table 4 - 6: Impact Assessment Results

Impact Method	Units	Base Case	Green Electricity	Bio-Ethanol
Air Acidification (CML)	g eq. H <sup>+</sup>	2103.4	<b>667.2</b>	1652.1
Depletion of non renewable resources (CML)	frac. of reserve	1.4E-12	-1.5E-12	<b>-2.4E-12</b>
Eutrophication (CML)	g eq. PO <sub>4</sub>	8902.6	<b>6953.9</b>	8152.0
Human Toxicity (CML)	g	77267	18211	<b>4105</b>
Terrestrial Eco-toxicity (CML)	t	1.05E-02	1.01E-02	<b>-8.93E-03</b>
IPCC-Greenhouse effect (direct, 20 years)	g eq. CO <sub>2</sub>	871184	<b>-6979590</b>	-2021046
Eco-indicator 95	millipoints	9470	-2153	<b>-27745</b>

Table 4-6 reveals the environmental impact scores for each system. Duplicate methods were used to verify the results. Depletion of non-renewable resources was the only duplicate method that did not yield the same ranking of results. The results of the EB(R) and CML methods differ by a factor of 10<sup>9</sup> and this discrepancy is attributed to a different unit of measurement. The figures in bold represent the best score for each indicator.

The impact category inventory shows that the green electricity and bioethanol score best in three indicators each.

The indicators where green electricity appears the better option lies in lower Nitrous Oxides (NO<sub>x</sub>), Sulfur Dioxide(SO<sub>2</sub>) and Carbon Dioxide (CO<sub>2</sub>) emissions. A NO<sub>x</sub> and SO<sub>2</sub> balance can be seen in Appendix 4. This fact is attributed to the electricity credits gained in this system.

The bio-ethanol system outcores the other two systems in the depletion of NRR's, human toxicity and terrestrial eco-toxicity. The reason for lower NRR score is the scarcity of crude oil having a higher weighting with respect to coal. The saved crude oil and coal in the bioethanol system is higher than the coal based savings in the green electricity option. The two toxicity midpoint indicators outscoring the other two systems is a result of the saved airborne lead emissions, where ethanol replaces the lead in gasoline.

Both systems outperform the base case. The overall indicator used (Eco-Indicator 95) sees the bioethanol system having the best environmental performance of the three system evaluated. This fact is qualified by the large weighting of airborne lead emissions saved in the bioethanol system.

#### **4.4 Evaluation of the Case Study**

As discussed in section 4.2, the above case study was prepared in order to develop insights into the applicability and usefulness of LCA in the business planning phase of a bioenergy project. The case study will now be evaluated in terms of the specific objectives laid out:

- Testing the value of LCA at conceptual level design with respect to its potential as a screening tool to various process options

The two alternative uses of bagasse were evaluated on a life cycle basis and their performance measured with respect to certain environmental impact categories. Even at this phase of design, where the uncertainties were large, it was clear that both systems outperformed the base case. This fact would therefore be a motivator to pursue an option to improve the current situation. Had one or both of the systems fared worse than the base case they could have been eliminated immediately.

- Verifying the ability of conceptual LCA to provide early assessment of potential environmental impacts of a product or process.

The results, while possibly containing large uncertainties nevertheless yielded inventory and impact indicators that were consistent amongst themselves, and could be used to rank alternatives.

- Assessing whether the results generated by the LCA are reliable enough to make an informed decision regarding the future of a project.

Having discussed the first two objectives, the reliability of LCA to determine the future of a project is subjective. Enough facts are available to trade off impacts and compare systems in terms of various criteria. (Energy consumption and wastes)

The case study was also able to provide a detailed list of areas of concern with regard assumptions made, data quality, and further iterations. Data quality and further iterations are inherent in LCA and so this is seen as an advantage in this use of LCA.

Both options explored, Green Electricity and Bioethanol, outperformed the base case in all impact categories. These two options provide a good case to put forward for further development. The comparison of the two improvement options did not yield an outright 'better' performer. Further analysis and selection criteria would be needed to choose between the two options.

- Evaluating the sensitivity of LCA to data and data quality

LCA is data intensive and the greater the data availability and the higher the quality of the data the better the results of the LCA. The case studied proved to be more sensitive to system definition rather than to issues of data. This fact was highlighted by the change in overall indicator (30000 millipoints in the Eco-Indicator 95) when including the final use of the ethanol, to replace the lead, in the gasoline. The saving of lead emissions in the end use of the product skews results far more than data sensitivity.

- Gaining insight into the role of taking a life cycle perspective in the bioenergy sector.

This fact was crucial in revealing the true environmental benefit of a bioenergy system. This was evident when including the growing of sugarcane in the life cycle. This process could have been excluded as it was common to all three systems but the carbon sequestered from the atmosphere was vital in distinguishing the system from other non-renewable systems.

## **4.5 Conclusions**

The value, strength and weaknesses of LCA in the conceptual design phase were investigated. The following conclusions can be drawn from the demonstrative case study:

### LCA proved to be a valuable screening tool at conceptual level design

The applicability of LCA at concept design level as an options development and screening tool are quite apparent. Even at this early stage, a poorly performing product can be eliminated as an option. Informed choices between competing processes and products can be drawn.

### Conceptual LCIA informed trends of environmental performance

The data available does not lend itself to true environmental impact assessment. The LCIA at this phase is used rather to predict potential problems at an early in a design. Removing error and assumptions would replace the trends shown with potential impacts.

### LCA sensitive to data and data quality

Uncertainty in sections of the design is inherently highlighted by the LCA. All areas of concern are noted for better modeling, new data sources, geographical locations and the like. This is provided by the framework offered by LCA.

### Life cycle systems definition is of great importance

The definition of system boundaries and the inclusion of all phases of a life cycle are of vital importance. Clear system definition at the outset of a project is crucial. The objectives need to be clearly defined in order to ascertain boundaries under investigation.

LCA can reveal the true benefit of renewable energy conversion processes at an early stage of design

The ecological value of a renewable energy system lies in the extent to which net carbon emissions can be reduced. All renewable carbon used will cancel with the carbon taken up in the growth of the crop (or waste). Exclusion of this fact yields inaccurate results as only the carbon released is accounted for and not offset against the uptake, which will equate it to a fossil energy system.

LCA has merits as a design tool in conceptual level engineering

This investigation of the value, strength and weaknesses of LCA revealed positive results. The tool proved to be a powerful product screening tool, as well as highlighting areas of optimization within a design. The early identification of environmental impacts was a great attribute. The data intensity, and sensitivity to methodological issues were weaknesses, but did not render the results meaningless.

# **Chapter 5: Heuristics for Flowsheet Development in the Pre-Feasibility Phase**

## **5.1 Introduction**

The structuring of flowsheets requires decisions that can generally not be justified by a quantitative analysis, but rather, are informed by sets of design rules, often referred to as heuristics. Consideration of sustainability has necessitated the development of new heuristics to complement those traditionally used, when objectives of design focused on technical feasibility and cost effectiveness.

Extended flowsheet heuristics that have developed as a specific response to such needs were reviewed in chapter 2.2.3. The support, which these extensions can offer to the task of flowsheet structuring for the better use of residual biomass, is investigated in this chapter, by means of a second case study linked thematically to the one presented in chapter 4.

The objectives of the case study and its topic are described in section 5.2, the case itself is presented in section 5.3, and an evaluation of the case study follows in section 5.4.

## **5.2 Case Study Objectives and Definition**

### **5.2.1 Case Study Objectives**

The case study aims to use recent developments in flowsheet heuristics (Douglas, 1992 ; Douglas, 1995 ; Fonyo et al., 1994 ; Rossiter and Klee, 1993) to develop a flowsheet for the processing of sugarcane bagasse to ethanol. The use of a hierarchical design approach and heuristics to guide the design process is tested in the context of a bio-energy system. The power of heuristics as options generating tools is of special interest in the design context. In the case study, an early process bioenergy flowsheet will be further developed by application of heuristics for environmentally conscious process design. The usefulness of the heuristics is to be probed by comparing the suggested flowsheet improvements against cited literature on the same bioenergy topic.

In order to apply heuristics the designer should be aware as to how useful the heuristics are in terms of:

- Relevance, and
- Power.

The applicability of heuristics to the bioenergy sector is thus to be evaluated in terms of these two criteria. The relevance of the heuristics is related to the ability to generate environmentally benign and more efficient process options. The power of a heuristic lies in the ability to produce not only many solutions to the given problem but novel solutions as well. From this, conclusions are to be drawn as to the applicability of process systems literature to the bio energy sector. This framework for the evaluation is illustrated graphically in Figure 5-1.

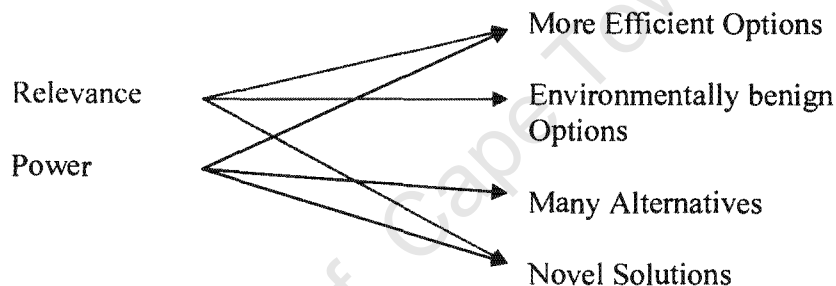


Figure 5- 1: Applicability of Heuristics

## 5.2.2 Case Study Definition

Case 1 confirmed that current practice in the sugar industry can be modified to create a situation where supply of a renewable feedstock would become available for further processing. It was estimated that each hectare of land under sugarcane plantation (in the South African case) could generate 5.2 tons of surplus bagasse for utilisation.

The further processing of bagasse is the point of departure for the case study. The production of ethanol from the bagasse is investigated. Process alternatives need to be generated and evaluated. The task is to use heuristics to improve the dilute acid hydrolysis flowsheet proposed by Kadam (2002).

The goal is to produce the best design by applying the Rossiter (1993) waste minimization techniques as discussed in Chapter 3.2. This involves generating process alternatives, and then screening them to produce the optimum flowsheet.

Figure 5-1 illustrates the input-output mass balance of the process for making ethanol from bagasse utilizing dilute acid hydrolysis.

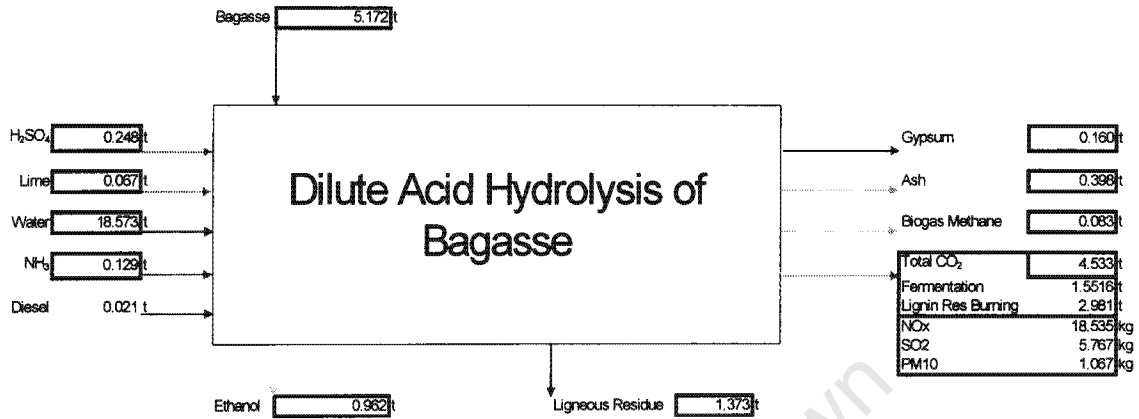
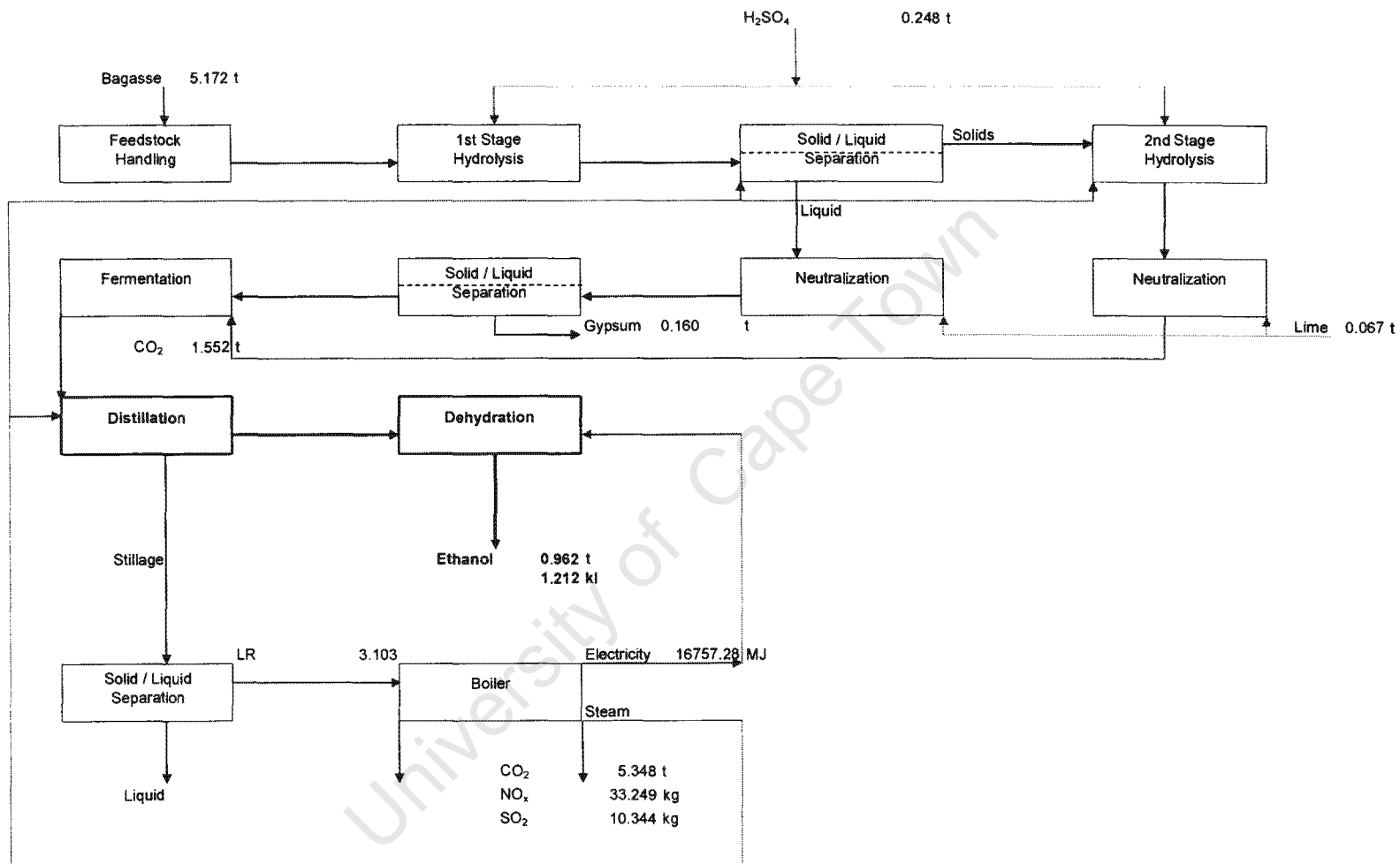


Figure 5- 2: Input / Output Analysis of Dilute Acid Hydrolysis of Bagasse

This level of detail was sufficient for Case 1 and conceptual level design. Case 2 extends the detail. Following the “Roadmap for Decision Making” by Basson and Petrie (2001), the next stage of tactical design is the feasibility stage, where input output analysis is exchanged for block flow diagrams. This case builds on the input/output approach, and it extends to detailed block flow and early process flow level, as illustrated by figure 5-2. (Basson and Petrie, 2001)



\*Adapted from Kadam 2002

Figure 5- 3: Dilute Acid Hydrolysis of Bagasse to Produce Ethanol

Figure 5-2 represents the dilute acid hydrolysis of bagasse and subsequent fermentation to ethanol. The bagasse received from the sugar mill is sent to the first hydrolysis stage where dilute sulfuric acid (1%) is used to convert the hemi-cellulose portion of the bagasse to fermentable 5-carbon sugars. The remaining solids pass into the second hydrolysis stage where the cellulose fraction is broken to produce 6-carbon sugars. The five and six carbon sugars are then fermented to produce ethanol. The remaining solid material referred to as ligneous residue (containing lignin and unconverted hemi-cellulose and cellulose) is combusted in a boiler for process utility requirements. The ethanol is distilled (95% purity) and then purified for use in the automotive industry (99.5% Ethanol). This flowsheet modeled by Kadam (2002), was chosen as the starting flowsheet technology for the case study. This technology has been around for a long time (Paterson-Jones, 1989) but has not become attractive for cost and environmental reasons.

This point is therefore the basis for employing recent literature on hierarchical design to systematically guide the development of a better process flowsheet. The questions that need to be answered, or at very least guided by the literature are:

Is this the best design for the further processing of bagasse to ethanol?

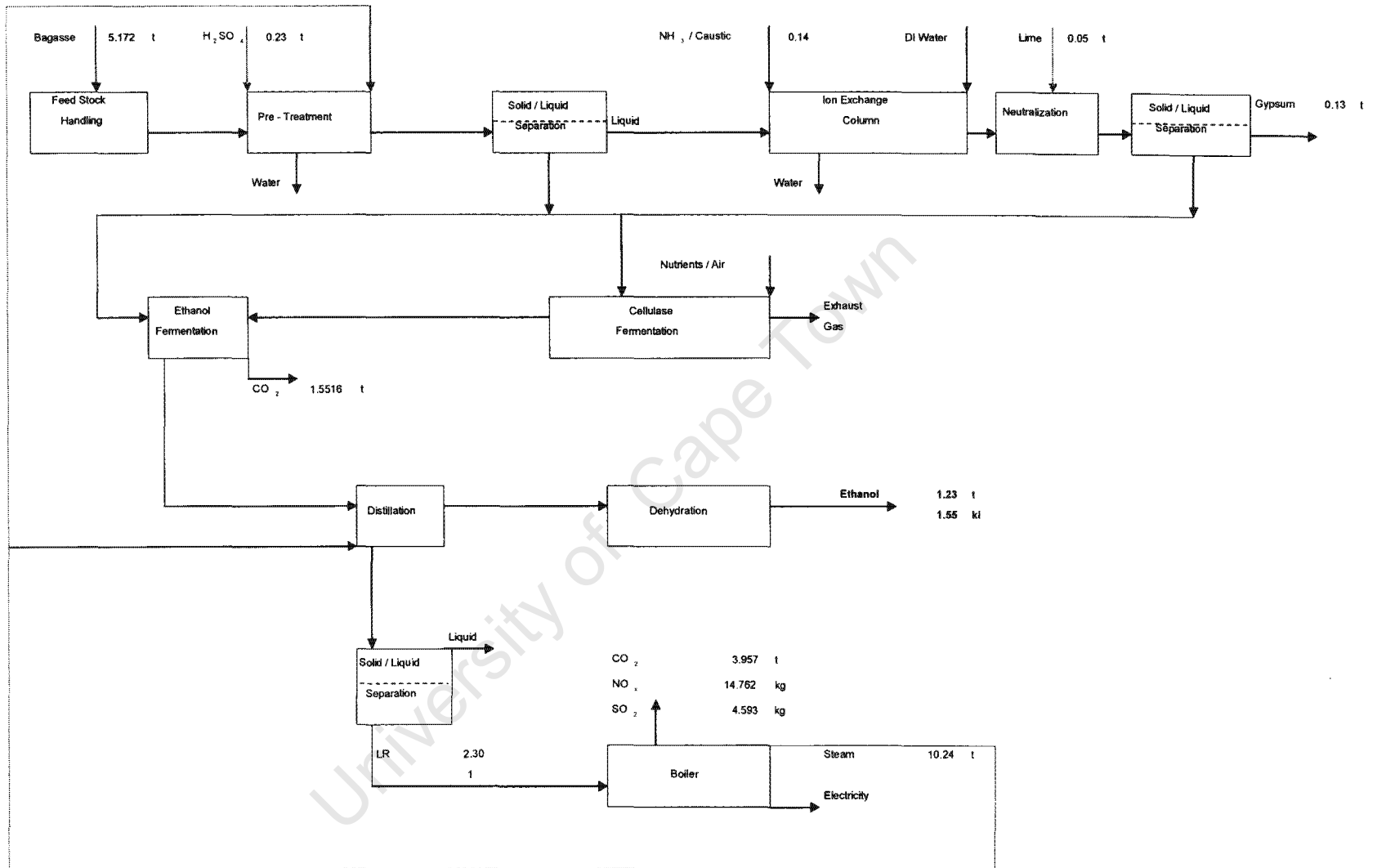
Are the wastes generated hazardous?

Is the yield of ethanol high?

What are the most energy intensive steps?

What measures can be put in place to lower these energy burdens?

Several authors (Kadam, 2002 ; Reith et al., 2001 ; Sun and Cheng, 2002) also proposed an enzyme hydrolysis process. Models predict the ethanol output to be higher than that of the acid hydrolysis as well as eliminating a portion of the acid (a high level waste of concern) needed. The interest therefore lies in whether the advanced heuristics can direct the flowsheet modifications towards the features found in this enzyme hydrolysis model. The improvements suggested by application of the heuristics will then be compared to Kadam's second option (seen in figure 5-3) .



\* Adapted from Kadam 2002

Figure 5- 4: Enzyme Hydrolysis of Bagasse to produce Ethanol

### **5.2.3 Approach**

Various recent additions to the literature on process design heuristics have been discussed in chapter 2. For the case study, it was decided to test the usefulness of Rossiter's 7-level hierarchy of decisions for pollution prevention (Rossiter and Klee, 1993). These heuristics were to be applied to the major process blocks identified in the Kadam dilute acid hydrolysis model.

The key streams for each sub system were identified, and the guiding questions were then applied to the sub systems. The key streams were waste streams, process feeds, or a combination of these according to the level under consideration. Any improvements suggested were then used to develop a flowsheet for each level.

Finally, the pieces of the flowsheet were integrated and a summary of the proposed changes presented. This was then compared to the features of newer processes for the hydrolysis of bagasse to ethanol.

## **5.3 Case Study: The Use of Heuristics to Guide Bioethanol Flowsheet Development**

The Rossiter (1993) heuristics, reviewed in Chapter 2.2.3, divide flowsheets into the broad categories of reaction and separation. More emphasis is placed on reaction since product and by-product formation occurs in this step. Separation details are dealt with in level 4 heuristics. Separation of by-products and wastes that can be recycled are considered in level 3.

### **5.3.1 Level 3 Heuristics – Recycle Structure and Product Formation Considerations**

The ethanol process to be developed utilizes the cellulosic feedstock known as bagasse from the sugar industry, amounts of which are sufficient to run a continuous process (level 1 decision). In the previous chapter, an input / output analysis was completed to quantitatively analyze the further processing of bagasse to ethanol (level 2 requirement). The level 3 analysis is therefore the starting point for this case study as level 1 and 2 have been covered.

