A LIFE CYCLE ASSESSMENT OF ETHANOL PRODUCED FROM SUGARCANE MOLASSES

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)

By

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September 2002

Synopsis

The environmental performance of production companies is increasingly becoming part of strategies for the competitive marketing of their products, as consumers grow more aware of environmental issues surrounding industry. Similar products can be compared by the tool of Life Cycle Assessment (LCA) from the perspective of their impacts on the environment from which their production resources are drawn and to which their burdens are released. There is the inherent perception that products made from renewable resources are environmentally more desirable than those which are produced from finite resources. This thesis investigates whether this conception is valid for the case of ethanol produced from biomass, by describing and interpreting the various stages of the production process by means of an LCA.

Sugarcane (*Saccharum officinarum*) contains 12 – 17% sugars on a wet basis, and 68 – 72% moisture. The sugar composition is 90% sucrose and 10% glucose or fructose. In the conventional sugar production industry, syrup containing about 34% sucrose (molasses) remains after sugar crystals are formed from the clarified juice. This sucrose can be fermented to produce ethanol whose uses include potable consumption and the production of chemicals, but there is growing interest in its possible use as an additive for motor-grade gasoline, as well as its use as neat fuel to replace crude-oil based fuels.

This thesis presents a cradle to gate life cycle study carried out with the aim of determining the environmental consequences of producing ethanol from sugarcane molasses. The investigation was done for a sugar producing company in the Kwa-Zulu Natal Province of South Africa, whose interests also lie in the beneficiation of value addition products from sugarcane.
The goal of the study was to produce a comprehensive inventory of all the energy and material inputs and outputs involved in the production of the 1 kl (1000 litres) of bio-ethanol, using Life Cycle Assessment (LCA). Concepts of *carbon closure* and fossil *energy ratio* were chosen to represent measures of the degree of renewability of the system, and the results were compared to values derived from the literature on life cycle assessments of similar bioenergy systems.

The following stages of the life cycle were investigated:

- Agricultural Production (sugarcane growing),
- Sugarcane to molasses Process (sugar production process, with molasses as by-product),
- Molasses to ethanol Process (fermentation of molasses sugars to ethanol, and distillation),

- Road Transportation (of sugarcane, and molasses)

The associated process flows, whose production life-cycles were also covered in the assessment, included the following processes:

- Coal Mining
- Electricity Generation
- Sulphuric Acid Production
- Lime Production
- Diesel Production
- Fertiliser Production

Primary data from the Agricultural, Sugarcane to molasses and Molasses to ethanol process was gathered from the production sites of the company; while TEAM™ software database information was used to model the transportation, coal mining, electricity generation, sulphuric acid lime and diesel production processes. Data published in the literature were used to assess the relative importance of fertiliser production.

A 26% mass-based allocation of the burdens associated with sugar production was made to the production of molasses. The results showed that the molasses to ethanol process is the most fossil energy intensive, requiring 0.74 ton of coal per kl of ethanol produced. This represented 86% of the total fossil energy input into the life cycle. Resultantly, a fossil energy ratio of 1.13 was calculated, with a corresponding carbon closure of 79% as a result of the fossil carbon dioxide emissions from the combustion of the coal.

The solar endowment in bagasse was found to be 1.1 times the value of the total fossil primary energy input, indicating the potential subsidy in fossil energy requirement that the bagasse could offer.

The sulphate and chloride emissions, and the COD (chemical oxygen demand) in the liquid effluent of the molasses to ethanol process were found to cause the environmental impact of highest relative concern, this being the eutrophication of aquatic eco-systems. The second highest impact of note was the contribution to climate change caused by fossil carbon dioxide, also originating from this process. Other applicable impact categories on a smaller scale were photochemical oxidant formation and air acidification.

Overall, the process showed no significant sensitivity to the allocation rule used, since the dominating molasses-to-ethanol sub-process was unaffected by the partition between sugarcane and molasses.

It was recommended that the integration of the two processes with respect to energy utilisation and management could significantly improve the fossil energy ratio and carbon closure figures of the production system, and subsequently minimise the impacts which are of concern from the current production profile.

Further recommendations on the improvement of the model of the overall process included the quantification of fugitive hydrocarbon vapour emissions, determination of accurate water usage figures, and the evaluation of the impact of fertiliser and pesticide usage in the agricultural stages of the ethanol product life-cycle.

Dedication

This thesis is dedicated to my parents Downs and Daphne Theka, for their immeasurable support, commitment and sacrifices, for the sake of my academic pursuits. Thank you.

Acknowledgements

I would like to thank all the people who helped me with their support, information and advice on this research.