The key to applying the level 3 heuristics correctly lies in identifying all wastes streams and how they relate to the reaction section. It is here that the data is readily available to determine the impact of reaction conditions on waste formation. (Rossiter and Klee, 1993)

For the conversion of cellulosic material to ethanol, there are three main phases in the reaction section, namely pretreatment, hydrolysis, and fermentation.

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Pre-Treatment		Hydrolysis		Fermentation	
Wastes	Formation	Wastes	Formation	Wastes	Formation
Spent Acid	Acid remaining that is not neutralized	Gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ )	Generated after lime neutralization of the stream	Carbon Dioxide	Product of the sugar reaction
Water	The steam added in the pre-treatment phase condenses and therefore the water needs to be recovered	Spent Acid	Acid remaining that is not neutralized		
		Ligneous Residue	Unreacted cellulose matter		

Figure 5- 5: Waste Formation Matrix for Level 3 Heuristics

Figure 5-5 identifies the wastes generated in each reaction step. The first stage considered is pre-treatment, where the hemicellulose is broken into 5-carbon sugars and at the same time decreasing the crystallinity of the remaining cellulose and increasing the porosity of the materials for subsequent reaction. (Sun and Cheng, 2002) The second step in the reaction series is hydrolysis, where the cellulose fraction is hydrolyzed to produce 6-carbon sugars. These 5- and 6-carbon sugars are then fermented in the third reaction step to produce ethanol.

The heuristics are then applied to each waste in the three reaction steps.

### 5.3.1.1 Pretreatment

The Kadam flowsheet employs acid pretreatment for the first hydrolysis phase, which produces water and spent acid as wastes. The reaction for the pretreatment phase is  $(C_5H_8O_4)_n + nH_2O \rightarrow nC_5H_{10}O_5$  (Paterson-Jones, 1989). The acid hydrolysis leads to side reactions of the sugar produced and therefore needs to be removed rapidly. This leads to low residence times and poor conversions. The wastes arising stem from unreacted feed materials (biomass, water and sulphuric acid).

The water, condensed steam, is regarded as a waste and included in the analysis. The remaining solids, comprising unreacted hemi-cellulose, cellulose and lignin, pass into the hydrolysis reactor, from which the lignin or ligneous residue emerges as a waste that is finally used as the energy feedstock for the process. It deserves consideration at most levels.

The first question - **Do any waste output streams contain feed or product material that could be recovered and recycled?** - applied to the waste streams raises concerns of feed and product loss in waste streams. While no product is lost (pentose sugars are deemed to be the product at this stage) as the liquid streams proceed to the fermentation section, feed loss occurs in the form of unconverted hemicellulose. The conversion efficiency of the hydrolysis steps (this includes the 2<sup>nd</sup> hydrolysis stage) is approximately 50%. The unreacted hemicellulose passes with the ligneous residue to the boilers to satisfy utility requirements.

The second question - **Can reaction conditions be altered to minimize formation of waste by-products?** - stimulates thought as to the selection of reaction conditions. While the heuristics do not expressly call for a change in

reaction mechanism, they could inspire such a thought by the emphasis on minimizing the formation of wastes. Applied to the acid waste resulting from pre-treatment, this question should stimulate much thought both as to minimization of acid losses, and to use of alternative pretreatment schemes not using acid. Applied to water formed as waste in the pretreatment process, prompts discussion of changing of reaction conditions so to move away from steam use in the pretreatment phase. Finally, applied to solid residue, this question leads to the observation that the low conversion efficiency results in more solid material, but that this material is fundamental to the process (in the form of utility requirements), yielding a different end product in the form of exportable electricity. Nevertheless, it might be possible to modify reaction conditions to improve conversion of hemicellulose, thus improving ethanol yield. This could be done with the aid of a solvent. Solvents can be used to reduce crystallinity of the cellulose and increase the porosity of the materials. (Sun and Cheng, 2002)

The third question - **Can waste by-products be recycled to extinction ?** - suggests investigating whether waste material can be re-introduced to the process to the extent that they will, at some stage, resurface in the product. The opportunity to form closed cycles of water and acid exist. The water, appearing as steam in the pretreatment phase could be returned to the utility section of the plant, or as a feed stream for the hydrolysis reaction. The strength of acid needed (1% dilution in the first hydrolysis phase) would be a major consideration in the recycling of acid.

### 5.3.1.2 Hydrolysis

Kadam's flowsheet employs dilute acid hydrolysis to convert the cellulose to hexoses (six-carbon sugars); the waste generated is spent acid. This waste is transformed to gypsum, which arises from the use of lime to neutralize the low pH streams, which are detrimental to fermentation. Gypsum has a low retail value and is considered as a waste, which cannot be recycled or reused.

The first question - **Do any waste output streams contain feed or product material that could be recovered and recycled?** – yields a “yes” when applied to spent acid in the hydrolysis section since the concentration of the acid in this phase tends to be higher compared to the pre-treatment phase.

The gypsum waste would contain some dissolved material (pentose and hexose sugars) in the damp filter cake. Normal operating conditions predict a filter cake

to be approximately 50% moisture. The gypsum waste streams therefore contains potential product that is lost.

The second question - **Can reaction conditions be altered to minimize formation of waste by-products?** - probes the changing of reaction conditions to increase the yield of the desired products. If a change of reaction mechanism is to be considered, then enzymatic hydrolysis in conjunction with acid pretreatment is a candidate. This changes the reaction conditions since the catalyst cellulase is used to promote hydrolysis.

The third question - **Can waste by-products be recycled to extinction?** – applied to the unutilized acid destined for neutralization by lime, prompts the following responses: Given that a more dilute acid is needed in the pre-treatment step, it may asked why a counter-current system is not employed, whereby the acidic hexose containing stream would be contacted with the solid feed for pretreatment; the liquid stream from the subsequent solid-liquid separation could then be sent to fermentation.

The waste by-products encountered stem from successive reactions, since the 5- and 6-carbon sugars degrade rapidly after formation. The degradation is attributed to the high sensitivity of the sugars to reactions conditions. The reaction conditions used in this phase are ideal for subsequent reaction to furfural. (Sun and Cheng, 2002)

An issue arising from the dilute acid hydrolysis process (pre-treatment and hydrolysis phases) is the amount of ethanol that could be produced if all the available fibrous material (hemicellulose and cellulose) is converted to fermentable sugars. Changing the process for higher conversion efficiency would affect the amount of exportable electricity as there would be less boiler fuel. The trade-off exists between producing ethanol or electricity. Increased ethanol production yields lower exportable electricity and vice versa.

This raises the possibility of routing a portion of bagasse straight to the boilers and the rest to ethanol production. Variations in price for each product could determine the route chosen, and provides scope to adjust to fluctuating market conditions in the energy sector.

### 5.3.1.3 Fermentation

The fermentation step converts five and six-carbon sugars to ethanol with carbon dioxide as a by-product. The five-carbon sugars are converted with the aid of modified yeast or bacteria but as yet no industry standard has emerged. The six carbon sugars with are converted using the *Saccharomyces cerevisiae* yeast. (Reith et al., 2001)

The first question - **Do any waste output streams contain feed or product material that could be recovered and recycled?** – does not aid modifications to the process as the only waste stream present is the carbon dioxide released in the fermenter which does not contain product or feed material.

The second question - **Can reaction conditions be altered to minimize formation of waste by-products?** – is again not helpful for increasing the efficiency or eliminating a waste since the carbon dioxide is the only waste stream and minimization of the formation of the CO<sub>2</sub> would mean a decrease in the ethanol yield.

The third question - **Can waste by-products be recycled to extinction ?** –. Is not directly applicable but research and development has shown the use of supercritical CO<sub>2</sub> can be used as an alternative pre-treatment method, while this does not recycle the waste to extinction, the CO<sub>2</sub> is turned from a waste to a process aid, before being released.

### 5.3.1.4 Summary of Modifications Arising from the use of Level 3 Heuristics

The proposed improvements from the various stages of the reaction systems are:

- Possible use of a solvent in the pretreatment phase
- Closed loop water recycle
- Addition of the enzyme cellulase in the hydrolysis step
- Eliminate gypsum formation
- Route a portion of the bagasse straight to the boilers for utility requirements
- Use some CO<sub>2</sub> (in super-critical form) generated in the pre-treatment section.

A possible flowsheet from applying the above mentioned proposed changes is illustrated in figure 5-5.

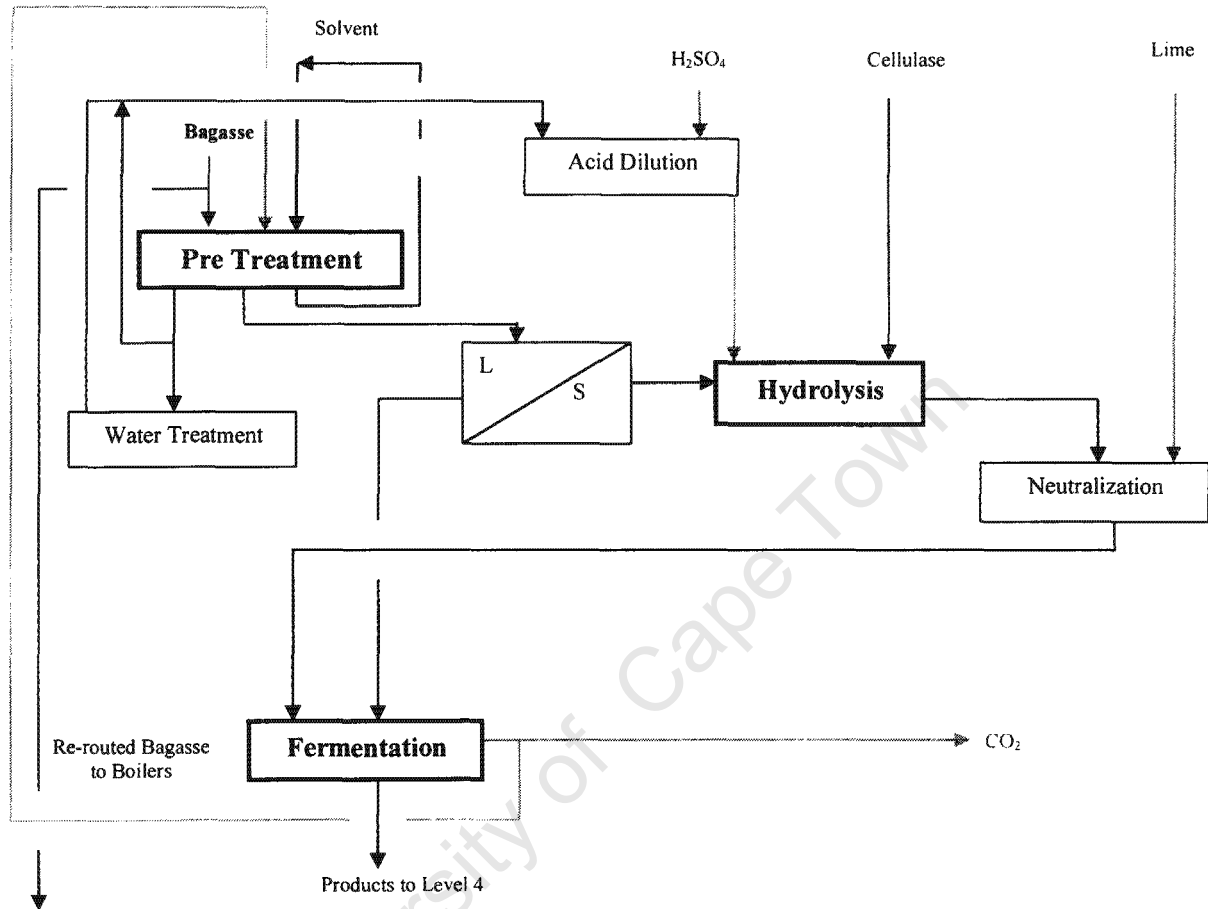


Figure 5- 6: Flowsheet design after applying Level 3 heuristics

The heuristics identify scope for pre-treatment optimization, providing numerous options.

The carbon dioxide, as mentioned earlier, poses a waste problem that cannot be solved without sacrificing the formation of the primary product ethanol. Changing reactor conditions can inhibit the formation of CO<sub>2</sub> only at the expense of the ethanol.

The second waste problem, gypsum, is a result of the technology used. The specific heuristics supplied by Rossiter do not provide a method of eliminating this waste and only serve to highlight the problem.

### **5.3.2 Level 4 Heuristics - Structuring the Separation System**

The level 4 heuristics deal with the structuring of the separation systems on the flowsheet. The products generated in the reaction section proceed to the separation system as well as the separations used within the reaction system.

The level 4 heuristics aim to evaluate the impact of separation technology on waste generation. This requires early identification of the waste streams. The reduction of emissions is achieved by either using alternate separation technologies, or re-arranging existing ones. The interactions of the separation system with the reactor and recycle systems are also considered. (Rossiter and Klee, 1993)

The level 4 heuristics are applied to the waste streams of the distillation and purification sections as illustrated in Figure 5-7.

Solid / Liquid Separation		Distillation		Dehydration	
Wastes	Formation	Wastes	Formation	Wastes	Formation
Gypsum	Removed from the process preceding the fermentation reaction	Distillation Tops	Product material - Ethanol water azeotrope, 95% EtOH	Ethanol product	Purification to fuel grade ethanol. 99.5% EtOH
		Distillation Bottoms	Liquid and solid material collected at the bottom of the distillation column	Water	Removed from the ethanol
		Liquid Waste	The liquid portion of the stillage separated from the solid material		

Figure 5- 7: Waste Formation Matrix for Level 4 heuristics

The fermentation products are sent to the first distillation stage where the ethanol is separated from rest of the products. The bottoms from the distillation contains solids and liquids. The tops from the first separation step proceed to product purification where the ethanol is purified from 95% to fuel grade ethanol (99.5%). The bottoms (solids and liquid) are centrifuged and the liquid stillage goes off as a waste and the solids are sent to the boiler to produce steam (utilities). (Lynd et al., 1996)

The gypsum waste arises from the addition of lime to neutralize the stream preceding the fermenter. The waste stream does contain product material, as a solid liquid separation results in the formation of a filter cake which contains moisture, and hence dissolved sugars. This fact was dealt with in the reaction system and will not be considered again.

The heuristics are then applied to the remaining waste streams.

### 5.3.2.1 Distillation

The distillation section receives fermenter product containing solids (ligneous residue) and liquids (dissolved ethanol). The top of the column collects the ethanol water azeotrope at approximately 95% purity. The stillage and solid material collect at the bottom of the column.

The first question - **Are any waste streams the result of poor or inappropriate separations?** – evaluates the technology chosen and the efficiency of the separation. The two streams leaving the distillation section are a product stream and a waste stream. The waste stream, bottoms, is result of the purpose: to separate the ethanol from the reactor products. The liquid waste (stillage) is again a result of function as the solid material is required as boiler fuel.

The second question - **Can any wastes (especially hazardous) be removed from the process effluents by adding new separations?** – does not apply to the only waste stream (liquid stillage) as it is removed in a separation and no further separation is needed.

The third question - **Are there any separation technologies that could replace or supplement existing separations and reduce releases?** – probes the use of new techniques to carry out the separation sequence. Knowledge of the liquid

waste stream is needed in order to justify use of a more efficient technology for the distillation of a solid and liquid system.

### 5.3.2.2 Dehydration

The ethanol water mixture forms an azeotrope and passes into the product purification stage. The concentration of ethanol required for use in the transportation market is 99.5%. This step therefore serves to remove the majority of the remaining water from the ethanol. As such there is only one waste stream and one product stream.

The first question - **Are any waste streams the result of poor or inappropriate separations?** – The only waste stream is water and can therefore be recycled.

The second question - **Can any wastes (especially hazardous) be removed from the process effluents by adding new separations?** – The water stream is not considered hazardous and no new separations are needed.

The third question - **Are there any separation technologies that could replace or supplement existing separations and reduce releases?** – The use of a more efficient method of azeotrope separation should be explored.

This question provides the basis for generating novel techniques and flowsheet design to recover the product. Highlighted techniques for further investigation into the separation of an ethanol water mixture (for high purities) are:

- Saline extraction
- Membrane Distillation
- Electrolytic Extraction
- Solvent extraction

Solvent extraction raises environmental issues, however, as further separation and recycling is needed to reuse the solvent creating higher energy use as well as possible waste streams. Distillation has been shown to be seldom economical when separating organic compounds dissolved in water. (Douglas, 1995)

The separation system chosen will be the major energy consumer within the system. The energy efficiency provides an optimization problem. The ligneous residue that remains after the first separation is large enough to provide steam

and electricity to drive the process. The use of this resource needs to be conserved, as any surplus the system is able to provide aids the environmental performance by replacing non-renewable resources.

### 5.3.2.3 Summary of Modifications Arising from the use of Level 4 Heuristics

The proposed changes from the separation system are:

- Modified distillation column to handle solid material, includes the use of a centrifuge.
- Solvent extraction of water
- Water recycled to other parts of the process

The proposed changes for the separation systems can be seen in Figure 5-8.

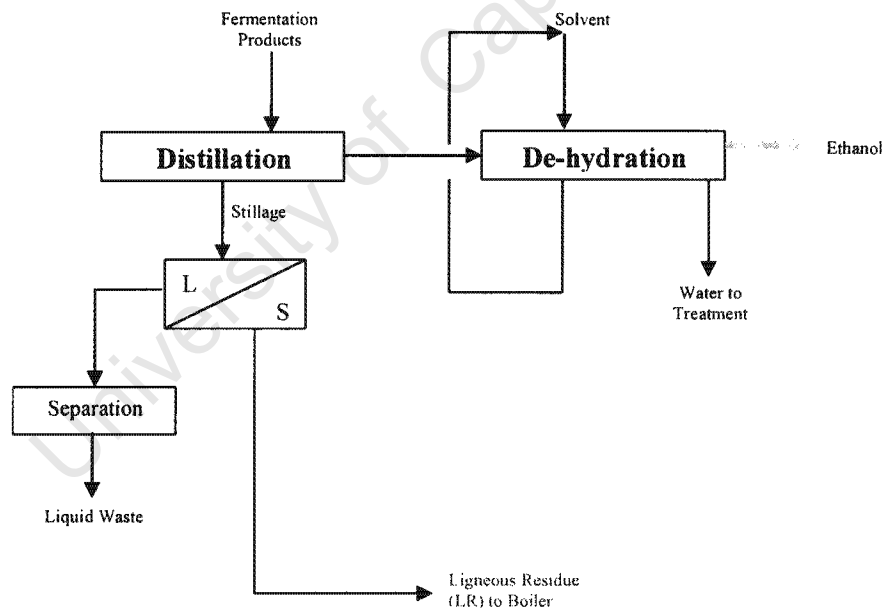


Figure 5- 8: Proposed changes for Level 4 heuristics

The heuristics prompt the use of novel solutions to separate the water from ethanol.

### 5.3.3 Level 6 Heuristics – Energy Systems

The energy systems employed in the process are evaluated in the level 6 analysis. Rossiter (1993) proposes that this section be governed by the use of pinch analysis, where insight into process integration is gained.

The major benefits of this section are the reduced steam consumption and fuel firing. This is critical for the net export of electricity. Appropriate utility selection can maximize cogeneration. (Rossiter and Klee, 1993)

Rossiter states that an employment of a heat exchanger network design reduces fuel firing and steam consumption, which is vital. Questions guiding this section of the design may seem intuitive but are essential nonetheless. The goals are to lower the energy consumption, whilst proving that energy at the lowest temperature possible, using a renewable (clean) source for fuel. (Rossiter and Klee, 1993)

The first question - **How far can the energy consumption of the process be reduced economically?** – involves a preliminary economic analysis which goes beyond the scope of this study.

The second question - **Can the temperature at which heat is delivered to the process be lowered?** – prompts the understanding of the way the energy is delivered to the system. Stretching the context of the question, this can be interpreted as a decision to gasify or combust the ligneous residue. The usual procedure to combust the fuel delivers low efficiencies in the region of 20-40%. (McKendry, 2002) The better use of fuel would be gasification, where the residue is converted to a combustible gas mixture at a slightly lower temperature than that of pure combustion, and can be used in a biomass integrated combined cycle system producing electricity at efficiencies as high as 50%. (McKendry, 2002)

The third question - **What fuels are used to provide heat for the process? Are cleaner fuels available?** – refers to fossil fuel based systems where fuel contents vary greatly. The fuel in a bioenergy system should be purely renewable and are inherently cleaner, as the carbon released was originally taken up from the atmosphere. Ligneous residue has a lower sulphur content compared to fossil fuels. (EPA, 1996)

The level 6 heuristics prompted the evaluation of the energy system employed. A further more detailed analysis, including pinch analysis, is needed to truly gain

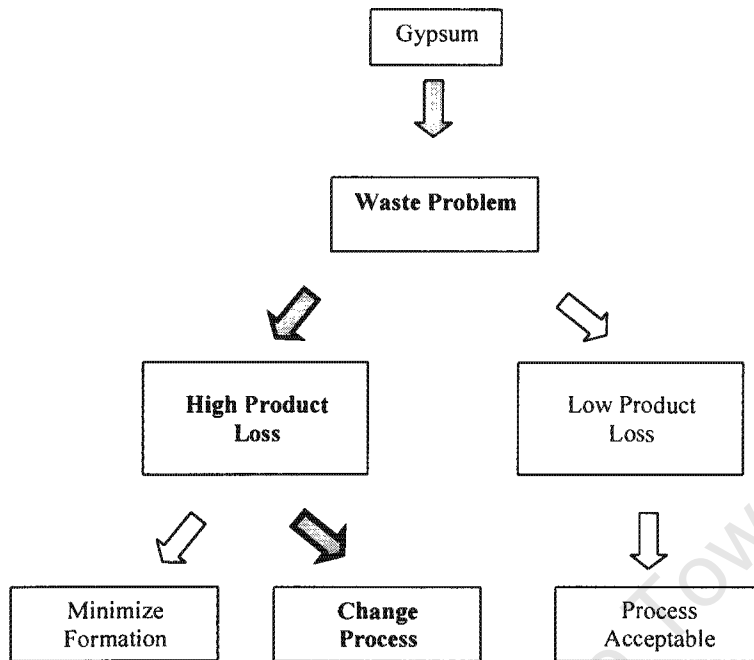
benefit from this section. The flowsheeting options for this section stretches to detailed PFD level where economic consideration can be carried out.

#### **5.4 Evaluation of Case Study**

In evaluating the improvement suggestions obtained, it should be borne in mind that the Rossiter heuristics have waste minimization as their main objective. The case study will be evaluated in terms of relevance and power as defined in section 4.2.1.

The pretreatment section was identified to have numerous improvement options which relates back to a powerful set of heuristics, defined earlier. While the heuristics probed understanding of the process, there were no direct heuristics in level 3 to use novel solutions. The heuristics therefore displayed some relevance, as the solutions provided were environmentally benign but no novel solutions were provided. A generous interpretation would guide the designer to seek out novel solutions.

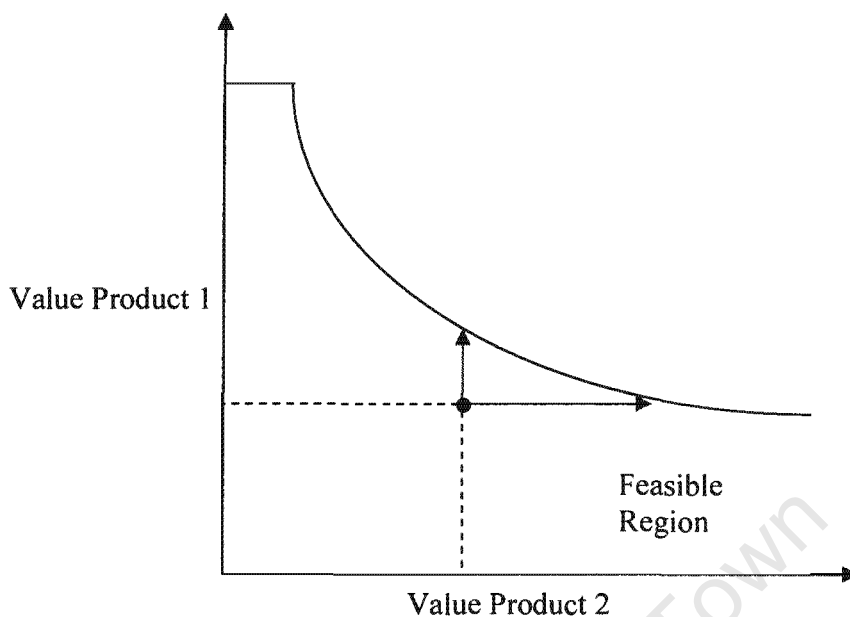
The use of acid in the process necessitates two neutralization steps as the fermentable sugars produced are highly sensitive to process conditions (temperature and pH). This gives rise to gypsum waste that cannot be recycled or reused, as well as some product loss when removing gypsum from the process. While the heuristics identify these issues and hence show some power, it seems (in this case study) that they do not give sufficient guidance to overcome this problem. Further more general heuristics are needed to address the problem; one solution might lie in application of Douglas' hierarchical approach, as illustrated in figure 5-6.



**Figure 5- 9: Application of Douglas' hierarchical approach to gypsum waste problem**

The waste is treated in a general manner where its significance with respect to product loss is evaluated. The Douglas heuristics thus explicitly suggest the possibility of a process change away from the acid technology. This is regarded as a powerful attribute.

The input/output analysis in case 1 revealed that surplus electricity could be produced. The amount of electricity is directly dependent on the technology used since, the better the conversion efficiency of the technology (with respect to ethanol), the lower the potential to export electricity. The heuristics were not able to deal with multi product systems, as all emphasis was placed on the desired product and the wastes related to it. Co-products were not dealt with. This is seen as a weakness in the power of the heuristics employed here.



**Figure 5- 10: Diagram Illustrating the Value Product Trade Off**

Figure 5-9 shows an operating point in the system. The value products considered can be moved along the curve. The curve is seen as the optimum, but the trade off exists when pushing system to produce more of product 1 over product 2. This is a favorable situation since the process can be changed to produce more of product should the need arise (i.e. increased market value of a product 1).

Achieving an operating point on the line is not always the case, and so pushing the system to produce more of one product without affecting the other is possible. This is achieved by increasing the efficiency of the process. This is an example of a co-product system where multi-objective optimization is used to produce the curve as well as determining the operating point/s. The heuristics presented do not deal with such systems.

The separation system investigation did not yield many insights to improving the process. The separation system for the production of ethanol is not complicated and the value of level 4 is rendered less useful. The level 4 heuristics do call for novel solutions when addressing the ethanol water separation which illustrates some relevance.

The investigation of the energy system reveals how Rossiter sees the development of a flowsheet, where subsequent levels need more detailed data. Some level 6 considerations were therefore beyond the scope of this study. Relevance is

introduced by the suggestion to use a clean fuel, and there is significant power in the question probing the temperature at which process heat is provided. A major factor in level 6 considerations is the use of pinch technology which is both relevant and powerful in the bioenergy design context.

## **5.5 Conclusions on the Use of Heuristics for Bioenergy Flowsheet Development**

The conclusions drawn from testing the Rossiter level 3, 4 and 6 heuristics in this case study are:

### The heuristics address the use of a hazardous material

Dilute sulphuric acid ( $H_2SO_4$ ) is used in the hydrolysis stage which creates waste and environmental problems. This is addressed by the heuristics, which is considered a strength. The heuristics, in conjunction with the hierarchical approach, were able to address the use of a hazardous material

### The heuristics have options generating potential

The level 3 heuristics of Rossiter guide the design of the bio-energy system, and in some instances, the heuristics proved to be options generating, specifically in the pre-treatment stage.

The overall view is that the heuristics were able to identify weaknesses within a design, and provoke thought for changes. In a broad sense, an experienced designer would find the heuristics options generating by stimulating thought for creative alternatives.

### Waste materials are clearly identified.

The heuristics identify waste streams early in the analysis and then attempt to eliminate them. This is a powerful tool to address waste issues.

### Primary Product Selection Changes the Process

Flowsheet modifications yield different amounts of the two products. The choice remains as to which is the primary product. This choice has implications for the process routes employed. The heuristics employed did not, however, deal with multi-product systems and this is seen as a weakness.

### Hierarchical design is a powerful tool

The level 3, 4 and 6 analyses proved helpful in producing a number of possible amendments to the modeled flowsheet as well as identifying wastes. The supplementary hierarchical approach was very powerful in determining the value of the process. This approach has merits in choosing between options or screening process alternatives.

### No Clear Evidence that the Enzyme Process is Favored over Dilute Acid Hydrolysis

The intuition that a biological process would indeed be a better option was hinted at with the use of heuristics. The neutralization step pointed the design away from acid use; coupled with the loss of product in the resulting gypsum waste stream, this called for a process change. This was identified by the use of a supplementary approach.

### Combination of Heuristics is Needed

The Rossiter heuristics showed value in identifying wastes and suggesting to the designer alternative routes and processes, but further analysis is needed in conjunction with the Rossiter approach in order address the limitations, where problem areas are identified but no sufficient explicit guidance to come up with alternatives is given.

## **Chapter 6: Conclusions and Recommendations**

The dissertation set out to prove the hypothesis that advances in process systems engineering could be applied to bioenergy systems within the agricultural sector to add value as well as create more efficient processes. In this final chapter, the findings will be summarized, conclusions drawn and recommendations presented. The chapter starts by summarizing the findings of the literature study and then proceeds to summarize the results of the two case studies.

### **6.1 Conclusions Drawn from Literature**

The endeavor to reach a more sustainable method of operation has prompted a myriad of changes in the field of process systems engineering over the last decade. Design engineers now have a social and professional responsibility to incorporate environmental concerns up front in a design.

#### **6.1.1 Process Systems Engineering**

The scope of process systems design has significantly expanded, and the systems under study include more than just recycle and separation. Also, within the expanded boundaries under consideration, the designer needs to address potential environmental impacts rather than merely consider concentrations or mass loads of key pollutants.

The fact that aggregated scores of potential impacts are under consideration within broad system boundaries has prompted the use of Life Cycle Assessment, and more specifically Life Cycle Impact Assessment, at various stages in the design cycle, most notably in the early design phase as a screening tool for ranking alternatives.

The choice between product or process alternatives often needs careful evaluation. The development of tools that can consider many criteria became apparent with the advent of increased computer power and the progression of mathematical programming. Setting up and solving of complex objective functions with multiple criteria became possible. The extension to this was the advance of addressing multiple competing objectives simultaneously in the field

of multi-objective optimisation. Environmental concerns can now be addressed concurrently with the more traditional economic objectives.

### **6.1.2 Bio-Energy Systems**

The renewable contribution to energy provision, globally, is small. This is set to change however as the replacement of fossil fuel derived energy products gathers momentum. The plan to implement new fuels to the energy sector is a global initiative of which South Africa is a part. The inherent environmental benefits of bio-fuels have been recognized.

The advancement of the bioenergy sector has come about rapidly. A change in political priorities coupled with the fact that all fossil fuel derived products can, potentially, be obtained from biomass sources places the bioenergy sector in a very good position.

The agricultural sector in South Africa has the potential to provide biomass feedstocks for further processing, specifically the sugar industry, where the infrastructure is already in place to convert biomass to energy, albeit at a low efficiency. The processing of bagasse (biomass) to liquid fuels is a lesser alternative. A biological process is suited to this residue due to the high moisture content and needs evaluation.

The recent rise of the bioenergy field has not been followed by traditional process systems engineering development. While generic design methods are largely applicable, there is no direct literature pertaining to design rules or tools for this new bio-technology field.

The case studies were then selected to validate the claims selected from various literature sources and to answer the key questions.

## **6.2 Conclusions from Case 1**

The value, strengths, and weaknesses of LCA in the context of conceptual design were explored. Two proposed bioenergy alternatives, utilizing agricultural residues, were compared against a base case of current sugar production. The two systems, 'green' electricity and bio-ethanol, were then evaluated with respect to environmental performance using selected midpoint indicators.

The applicability of LCA at concept design level as a screening tool are apparent from the case study. Even at the early design stage, environmentally poorly performing products or processes can be eliminated as an option. Informed choices between competing processes and products can be drawn.

Uncertainty in sections of the design is inherently highlighted by the LCA. All areas of concern are noted for better modeling, new data sources, geographical locations and the like. The framework used in LCA expressly shows this.

Conceptual engineering as a science has developed to a decidedly structured field. The broadening of system boundaries in the design prescribes to a life cycle approach, and the use of LCA in this design phase is a logical progression.

The use of LCIA in the conceptual design phase was able to inform trends of environmental performance with the midpoint indicators selected. The analysis of performance was used to screen the discrete alternatives.

As a final conclusion from case 1, it can be noted that the net carbon emissions of a renewable energy system remains one of the biggest motivating factors for its development. The use of LCA was able to highlight the benefit of a bioenergy system by accounting for the uptake as well as the release of the carbon.

### **6.3 Conclusions from Case 2**

The second case study investigated the extended flowsheet heuristics that have developed as a specific response to the needs identified for waste minimization. The previous case study revealed a potential biomass feedstock for further processing to ethanol. The structuring of a better flowsheet, and the support these extensions can offer, was examined.

The ability to generate options by applying structured questions to identified sections of a primitive design flowsheet showed potential for the bioenergy system chosen. Direct options generation was not clear however. The heuristics employed served to highlight weaknesses in the design. An experienced designer would be able to employ these heuristics to generate creative process alternatives.

The hierarchical approach of Douglas, used in a supplementary fashion in this case study, proved powerful in determining the value of a process. This dual approach used, served to choose between or screen discrete process alternatives.

Multi-product systems are becoming more common and the heuristics did not adequately deal with this situation. Flexibility of a plant to adjust to fluctuating demand for products is vital in competitive markets, but the environmental dimensions of production changes need to be understood as well.

At the outset of this case study, it was postulated that the emerging biological process will be more effective than the chemical process. The shaping of the flowsheet with the aid of the heuristics did not expressly yield this result. Whilst the initial design solution was shown to have opportunities for improvement, none of the questioning explicitly prompted the use of a biological process. Again, the supplementary route was more favourable for prompting a process change.

In conclusion, the Rossiter (1993) heuristics showed value in identifying wastes and suggesting to the designer alternative routes and processes, but further analysis is needed in conjunction with the Rossiter approach in order to address the limitations shown.

## 6.4 Key Questions Revisited

The key questions framed in Chapter 1 will now be revisited with respect to the findings in the dissertation.

### 6.4.1 Possible Contributions of Modern Bio-Energy

- *To what extent can the processing of crop residues into modern energy carriers contribute to meeting energy supply?*

The share of renewable energy in the energy mix in many countries is increasing. The medium term targets in South Africa are modest and attainable. Crop residues are relatively abundant and cheap, and can therefore aid the transition to renewable resources by providing a multitude of biomass derived products. Having satisfied mill requirements the 'free' bagasse would be able to produce 6.9 MWh of 'green' electricity per hectare of sugar cane farmed. The alternative system, bio-ethanol for the transportation sector, would produce 1.2kl of ethanol as well as 2 MWh of 'green' electricity per hectare.

### 6.4.2 Options Generating Tools

- *What tools have been developed for generating various product and process options?*

Hierarchical decision procedures and methods of structured thinking have been part of design methodologies for a long time now. These methods have developed over time to address environmental concerns and generate cleaner process options by putting forward questions the design must answer. The response to the questions generates different processing options. The Rossiter heuristics for waste minimization provided a 7 level hierarchy, with each level requiring more data, where questions are posed to aid the designer generate process alternatives. This in conjunction with Douglas' (1992) hierarchical approach appeared to be valuable, in the bioenergy sector, in creating cleaner, more efficient process flowsheets.

### 6.4.3 Options Screening and Assessing Tools

- *What tools are available for assessing the various process and product options that could be generated?*

Assessment techniques have developed to provide accurate information for a designer, from which informed decisions can be made. The emergence of LCA as an assessment tool has become more widespread. The advancement of process simulators to generate accurate information has led to assessment becoming easier for the designer. The modeling of complex systems has therefore become more accurate, providing data for LCA type analyses where data quality is critical.

- *What tools are available for the screening of the product and process options generated?*

LCA in bioenergy product development was a valuable assessment tool, where flows in a system can be monitored and compared. LCIA has emerged as a screening tool for products and processes, where the selection of midpoint indicators yields potential impacts based on certain criteria, from which options can be ranked accordingly.

## 6.5 Concluding Statement

The hypothesis developed at the outset of this dissertation was:

- *Selected recent advances in the process systems engineering sector applied to the design of bioenergy systems can aid the agricultural processing industry in maximizing the value added by utilisation of crop residues, by enabling designers to create more efficient processes.*

Having presented the literature review pertaining to the topic the hypothesis was reframed to yield, firstly:

- *Application of Life Cycle Assessment at a Concept Design stage will show that producing a liquid fuel from biomass residue, namely ethanol via hydrolysis of bagasse to sugars followed by fermentation, represents an energetically and environmentally superior utilisation of this crop residue than conversion via heat and steam to electricity.*

The bio-ethanol system outperformed the green electricity system in three out of the six midpoint indicators chosen, and the overall indicator used. The conversion efficiency of the proposed combustion of the bagasse for electricity was poor. Whilst it cannot be concluded from the case study that the bio-ethanol system is a better option environmentally and energetically than the green electricity system, the illustrative application of life cycle assessment at this stage of the design has showed how this tool can be used to guide process designers to select more efficient processes.

Further,

- *The application of recently developed process design heuristics for environmentally conscious design to an ethanol from bagasse flowsheet will identify opportunities for more efficient processing, thus generating more value to the sugar industry.*

The heuristics proved useful for stimulating options development for the further processing of bagasse to ethanol process. The heuristics did not, however, explicitly guide the design towards the 'better' biological option. Heuristics are gained from experience and this will guide the development of further heuristics in the bio-energy field as it matures in the future. Nevertheless, any process improvements derived from the application of these new heuristics should be translating to more efficient processing, and thus should contribute to maximizing value-addition in this industry.

There is therefore an appeal that can be made from the conclusions discussed above, where an attitude change from all process designers is needed to embrace environmentally conscious process design. This includes all facets of design from concept to closure.

## **6.6 Recommendations**

Following the conclusions drawn from the dissertation, the subsequent recommendations are offered:

- There is great value in using LCA and LCIA in conceptual engineering. There is a need for more widespread use of these screening and analysis tools in the context of bioenergy.
- Heuristics dealing with multi-product systems must be developed, especially if the integrated bio-refinery proposed by Lynd (1996) is to be a key feature of future biomass processing.
- The use of biomass derived liquid fuels in South Africa needs to be explored further. The opportunity to supplement the liquid fuels market with 'cleaner' alternatives is very real. This would also contribute to the renewable energy targets that have been proposed.
- Additional work in the field of PSE, with respect to bio-energy systems, is needed. Currently there is little literature pertaining to bio-energy process systems engineering. This field has shown great potential, and hence PSE applications should be valuable in helping to realize superior design outcomes for future process plant.

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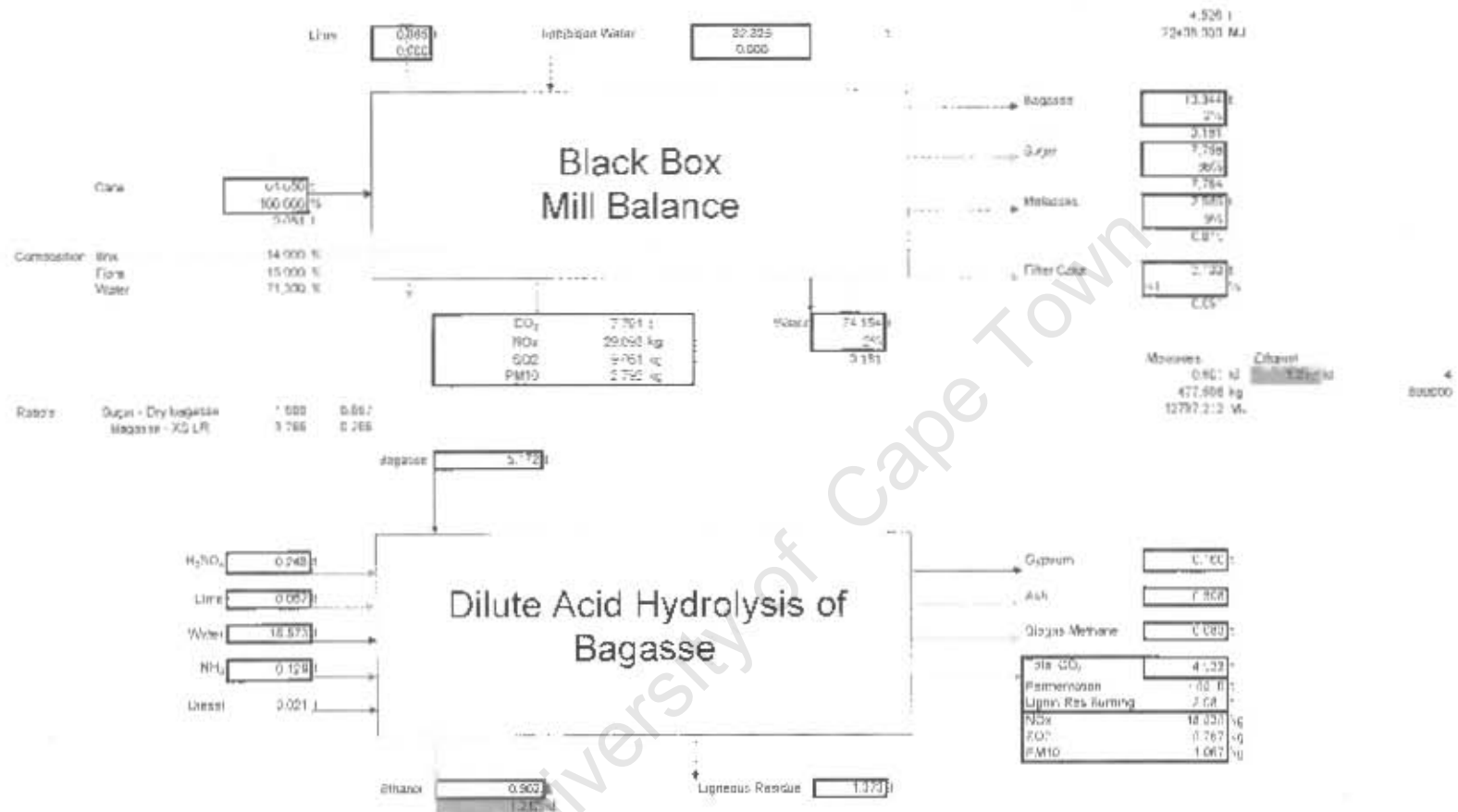
## Appendix 1: Scale Figures Used for Comparative Purposes

Electricity	34852	kWh	*	3.06E+11	kWh	
	3.15E+07			305566	GWh	
	1.10E+12	MJ		9.23E+10	kg Coal for e	
	1150	PJ		2743.91	PJ	
	83.09%	% Coal		274		
SA Energy	5.54E+15	BTU	7	1.62E+12	kWh	
	5.84E+18	J		1.62E+06	GWh	
	5.54E+00	EJ				
SA Liquid Fuels	786031	Paraffin	m <sup>3</sup>	1.6	Paraffin	PJ
	10340000	Petro	m <sup>3</sup>	320.1	Petrol	PJ
	6490002	Diesel	m <sup>3</sup>	241.0	Diese-	PJ
				502.7		
Coal	1.54E+11	Coal	kg	1.54E+11	2.13E+07	BTU
	6.50E+03	LHV	Kcal/g			
	1.00E+15	Cr.		51.43%	2.25E+07	kJ/l
	4195.23	PJ			22.47	MJ/kg
Crop Residue Conversion	1.57E+06	Bagasse	kg			
Bagasse	8.02E+09	Ethanol	kg	8.37E+09	Solar Feed	kg
	50.37	kg/lue s	PJ	50.97	Hes.	PJ
	8.55%			20.38006908	Prob	PJ
				1.84%		
	Ratio	0.20		2.27E+06		
Cereals	1.50E+10	Cereal Residue	kg			
	2.40E+11		Mt			
	240	Avail	PJ			
	36	Prob	PJ			
Comparison - India and Brazil	India			Brazil		
	4.2E+10	Bagasse	kg	4.3E+10	Bagasse	kg
6.64E+11		MJ	7.2E+11		MJ	
354		PJ	298		PJ	
273.6	22.2%	PJ	298	2% S&S	PJ	

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Appendix 2: Input / Output Analysis



Energy Bal	24,270 t	Out	7,508 t	47% % C	1800 MJ/t
	59628 MJ		66190 MJ		3% E Bal

In		Out	
Sugars	14282 t	Biogas Methane	0.0571 t
Dry Sol	50166 t	Lignocellulose Resid.	0.0455 t
		Phenol	0.5318 t
		CO <sub>2</sub> from ferm	0.4232 t
		CO <sub>2</sub> from burning	2.8121 t
	2.8418	0.00%	7.4455

100% CO<sub>2</sub>  
0.3

Proximate	Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	Asp
	46.50%	6.32%	42.65%	0.36%	3.17%	3.32%

Lign Res Burning	CO <sub>2</sub>	2.987 t (K) ash	
	NO <sub>x</sub>	14.713 kg	0.001
	SO <sub>x</sub>	4.577 kg	
	PM 10	0.247 kg	

S.O. consistency	62.341 kg
	62.341 kg

#### Assumptions

- 1 Kadam (2002) numbers used for dilute acid hydrolysis
- 2 Lignocellulose residue referenced value 18608 IJFM, using 18000 as a lower heating value
- 3 Energy balance over IBR uses same constituents as for Carbon balance
- 4 CO<sub>2</sub> emissions from fermentation is taken as 30% of bagasse fat, from Guzman et al, this figure can be calculated during a more detailed stage
- 5 CO<sub>2</sub> emissions from Lignocellulose residue burning are assumed to be from complete combustion of Carbon in the residue, this estimate is high
- 6 PM 10 emissions calculated using EPA documented figure assumes the use of a wet scrubber