Special thanks go to my supervisor Dr. Harro von Blottnitz for his excellent guidance on the project and personal support, and to all the staff from the Company who assisted me with gathering and compiling the required data.

I would also like to thank my friends Christiaan Ndoro, Zimiti Mudondo and Benjamin Wandawanda, for their assistance with editing and proofreading of the thesis.

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Glossary of Acronyms

BOD	Biological Oxygen Demand
CML	Centre of Environmental Science, Leiden University
COD	Chemical Oxygen Demand
CST	Critical Surface-Time
ETBE	Ethyl Tertiary Butyl Ether
GWP	Global Warming Potential
IPCC	International Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MTBE	Methyl Tertiary Butyl Ether
TEAM™	Tools for Environmental Analysis and Management
USES	Uniform System for the Evaluation of Substances
VOC	Volatile Organic Compound
WMO	World Meteorological Organization

1. INTRODUCTION

1.1 Background

Effective media communication on the detrimental effects of human activities to our own environment has resulted in an increased global environmental awareness, and this in turn has paved the way for a revolution in the thinking and approach taken by industry with regards to environmental management. Environmental legislation has become more stringent, and the market response is inclined in favour of products of a less detrimental environmental profile. Resultantly, environmental differentiation is fast becoming a basis for competitive strategy. A company can use its environmental profile to gain advantage over its competitors by attracting new customers and building customer loyalty, and it also allows them to charge a premium price for their products while erecting barriers for potential new entrants. Environmental reporting by companies has become a communication tool to convince a broad range of stakeholders, including consumers, of their commitment to environmental protection. Corporate environmental reports can range from a simple public relations statement, to a detailed in-depth examination of policy, practices and future direction (Roy & Vezina, 2001).

Products made in South Africa, and sold into sophisticated European and American markets, face competition from other producers from these regions, and are hence compelled to meet both the standards of their competitors, and the demands of their consumers.
Ethanol from biomass is an example of such products; it can be produced from a range of energy and food crops, and, at least in theory, also from cellulosic and hemi-cellulosic biomass sources. A variety of markets for the consumption of this product exist, and a general overview is shown below:

- **Transport market** - gasoline blending with neat ethanol, gasoline reformulation with ETBE, bioethanol for new generation cars (fuel cells, hybrid etc), bioethanol fuels for agricultural machinery)
- **Cogeneration market** – bioethanol for: abatement (reburning) of NO_X in fossil fuel plants, CO_2 trade-off fuel, steam injection turbines, combined-cycle power plants, diesel-powered generators)
- **Domestic market** – cooking stoves, lighting, refrigeration, heating and cooling devices

- **Chemicals market** – ethylene, hydrogen production, glycol ethers, ethyl acrylate, acetic acids, ethylamines, ethyl acetate, acetaldehyde, ethyl ether.
- **Potable alcohol market** – ethanol is used in liquors of all sorts, examples being gin, vodka, tequila, brandy and sherry, amongst others.

Currently, the transport market accounts for 20% of present consumption, while the power and heat market consumes 10%. The chemicals and domestic markets combined account for the remaining fraction of the ethanol market.

In the long-term, the breakdown of this global market capacity is projected by Grassi (2000) as follows:

Table 1 Global market capacity potential for bio-ethanol

Market	Projected capacity (million tpa)
Transport	550
Power and heat	500
Domestic	>100
Chemicals	200

It can be seen from these projection figures that the transport market is expected to increase from the current 20% share to at least 39%, representing an approximately 100% increase in the transport energy sector and hence shifting the dominance in favour of transport energy (Grassi, 2000).

This shift from predominance for domestic and chemical markets to fuel (energy) markets is foreseen, based on the possible replacement of MTBE (Methyl Tertiary Butyl Ether) and lead in gasoline. Ethanol is an octane booster for gasoline, and can be blended with gasoline to replace conventional additives that have since been identified to cause groundwater contamination and potential human health problems. In the United States alone, the demand for motor fuel is around 450 billion litres per annum, and with a 4% shortfall resulting from the removal of MTBE, an ethanol production of 11 – 15 billion litres would be required, compared to the current production of 5 billion litres (Lyons, 1999).

In many African countries however, the use of lead in gasoline is still dominant because of the comparative cost of the alternative additives. The investigation by Thomas and Kwong (2001) determined that within the potential of sub-Saharan countries have great potential to produce ethanol from sugarcane and molasses for blending with ethanol. It was also determined that, for a 20% ethanol blend in gasoline, 2.4 billion litres would be required to replace the 9000 tons lead per year used in Africa. In the evaluation of the sugarcane industry in these sub-Saharan countries, up to 0.5 billion litres ethanol per year can be produced from molasses only, and up to 4 billion litres if all sugarcane is converted to ethanol. From these figures, it can be seen that the potential to meet the required ethanol capacity (2.4 billion litres per yr) for lead replacement in Africa is collectively feasible.