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Appendix 3A

System: Sugar Production (base case)

Inventory: Base Case - 07-04-03

Flow	Units	Sugar Production (base case)	Diesel Oil Production	Ammonia (NH3) Production	Lime (Slaked, Ca(OH)2) Production	Electricity (South Africa, 1996) Production	Road Transport (Truck 28 t, Diesel Oil, kg.km)	Agricultural Ops	Fertilizer Production	Sugarcane Processing - Base Case
(r) Barium Sulphate (BaSO4, in ground)	kg	0.0176091	0.006375	0	1.12E-02	1.02E-08	0	0	0	0
(r) Bauxite (Al2O3, ore)	kg	0.0062131	0.00616747	0	4.40E-05	7.47E-07	0	0	0	0
(r) Bentonite (Al2O3, ASiO2.H2O, in ground)	kg	0.00196343	0.000902211	0	1.06E-03	9.68E-08	0	0	0	0
(r) Calcium Sulphate (CaSO4, ore)	kg	0.00112283	0.00112113	0	1.49E-06	0	0	0	0	0
(r) Chromium (Cr, ore)	kg	3.36E-06	1.23E-06	0	2.16E-06	1.97E-10	0	0	0	0
(r) Clay (in ground)	kg	0.0105335	0.00746783	0	2.10E-03	0.000981401	0	0	0	0
(r) Coal (in ground)	kg	6.84624	0.0231824	1.61619	3.03E-02	5.17452	0	0	0	0
(r) Copper (Cu, ore)	kg	1.72E-05	6.24E-06	0	1.10E-05	1.00E-09	0	0	0	0
(r) Gravel (unspecified)	kg	0.153425	0.153221	0	2.04E-04	0	0	0	0	0
(r) Iron (Fe, ore)	kg	0.0594058	0.0167633	0.000541008	3.31E-02	0.00700001	0	0	0	0
(r) Iron Sulphate (FeSO4, ore)	kg	0.000167605	6.96E-08	0	9.28E-11	0.000167536	0	0	0	0
(r) Lead (Pb, ore)	kg	5.36E-06	1.95E-06	0	3.43E-06	3.13E-10	0	0	0	0
(r) Lignite (in ground)	kg	0.0279076	0.0101031	0	1.78E-02	2.21E-06	0	0	0	0
(r) Limestone (CaCO3, in ground)	kg	98.811	0.0470503	0.0453094	97.862	0.856651	0	0	0	0
(r) Manganese (Mn, ore)	kg	1.87E-06	7.14E-07	0	1.26E-06	1.15E-10	0	0	0	0
(r) Natural Gas (in ground)	kg	63.2247	4.69841	51.3162	6.92149	0.0885875	0	0	0	0
(r) Nickel (Ni, ore)	kg	1.15E-06	4.15E-07	0	7.31E-07	8.67E-11	0	0	0	0
(r) Oil (in ground)	kg	212.054	211.525	0.210382	0.30345	0.0149671	0	0	0	0
(r) Pyrite (FeS2, ore)	kg	0.0262234	0.0102177	0	1.90E-02	1.84E-06	0	0	0	0
(r) Sand (in ground)	kg	0.00347672	0.00268885	0	3.34E-04	0.000453515	0	0	0	0
(r) Silver (Ag, ore)	kg	8.54E-06	3.09E-06	0	5.45E-08	4.97E-12	0	0	0	0
(r) Sodium Chloride (NaCl, in ground or in sea)	kg	0.0274844	0.0280501	0.243453	1.16E-04	0.00322426	0	0	0	0
(r) Sulphur (S, in ground)	kg	0.0266448	0	0.0266448	0	0	0	0	0	0
(r) Uranium (U, ore)	kg	0.000184655	3.64E-07	0.00016663	6.41E-07	1.70E-05	0	0	0	0
(r) Zinc (Zn, ore)	kg	1.25E-07	4.53E-08	0	7.99E-08	7.29E-12	0	0	0	0
Ammonia (NH3)	kg	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0	0	67.626	0
Diesel Oil	kg	0	0	0	0.00E+00	0	138.998	61.4434	0	0
Electricity	MJ elec	22.7773	10.46	0	0	0	0	0	0	0
Explosive (unspecified)	kg	5.57E-06	8.13E-07	0	1.05E-09	4.75E-06	0	0	0	0
Fertiliser	kg	0.00E+00	0.00E+00	0	0.00E+00	0	0	426.044	0	0
Iron Scrap	kg	0.176893	0.174857	0	2.33E-04	0.00100276	0	0	0	0
Land Use (II -> III)	m2a	0.000316019	0.000315598	0	4.20E-07	0	0	0	0	0
Land Use (II -> IV)	m2a	0.000384771	0.000384259	0	5.12E-07	0	0	0	0	0
Land Use (III -> IV)	m2a	10000.1	4.35E-07	0	5.60E-10	0	0	10000.1	0	0
Lime (slaked, Ca(OH)2)	kg	0	0	0	0.00E+00	0	0	0	0	64.65
Raw Materials (unspecified)	kg	0.397253	0.158032	0	2.11E-04	2.39E-01	0	0	0	0
Sugarcane	t	0	0	0	0.00E+00	0.00E+00	0	0	0	64.65
Transport: Road (diesel oil, kg.km)	kg.km	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0	0	0	3.23E+06
Water Used (total)	litre	1641.02	8.67E+02	743.885	1.95E+01	10.9785	0	0	0	0
Water: Public Network	litre	743.885	0	743.885	0.00E+00	0.00E+00	0	0	0	0
Water: Unspecified Origin	litre	897.125	886.708	0	19.4501	10.9677	0	0	0	0
Wood	kg	0.0271974	0.00235093	0	2.93E-04	0.0271679	0	0	0	0
(a) Acetaldehyde (CH3CHO)	g	4.84E-04	1.67E-04	0	2.93E-04	3.94E-04	0	0	0	0
(a) Acetic Acid (CH3COOH)	g	0.0651444	0.0235127	0	4.16E-02	1.78E-05	0	0	0	0
(a) Acetone (CH3COCH3)	g	8.24E-05	2.94E-05	0	4.94E-05	3.70E-05	0	0	0	0
(a) Acetylene (C2H2)	g	0.0465759	1.94E-05	0	2.58E-08	0.0465566	0	0	0	0
(a) Aldehyde (unspecified)	g	2.61E-03	2.32E-03	0	1.50E-04	1.35E-04	0	0	0	0
(a) Alkane (unspecified)	g	5.26073	4.41E+00	0	8.06E-01	4.30E-02	0	0	0	0
(a) Alkene (unspecified)	g	0.0492939	0.00100317	0	1.73E-03	0.0485576	0	0	0	0
(a) Alkyne (unspecified)	g	2.67E-05	1.04E-05	0	1.83E-05	1.67E-09	0	0	0	0
(a) Aluminium (Al)	g	8.96E-01	8.07E-04	0	7.66E-04	8.94E-01	0	0	0	0
(a) Ammonia (NH3)	g	0.0699198	0.00453185	0.067626	3.04E-04	0.0174585	0	0	0	0
(a) Antimony (Sb)	g	0.00017256	7.17E-08	0	9.55E-11	1.72E-04	0	0	0	0
(a) AOX (Adsorbable Organic Halogens)	g	7.46E-13	3.10E-16	0	4.13E-19	7.46E-13	0	0	0	0
(a) Aromatic Hydrocarbons (unspecified)	g	0.0338169	1.73E-06	0.033813	2.31E-09	4.19E-06	0	0	0	0
(a) Arsenic (As)	g	0.00486146	3.12E-03	0	1.24E-05	0.00172858	0	0	0	0
(a) Barium (Ba)	g	0.0107424	1.05E-05	0	1.06E-05	0.0107213	0	0	0	0
(a) Benzaldehyde (C6H5CHO)	g	5.19E-09	1.89E-09	0	3.31E-08	3.02E-13	0	0	0	0
(a) Benzene (C6H6)	g	1.80825	1.58249	0	1.13E-01	8.34E-02	0.138998	0	0	0
(a) Benzofluorene (C20H12)	g	0.000855709	1.19E-05	0	5.50E-06	1.43E-04	0.000694988	0	0	0
(a) Beryllium (Be)	g	1.76E-04	9.69E-08	0	4.57E-08	1.76E-04	0	0	0	0
(a) Boron (B)	g	0.0855031	0.000245046	0	3.71E-04	0.0848868	0	0	0	0
(a) Bromium (Br)	g	0.0170403	2.73E-05	0	3.56E-05	0.0169774	0	0	0	0
(a) Butane (n-C4H10)	g	1.59E+01	1.58E+01	0	2.69E-01	1.54E-03	0	0	0	0
(a) Butene (1-C4H8CH2CHCH2)	g	0.380113	0.379515	0	5.81E-04	1.78E-05	0	0	0	0
(a) Cadmium (Cd)	g	0.0147021	0.00779156	0	2.29E-06	9.84E-06	0.00678825	0	0	0
(a) Calcium (Ca)	g	0.137383	0.0263165	0	1.85E-03	0.107215	0	0	0	0
(a) Carbon Dioxide (CO2, fossil)	g	706616	58996.1	142015	60734.70	8513.31	0	0	0	0
(a) Carbon Dioxide (CO2, green)	g	1.67E+07	0	0	0.00E+00	0	436388	0	0	1.67E+07
(a) Carbon Monoxide (CO)	g	1270.02	3.70E+01	3.3613	9.85E+00	11.0112	1208.96	0	0	0
(a) Carbon Tetrafluoride (CF4)	g	4.17E-06	1.51E-06	0	2.66E-06	2.43E-10	0	0	0	0



(ar) Uranium (U238)	HBa	3.53E-07	3.52E-07	0	4.69E-10	0.00E+00	0	0	0	0
(s) Aluminium (Al)	g	2.25E-01	8.14E-02	0	1.43E-01	1.31E-05	0	0	0	0
(s) Arsenic (As)	g	8.98E-05	3.25E-05	0	5.73E-05	5.23E-09	0	0	0	0
(s) Cadmium (Cd)	g	4.06E-08	1.47E-08	0	2.59E-08	2.36E-12	0	0	0	0
(s) Calcium (Ca)	g	0.699062	0.325125	0	5.73E-01	5.23E-05	0	0	0	0
(s) Carbon (C)	g	6.74E-01	2.44E-01	0	4.30E-01	3.92E-05	0	0	0	0
(s) Chromium (Cr III, Cr VI)	g	1.12E-03	4.07E-04	0	7.17E-04	6.54E-08	0	0	0	0
(s) Cobalt (Co)	g	4.12E-08	1.49E-08	0	2.63E-08	2.40E-12	0	0	0	0
(s) Copper (Cu)	g	2.06E-07	7.47E-08	0	1.32E-07	1.20E-11	0	0	0	0
(s) Iron (Fe)	g	0.448908	0.162518	0	2.86E-01	2.61E-05	0	0	0	0
(s) Lead (Pb)	g	9.43E-07	3.41E-07	0	6.02E-07	5.49E-11	0	0	0	0
(s) Manganese (Mn)	g	0.00898062	0.00325125	0	5.73E-03	5.23E-07	0	0	0	0
(s) Mercury (Hg)	g	7.48E-09	2.71E-09	0	4.77E-09	4.36E-13	0	0	0	0
(s) Nickel (Ni)	g	3.10E-07	1.12E-07	0	1.90E-07	1.80E-11	0	0	0	0
(s) Nitrogen (N)	g	3.52E-06	1.27E-06	0	2.24E-06	2.05E-10	0	0	0	0
(s) Oils (unspecified)	g	0.00133354	0.00349276	0	6.51E-04	7.76E-09	0	0	0	0
(s) Phosphorus (P)	g	0.0112442	0.00407073	0	7.17E-03	6.54E-07	0	0	0	0
(s) Sulphur (S)	g	0.134716	0.0487713	0	6.59E-02	7.84E-06	0	0	0	0
(s) Zinc (Zn)	g	0.00337508	0.00122168	0	2.15E-03	1.96E-07	0	0	0	0
(w) Acids (H+)	g	0.0389042	0.00348773	0.033613	6.34E-05	0.00154015	0	0	0	0
(w) Aldehyde (unspecified)	g	9.62E-05	3.48E-05	0	6.13E-05	0.00E+00	0	0	0	0
(w) Alkane (unspecified)	g	2.7101	2.70479	0	5.19E-03	1.27E-04	0	0	0	0
(w) Alkene (unspecified)	g	0.250158	0.249660	0	4.77E-04	1.17E-05	0	0	0	0
(w) Aluminium (Al3+)	g	0.170128	0.0837007	0	8.95E-02	1.69E-02	0	0	0	0
(w) Ammonia (NH4+ NH3, as N)	g	17.8439	17.7376	0.033613	2.55E-02	4.69E-02	0	0	0	0
(w) AOX (Adsorbable Organic Halogens)	g	0.0442247	0.0441581	0	6.45E-05	2.05E-09	0	0	0	0
(w) Aromatic Hydrocarbons (unspecified)	g	10.8483	10.8219	0	2.57E-02	6.75E-04	0	0	0	0
(w) Arsenic (As3+ As5+)	g	0.00887795	0.00872138	0	1.49E-04	7.89E-06	0	0	0	0
(w) Barium (Ba++)	g	52.1723	52.09	0	7.99E-02	0.00248916	0	0	0	0
(w) Barytes	g	3.19E+00	1.15328	0	2.03E+00	1.85E-04	0	0	0	0
(w) Benzene (C6H6)	g	2.71095	2.70563	0	5.19E-03	1.27E-04	0	0	0	0
(w) BOD5 (Biochemical Oxygen Demand)	g	0.98926	0.945455	0.033613	9.86E-03	1.34E-04	0	0	0	0
(w) Borel (B III)	g	3.38E-01	3.37E-01	0	6.49E-04	1.58E-05	0	0	0	0
(w) Cadmium (Cd++)	g	0.0148054	0.0145753	0	2.81E-05	2.02E-06	0	0	0	0
(w) Calcium (Ca++)	g	670.139	668.595	0	1.51E+00	3.25E-02	0	0	0	0
(w) Cerium (Ce++)	g	2.08E-02	2.08E-02	0	0.00E+00	0.00E+00	0	0	0	0
(w) Cesium (Cs++)	g	2.86E-05	0.00E+00	0	2.77E-05	9.73E-07	0	0	0	0
(w) Chlorides (Cl-)	g	10807.5	10740.8	8.15368	16.331	44.2337	0	0	0	0
(w) Chlorinated Matter (unspecified, as Cl)	g	0.585603	0.183369	0	3.23E-01	2.95E-05	0	0	0	0
(w) Chloroform (CHCl3)	g	5.43E-07	1.67E-07	0	3.47E-07	3.18E-11	0	0	0	0
(w) Chromium (Cr III)	g	0.00236029	0.000854895	0	1.51E-03	1.37E-07	0	0	0	0
(w) Chromium (Cr III, Cr VI)	g	0.0503283	0.0502415	0	6.69E-05	1.79E-05	0	0	0	0
(w) Chromium (Cr VI)	g	4.43E-06	1.61E-06	0	2.63E-08	2.58E-12	0	0	0	0
(w) Cobalt (Co I, Co II, Co III)	g	1.46E-04	5.28E-05	0	9.30E-05	8.48E-09	0	0	0	0
(w) COD (Chemical Oxygen Demand)	g	3.14E+01	3.13E+01	0.033613	1.44E-01	1.80E-03	0	0	0	0
(w) Copper (Cu+ Cu++)	g	3.00E-02	2.96E-02	0	3.69E-04	4.97E-06	0	0	0	0
(w) Cyanides (CN-)	g	0.0850742	4.44E-02	0.033613	2.01E-04	6.70E-03	0	0	0	0
(w) Dissolved Matter (unspecified)	g	4.04E+00	7.21E-01	0.033613	2.63E-02	3.2587	0	0	0	0
(w) Dissolved Organic Carbon (DOC)	g	1.79E-01	6.49E-02	0	1.14E-01	1.05E-05	0	0	0	0
(w) Ethylbenzene (C6H5C2H5)	g	0.500074	0.499362	0	6.88E-04	2.34E-05	0	0	0	0
(w) Fluorides (F-)	g	0.280381	0.21825	0.033613	1.83E-02	9.97E-03	0	0	0	0
(w) Formaldehyde (CH2O)	g	6.86E-09	2.49E-09	0	4.39E-09	4.01E-13	0	0	0	0
(w) Hexachloroethane (C2Cl6)	g	9.58E-13	3.47E-13	0	6.11E-13	5.58E-17	0	0	0	0
(w) Hydrocarbons (unspecified)	g	0.0339142	5.49E-05	0.033613	3.92E-05	7.11E-06	0	0	0	0
(w) Hypochlorite (ClO-)	g	1.63E-04	5.91E-05	0	1.04E-04	0	0	0	0	0
(w) Hypochlorous Acid (HClO)	g	1.63E-04	5.91E-05	0	1.04E-04	0.00E+00	0	0	0	0
(w) Inorganic Dissolved Matter (unspecified)	g	0.00204385	0.00170178	0	2.18E-05	0.000320058	0	0	0	0
(w) Iode (I-)	g	2.06279	2.07991	0	2.78E-03	9.74E-05	0	0	0	0
(w) Iron (Fe++ Fe3+)	g	2.67896	2.59091	0.033613	7.08E-02	1.33E-02	0	0	0	0
(w) Lead (Pb++ Pb4+)	g	0.0442327	0.00817145	0.033613	9.42E-04	0.000326582	0	0	0	0
(w) Magnesium (Mg++)	g	17.4046	17.3203	0	8.16E-02	0.00275553	0	0	0	0
(w) Manganese (Mn II, Mn IV, Mn VII)	g	1.01E+00	1.00E+00	0	2.99E-03	4.23E-03	0	0	0	0
(w) Mercury (Hg+ Hg++)	g	8.88E-05	8.84E-05	0	1.15E-07	6.73E-09	0	0	0	0
(w) Metals (unspecified)	g	0.055075	0.00128789	0.033613	1.15E-05	0.00039517	0	0	0	0
(w) Methylene Chloride (CH2Cl2)	g	0.00155692	0.00056365	0	9.93E-04	9.06E-08	0	0	0	0
(w) Molybdenum (Mo II, Mo III, Mo IV, Mo V, Mo VI)	g	0.00869073	0.00864353	0	1.15E-05	3.57E-05	0	0	0	0
(w) Nickel (Ni++ Ni3+)	g	0.0511984	5.04E-02	0	4.22E-04	3.33E-04	0	0	0	0
(w) Nitrates (NO3-)	g	31.2703	31.2253	0	4.29E-02	2.15E-03	0	0	0	0
(w) Nitrites (NO2-)	g	4.05E-05	1.47E-05	0	2.58E-05	2.36E-09	0	0	0	0
(w) Nitrogenous Matter (Kjeldahl, as N)	g	0.000184938	0	0	0.00E+00	1.85E-04	0	0	0	0
(w) Nitrogenous Matter (unspecified, as N)	g	4.47787	4.44E+00	0.033613	8.17E-03	0.000237038	0	0	0	0
(w) Oils (unspecified)	g	17.8673	17.6189	0.033613	3.14E-01	3.06E-03	0	0	0	0
(w) Organic Dissolved Matter (chlorinated)	g	0.033613	0	0.033613	0	0	0	0	0	0
(w) Organic Dissolved Matter (unspecified)	g	0.0339118	2.28E-05	0.033613	3.92E-05	3.69E-05	0	0	0	0
(w) Phenol (C6H5OH)	g	2.44463	2.40587	0.033613	4.83E-03	1.16E-04	0	0	0	0
(w) Phosphates (PO4 3-, HPO4--, H2PO4-, H3PO4, as P)	g	0.00131114	0.000472469	0	8.33E-04	6.10E-06	0	0	0	0
(w) Phosphorus (P)	g	0.0866171	0.088458	0	1.55E-04	4.05E-06	0	0	0	0
(w) Phosphorus Pentoxide (P2O5)	g	0.000159896	6.84E-08	0	8.85E-11	1.60E-04	0	0	0	0
(w) Polycyclic Aromatic Hydrocarbons (PAH, unspecified)	g	0.270831	0.270395	0	3.73E-04	6.29E-05	0	0	0	0