But do products made from renewable resources, such as ethanol from biomass, necessarily have an inherent environmental competitive advantage over their counterparts, on the basis of their natural origin? Market perception is definitely of this opinion, and products that are renewable are viewed as being of a "greener" profile, and are hence preferred over other products of the same category. From an overview perspective, this appears a well-justified ideology; biomass is a renewable resource through the natural carbon cycle of photosynthesis through which it can be re-generated. But how sustainable is the collective of processes which combine to make these so-called renewable products? This question can only be comprehensively answered by scrutinising their full life-cycle and accounting for all the energy and material inputs and outputs involved in their production, as well as the environmental burdens created in the process and their impacts.

Life-cycle assessment (LCA) offers an approach to analyse and answer the questions above, it is an effective evaluation tool for the determination of the effects to the environment relating to a particular product, because of its cradle-to-grave approach, which calls for the inclusion of all indirect inputs and outputs in the analysis. The results of an LCA are primarily a comprehensive production inventory, which can then be translated into environmental impacts in different categories of concern, as well as other performance evaluation indices directed at determining how intensively damaging a product is to the global environment.

1.2 Problem statement

Liquid bio-fuels form an important subset of so-called "bioenergy" systems, which represent one of the emerging renewable energy options, other examples being solar, wind and hydro-energy. The exploration of these alternative energy options comes in the wake of the realisation that current fossil energy consumption is not sustainable. This derives from the observations that, amongst other environmental concerns, future generations would not be awarded equal privilege to energy exploitation due to limited availability, and that the current dispersion of combustion products into the global environment also seems to be resulting in detrimental changes in climate.

Bio-ethanol, used as fuel, is a specific product from the renewable energy source of biomass, which can be grown purposefully through energy crops or vegetation, but is also naturally occurring. The inherent question presented in the previous section, which is the essence of the investigation in this study, is revisited here:

Are the current patterns of production and use of products from replenishable raw materials sustainable?

The production of bio-ethanol in the African context, where it is mainly a by-process of the sugar production industry, has (with the exception of several Mauritian studies) not been investigated from a life-cycle perspective.

As will be discussed in chapter 2, the comparative performance of bio-fuel production systems has been scrutinised in the context of their energy inputs and outputs, carbon balance profile, resource use and environmental burdens, amongst other issues of concern with respect to sustainability. Currently, this level of information detail on ethanol production from molasses has yet to be attained. The results of life-cycle approaches to bio-energy systems analyses which have been previously done show that different aspects of the production profile may be isolated as being of key concern for the different studies. This makes the particular assessment of the performance of bio-ethanol production of this nature imperative, before commenting on the sustainability of the overall process.

Hence, the following problem statement is presented:

There is lacking in the understanding of the extent to which the renewability of bio-ethanol produced from sugarcane molasses, as produced in Africa, can be stated. Its processing and use are yet to be determined as sustainable through a comprehensive

study of all energy and material inputs and outputs involved in the entire life cycle of the product, and their consequences on the receiving environment.

1.3 Objectives of the research

The primary objectives of this life-cycle study are as follows:

- to document a comprehensive life-cycle inventory for the production of ethanol from the fermentation of molasses from the sugar-processing industry;
- to derive from this inventory an understanding of the implications of the overall process, in terms of environmental burdens and their subsequent impact on the recipient environment.

  The energy and resource requirements, and the resulting environmental outputs can be translated into assessment measures and indices which give an indication of the severity of the overall process in global and regional terms.

Another objective of the study was related to the direct use of the information by the company involved, and this is to record data at the distillery in such a way that it is of use in the monitoring of their environmental performance internally, by the use of relevant indicators.

1.4 Statement of hypothesis

Based on the objectives stated above, the hypothesis put forward in this research is then:

Current practices of ethanol production from sugarcane molasses are sustainable in principle, but may require modifications in the cane growing and processing, and the conversion process involved. Further, such modifications can be effectively identified through a life-cycle analysis.

The hypothesis stated here is made with insight into the key questions raised from similar studies, as uncovered by the literature. It is important to note that the process under scrutiny here has the prime purpose of producing sugar, and molasses is a by-product stream from which a value-addition product is produced. The results of this study shall hence be carefully analysed with the observation that the conversion processes involved are not directly orientated towards the production of molasses.