(w) Potassium (K+)	g	92.0331	91.8639	0	0.164938	0.00430907	0	0	0
(w) Rubidium (Rb+)	g	0.208276	0.207898	0	2.77E-04	6.74E-06	0	0	0
(w) Salts (unspecified)	g	0.153485	0.0222315	0	3.91E-02	0.0821463	0	0	0
(w) Saponifiable Oils and Fats	g	101.64	101.5	0	1.35E-01	4.76E-03	0	0	0
(w) Selenium (Se II, Se IV, Se VI)	g	8.89E-03	8.84E-03	0	1.15E-05	3.11E-05	0	0	0
(w) Silicon Dioxide (SiO2)	g	5.58E-04	2.02E-04	0	3.58E-04	3.25E-08	0	0	0
(w) Silver (Ag+)	g	0.0124968	0.0124794	0	1.86E-05	5.85E-07	0	0	0
(w) Sodium (Na+)	g	6.51E+03	8.49E+03	0.846763	9.32E+00	2.57E+00	0	0	0
(w) Strontium (Sr II)	g	1.25E+02	1.25E+02	0	1.74E-01	2.20E-02	0	0	0
(w) Sulphates (SO4-)	g	1.78E+02	173.218	0.811511	1.06598	2.78E+00	0	0	0
(w) Sulphides (S-)	g	0.33783	0.337328	0	4.84E-04	1.71E-05	0	0	0
(w) Sulphites (SO3-)	g	3.85E-08	9.71E-07	0	1.71E-08	1.17E-06	0	0	0
(w) Sulphurated Matter (unspecified, as S)	g	4.12E-08	3.92E-08	0	5.23E-08	1.89E-07	0	0	0
(w) Suspended Matter (unspecified)	g	1.89E+01	4.98E+00	4.73382	7.14E+00	9.32E-02	0	0	0
(w) Tars (unspecified)	g	1.74E-08	1.74E-08	0	2.32E-08	7.80E-11	0	0	0
(w) Tetrachloroethylene (C2Cl4)	g	2.34E-09	8.48E-10	0	1.49E-09	1.93E-13	0	0	0
(w) Tin (Sn++ Sn4+)	g	1.09E-07	0	0	0.00E+00	1.09E-07	0	0	0
(w) Titanium (Ti+ Ti4+)	g	0.00587722	0.00212089	0	3.74E-03	1.93E-05	0	0	0
(w) TOC (Total Organic Carbon)	g	154.897	152.853	0	1.94E+00	0.00721886	0	0	0
(w) Toluene (C6H5CH3)	g	2.2526	2.24806	0	4.43E-03	1.05E-04	0	0	0
(w) Trichloroethane (1,1,1-CH3CCl3)	g	5.28E-09	1.91E-09	0	3.37E-09	3.07E-13	0	0	0
(w) Trichloroethylene (C2HCl3)	g	1.45E-07	5.28E-08	0	9.27E-08	8.46E-12	0	0	0
(w) Triethylene Glycol (C8H14O4)	g	1.79E-01	6.49E-02	0	1.14E-01	1.04E-05	0	0	0
(w) Vanadium (V3+ V5+)	g	0.00877562	0.00864353	0	1.15E-05	1.21E-04	0	0	0
(w) VOC (Volatile Organic Compounds)	g	7.27624	7.26822	0	9.88E-03	0.000340413	0	0	0
(w) Water (unspecified)	litre	5.04887	0.0123961	0	1.85E-05	5.03E+00	0	0	0
(w) Water, Chemically Polluted	litre	35.7119	35.8071	0	4.74E-02	0.0573953	0	0	0
(w) Xylene (C6H4(CH3)2)	g	19.5807	19.5526	0	2.72E-02	0.000916084	0	0	0
(w) Zinc (Zn++)	g	0.0910175	0.0879242	0	2.74E-03	0.000354868	0	0	0
(wr) Radioactive Substance (unspecified)	kBq	3.00E-07	1.25E-10	0	1.86E-13	3.00E-07	0	0	0
(wr) Radium (Ra224)	kBq	1.04E+00	1.03995	0	1.39E-03	4.87E-05	0	0	0
(wr) Radium (Ra226)	kBq	2.23357	2.07989	0	2.77E-03	0.150909	0	0	0
(wr) Radium (Ra228)	kBq	2.08278	2.07989	0.00E+00	2.77E-03	9.74E-05	0	0	0
(wr) Thorium (Th228)	kBq	4.16555	4.15981	0	5.54E-03	0.000194881	0	0	0
Ammonia (NH3)	kg	0	0.00E+00	67.628	0.00E+00	0	0	0	0
Bagasse	t	0	0	0	0.00E+00	0	0	0	0
Diesel Oil	t	0	200.441	0	0.00E+00	0	0	0	0
Electricity	kWh elec	0.00E+00	0	0	0	3.32E+01	0	0	0
Fertiliser	kg	0	0	0	0.00E+00	0.00E+00	0	426.044	0
Lime (leaked, Ca(OH)2)	kg	0	0	0	6.47E+01	0	0	0	0
Molasses	t	2.586	0	0	0.00E+00	0	0	0	2.586
Recovered Matter (total)	kg	0.0115833	0.00248982	0	3.32E-08	9.09E-03	0	0	0
Recovered Matter (unspecified)	kg	1.16E-02	2.49E-03	0	3.32E-08	9.08E-03	0	0	0
Recovered Matter: Iron Scrap	kg	9.26E-06	0	0	0	9.26E-06	0	0	0
Sugar	t	7.79E+00	0	0	0.00E+00	0.00E+00	0	0	7.758
Sugarcane	t	0	0	0	0.00E+00	0	0.00E+00	64.65	0
Transport Road (diesel oil, kg km)	kg km	0	0.00E+00	0	0.00E+00	0	3.23E+06	0	0
Waste (hazardous)	kg	0.208242	0.20737	3.38E-05	2.78E-04	0.000561838	0	0	0
Waste (incineration)	kg	0.120617	1.15E-01	0	5.89E-03	0.000176648	0	0	0
Waste (municipal and industrial)	kg	0.00181212	2.24E-05	0.00101439	1.28E-07	0.000775243	0	0	0
Waste (total)	kg	4.17588	0.880571	0.448867	8.92E-03	2.94E+00	0	0	0
Waste (unspecified)	kg	9.77E-01	0.0281415	0	3.80E-05	9.49E-01	0	0	0
Waste: Highly Radioactive (class C)	kg	2.28E-06	0	0	0.00E+00	2.28E-06	0	0	0
Waste: Low Radioactive (class A)	kg	0.127123	0.12687	0	1.69E-04	8.34E-05	0	0	0
Waste: Mineral (inert)	kg	2.35192	0.358219	0.351655	4.77E-04	1.84E+00	0	0	0
Waste: Mining	kg	0.11194	0.00E+00	0	0.00E+00	1.18E-01	0	0	0
Waste: Non Mineral (inert)	kg	0.0151352	1.51E-02	0	1.23E-05	3.90E-05	0	0	0
Waste: Non Toxic Chemicals (unspecified)	kg	0.00148888	9.26E-07	0.00148777	1.23E-05	1.85E-07	0	0	0
Waste: Radioactive	kg	2.02E-02	2.02E-02	0	0.00E+00	0.00E+00	0	0	0
Waste: Radioactive (unspecified)	kg	2.79E-05	0	0	2.70E-05	9.48E-07	0	0	0
Waste: Slags and Ash (unspecified)	kg	0.352560	1.21E-02	0.0946763	1.61E-05	0.245793	0	0	0
CM1_Air Acidification	g eq. H+	2103.419269	1.24E+01	6.25973501	8.09E-01	1.82E+00	120.8673913	0	1951.335054
(a) Ammonia (NH3)	g eq. H+	0.0052894	2.67E-04	3.98E-03	1.79E-05	1.03E-03	0	0	0
(a) Hydrogen Chloride (HCl)	g eq. H+	0.150217808	9.82E-03	2.41E-02	2.06E-04	0.116110885	0	0	0
(a) Hydrogen Fluoride (HF)	g eq. H+	9.48E-03	1.78E-03	0	5.21E-05	7.63E-03	0	0	0
(a) Hydrogen Sulphide (H2S)	g eq. H+	1.87E-02	3.55E-03	0.001989	6.26E-03	6.90E-03	0	0	0
(a) Nitrogen Oxides (NOx as NO2)	g eq. H+	1464.204348	3.12E+00	4.118369565	4.35E-01	0.427571739	120.8673913	0	1355.241304
(a) Sulphur Oxides (SOx as SO2)	g eq. H+	819.03125	9.30E+00	2.1133125	1.59E-01	1.953925	0	0	606.09375
CM1_Depletion of non renewable resources	frac. of reserve	1.39E-12	9.23E-13	4.09E-13	5.52E-14	3.82E-15	0	0	0
(r) Bauxite (Al2O3 ore)	frac. of reserve	2.22E-16	2.20E-16	0.00E+00	1.60E-18	2.87E-20	0	0	0
(r) Coal (in ground)	frac. of reserve	2.30E-15	7.78E-18	5.43E-16	1.02E-17	1.74E-15	0	0	0
(r) Copper (Cu ore)	frac. of reserve	2.82E-17	1.02E-17	0.00E+00	1.80E-17	1.64E-21	0	0	0
(r) Iron (Fe ore)	frac. of reserve	5.94E-16	1.89E-16	5.41E-18	3.31E-18	7.00E-17	0	0	0
(r) Lead (Pb ore)	frac. of reserve	4.48E-17	1.62E-17	0	2.86E-17	2.81E-21	0	0	0
(r) Manganese (Mn ore)	frac. of reserve	3.94E-19	1.43E-19	0.00E+00	2.52E-19	2.30E-23	0	0	0
(r) Natural Gas (in ground)	frac. of reserve	4.87E-13	3.77E-14	3.95E-13	5.33E-14	6.82E-16	0	0	0
(r) Nickel (Ni ore)	frac. of reserve	1.04E-17	3.77E-18	0.00E+00	8.85E-18	8.07E-22	0	0	0
(r) Oil (in ground)	frac. of reserve	8.87E-13	8.85E-13	8.80E-16	1.27E-15	6.26E-17	0	0	0

Methods

(r) Silver (Ag, ore)	frac. of reserve	2.03E-16	7.36E-17	0.00E+00	1.30E-16	1.18E-20	0	0	0	0
(r) Uranium (U, ore)	frac. of reserve	1.36E-14	2.71E-17	1.24E-14	4.78E-17	1.27E-15	0	0	0	0
(r) Zinc (Zn, ore)	frac. of reserve	3.79E-19	1.37E-19	0	2.42E-19	2.21E-23	0	0	0	0
<b>GM1_Eutrophication</b>										
(e) Ammonia (NH3)	g eq. PO4	8902.674899	29.09025481	24.05870591	2.64E+00	2.609395834	739.282461	0	0	8104.343
(e) Ammonia (NH3)	g eq. PO4	0.03147193	0.001568148	0.0236891	1.09E-04	0.006110475	0	0	0	0
(e) Nitrogen Oxides (NOx as NO2)	g eq. PO4	6.88E+03	1.86E+01	24.61589	2.60E+00	2.56E+00	772.787	0	0	8104.343
(e) Nitrous Oxide (N2O)	g eq. PO4	1.67E+01	1.70E-01	0	1.78E-02	2.62E-02	18.495461	0	0	0
(w) Ammonia (NH4+, NH3, as N)	g eq. PO4	7.49E+00	7.45E+00	0.01420146	1.07E-02	1.97E-02	0	0	0	0
(w) COD (Chemical Oxygen Demand)	g eq. PO4	6.92E-01	6.88E-01	0.000743886	3.17E-03	3.96E-05	0	0	0	0
(w) Nitrogenous Matter (Kjeldahl, as N)	g eq. PO4	7.77E-05	0.00E+00	0	0.00E+00	7.77E-05	0	0	0	0
(w) Nitrogenous Matter (unspecified, as N)	g eq. PO4	1.88E+00	1.86E+00	0.01420146	3.43E-03	9.86E-05	0	0	0	0
(w) Phosphates (PO4 3-, HPO4-, H2PO4-, H3PO4, as P)	g eq. PO4	4.01E-03	1.45E-03	0	2.55E-03	1.87E-05	0	0	0	0
(w) Phosphorus (P)	g eq. PO4	2.85E-01	2.85E-01	0	4.75E-04	1.24E-05	0	0	0	0
(w) Phosphorus Pentoxide (P2O5)	g eq. PO4	2.14E-04	8.98E-08	0.00E+00	1.18E-10	2.14E-04	0	0	0	0
<b>GM1_Human Toxicity</b>										
(a) Ammonia (NH3)	g	7.73E+04	6.70E+02	234.389529	2.31E+01	7.91E+01	4361.138615	0	0	71900.059
(a) Arsenic (As)	g	1.89E-03	9.52E-05	0.001420146	6.37E-06	3.87E-04	0	0	0	0
(a) Barium (Ba)	g	2.28E+01	1.47E+01	0	5.84E-02	8.13E+00	0	0	0	0
(a) Benzene (C6H6)	g	1.83E-02	1.78E-05	0	1.81E-05	1.82E-02	0	0	0	0
(a) Benz(a)pyrene (C20H12)	g	7.40E+00	6.17E+00	0	4.42E-01	2.47E-01	0.5420922	0	0	0
(a) Bromine (Br)	g	1.45E-02	2.03E-04	0	9.35E-05	2.44E-03	0.011814796	0	0	0
(a) Cadmium (Cd)	g	0.00056233	9.90E-07	0.00E+00	1.18E-06	5.80E-04	0	0	0	0
(a) Carbon Monoxide (CO)	g	8.53E+00	4.52E+00	0	1.33E-02	5.78E-02	3.937185	0	0	0
(a) Copper (Cu)	g	15.24024	0.4442618	0.0405756	1.18E-01	0.1321344	14.50752	0	0	0
(a) Cyanide (CN-)	g	0.003146376	2.81E-03	0	1.96E-05	3.15E-04	0	0	0	0
(a) Fluorides (F-)	g	0.000166418	3.40E-06	0	5.87E-08	1.57E-04	0	0	0	0
(a) Heptane (C7H16)	g	1.83E-02	2.05E-05	0.01623024	2.73E-08	3.90E-07	0	0	0	0
(a) Hydrogen Sulphide (H2S)	g	6.08E+00	8.07E+00	0	6.84E-03	2.84E-04	0	0	0	0
(a) Iron (Fe)	g	2.46E-01	4.71E-02	0.02637414	8.30E-02	9.16E-02	0	0	0	0
(a) Lead (Pb)	g	1.88E-02	1.70E-03	0	1.03E-04	1.50E-02	0	0	0	0
(a) Manganese (Mn)	g	1.36E+01	2.23E+00	5.41E+00	4.47E-02	1.12E+00	4.809968	0	0	0
(a) Mercury (Hg)	g	5.17E-01	1.05E-01	0	1.85E-01	2.27E-01	0	0	0	0
(a) Molybdenum (Mo)	g	8.46E-02	4.72E-02	0	6.60E-03	3.09E-02	0	0	0	0
(a) Nickel (Ni)	g	1.40E-02	1.28E-02	0	1.71E-05	1.15E-03	0	0	0	0
(a) Nitrogen Oxides (NOx as NO2)	g	7.32E+01	7.32E+01	0	2.30E-01	8.34E-01	0	0	0	0
(a) Phenol (C6H5OH)	g	5.35E+04	1.12E+02	1.48E+02	1.58E+01	1.53E+01	4336.722	0	0	48626.058
(a) Sulphur Oxides (SOx as SO2)	g	2.32E-06	8.07E-09	0	1.42E-06	1.30E-12	0	0	0	0
(a) Tin (Sn)	g	2.38E+04	3.57E+02	81.1512	6.11E+00	5.24E+01	0	0	0	23274
(a) Toluene (C6H5CH3)	g	9.59E-07	3.98E-10	0	5.31E-13	9.58E-07	0	0	0	0
(a) Vanadium (V)	g	0.09445568	9.17E-02	0.00E+00	2.29E-03	4.98E-04	0	0	0	0
(a) Xylene (C6H4(CH3)2)	g	7.53E+01	7.47E+01	0.00E+00	1.29E-01	4.31E-01	0	0	0	0
(s) Zinc (Zn)	g	3.36E+00	3.34E+00	0	5.15E-03	1.88E-02	0	0	0	0
(s) Arsenic (As)	g	6.09E-01	3.40E-04	0	3.04E-05	1.75E-04	0.6060349	0	0	0
(s) Barium (Ba++)	g	3.86E-06	1.40E-06	0	2.46E-06	2.25E-10	0	0	0	0
(s) Cadmium (Cd)	g	2.84E-07	1.03E-07	0	1.81E-07	1.66E-11	0	0	0	0
(s) Cobalt (Co)	g	2.88E-09	9.70E-10	0	1.71E-09	1.56E-13	0	0	0	0
(s) Copper (Cu)	g	0.00	3.88E-10	0	0.00	6.24E-14	0	0	0	0
(s) Lead (Pb)	g	2.36E-06	8.54E-09	0	0.00	1.37E-12	0	0	0	0
(s) Mercury (Hg)	g	1.12E-09	4.06E-10	0	7.16E-10	6.53E-14	0	0	0	0
(s) Nickel (Ni)	g	4.34E-09	1.57E-09	0	2.77E-09	2.52E-13	0	0	0	0
(s) Zinc (Zn)	g	2.36E-05	8.55E-06	0.00E+00	1.51E-05	1.37E-09	0	0	0	0
(w) Ammonia (NH4+, NH3, as N)	g	0.03033463	0.03015392	5.75E-05	4.33E-05	7.98E-05	0	0	0	0
(w) Arsenic (As3+, As5+)	g	1.24E-02	1.22E-02	0	2.08E-04	1.10E-05	0	0	0	0
(w) Barium (Ba++)	g	7.30E+00	7.29E+00	0	1.12E-02	3.46E-04	0	0	0	0
(w) Benzene (C6H6)	g	1.79E+00	1.7857158	0	3.43E-03	8.37E-05	0	0	0	0
(w) Cadmium (Cd++)	g	0.04235596	0.04226837	0	8.16E-05	5.85E-08	0	0	0	0
(w) Chromium (Cr III)	g	0.001345365	0.000487062	0	8.88E-04	7.83E-08	0	0	0	0
(w) Chromium (Cr III, Cr VI)	g	0.028685991	2.95E-02	0	3.81E-05	1.02E-05	0	0	0	0
(w) Chromium (Cr VI)	g	0.000181813	6.59E-06	0	1.16E-04	1.06E-08	0	0	0	0
(w) Cobalt (Co I, Co II, Co III)	g	0.00281516	1.05E-04	0	1.85E-04	1.70E-08	0	0	0	0
(w) Copper (Cu+, Cu++)	g	0.000600078	5.83E-04	0.00E+00	7.38E-06	9.94E-06	0	0	0	0
(w) Fluorides (F-)	g	0.011495621	0.008948283	0.001388333	7.52E-04	4.09E-04	0	0	0	0
(w) Iron (Fe++, Fe3+)	g	9.84E-03	9.22E-03	1.22E-04	2.55E-04	4.79E-05	0	0	0	0
(w) Lead (Pb++, Pb4+)	g	3.50E-02	7.25E-03	0.02671227	7.44E-04	2.58E-04	0	0	0	0
(w) Mercury (Hg+, Hg++)	g	4.07E-04	4.06E-04	0.00E+00	5.41E-07	3.16E-08	0	0	0	0
(w) Molybdenum (Mo II, Mo III, Mo IV, Mo V, Mo VI)	g	2.52E-03	2.51E-03	0	3.34E-06	1.03E-05	0	0	0	0
(w) Nickel (Ni++ Ni3+)	g	7.17E-04	7.06E-04	0.00E+00	5.91E-06	4.66E-06	0	0	0	0
(w) Ods (unspecified)	g	1.65E-02	1.62E-02	3.11E-05	2.88E-04	2.81E-06	0	0	0	0
(w) Phosphates (PO4 3-, HPO4-, H2PO4-, H3PO4, as P)	g	5.39E-06	1.94E-06	0.00E+00	3.41E-09	2.50E-10	0	0	0	0
(w) Tetrachloroethylene (C2Cl4)	g	4.22E-10	1.53E-10	0.00E+00	2.89E-10	2.45E-14	0	0	0	0
(w) Tin (Sn++, Sn4+)	g	1.52E-10	0.00E+00	0	0.00E+00	1.52E-10	0	0	0	0
(w) Xylene (C6H4(CH3)2)	g	5.68E+00	5.67E+00	0.00E+00	7.89E-03	2.68E-04	0	0	0	0
(w) Zinc (Zn++)	g	2.64E-04	2.55E-04	0	7.94E-06	1.03E-06	0	0	0	0