1.5 Approach

The argument presented in the problem statement (section 1.2) hence sets the platform for the analysis of this study. In order to prove the hypothesis stated above, the following approach is proposed:

Initially, the relevance of using life-cycle assessment (LCA) to arrive at the detail of information required to characterise the sustainability of the current production practices needs to be affirmed. To this end, literature on sustainability of industrial production is reviewed, and examples of the applicability of the methodology to this type of problem are sought out.
A more detailed review of previous life cycle based studies on bio-energy systems is then presented, to highlight the issues of concern which have arisen, and which may be relevant to this particular investigation. This work also serves to identify the gaps or inadequacies of the published studies. Finally, this review shall identify the different assessment methods and indices that have previously been used to describe the renewability of bio-energy systems.
From this platform, a life cycle analysis, with its typical four phases of goal and scope, inventory, impact assessment, and interpretation is launched of current bio-ethanol production in a South African setting. The system analysed here is limited to one particular production operation. Nevertheless, the sugar processing and alcohol production technologies used are largely conventional in Africa, and hence the analysis is relevant for generalisation.

Finally, the results of this life cycle assessment can be compared with the results from previous studies, and hence conclusions on the fore-stated hypothesis can be duly made.
The extent of the contribution made by this study is limited by its goals and scope, and the presentation of these limitations outlines what expectations this analysis should be able to meet.

1.6 Limitations

The main limitation of this LCA is the exclusion of the end-use of the ethanol product. This is because its current main use is as potable alcohol, while the study seeks to lay a foundation for the exploration of different possible uses, particularly as biofuel. Resultantly, this is only a cradle-to-gate life cycle analysis, with the ethanol product as the gate end of the study. By exclusion of the end-use of this ethanol, the results could be used comparatively with other production life-cycles to explore the advantages and disadvantages of each where different end-uses are investigated, such as its use as a substitute fuel or gasoline additive.

Another limitation is the fact that this data is specific to the production profile of one company only, and not averaged to represent general production pattern of this nature. This means that some results will be specific to the company alone, and may not necessarily reflect the practices of other similar producers.

Other limitations are in the detail of the data gathered, pertaining to data recording practices at the production sites, as well as physical constraints, to be further discussed under the relevant sections.

1.7 Structure of the thesis

The following outline has been used to present the detail of the thesis in the chapters to follow:

- Chapter 2 is the literature review chapter. The subsections discuss, firstly, how life cycle assessment can be used to measure process sustainability.

  The subsequent sections then investigate the different measures of sustainability used in other studies, and present their results. The sources and technology (present and future) for producing bio-ethanol are scrutinised, leading to the particular findings of the study in the next chapter.
- Chapter 3 presents the goal and scope of the LCA.
- Chapter 4 outlines the data gathering procedures used in the study, and also discusses the modelling of the overall process using the TEAM™ software, which leads to the inventory results in the subsequent chapter.
- The life-cycle inventory is presented in Chapter 5; the key flows are isolated and discussed, giving reason for their highlighting, and how this relates to the impact assessment to follow. An interpretation of the figures in the inventory is made here, and life-cycle based indicators related to those presented in the literature review are also presented. A sensitivity analysis is also shown here, examining the effect of allocation and minima and maxima of key flows.
- Chapter 6 presents the impact categories of interest to this study, followed by the actual figures for impact assessment as generated by the TEAM software. An interpretation of the impact assessment is presented, and the discussion on this chapter then leads to the conclusions and recommendations to follow.
- Chapter 7 is the conclusions and recommendations chapter, and draws on the interpretation of the inventory and the impact assessment, in line with the hypothesis and objectives of the research.

2. LITERATURE REVIEW

This chapter presents the key literature relevant to this study, in line with the objectives and the approach as described in the previous chapter.

A discussion of how LCA addresses concerns of sustainability is first presented, followed by details of production of bioenergy from biomass, and bio-ethanol in particular. The life cycle analyses of bio-energy systems and their results are then presented, and finally the main issues of concern raised in the production of energy from biomass are highlighted.