<b>CML_Terrestrial Eco-toxicity</b>	t	1.05E-02	3.61E-03	0.00E+00	6.71E-03	6.12E-07	0	0	0	0
(s) Arsenic (As)	t	3.23E-04	1.17E-04	0	2.06E-04	1.88E-08	0	0	0	0
(s) Cadmium (Cd)	t	5.28E-07	1.91E-07	0.00E+00	3.37E-07	3.07E-11	0	0	0	0
(s) Chromium (Cr III, Cr VI)	t	4.72E-04	1.71E-04	0	3.01E-04	2.75E-08	0	0	0	0
(s) Chromium (Cr III, Cr VI)	t	4.72E-04	1.71E-04	0.00E+00	3.01E-04	2.75E-08	0	0	0	0
(s) Chromium (Cr III, Cr VI)	t	4.72E-04	1.71E-04	0	3.01E-04	2.75E-08	0	0	0	0
(s) Cobalt (Co)	t	1.73E-08	6.27E-09	0	1.10E-08	1.01E-12	0	0	0	0
(s) Copper (Cu)	t	1.59E-07	5.75E-08	0.00E+00	1.01E-07	9.24E-12	0	0	0	0
(s) Lead (Pb)	t	4.06E-07	1.47E-07	0	2.59E-07	2.38E-11	0	0	0	0
(s) Mercury (Hg)	t	2.17E-07	7.86E-08	0.00E+00	1.38E-07	1.28E-11	0	0	0	0
(s) Nickel (Ni)	t	5.26E-07	1.91E-07	0	3.38E-07	3.08E-11	0	0	0	0
(s) Zinc (Zn)	t	8.78E-03	3.18E-03	0.00E+00	5.60E-03	5.11E-07	0	0	0	0
<b>EBIR_Depletion of non renewable resources</b>	unit	1.44E-03	9.36E-04	4.17E-04	7.84E-05	3.80E-06	0	0	0	0
(r) Barium Sulphate (BaSO4, in ground)	unit	3.67E-05	1.33E-05	0	2.34E-05	2.13E-09	0	0	0	0
(r) Bauxite (Al2O3, ore)	unit	1.83E-07	1.81E-07	0	1.32E-09	2.20E-11	0	0	0	0
(r) Chromium (Cr, ore)	unit	6.51E-10	2.36E-10	0.00E+00	4.15E-10	3.79E-14	0	0	0	0
(r) Coal (in ground)	unit	2.30E-06	7.78E-09	5.43E-07	1.02E-08	1.74E-06	0	0	0	0
(r) Copper (Cu, ore)	unit	2.65E-08	9.59E-09	0.00E+00	1.69E-08	1.54E-12	0	0	0	0
(r) Iron (Fe, ore)	unit	3.71E-07	1.17E-07	3.38E-09	2.07E-07	4.38E-08	0	0	0	0
(r) Lead (Pb, ore)	unit	3.84E-08	1.39E-08	0	2.45E-08	2.24E-12	0	0	0	0
(r) Lignite (in ground)	unit	9.36E-09	3.39E-09	0	5.97E-09	7.40E-13	0	0	0	0
(r) Manganese (Mn, ore)	unit	3.94E-10	1.43E-10	0.00E+00	2.52E-10	2.30E-14	0	0	0	0
(r) Natural Gas (in ground)	unit	4.86E-04	3.77E-05	0.0039474	5.32E-05	8.81E-07	0	0	0	0
(r) Nickel (Ni, ore)	unit	6.19E-09	2.96E-09	0.00E+00	5.22E-09	4.77E-13	0	0	0	0
(r) Oil (in ground)	unit	8.87E-04	8.85E-04	8.80E-07	1.27E-06	6.28E-08	0	0	0	0
(r) Silver (Ag, ore)	unit	2.03E-07	7.36E-08	0.00E+00	1.30E-07	1.19E-11	0	0	0	0
(r) Sulphur (S, in ground)	unit	8.02E-06	0.00E+00	8.02E-06	0.00E+00	0.00E+00	0	0	0	0
(r) Uranium (U, ore)	unit	1.38E-05	2.71E-08	1.24E-05	4.78E-08	1.27E-06	0	0	0	0
(r) Zinc (Zn, ore)	unit	2.85E-10	1.03E-10	0	1.82E-10	1.68E-14	0	0	0	0
<b>Eco-Indicator 95</b>	millipoints	9.47E+03	1.01E+03	8.36E+01	6.34E+01	1.58E+01	813.4727782	0	0	7705.291786
(a) Acetone (CH3COCH3)	millipoints	2.05E-06	7.32E-07	0	1.23E-06	9.22E-08	0	0	0	0
(a) Acetylene (C2H2)	millipoints	1.09E-03	4.55E-07	0.00E+00	6.06E-10	1.05E-03	0	0	0	0
(a) Aldehyde (unspecified)	millipoints	1.62E-04	1.44E-04	0.00E+00	9.32E-08	8.34E-06	0	0	0	0
(a) Ammonia (NH3)	millipoints	1.90E-02	9.55E-04	0.014258249	6.40E-05	3.88E-03	0	0	0	0
(a) Arsenic (As)	millipoints	1.96E-01	1.28E-01	0.00E+00	5.01E-04	6.98E-02	0	0	0	0
(a) Benzene (C6H6)	millipoints	6.84E-02	5.78E-02	0.00E+00	4.14E-03	2.32E-03	0.005078673	0	0	0
(a) Benz(a)pyrene (C20H12)	millipoints	7.85E-01	1.09E-02	0	5.05E-03	1.31E-01	0.63760367	0	0	0
(a) Cadmium (Cd)	millipoints	6.70E+01	3.55E+01	0.00E+00	1.04E-01	4.53E-01	30.94975857	0	0	0
(a) Carbon Dioxide (CO2, fossil)	millipoints	1.35E+02	1.13E+01	27.1021426	1.16E+01	1.62E+00	63.28028592	0	0	0
(a) Ethanol (C2H5OH)	millipoints	2.28E-06	7.90E-07	0.00E+00	1.21E-06	2.78E-07	0	0	0	0
(a) Ethylene (C2H4)	millipoints	6.99E-01	3.74E-01	0.00E+00	4.72E-01	5.37E-02	0	0	0	0
(a) Formaldehyde (CH2O)	millipoints	2.96E-03	9.26E-04	0	1.64E-03	4.00E-04	0	0	0	0
(a) Halon 1301 (CF3Br)	millipoints	74.56300987	7.44E+01	0	1.12E-01	3.49E-03	0	0	0	0
(a) Hydrocarbons (except methane)	millipoint	117.6232779	82.29787648	0	4.30E-01	0.08605004	34.80984277	0	0	0
(a) Hydrocarbons (unspecified)	millipoints	2.20E-01	8.56E-03	0.209083819	2.43E-04	2.58E-03	0	0	0	0
(a) Hydrogen Chloride (HCl)	millipoint	4.30E-01	2.81E-02	0.068918058	5.88E-04	3.32E-01	0	0	0	0
(a) Hydrogen Fluoride (HF)	millipoint	2.70E-02	5.08E-03	0	1.49E-04	2.17E-02	0	0	0	0
(a) Lead (Pb)	millipoint	7.762586788	1.27E+00	3.083281319	2.55E-02	0.639110883	2.741268879	0	0	0
(a) Manganese (Mn)	millipoint	3.93E-01	8.00E-02	0	1.41E-01	1.72E-01	0	0	0	0
(a) Mercury (Hg)	millipoint	6.43E-02	3.58E-02	0	5.01E-03	2.34E-02	0	0	0	0
(a) Methane (CH4)	millipoint	6.92E+00	3.15E+00	3.539419661	6.26E-02	9.46E-02	0.055631547	0	0	0
(a) Nickel (Ni)	millipoint	63.82543123	62.81192664	0	1.97E-01	7.16E-01	0	0	0	0
(a) Nitrogen Oxides (NOx as NO2)	millipoint	5423.692149	11.39450884	15.04235002	1.59E+00	1.58E+00	441.6827927	0	0	4952.42561
(a) Nitrous Oxide (N2O)	millipoint	3.19E+00	3.35E-02	0	3.40E-03	5.01E-03	3.147988768	0	0	0
(a) Particulates (unspecified)	millipoints	67.25475354	1.60275362	1.859641557	4.41E+01	3.49E+00	16.18252563	0	0	0
(a) Pentane (C5H12)	millipoint	1.11E+00	1.09E+00	0	2.05E-02	5.22E-05	0	0	0	0
(a) Phenol (C6H5OH)	millipoint	4.24E-09	1.53E-08	0	2.70E-09	2.47E-13	0	0	0	0
(a) Polycyclic Aromatic Hydrocarbons (PAH, unspecified)	millipoint	3.995729773	1.44E+00	0	2.55E+00	1.99E-04	0	0	0	0
(a) Propane (C3H8)	millipoint	9.89E-01	9.60E-01	0	1.96E-02	6.40E-03	0	0	0	0
(a) Propionaldehyde (CH3CH2CHO)	millipoint	1.20E-09	4.38E-10	0	7.68E-10	7.01E-14	0	0	0	0
(a) Propylene (CH2CHCH3)	millipoint	0.118874088	1.09E-01	0	1.62E-04	7.32E-03	0	0	0	0
(a) Sulphur Oxides (SOx as SO2)	millipoint	2.81E+03	4.72E+01	9.569624799	7.23E-01	8.19E+00	0	0	0	2752.868175
(a) Tars (unspecified)	millipoint	1.23E-06	1.23E-06	0	1.84E-09	5.37E-11	0	0	0	0
(a) Toluene (C6H5CH3)	millipoint	1.91E-01	1.85E-01	0	4.83E-03	1.01E-03	0	0	0	0
(w) Ammonia (NH4+, NH3, as N)	millipoint	0.984817064	0.978950294	0.001866183	1.41E-03	2.59E-03	0	0	0	0
(w) Arsenic (As3+, As5+)	millipoint	8.10E-01	7.95E-01	0	1.36E-02	7.20E-04	0	0	0	0
(w) Barium (Ba++)	millipoint	666.0356345	664.9849864	0	1.02E+00	3.15E-02	0	0	0	0
(w) Boron (B III)	millipoint	0.924696765	0.923047599	0	1.78E-03	4.33E-05	0	0	0	0
(w) Cadmium (Cd++)	millipoint	4.00E+00	3.99E+00	0	7.70E-03	5.52E-04	0	0	0	0
(w) Chromium (Cr III, Cr VI)	millipoint	0.917813507	0.916266986	0.00E+00	1.22E-03	3.28E-04	0	0	0	0
(w) COD (Chemical Oxygen Demand)	millipoint	9.08E-02	9.04E-02	9.78E-05	4.17E-04	5.20E-06	0	0	0	0
(w) Copper (Cu+, Cu++)	millipoint	1.37E-02	1.35E-02	0	1.88E-04	2.27E-06	0	0	0	0
(w) Lead (Pb++, Pb4+)	millipoint	4.035238613	0.836310308	3.083281319	6.58E-02	2.98E-02	0	0	0	0
(w) Manganese (Mn II, Mn IV, Mn VII)	millipoint	1.84E+00	1.83E+00	0	5.46E-03	7.71E-03	0	0	0	0
(w) Mercury (Hg+, Hg++)	millipoint	7.89E-02	7.88E-02	0	1.05E-04	6.14E-06	0	0	0	0
(w) Molybdenum (Mo II, Mo III, Mo IV, Mo V, Mo VI)	millipoint	0.110946534	0.110343975	0	1.47E-04	4.56E-04	0	0	0	0

(w) Nickel (Ni <sup>++</sup> , Ni <sup>3+</sup> )	millipoint	2.33E+00	2.30E+00	0	1.93E-02	1.52E-02	0	0	0	0
(w) Phosphates (PO4 <sup>3-</sup> , HPO4 <sup>2-</sup> , H2PO4 <sup>-</sup> , H3PO4, as P)	millipoint	5.25E-04	1.89E-04	0	3.33E-04	2.44E-06	0	0	0	0
(w) Phosphorus (P)	millipoints	0.034692189	0.034628466	0	6.21E-05	1.62E-06	0	0	0	0
<b>ETH-Air Acidification</b>	g eq. H+	2103.419269	12.43389394	6.25973501	6.00E-01	1.92E+00	120.8673913	0	0	1661.335054
(a) Ammonia (NH3)	g eq. H+	5.29E-03	2.67E-04	0.003978	1.79E-05	1.03E-03	0	0	0	0
(a) Hydrogen Chloride (HCl)	g eq. H+	0.160217808	9.82E-03	2.41E-02	2.06E-04	1.16E-01	0	0	0	0
(a) Hydrogen Fluoride (HF)	g eq. H+	0.0084641	0.00178288	0	5.21E-05	0.0076291	0	0	0	0
(a) Hydrogen Sulphide (H2S)	g eq. H+	1.87E-02	3.55E-03	0.001989	6.29E-03	6.90E-03	0	0	0	0
(a) Nitrogen Oxides (NOx as NO2)	g eq. H+	1484.204348	3.118130435	4.116369565	0.434778261	0.427571739	120.8673913	0	0	1355.241304
(a) Sulphur Oxides (SOx as SO2)	g eq. H+	619.03125	9.30034375	2.1133125	0.159086563	1.363825	0	0	0	606.09375
<b>IPCC Greenhouse effect (direct, 20 years)</b>	g eq. CO2	871184.3553	124902.3291	215591.96	62473.05859	10512.27527	457705.5798	0	0	0
(a) Carbon Dioxide (CO2, fossil)	g eq. CO2	708818	58988.1	142015	60734.7	8513.31	436388	0	0	0
(a) Carbon Tetrafluoride (CF4)	g eq. CO2	0.016255239	0.005884906	0	0.010369437	9.46E-07	0	0	0	0
(a) Halon 1301 (CF3Br)	g eq. CO2	340.727	340.16849	0	0.51238951	0.015941726	0	0	0	0
(a) Methane (CH4)	g eq. CO2	143793.84	85379.2	73576.96	1716.0576	1966.8864	1158.4808	0	0	0
(a) Nitrous Oxide (N2O)	g eq. CO2	20429.772	214.82472	0	21.778251	32.062932	20161.119	0	0	0

University of Cape Town

Appendix 3B

System: Green Electricity

Inventory: GreenElec 17-03-03b

	Flow	Units	Green Electricity	Diesel Oil Production	Ammonia (NH3) Production	Lime (Slaked, Ca(OH)2) Production	Electricity (South Africa, 1996) Production	Road Transport (Truck 28 t, Diesel Oil, kg.km)	Agricultural Ops	Energy Module (bagasse)	Fertilizer Production	Sugarcane Processing
Inputs:	(r) Barium Sulphate (BaSO4, in ground)	kg	0.0168438	0.006375	0	1.12E-02	-0.000764301	0	0	0	0	0
	(r) Bauxite (Al2O3, ore)	kg	0.00655535	0.00616747	0	4.49E-05	-0.000557007	0	0	0	0	0
	(r) Bentonite (Al2O3.4SiD2.H2O, in ground)	kg	0.00159113	0.000602211	0	1.06E-03	-7.22E-05	0	0	0	0	0
	(r) Calcium Sulphate (CaSO4, ore)	kg	0.00112263	0.00112113	0	1.49E-06	0	0	0	0	0	0
	(r) Chromium (Cr, ore)	kg	3.24E-06	1.23E-06	0	2.16E-06	-1.47E-07	0	0	0	0	0
	(r) Clay (in ground)	kg	-0.70746	0.00746783	0	2.10E-03	-0.717032	0	0	0	0	0
	(r) Coal (in ground)	kg	-3857.59	0.0231824	1.61819	0.03	-3859.26	0	0	0	0	0
	(r) Copper (Cu, ore)	kg	1.65E-05	6.24E-06	0	1.10E-05	-7.48E-07	0	0	0	0	0
	(r) Gravel (unspecified)	kg	0.153425	0.153221	0	2.04E-04	0	0	0	0	0	0
	(r) Iron (Fe, ore)	kg	-5.16834	0.0187833	0.000541008	3.31E-02	-5.22075	0	0	0	0	0
	(r) Iron Sulphate (FeSO4, ore)	kg	-0.124951	6.96E-08	0	9.28E-11	-0.124951	0	0	0	0	0
	(r) Lead (Pb, ore)	kg	5.14E-06	1.95E-06	0	3.43E-06	-2.33E-07	0	0	0	0	0
	(r) Lignite (in ground)	kg	0.0262599	0.0101031	0	1.78E-02	-0.00164544	0	0	0	0	0
	(r) Limestone (CaCO3, in ground)	kg	-540.953	0.0470503	0.0453094	97.862	-638.908	0	0	0	0	0
	(r) Manganese (Mn, ore)	kg	1.89E-06	7.14E-07	0	1.26E-06	-8.56E-08	0	0	0	0	0
	(r) Natural Gas (in ground)	kg	-2.93421	4.89641	51.3162	6.92149	-66.0704	0	0	0	0	0
	(r) Nickel (Ni, ore)	kg	1.10E-06	4.15E-07	0	7.31E-07	-4.98E-08	0	0	0	0	0
	(r) Oil (in ground)	kg	200.876	211.525	0.210392	0.30345	-11.1627	0	0	0	0	0
	(r) Pyrite (FeS2, ore)	kg	0.0269968	0.0102177	0	1.80E-02	-0.001225	0	0	0	0	0
	(r) Sand (in ground)	kg	-0.335217	0.00268885	0	3.34E-04	-0.338241	0	0	0	0	0
	(r) Silver (Ag, ore)	kg	8.17E-08	3.09E-08	0	5.45E-08	-3.71E-08	0	0	0	0	0
	(r) Sodium Chloride (NaCl, in ground or in sea)	kg	-2.1331	0.0280501	0.243453	1.16E-04	-2.40472	0	0	0	0	0
	(r) Sulphur (S, in ground)	kg	0.0280648	0	0.0280648	0	0	0	0	0	0	0
	(r) Uranium (U, ore)	kg	-0.0125262	3.84E-07	0.00016663	6.41E-07	-0.0126939	0	0	0	0	0
	(r) Zinc (Zn, ore)	kg	1.20E-07	4.53E-08	0	7.99E-08	-5.43E-09	0	0	0	0	0
	Ammonia (NH3)	kg	0	0.00E+00	0	0.00E+00	0	0	0	0	67.626	0
	Bagasse	t	0	0	0	0.00E+00	0	0	0	5.172	0	0
	Diesel Oil	kg	0	0	0	0.00E+00	0	138.998	61.4434	0	0	0
	Electricity	MJ elec	0	22.7773	0	1.05E+01	0	0	0	0	0	0
	Explosive (unspecified)	kg	-0.00354249	8.13E-07	0	1.08E-09	-0.00354331	0	0	0	0	0
	Fertiliser	kg	0	0	0	0.00E+00	0	0	426.044	0	0	0
	Iron Scrap	kg	-0.5728	0.174857	0	0.000232913	-0.74789	0	0	0	0	0
	Land Use (I -> II)	m2a	0.000316019	0.000315598	0	4.20E-07	0	0	0	0	0	0
	Land Use (II -> IV)	m2a	0.000384771	0.000384259	0	5.12E-07	0	0	0	0	0	0
	Land Use (III -> IV)	m2a	10000.1	4.35E-07	0	5.80E-10	0	0	10000.1	0	0	0
	Lime (slaked, Ca(OH)2)	kg	0	0	0	0.00E+00	0	0	0	0	0	64.65
	Raw Materials (unspecified)	kg	-178.101	0.158032	0	2.11E-04	-178.259	0	0	0	0	0
	Sugarcane	t	0	0.00E+00	0	0.00E+00	0	0	0	0	0	64.65
	Transport: Road (diesel oil, kg.km)	kg.km	0	0.00E+00	0	0.00E+00	0	0	0	0	0	3.23E+06
	Water Used (total)	litre	-6556.44	866.708	743.885	1.95E+01	-8186.48	0	0	0	0	0
	Water: Public Network	litre	743.885	0	743.885	0	0	0	0	0	0	0
	Water: Unspecified Origin	litre	-7293.06	866.708	0	1.95E+01	-8179.22	0	0	0	0	0
	Wood	kg	-2.03E+01	2.35E-04	0	3.94E-04	-2.03E+01	0	0	0	0	0
Outputs:	(a) Acetaldehyde (CH3CHO)	g	-0.00231476	0.000166995	0	2.93E-04	-0.00277488	0	0	0	0	0
	(a) Acetic Acid (CH3COOH)	g	0.0518244	0.0235127	0	4.16E-02	-0.0133022	0	0	0	0	0
	(a) Acetone (CH3COCH3)	g	-0.00268332	2.94E-05	0	4.94E-05	-0.00278206	0	0	0	0	0
	(a) Acetylene (C2H2)	g	-3.47E+01	1.94E-05	0	2.58E-08	-3.47E+01	0	0	0	0	0
	(a) Aldehyde (unspecified)	g	-0.0978538	2.32E-03	0	1.50E-04	-0.100328	0	0	0	0	0
	(a) Alkane (unspecified)	g	-26.8823	4.41168	0	8.06E-01	-32.1	0	0	0	0	0
	(a) Alkene (unspecified)	g	-34.7209	1.00E-03	0	1.73E-03	-34.7236	0	0	0	0	0
	(a) Alkyne (unspecified)	g	2.75E-05	1.04E-05	0	1.83E-05	-1.25E-06	0	0	0	0	0
	(a) Aluminium (Al)	g	-668.968	0.000806526	0	0.000766232	-668.968	0	0	0	0	0
	(a) Ammonia (NH3)	g	-12.9484	4.53E-03	0.067626	3.04E-04	-13.0209	0	0	0	0	0
	(a) Antimony (Sb)	g	-0.128645	7.17E-08	0	9.55E-11	-0.128645	0	0	0	0	0
	(a) AOX (Adsorbable Organic Halogens)	g	-5.56E-10	3.10E-18	0	4.13E-19	-5.56E-10	0	0	0	0	0
	(a) Aromatic Hydrocarbons (unspecified)	g	0.0306886	1.73E-06	0.033813	2.31E-09	-0.00312608	0	0	0	0	0
	(a) Arsenic (As)	g	-1.28683	0.00311946	0	1.24E-05	-1.28996	0	0	0	0	0
	(a) Barium (Ba)	g	-7.99611	1.05E-05	0	1.06E-05	-7.99613	0	0	0	0	0
	(a) Benzaldehyde (C6H5CHO)	g	4.96E-09	1.88E-09	0	3.31E-09	-2.25E-10	0	0	0	0	0
	(a) Benzene (C6H6)	g	-45.4487	1.58249	0	1.13E-01	-47.2835	0.138998	0	0	0	0

(a) Benzo(a)pyrene (C20H12)	g	-1.06E-01	1.19E-05	0	5.50E-06	-1.07E-01	0.000694988	0	0	0
(a) Beryllium (Be)	g	-0.130957	9.89E-08	0	4.57E-08	-0.130957	0	0	0	0
(a) Boron (B)	g	-83.3067	0.000245646	0	0.000370713	-83.3103	0	0	0	0
(a) Bromium (Br)	g	-1.27E+01	2.73E-05	0	3.56E-05	-1.27E+01	0	0	0	0
(a) Butane (n-C4H10)	g	14.764	15.6444	0	0.26917	-1.14964	0	0	0	0
(a) Butene (1-CH3CH2CHCH2)	g	0.366833	0.379515	0	0.000580594	-1.33E-02	0	0	0	0
(a) Cadmium (Cd)	g	-0.0695132	0.00779156	0	2.29E-05	-0.0741159	0.00678825	0	0	0
(a) Calcium (Ca)	g	-79.933	0.0283185	0	1.85E-03	-79.9632	0	0	0	0
(a) Carbon Dioxide (CO2, fossil)	g	-5.65E+06	58966.1	142015	6.07E+04	-6.35E+06	436388	0	0	0
(a) Carbon Dioxide (CO2, green)	g	1.67E+07	0.00E+00	0	0.00E+00	0	0	8.91E+06	0	7.79E+06
(a) Carbon Monoxide (CO)	g	-6.95E+03	3.70E+01	3.3813	9.65E+00	-8.21E+03	1208.96	0	0	0
(a) Carbon Tetrafluoride (CF4)	g	3.99E-06	1.51E-06	0	2.68E-06	-1.81E-07	0	0	0	0
(a) Chlorinated Matter (unspecified, as Cl)	g	0.033813	0.00E+00	0.033813	0.00E+00	0	0	0	0	0
(a) Chlorine (Cl2)	g	0.0334878	0	0.033813	0.00E+00	-3.25E-04	0	0	0	0
(a) Chromium (Cr III, Cr VI)	g	-1.55468	0.00382012	0	4.90E-05	-1.55865	0	0	0	0
(a) Cobalt (Co)	g	-0.192671	7.79E-03	0	1.97E-05	-0.200481	0	0	0	0
(a) Copper (Cu)	g	-9.68E-01	0.0117144	0	8.16E-05	-9.80E-01	0	0	0	0
(a) Cyanide (CN-)	g	-0.174919	5.07E-06	0	8.76E-06	-0.174933	0	0	0	0
(a) Dioxins (unspecified)	g	-1.26E-06	7.47E-11	0	1.24E-10	-1.26E-06	0	0	0	0
(a) Ethane (C2H6)	g	-81.4242	53.0533	0	1.18E+00	-135.655	0	0	0	0
(a) Ethanol (C2H5OH)	g	-0.00546626	2.11E-05	0	3.23E-05	-0.00551961	0	0	0	0
(a) Ethylbenzene (C8H10)	g	0.366833	0.379515	0	5.80E-04	-0.0132621	0	0	0	0
(a) Ethylene (C2H4)	g	-280.018	2.67188	0	3.7142	-286.061	0	0	0	0
(a) Fluorides (F-)	g	0.0332501	4.27E-05	0.033813	5.69E-08	-0.000605651	0	0	0	0
(a) Fluorine (F2)	g	-1.76E-04	0.00E+00	0	0.00E+00	-1.76E-04	0	0	0	0
(a) Formaldehyde (CH2O)	g	-5.02318	0.0157236	0	2.78E-02	-5.06671	0	0	0	0
(a) Halogenated Matter (unspecified)	g	-7.31E-12	4.07E-18	0	5.42E-21	-7.31E-12	0	0	0	0
(a) Halon 1301 (CF3Br)	g	0.041823	0.0430631	0	6.49E-05	-0.00150502	0	0	0	0
(a) Heptane (C7H16)	g	3.66774	3.79E+00	0	5.40E-03	-0.132594	0	0	0	0
(a) Hexane (C6H14)	g	7.33656	7.58985	0	1.08E-02	-0.264135	0	0	0	0
(a) Hydrocarbons (except methane)	g	916.678	1.41E+03	0	7.38E+00	-1102.54	588.013	0	0	0
(a) Hydrocarbons (unspecified)	g	-25.7088	0.130133	3.17842	3.70E-03	-29.0211	0	0	0	0
(a) Hydrogen (H2)	g	-1.50E-04	8.36E-11	0	1.11E-13	-1.50E-04	0	0	0	0
(a) Hydrogen Chloride (HCl)	g	-3159.57	0.358274	0.879137	7.50E-03	-3160.81	0	0	0	0
(a) Hydrogen Fluoride (HF)	g	-113.762	0.0356576	0	0.00104212	-113.799	0	0	0	0
(a) Hydrogen Sulphide (H2S)	g	-87.2738	0.0604277	0.033813	1.06E-01	-87.4744	0	0	0	0
(a) Iodine (I)	g	-3.16399	1.16E-05	0	1.74E-05	-3.16402	0	0	0	0
(a) Iron (Fe)	g	-267.122	0.0404347	0	0.00245488	-267.165	0	0	0	0
(a) Ianthanum (La)	g	-0.210211	1.17E-07	0	1.56E-10	-0.210211	0	0	0	0
(a) Lead (Pb)	g	-5.14922	0.0139654	0.033813	2.79E-04	-5.22734	0.0300623	0	0	0
(a) Magnesium (Mg)	g	-233.688	0.00032481	0	3.43E-04	-233.688	0	0	0	0
(a) Manganese (Mn)	g	-1.40533	0.000877209	0	0.00154431	-1.40775	0	0	0	0
(a) Mercaptans	g	0.033813	0	0.033813	0.00E+00	0	0	0	0	0
(a) Mercury (Hg)	g	-0.191294	0.000393117	0	5.50E-05	-0.191742	0	0	0	0
(a) Metals (unspecified)	g	0.0259032	2.66E-05	0.033813	3.54E-08	-0.00793643	0	0	0	0
(a) Methane (CH4)	g	-20704.9	1021.55	1149.64	26.8134	22921	18.0697	0	0	0
(a) Methanol (CH3OH)	g	-0.0093219	2.47E-05	0	3.54E-05	-0.00938199	0	0	0	0
(a) Molybdenum (Mo)	g	-2.58E-01	3.89E-03	0	5.18E-06	-2.59E-01	0	0	0	0
(a) Nickel (Ni)	g	-1.16676	1.56E-01	0	4.89E-04	-1.3231	0	0	0	0
(a) Nitrogen Oxides (NOx as NO2)	g	53584.8	1.43E+02	189.353	2.00E+01	-14669	5559.9	33248.6	0	29092.5
(a) Nitrous Oxide (N2O)	g	-10.653	0.650984	0	6.60E-02	-7.25E+01	61.0943	0	0	0
(a) Organic Matter (unspecified)	g	3.27605	0.00336532	3.51655	4.49E-08	-0.243872	0	0	0	0
(a) Particulate Emissions	kg	2.79176	0	0	0	0	0	0	0	2.79176
(a) Particulates (unspecified)	g	-4.49E+04	3.03E+01	35.1655	8.35E+02	-4.93E+04	305.795	3190.59	0	0
(a) Pentane (C5H12)	g	1.88E+01	1.92E+01	0	3.60E-01	-0.681333	0	0	0	0
(a) Phenol (C6H5OH)	g	3.81E-08	1.44E-08	0	2.54E-08	-1.73E-09	0	0	0	0
(a) Phosphorus (P)	g	-5.89398	9.87E-06	0	1.14E-05	-5.89398	0	0	0	0
(a) Phosphorus Pentoxide (P2O5)	g	-0.00399845	2.23E-09	0	2.97E-12	-0.00399845	0	0	0	0
(a) Polycyclic Aromatic Hydrocarbons (PAH, unspecified)	g	0.00419263	0.00157194	0	2.78E-03	-1.62E-04	0	0	0	0
(a) Potassium (K)	g	-79.9522	0.00330804	0	5.75E-03	-79.9613	0	0	0	0
(a) Propane (C3H8)	g	-64.5185	1.63E+01	0	3.33E-01	-81.1823	0	0	0	0
(a) Propionaldehyde (CH3CH2CHO)	g	1.37E-06	5.17E-09	0	9.10E-09	-6.19E-10	0	0	0	0
(a) Propionic Acid (CH3CH2COOH)	g	1.88E-05	6.80E-06	0	1.20E-05	0.00E+00	0	0	0	0
(a) Propylene (CH2CHCH3)	g	-37.1129	7.59E-01	0	1.12E-03	-37.873	0	0	0	0
(a) Scandium (Sc)	g	-0.07132	3.97E-08	0	5.29E-11	-0.07132	0	0	0	0
(a) Selenium (Se)	g	-1.26309	3.17E-03	0	1.02E-04	-1.26636	0	0	0	0
(a) Silicon (Si)	g	-999.197	1.75E-03	0	2.10E-03	-999.201	0	0	0	0
(a) Sodium (Na)	g	-39.8213	0.179147	0	3.86E-04	-40.0008	0	0	0	0
(a) Strontium (Sr)	g	-13.0519	8.85E-06	0	2.78E-06	-13.0519	0	0	0	0

Energy

(a) Sulphur Oxides (SOx as SO2)	g	-12786.4	297.611	67.626	5.09E+00	-32551.8	0	0	10344	0	9051
(a) Tars (unspecified)	g	0.00011804	0.000121846	0	1.62E-07	-3.97E-06	0	0	0	0	0
(a) Thallium (Tl)	g	-0.0852597	3.64E-08	0	4.84E-11	-0.0852597	0	0	0	0	0
(a) Thorium (Th)	g	-0.134518	7.50E-08	0	9.99E-11	-0.134518	0	0	0	0	0
(a) Tin (Sn)	g	-0.0420421	2.34E-08	0	3.12E-11	-0.0420421	0	0	0	0	0
(a) Titanium (Ti)	g	-2.34E+01	1.71E-05	0	7.14E-06	-23.3688	0	0	0	0	0
(a) Toluene (C6H5CH3)	g	-7.12E+00	2.35E+00	0	5.87E-02	-9.52824	0	0	0	0	0
(a) Uranium (U)	g	-0.130519	7.27E-08	0	9.69E-11	-0.130519	0	0	0	0	0
(a) Vanadium (V)	g	-2.05568	6.23E-01	0	1.07E-03	-2.67964	0	0	0	0	0
(a) Xylene (C6H4(CH3)2)	g	-4.85E+00	1.52E+00	0	2.34E-03	-6.37287	0	0	0	0	0
(a) Zinc (Zn)	g	1.45E+01	1.03E-02	0	9.21E-04	-3.95143	18.4253	0	0	0	0
(a) Zirconium (Zr)	g	-0.0899611	5.57E-08	0	7.42E-11	-0.0899612	0	0	0	0	0
(ar) Lead (Pb210)	kBq	-2.98E+00	1.86E-06	0	2.20E-09	-2.98064	0	0	0	0	0
(ar) Polonium (Po210)	kBq	3.00E-06	2.99E-06	0	3.99E-09	0	0	0	0	0	0
(ar) Potassium (K40)	kBq	4.58E-07	4.58E-07	0	6.10E-10	0	0	0	0	0	0
(ar) Radioactive Substance (unspecified)	kBq	-0.0242719	1.35E-08	0	1.80E-11	-0.024272	0	0	0	0	0
(ar) Radium (Ra226)	kBq	-9.79E-01	4.23E-07	0	5.63E-10	-9.79E-01	0	0	0	0	0
(ar) Radium (Ra228)	kBq	2.29E-07	2.29E-07	0	3.05E-10	0.00E+00	0	0	0	0	0
(ar) Radon (Rn220)	kBq	7.05E-06	7.04E-06	0	9.38E-09	0	0	0	0	0	0
(ar) Radon (Rn222)	kBq	-28.7513	0.116326	0	0.000154948	-28.8678	0	0	0	0	0
(ar) Thorium (Th228)	kBq	1.94E-07	1.94E-07	0	2.58E-10	0.00E+00	0	0	0	0	0
(ar) Thorium (Th232)	kBq	1.23E-07	1.23E-07	0	1.84E-10	0.00E+00	0	0	0	0	0
(ar) Uranium (U238)	kBq	3.53E-07	3.52E-07	0	4.69E-10	0.00E+00	0	0	0	0	0
(s) Aluminium (Al)	g	0.215014	0.0813782	0	0.143392	-0.00975637	0	0	0	0	0
(s) Arsenic (As)	g	8.59E-05	3.25E-05	0	5.73E-05	-3.90E-06	0	0	0	0	0
(s) Cadmium (Cd)	g	3.89E-08	1.47E-08	0	2.59E-08	-1.76E-09	0	0	0	0	0
(s) Calcium (Ca)	g	8.59E-01	3.25E-01	0	5.73E-01	-3.90E-02	0	0	0	0	0
(s) Carbon (C)	g	6.45E-01	2.44E-01	0	4.30E-01	-2.93E-02	0	0	0	0	0
(s) Chromium (Cr III, Cr VI)	g	1.08E-03	4.07E-04	0	7.17E-04	-4.88E-05	0	0	0	0	0
(s) Cobalt (Co)	g	3.94E-08	1.49E-08	0	2.63E-08	-1.79E-09	0	0	0	0	0
(s) Copper (Cu)	g	1.97E-07	7.47E-08	0	1.32E-07	-8.95E-09	0	0	0	0	0
(s) Iron (Fe)	g	0.429397	0.162518	0	2.86E-01	-0.0194842	0	0	0	0	0
(s) Lead (Pb)	g	9.02E-07	3.41E-07	0	6.02E-07	-4.09E-08	0	0	0	0	0
(s) Manganese (Mn)	g	0.0085903	0.00325125	0	5.73E-03	-0.00038979	0	0	0	0	0
(s) Mercury (Hg)	g	7.16E-09	2.71E-09	0	4.77E-09	-3.25E-10	0	0	0	0	0
(s) Nickel (Ni)	g	2.96E-07	1.12E-07	0	1.98E-07	-1.34E-08	0	0	0	0	0
(s) Nitrogen (N)	g	3.37E-06	1.27E-06	0	2.24E-06	-1.53E-07	0	0	0	0	0
(s) Oils (unspecified)	g	0.00127558	0.00048278	0	8.51E-04	-5.79E-05	0	0	0	0	0
(s) Phosphorus (P)	g	0.0107555	0.00407073	0	7.17E-03	-0.000488039	0	0	0	0	0
(s) Sulphur (S)	g	0.128861	0.0487713	0	8.59E-02	-0.00584715	0	0	0	0	0
(s) Zinc (Zn)	g	0.00322839	0.00122188	0	2.15E-03	-1.46E-04	0	0	0	0	0
(w) Acids (H+)	g	-1.11131	0.00348773	0.033813	6.34E-05	-1.14868	0	0	0	0	0
(w) Aldehyde (unspecified)	g	9.62E-05	3.48E-05	0	6.13E-05	0	0	0	0	0	0
(w) Alkane (unspecified)	g	2.61539	2.70479	0	0.0051875	-0.0945828	0	0	0	0	0
(w) Alkene (unspecified)	g	0.241415	0.249669	0	4.77E-04	-0.0087306	0	0	0	0	0
(w) Aluminium (Al3+)	g	-12.4514	0.0837007	0	6.95E-02	-12.6046	0	0	0	0	0
(w) Ammonia (NH4+, NH3, as N)	g	-17.2063	17.7376	0.033813	2.55E-02	-35.0032	0	0	0	0	0
(w) AOX (Adsorbable Organic Halogens)	g	0.0426937	0.0441581	0	6.45E-05	-0.00152888	0	0	0	0	0
(w) Aromatic Hydrocarbons (unspecified)	g	10.344	10.8219	0	0.0257331	-0.503624	0	0	0	0	0
(w) Arsenic (As3+, As5+)	g	0.00298422	0.00872138	0	0.000148675	-0.00588584	0	0	0	0	0
(w) Barium (Ba++)	g	50.3283	52.09	0	7.99E-02	-1.84155	0	0	0	0	0
(w) Barytes	g	3.0471	1.15326	0	2.0321	-0.138264	0	0	0	0	0
(w) Benzene (C6H6)	g	2.61621	2.70563	0	0.00519469	-0.094613	0	0	0	0	0
(w) BOD5 (Biochemical Oxygen Demand)	g	8.89E-01	9.45E-01	0.033813	9.88E-03	-1.00E-01	0	0	0	0	0
(w) Boron (B III)	g	0.326274	0.337422	0	6.49E-04	-1.18E-02	0	0	0	0	0
(w) Cadmium (Cd++)	g	0.0130986	0.0145753	0	2.81E-05	-0.00150479	0	0	0	0	0
(w) Calcium (Ca++)	g	6.46E+02	6.69E+02	0	1.51E+00	-2.43E+01	0	0	0	0	0
(w) Cerium (Ce++)	g	2.08E-02	2.08E-02	0	0.00E+00	0.00E+00	0	0	0	0	0
(w) Cesium (Cs++)	g	-0.000697739	0	0	2.77E-05	-0.000725392	0	0	0	0	0
(w) Chlorides (Cl-)	g	-22226.4	10740.8	6.15396	1.63E+01	-32989.7	0	0	0	0	0
(w) Chlorinated Matter (unspecified, as Cl)	g	0.484489	0.183369	0	3.23E-01	-0.0219841	0	0	0	0	0
(w) Chloroform (CHCl3)	g	5.20E-07	1.97E-07	0	3.47E-07	-2.36E-08	0	0	0	0	0
(w) Chromium (Cr III)	g	0.00225771	0.000854495	0	0.00150568	-1.02E-04	0	0	0	0	0
(w) Chromium (Cr III, Cr VI)	g	0.0369696	0.0502415	0	6.69E-05	-0.0133388	0	0	0	0	0
(w) Chromium (Cr VI)	g	4.24E-08	1.61E-08	0	2.83E-08	-1.92E-09	0	0	0	0	0
(w) Cobalt (Co I, Co II, Co III)	g	1.39E-04	5.28E-05	0	9.30E-05	-6.33E-06	0	0	0	0	0
(w) COD (Chemical Oxygen Demand)	g	3.01E+01	3.13E+01	0.033813	1.44E-01	-1.34E+00	0	0	0	0	0
(w) Copper (Cu+, Cu++)	g	0.0262913	2.96E-02	0	3.69E-04	-0.00370762	0	0	0	0	0
(w) Cyanides (CN-)	g	-4.92E+00	4.44E-02	0.033813	2.01E-04	-5.00035	0	0	0	0	0



Methods

Electricity	MJ elec	0	0	0	0.00E+00	-24792.4	0	0	24825.6	0	0
Fertiliser	kg	0	0	0	0.00E+00	0	0	0	0	426.044	0
Lime (slaked, Ca(OH)2)	kg	0	0	0	64.65	0	0	0	0	0	0
Molasses	t	2.586	0	0	0.00E+00	0	0	0	0	0	2.586
Recovered Matter (total)	kg	-6.77711	2.49E-03	0	3.32E-06	-6.78E+00	0	0	0	0	0
Recovered Matter (unspecified)	kg	-6.7702	0.00248982	0	3.32E-06	-6.77289	0	0	0	0	0
Recovered Matter: Iron Scrap	kg	-0.00690473	0	0	0.00E+00	-0.00690473	0	0	0	0	0
Sugar	t	7.758	0	0	0.00E+00	0	0	0	0	0	7.758
Sugarcane	t	0	0	0	0.00E+00	0	0	64.65	0	0	0
Transport: Road (diesel oil, kg km)	kg km	0	0	0	0.00E+00	0	3.23E+06	0	0	0	0
Waste (hazardous)	kg	-0.21135	0.20737	3.38E-05	2.76E-04	-0.41903	0	0	0	0	0
Waste (incineration)	kg	-0.0113067	0.114546	0	5.89E-03	-0.131747	0	0	0	0	0
Waste (municipal and industrial)	kg	-0.571155	2.24E-05	0.00101439	1.28E-07	-0.578192	0	0	0	0	0
Waste (total)	kg	-2116.44	0.890571	0.448867	6.92E-03	-2117.77	0	0	0	0	0
Waste (unspecified)	kg	-707.458	0.0281415	0	3.80E-05	-707.466	0	0	0	0	0
Waste: Highly Radioactive (class C)	kg	-0.00170283	0	0	0.00E+00	-0.00170283	0	0	0	0	0
Waste: Low Radioactive (class A)	kg	0.0648034	0.12687	0	0.000168994	-0.0622358	0	0	0	0	0
Waste: Mineral (mer)	kg	-1225.1	0.356219	0.351655	4.77E-04	-1225.8	0	0	0	0	0
Waste: Mining	kg	-88.3054	0	0	0.00E+00	-88.3054	0	0	0	0	0
Waste: Non Mineral (inert)	kg	-0.0139817	0.0150761	0	2.01E-05	-0.029078	0	0	0	0	0
Waste: Non Toxic Chemicals (unspecified)	kg	0.00135107	9.26E-07	0.00148777	1.23E-09	-1.38E-04	0	0	0	0	0
Waste: Radioactive	kg	0.0202385	0.0202385	0	0.00E+00	0	0	0	0	0	0
Waste: Radioactive (unspecified)	kg	-0.000680082	0	0	2.70E-05	-0.000707041	0	0	0	0	0
Waste: Slags and Ash (unspecified)	kg	-183.211	0.0120831	0.0946763	1.61E-05	-183.318	0	0	0	0	0
CML_Air Acidification	g eq. H+	867.1648713	1.24E+01	6.25973501	6.00E-01	-1434.334027	120.8673913	1046.045652	0	915.2894022	0
(a) Ammonia (NH3)	g eq. H+	-0.761670588	2.67E-04	0.003978	1.79E-05	-0.765935294	0	0	0	0	0
(a) Hydrogen Chloride (HCl)	g eq. H+	-86.56356164	9.82E-03	2.41E-02	2.06E-04	-86.59753425	0	0	0	0	0
(a) Hydrogen Fluoride (HF)	g eq. H+	-5.6881	1.78E-03	0	5.21E-05	-5.68995	0	0	0	0	0
(a) Hydrogen Sulphide (H2S)	g eq. H+	-5.133752941	3.55E-03	0.001989	6.26E-03	-5.145552941	0	0	0	0	0
(a) Nitrogen Oxides (NOx as NO2)	g eq. H+	1164.886957	3.12E+00	4.116369565	4.35E-01	-318.8913043	120.8673913	722.7956522	0	632.4456522	0
(a) Sulphur Oxides (SOx as SO2)	g eq. H+	-399.575	9.30034375	2.1133125	0.159086563	-1017.24375	0	323.25	0	282.84375	0
CML_Depletion of non renewable resources	frac. of reserve	-1.46E-12	9.23E-13	4.09E-13	5.52E-14	-2.65E-12	0	0	0	0	0
(r) Bauxite (Al2O3, ore)	frac. of reserve	2.02E-16	2.20E-16	0	1.60E-18	-1.99E-17	0	0	0	0	0
(r) Coal (in ground)	frac. of reserve	-1.29E-12	7.78E-18	5.43E-16	1.02E-17	-1.30E-12	0	0	0	0	0
(r) Copper (Cu, ore)	frac. of reserve	2.70E-17	1.02E-17	0	1.80E-17	-1.23E-18	0	0	0	0	0
(r) Iron (Fe, ore)	frac. of reserve	-5.17E-14	1.88E-16	5.41E-18	3.31E-16	-5.22E-14	0	0	0	0	0
(r) Lead (Pb, ore)	frac. of reserve	4.29E-17	1.62E-17	0	2.86E-17	-1.94E-18	0	0	0	0	0
(r) Manganese (Mn, ore)	frac. of reserve	3.77E-19	1.43E-19	0	2.52E-19	-1.71E-20	0	0	0	0	0
(r) Natural Gas (in ground)	frac. of reserve	-2.26E-14	3.77E-14	3.95E-13	5.33E-14	-5.09E-13	0	0	0	0	0
(r) Nickel (Ni, ore)	frac. of reserve	9.97E-18	3.77E-18	0	6.65E-18	-4.52E-19	0	0	0	0	0
(r) Oil (in ground)	frac. of reserve	8.40E-13	8.85E-13	8.80E-16	1.27E-15	-4.67E-14	0	0	0	0	0
(r) Silver (Ag, ore)	frac. of reserve	1.94E-16	7.36E-17	0	1.30E-16	-8.83E-18	0	0	0	0	0
(r) Uranium (U, ore)	frac. of reserve	-9.35E-13	2.71E-17	1.24E-14	4.78E-17	-9.47E-13	0	0	0	0	0
(r) Zinc (Zn, ore)	frac. of reserve	3.63E-19	1.37E-19	0	2.42E-19	-1.65E-20	0	0	0	0	0
CML_Eutrophication	g eq. PO4	6953.886244	29.09025481	24.66870591	2.638228217	-1946.138116	739.282461	4322.318	0	3782.025	0
(a) Ammonia (NH3)	g eq. PO4	-4.53E+00	1.59E-03	0.0236691	1.06E-04	-4.56E+00	0	0	0	0	0
(a) Nitrogen Oxides (NOx as NO2)	g eq. PO4	6966.024	18.64642	24.61589	2.599974	-1906.97	722.787	4322.318	0	3782.025	0
(a) Nitrous Oxide (N2O)	g eq. PO4	-2.87631	1.78E-01	0	1.78E-02	-19.585334	16.495461	0	0	0	0
(w) Ammonia (NH4+, NH3, as N)	g eq. PO4	-7.226646	7.449792	0.01420146	1.07E-02	-14.701344	0	0	0	0	0
(w) COD (Chemical Oxygen Demand)	g eq. PO4	0.6622	0.6877904	0.000743866	0.003174644	-0.02950904	0	0	0	0	0
(w) Nitrogenous Matter (Kjeldahl, as N)	g eq. PO4	-0.05793018	0	0	0.00E+00	-0.05793018	0	0	0	0	0
(w) Nitrogenous Matter (unspecified, as N)	g eq. PO4	1.86273	1.8628932	0.01420146	3.43E-03	-0.07425096	0	0	0	0	0
(w) Phosphates (PO4 3-, HPO4-, H2PO4-, H3PO4, as P)	g eq. PO4	-9.93E-03	1.45E-03	0	2.55E-03	-1.39E-02	0	0	0	0	0
(w) Phosphorus (P)	g eq. PO4	2.56E-01	2.65E-01	0	4.75E-04	-9.25E-03	0	0	0	0	0
(w) Phosphorus Pentoxide (P2O5)	g eq. PO4	-1.59E-01	8.88E-08	0	1.18E-10	-1.59E-01	0	0	0	0	0
CML_Human Toxicity	g	1.82E+04	6.70E+02	234.369529	2.31E+01	-5.90E+04	4361.138615	38346.708	0	33553.35	0
(a) Ammonia (NH3)	g	-2.72E-01	9.52E-05	0.001420146	6.37E-06	-2.73E-01	0	0	0	0	0
(a) Arsenic (As)	g	-6.05E+03	1.47E+01	0	5.64E-02	-6.06E+03	0	0	0	0	0
(a) Barium (Ba)	g	-1.38E+01	1.78E-05	0	1.81E-05	-1.38E+01	0	0	0	0	0
(a) Benzene (C6H6)	g	-177.24993	6.171711	0.00E+00	4.42E-01	-164.40565	0.5420622	0	0	0	0
(a) Benzo(a)pyrene (C20H12)	g	-1.804754	0.000202713	0	9.35E-05	-1.816875	0.011814796	0	0	0	0
(a) Bromium (Br)	g	-0.417846	9.00E-07	0	1.18E-06	-0.4176493	0	0	0	0	0
(a) Cadmium (Cd)	g	-34.517656	4.5191048	0	1.33E-02	-42.987222	3.937185	0	0	0	0
(a) Carbon Monoxide (CO)	g	-83.4402	0.4442616	0.0405756	1.16E-01	-98.54832	14.50752	0	0	0	0
(a) Copper (Cu)	g	-2.32E-01	2.81E-03	0	1.96E-05	-2.35E-01	0	0	0	0	0
(a) Cyanide (CN-)	g	-0.11719573	3.40E-06	0	5.87E-06	-1.17E-01	0	0	0	0	0

(a) Fluorides (F-)	g	1.60E-02	2.05E-05	0.01623024	2.73E-08	-2.91E-04	0	0	0	0
(a) Heptane (C7H16)	g	5.868384	6.071888	0	8.64E-03	-2.12E-01	0	0	0	0
(a) Hydrogen Sulphide (H2S)	g	-68.073564	0.047133806	0.02637414	8.30E-02	-6.82E+01	0	0	0	0
(a) Iron (Fe)	g	-11.219124	0.001698257	0	1.03E-04	-11.22093	0	0	0	0
(a) Lead (Pb)	g	-823.8752	2.234464	5.41008	4.47E-02	-836.3744	4.809988	0	0	0
(a) Manganese (Mn)	g	-168.6396	0.10528508	0	1.85E-01	-168.93	0	0	0	0
(a) Mercury (Hg)	g	-22.95528	0.04717404	0	6.60E-03	-2.30E+01	0	0	0	0
(a) Molybdenum (Mo)	g	-8.43E-01	1.28E-02	0	1.71E-05	-8.56E-01	0	0	0	0
(a) Nickel (Ni)	g	-548.3722	73.2495	0	2.30E-01	-621.857	0	0	0	0
(a) Nitrogen Oxides (NOx as NO2)	g	41796.144	111.87852	147.69534	1.56E+01	-11441.82	4336.722	25933.906	0	22692.15
(a) Phenol (C6H5OH)	g	2.13E-08	8.07E-09	0.00E+00	1.42E-08	-9.67E-10	0	0	0	0
(a) Sulphur Oxides (SOx as SO2)	g	-1.53E+04	3.57E+02	81.1512	6.11E+00	-3.91E+04	0	12412.8	0	10861.2
(a) Tin (Sn)	g	-7.15E-04	3.98E-10	0	5.31E-13	-7.15E-04	0	0	0	0
(a) Toluene (C6H5CH3)	g	-2.78E-01	0.09166677	0	0.002290786	-3.72E-01	0	0	0	0
(a) Vanadium (V)	g	-2.47E+02	7.47E+01	0	1.29E-01	-3.22E+02	0	0	0	0
(a) Xylene (C6H4(CH3)2)	g	-10.67539	3.339754	0	5.15E-03	-14.020314	0	0	0	0
(a) Zinc (Zn)	g	4.78E-01	0.000340243	0	3.04E-05	-0.13039719	0.6080349	0	0	0
(s) Arsenic (As)	g	3.69E-06	1.40E-06	0	2.46E-06	-1.68E-07	0	0	0	0
(s) Cadmium (Cd)	g	2.72E-07	1.03E-07	0	1.81E-07	-1.23E-08	0	0	0	0
(s) Cobalt (Co)	g	2.56E-09	9.70E-10	0	1.71E-09	-1.18E-10	0	0	0	0
(s) Copper (Cu)	g	1.03E-09	3.88E-10	0.00E+00	6.84E-10	-4.66E-11	0	0	0	0
(s) Lead (Pb)	g	2.26E-08	8.54E-09	0	1.50E-08	-1.02E-09	0	0	0	0
(s) Mercury (Hg)	g	1.07E-09	4.06E-10	0	7.18E-10	-4.87E-11	0	0	0	0
(s) Nickel (Ni)	g	4.15E-09	1.57E-09	0	2.77E-09	-1.88E-10	0	0	0	0
(s) Zinc (Zn)	g	2.26E-05	8.55E-06	0	1.51E-05	-1.03E-06	0	0	0	0
(w) Ammonia (NH4+, NH3, as N)	g	-0.02925071	0.03015392	5.75E-05	4.33E-05	-0.05950544	0	0	0	0
(w) Arsenic (As3+, As5+)	g	0.004177908	0.012209932	0	0.000208145	-0.008240176	0	0	0	0
(w) Barium (Ba++)	g	7.045962	7.2926	0	1.12E-02	-0.257817	0	0	0	0
(w) Benzene (C6H6)	g	1.7269986	1.7857158	0	0.003428495	-0.06244458	0	0	0	0
(w) Cadmium (Cd++)	g	0.03798594	0.04228837	0	8.16E-05	-0.004363891	0	0	0	0
(w) Chromium (Cr III)	g	0.001286895	0.000487062	0	0.000858226	-5.84E-05	0	0	0	0
(w) Chromium (Cr III, Cr VI)	g	0.021072672	0.028637655	0	3.81E-05	-0.007603116	0	0	0	0
(w) Chromium (Cr VI)	g	0.000173911	6.58E-05	0	1.16E-04	-7.89E-06	0	0	0	0
(w) Cobalt (Co I, Co II, Co III)	g	0.000278846	1.06E-04	0	1.86E-04	-1.27E-05	0	0	0	0
(w) Copper (Cu+, Cu++)	g	0.000525826	5.93E-04	0.00E+00	7.38E-06	-7.42E-05	0	0	0	0
(w) Fluorides (F-)	g	-0.29380887	0.00894825	0.001386333	7.52E-04	-0.30489568	0	0	0	0
(w) Iron (Fe++, Fe3+)	g	-0.026159364	9.22E-03	0.000121727	2.55E-04	-0.035755308	0	0	0	0
(w) Lead (Pb++, Pb4+)	g	-0.15771955	0.007245446	0.02671227	7.44E-04	-0.19242188	0	0	0	0
(w) Mercury (Hg+, Hg++)	g	0.000383202	0.000406246	0	5.41E-07	-2.36E-05	0	0	0	0
(w) Molybdenum (Mo II, Mo III, Mo IV, Mo V, Mo VI)	g	-0.005207733	0.002506624	0	3.34E-06	-0.007717683	0	0	0	0
(w) Nickel (Ni++, Ni3+)	g	-2.76E-03	7.06E-04	0.00E+00	5.91E-06	-3.47E-03	0	0	0	0
(w) Oils (unspecified)	g	1.44E-02	1.62E-02	0	3.11E-05	2.88E-04	-2.10E-03	0	0	0
(w) Phosphates (PO4 3-, HPO4--, H2PO4-, H3PO4, as P)	g	-1.33E-07	1.94E-08	0.00E+00	3.41E-08	-1.87E-07	0	0	0	0
(w) Tetrachloroethylene (C2Cl4)	g	4.03E-10	1.53E-10	0	2.69E-10	-1.83E-11	0	0	0	0
(w) Tin (Sn++, Sn4+)	g	-1.13E-07	0.00E+00	0.00E+00	0.00E+00	-1.13E-07	0	0	0	0
(w) Xylene (C6H4(CH3)2)	g	5.48E+00	5.67E+00	0	7.89E-03	-1.98E-01	0	0	0	0
(w) Zinc (Zn++)	g	-5.05E-04	2.55E-04	0	7.94E-06	-7.68E-04	0	0	0	0
<b>CML-Terrestrial Eco-toxicity</b>	t	1.01E-02	3.81E-03	0	6.71E-03	-4.56E-04	0	0	0	0
(s) Arsenic (As)	t	3.09E-04	1.17E-04	0.00E+00	2.06E-04	-1.40E-05	0	0	0	0
(s) Cadmium (Cd)	t	5.05E-07	1.91E-07	0	3.37E-07	-2.29E-08	0	0	0	0
(s) Chromium (Cr III, Cr VI)	t	4.52E-04	1.71E-04	0.00E+00	3.01E-04	-2.05E-05	0	0	0	0
(s) Chromium (Cr III, Cr VI)	t	4.52E-04	1.71E-04	0	3.01E-04	-2.05E-05	0	0	0	0
(s) Chromium (Cr III, Cr VI)	t	4.52E-04	1.71E-04	0	3.01E-04	-2.05E-05	0	0	0	0
(s) Cobalt (Co)	t	1.66E-08	6.27E-09	0	1.10E-08	-7.51E-10	0	0	0	0
(s) Copper (Cu)	t	1.52E-07	5.75E-08	0	1.01E-07	-6.89E-09	0	0	0	0
(s) Lead (Pb)	t	3.88E-07	1.47E-07	0	2.59E-07	-1.76E-08	0	0	0	0
(s) Mercury (Hg)	t	2.08E-07	7.86E-08	0	1.38E-07	-9.42E-09	0	0	0	0
(s) Nickel (Ni)	t	5.04E-07	1.91E-07	0	3.36E-07	-2.28E-08	0	0	0	0
(s) Zinc (Zn)	t	8.39E-03	3.18E-03	0	5.60E-03	-3.81E-04	0	0	0	0
<b>EB(R)-Depletion of non renewable resources</b>	unit	-1.40E-03	9.36E-04	4.17E-04	7.84E-05	-2.83E-03	0	0	0	0
(r) Barium Sulphate (BaSO4, in ground)	unit	3.51E-05	1.33E-05	0	2.34E-05	-1.59E-06	0	0	0	0
(r) Bauxite (Al2O3, ore)	unit	1.68E-07	1.81E-07	0	1.32E-09	-1.64E-08	0	0	0	0
(r) Chromium (Cr, ore)	unit	6.23E-10	2.36E-10	0	4.15E-10	-2.83E-11	0	0	0	0
(r) Coal (in ground)	unit	-1.29E-03	7.78E-09	5.43E-07	1.02E-08	-1.30E-03	0	0	0	0
(r) Copper (Cu, ore)	unit	2.53E-08	9.59E-09	0.00E+00	1.69E-08	-1.15E-09	0	0	0	0
(r) Iron (Fe, ore)	unit	-3.23E-05	1.17E-07	3.38E-09	2.07E-07	-3.26E-05	0	0	0	0
(r) Lead (Pb, ore)	unit	3.67E-08	1.39E-08	0	2.45E-08	-1.67E-09	0	0	0	0

(r) Lignite (in ground)	unit	8.81E-09	3.39E-09	0	5.97E-09	-5.52E-10	0	0	0	0	0
(r) Manganese (Mn, ore)	unit	3.77E-10	1.43E-10	0.00E+00	2.52E-10	-1.71E-11	0	0	0	0	0
(r) Natural Gas (in ground)	unit	-2.26E-05	3.77E-05	0.00039474	5.32E-05	-5.08E-04	0	0	0	0	0
(r) Nickel (Ni, ore)	unit	7.83E-09	2.96E-09	0.00E+00	5.22E-09	-3.55E-10	0	0	0	0	0
(r) Oil (in ground)	unit	8.40E-04	8.85E-04	8.80E-07	1.27E-06	-4.67E-05	0	0	0	0	0
(r) Silver (Ag, ore)	unit	1.94E-07	7.36E-08	0	1.30E-07	-8.83E-09	0	0	0	0	0
(r) Sulphur (S, in ground)	unit	8.02E-06	0.00E+00	8.02E-06	0.00E+00	0.00E+00	0	0	0	0	0
(r) Uranium (U, ore)	unit	-9.34E-04	2.71E-08	1.24E-05	4.78E-08	-9.47E-04	0	0	0	0	0
(r) Zinc (Zn, ore)	unit	2.72E-10	1.03E-10	0	1.82E-10	-1.23E-11	0	0	0	0	0
Eco-indicator 95	millipoints	-2.15E+03	1.01E+03	63.80196511	6.34E+01	-1.18E+04	613.4727782	0	4278.125838	0	3595.801774
(a) Acetone (CH3COCH3)	millipoints	-6.68E-05	7.32E-07	0.00E+00	1.23E-06	-6.88E-05	0	0	0	0	0
(a) Acetylene (C2H2)	millipoints	-6.16E-01	4.55E-07	0.00E+00	6.06E-10	-8.16E-01	0	0	0	0	0
(a) Aldehyde (unspecified)	millipoints	-6.07E-06	1.44E-04	0	9.32E-06	-6.22E-03	0	0	0	0	0
(a) Ammonia (NH3)	millipoints	-2.730037419	9.55E-04	0.014258249	6.40E-05	-2.745323301	0	0	0	0	0
(a) Arsenic (As)	millipoints	-51.94543122	0.125923158	0	5.01E-04	-52.07177985	0	0	0	0	0
(a) Benzene (C6H6)	millipoints	-1.66E+00	5.78E-02	0	4.14E-03	-1.73E+00	0.005078673	0	0	0	0
(a) Benzo(a)pyrene (C20H12)	millipoints	-97.39633031	1.09E-02	0	5.05E-03	-98.05045875	0.63760367	0	0	0	0
(a) Cadmium (Cd)	millipoints	-2.71E+02	3.55E+01	0	1.04E-01	-3.38E+02	30.94975957	0	0	0	0
(a) Carbon Dioxide (CO2, fossil)	millipoints	-1078.492184	1.13E+01	27.1021426	1.16E+01	-1211.719496	83.28028592	0	0	0	0
(a) Ethanol (C2H5OH)	millipoints	-2.05E-04	7.90E-07	0	1.21E-06	-2.07E-04	0	0	0	0	0
(a) Ethylene (C2H4)	millipoints	-39.18177011	0.373885208	0	4.72E-01	-40.02734231	0	0	0	0	0
(a) Formaldehyde (CH2O)	millipoints	-0.295909521	9.26E-04	0	1.64E-03	-0.298473821	0	0	0	0	0
(a) Halon 1301 (CF3Br)	millipoints	71.95771295	74.44735335	0	1.12E-01	-2.601873895	0	0	0	0	0
(a) Hydrocarbons (except methane)	millipoint	53.3590692	82.29787648	0	0.429515599	-64.1779427	34.80984277	0	0	0	0
(a) Hydrocarbons (unspecified)	millipoints	-1.69E+00	8.56E-03	0.209083619	2.43E-04	-1.91E+00	0	0	0	0	0
(a) Hydrogen Chloride (HCl)	millipoint	-247.6877066	0.028086121	0.068918058	5.88E-04	-247.7849137	0	0	0	0	0
(a) Hydrogen Fluoride (HF)	millipoint	-16.21477783	5.08E-03	0	1.49E-04	-16.22005153	0	0	0	0	0
(a) Lead (Pb)	millipoint	-469.5381608	1.273452723	3.083281319	2.55E-02	-476.6616322	2.741268979	0	0	0	0
(a) Manganese (Mn)	millipoint	-128.1467996	8.00E-02	0	1.41E-01	-128.3674704	0	0	0	0	0
(a) Mercury (Hg)	millipoint	-17.44338617	3.58E-02	0	5.01E-03	-17.48423762	0	0	0	0	0
(a) Methane (CH4)	millipoint	-63.74458973	3.145066416	3.539419661	8.26E-02	-70.56734112	0.055631547	0	0	0	0
(a) Nickel (Ni)	millipoint	-470.9856883	8.29E+01	0	1.97E-01	-534.0954131	0	0	0	0	0
(a) Nitrogen Oxides (NOx as NO2)	millipoint	4256.818308	11.39450884	15.04235002	1.59E+00	-1165.316802	441.6827927	0	2641.294718	0	2311.130892
(a) Nitrous Oxide (N2O)	millipoint	-0.548914127	3.35E-02	0	3.40E-03	-3.733842398	3.147988768	0	0	0	0
(a) Particulates (unspecified)	millipoints	-2371.839206	1.60E+00	1.858641557	4.41E+01	-2604.238771	16.16252563	0	168.6358267	0	0
(a) Pentane (C5H12)	millipoint	1.075811173	1.093978951	0	2.05E-02	-0.038897142	0	0	0	0	0
(a) Phenol (C6H5OH)	millipoint	4.05E-09	1.53E-09	0	2.70E-09	-1.84E-10	0	0	0	0	0
(a) Polycyclic Aromatic Hydrocarbons (PAH, unspecified)	millipoint	3.846895987	1.442314174	0	2.55321374	-1.49E-01	0	0	0	0	0
(a) Propane (C3H8)	millipoint	-3.791679791	0.9597369	0	1.96E-02	-4.770992603	0	0	0	0	0
(a) Propionaldehyde (CH3CH2CHO)	millipoint	1.15E-09	4.36E-10	0	7.68E-10	-5.23E-11	0	0	0	0	0
(a) Propylene (CH2CHCH3)	millipoint	-5.348847538	0.109393761	0	1.62E-04	-5.458395643	0	0	0	0	0
(a) Sulphur Oxides (SOx as SO2)	millipoint	-1.81E+03	4.22E+01	9.598624799	7.23E-01	-4.62E+03	0	1488.195294	0	1284.670882	0
(a) Tars (unspecified)	millipoint	1.19E-06	1.23E-06	0	1.64E-09	-4.01E-08	0	0	0	0	0
(a) Toluene (C6H5CH3)	millipoint	-0.560828097	0.185162835	0	4.63E-03	-0.750618368	0	0	0	0	0
(w) Ammonia (NH4+, NH3, as N)	millipoint	-9.50E-01	9.79E-01	0.001866163	1.41E-03	-1.93E+00	0	0	0	0	0
(w) Arsenic (As3+, As5+)	millipoint	0.272119888	0.795270104	0	1.36E-02	-0.53670779	0	0	0	0	0
(w) Barium (Ba++)	millipoint	642.4949873	684.9849884	1.019501517	-23.50937035	0	0	0	0	0	0
(w) Boron (B III)	millipoint	8.93E-01	9.23E-01	0	1.78E-03	-3.23E-02	0	0	0	0	0
(w) Cadmium (Cd++)	millipoint	3.583237395	3.987201685	0	7.70E-03	-0.411648558	0	0	0	0	0
(w) Chromium (Cr III, Cr VI)	millipoint	0.674223979	0.918266988	0	1.22E-03	-0.243263081	0	0	0	0	0
(w) COD (Chemical Oxygen Demand)	millipoint	0.087017324	0.090380067	9.79E-05	4.17E-04	-0.003877677	0	0	0	0	0
(w) Copper (Cu+, Cu++)	millipoint	1.20E-02	1.35E-02	0	1.68E-04	-1.69E-03	0	0	0	0	0
(w) Lead (Pb++, Pb4+)	millipoint	-18.2048827	0.836310308	3.083281319	8.59E-02	-2.22E+01	0	0	0	0	0
(w) Manganese (Mn II, Mn III, Mn VII)	millipoint	-3.917070327	1.831457979	0	5.46E-03	-5.753981244	0	0	0	0	0
(w) Mercury (Hg+, Hg++)	millipoint	7.43E-02	7.88E-02	0	1.05E-04	-4.58E-03	0	0	0	0	0
(w) Molybdenum (Mo II, Mo III, Mo IV, Mo V, Mo VI)	millipoint	-2.29E-01	0.110343975	0.00E+00	1.47E-04	-0.339739796	0	0	0	0	0
(w) Nickel (Ni++, Ni3+)	millipoint	-8.99E+00	2.30E+00	0	1.93E-02	-1.13E+01	0	0	0	0	0
(w) Phosphates (PO4 3-, HPO4--, H2PO4-, H3PO4, as P)	millipoint	-1.30E-03	1.89E-04	0	3.33E-04	-1.82E-03	0	0	0	0	0
(w) Phosphorus (P)	millipoints	0.033480045	0.034628468	0	6.21E-05	-1.21E-03	0	0	0	0	0
ETH-Air Acidification	g eq. H+	6.67E+02	12.43389394	6.25873501	6.00E-01	-1.43E+03	120.8673913	0	1046.045652	0	915.2894022
(a) Ammonia (NH3)	g eq. H+	-0.761670586	2.67E-04	0.003978	1.79E-05	-0.765935294	0	0	0	0	0
(a) Hydrogen Chloride (HCl)	g eq. H+	-8.66E+01	9.82E-03	2.41E-02	2.06E-04	-8.66E+01	0	0	0	0	0
(a) Hydrogen Fluoride (HF)	g eq. H+	-5.8881	0.00178288	0	5.21E-05	-5.89E+00	0	0	0	0	0
(a) Hydrogen Sulphide (H2S)	g eq. H+	-5.133752941	3.55E-03	0.001989	6.26E-03	-5.145552941	0	0	0	0	0
(a) Nitrogen Oxides (NOx as NO2)	g eq. H+	1164.886957	3.118130435	4.116369565	0.434778261	-318.8913043	120.8673913	0	722.7956522	0	632.4456522
(a) Sulphur Oxides (SOx as SO2)	g eq. H+	-399.575	9.30034375	2.1133125	0.159086563	-1017.24375	0	323.25	0	282.84375	0

IPCC Greenhouse effect (direct, 20 years)	g eq. CO2	-6979590.253	124902.3291	215591.96	62473.05859	-7040269.078	457705.5798	0	0	0	0
(a) Carbon Dioxide (CO2, fossil)	g eq. CO2	-5651290	58968.1	142015	60734.7	-6349400	436388	0	0	0	0
(a) Carbon Tetrafluoride (CF4)	g eq. CO2	0.015548754	0.005884866	0	0.010369437	-0.000705533	0	0	0	0	0
(a) Halon 1301 (CF3Br)	g eq. CO2	328.8217	340.19649	0	0.51236951	-11.889658	0	0	0	0	0
(a) Methane (CH4)	g eq. CO2	-1325113.6	65379.2	73576.96	1716.0576	-1466944	1156.4608	0	0	0	0
(a) Nitrous Oxide (N2O)	g eq. CO2	-3515.49	214.82472	0	21.778251	-23913.186	20161.119	0	0	0	0

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## Appendix 4

Base Case - Sugar Production		
Emission	Nitrogen Oxides (g)	Sulphur Oxides (g)
Diesel Oil Production	143.43	297.61
Ammonia (NH <sub>3</sub> ) Production	189.35	67.63
Lime (Slaked, Ca(OH) <sub>2</sub> ) Production	20.00	5.09
Electricity (South Africa, 1996) Production	19.67	43.65
Road Transport	5559.90	0.00
Agricultural Operations	0.00	0.00
Fertilizer Production	0.00	0.00
Sugarcane Processing - Base Case	62341.10	19395.00
Credits	None	0.00
<b>Total</b>	<b>Base Case</b>	<b>68273.46</b>

Green Electricity Option		
Emission	Nitrogen Oxides (g)	Sulphur Oxides (g)
Diesel Oil Production	143.43	297.61
Ammonia (NH <sub>3</sub> ) Production	189.35	67.63
Lime (Slaked, Ca(OH) <sub>2</sub> ) Production	20.00	5.09
Road Transport	5559.90	0.00
Agricultural Operations	0.00	0.00
Energy Module (bagasse)	33248.60	10344.00
Fertilizer Production	0.00	0.00
Sugarcane Processing	29092.50	9051.00
Credits	Electricity (South Africa, 1996) Production	-14669.00
<b>Total</b>	<b>Green Electricity Option</b>	<b>53584.79</b>

Bio-Ethanol Option		
Emission	Nitrogen Oxides (g)	Sulphur Oxides (g)
Diesel Oil Production	158.24	328.33
Ammonia (NH <sub>3</sub> ) Production	189.72	67.76
Sulphuric Acid (H <sub>2</sub> SO <sub>4</sub> ) Production	77.24	2025.07
Lime (Slaked, Ca(OH) <sub>2</sub> ) Production	40.80	10.39
Road Transport	5559.90	0.00
Acid Dilution	0.00	0.00
Agricultural Operations	0.00	0.00
Energy Module (Ligneous Residue)	14680.00	4566.79
Fertilizer Production	0.00	0.00
Gasoline Equivalence Converter	0.00	0.00
Integrated Bio-refinery	18569.30	5777.12
Sugarcane Processing	29092.50	9051.00
Credits	Electricity (South Africa, 1996) Production	-4443.03
	Leaded Gasoline Production	-868.56
<b>Total</b>	<b>Bio-Ethanol Option</b>	<b>63056.10</b>

**Appendix 5: Examiner's Comments on Life Cycle  
Methodology Employed in Case 1**

University of Cape Town