2.1 Using life-cycle assessment (LCA) to measure sustainability

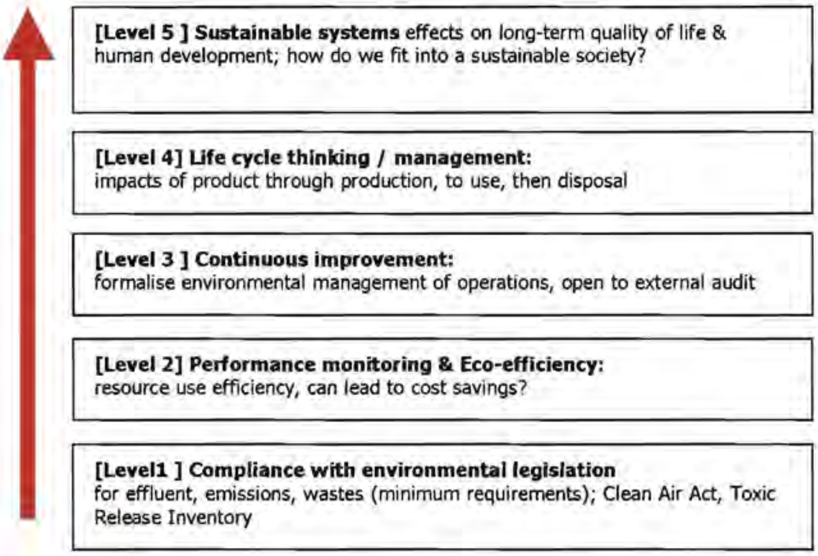
LCA has been chosen as the preferred tool for the evaluation presented in this study, and the section here shall present the features of this tool which make it suitable to evaluate sustainability of production systems.

The technical definitions of life-cycle assessment (LCA) as a process evaluation tool, as well as its operational hierarchy and generic methodology shall not be discussed, as the target audience for this analysis is deemed to be knowledgeable in the foresaid field. The reader is encouraged to consult literature references on life-cycle methodology; the guiding documents from which the adaptation used here was obtained are the ISO standards on life-cycle assessment methodology, the TEAM™ software (discussed later) manual, and reference to the thesis by Rwodzi (2000).

LCA is a method for assessment of the environmental impact of products, processes or services from raw materials to waste products. Although this method is often used to compare products with the same function, it can also be used to identify "hot spots", which are parts of the life cycle which are critical to the overall environmental impact (Anderson et al.,1998).

It is viewed as an effective tool for sustainable performance, because it holds companies responsible for considering the upstream and downstream implications of their activities, and hence take action to mitigate them. The inter-connected industrial system from which a product is made is carefully considered, paying attention both to the products and by-products, as well as waste streams, in view of processing and service operations. Consumers are also considered an integral part of the cycle; they use the products and energy resources, then return them to the industrial eco-system for reprocessing and re-use (DeSimone & Popoff, 1997).

Recent works suggest that there is a five level hierarchy of involvement in the concept of building sustainable systems of production and consumption. A model developed at the University of Cape Town, similar to work published elsewhere (Veleva, 2001), is shown below:



[Level 5] Sustainable systems effects on long-term quality of life & human development; how do we fit into a sustainable society?

[Level 4] Life cycle thinking / management:
impacts of product through production, to use, then disposal

[Level 3] Continuous improvement:
formalise environmental management of operations, open to external audit

[Level 2] Performance monitoring & Eco-efficiency:
resource use efficiency, can lead to cost savings?

[Level1] Compliance with environmental legislation
for effluent, emissions, wastes (minimum requirements); Clean Air Act, Toxic Release Inventory

Figure 2.1 Hierarchy of sustainable production levels

Level one monitoring only evaluates the extent to which a company is in compliance with regulations, and typically these would be specified by the Occupational Safety and Health Act or Toxic Release Inventory, for example. Level two reports a facility's inputs and outputs, emissions, products and waste, and can measure resource use efficiency and can be used for maintaining a competitive advantage.

Level three is a step further than the previous level, where the company opens itself to external environmental auditing and begins to take note of the impact of its process on a global scale e.g. greenhouse gas emissions per year.

Level four monitoring goes beyond the boundary of the firm's processes and extends the level three reporting to their supply chain, product distribution and ultimate disposal. This is the level at which life-cycle assessment (LCA) can be used to follow up on the upstream processes that provide the raw materials, and downstream to the end use of the product.

The study presented here sits at the fourth level. This level is very crucial because it is the first level at which observation is made beyond the site boundaries of the process, to incorporate the burdens of upstream production involved with the various flows and utilities associated with the final product. The information compiled at the fourth level creates an overall picture of the full implications of a product's manufacture and use, and supplies the background for the analysis which follows in the fifth level.

Level five essentially involves a multi-disciplinary analysis; it shows how an individual company's performance fits into a global picture of a sustainable society, looking at the effects of production on the long-term quality of life and human development. The socio-economic aspects, as well as the environmental debates surrounding the benefit and/or detriment of a particular product are assessed at this level.

A level five analysis can only be made comprehensively once the detail from the previous level is compiled, and therefore the fourth level approach used in this assessment is the appropriate starting point for a company which aims to establish its contribution to a regional or global sustainability profile, as is the case here.

2.2 Review of bio-energy and bio-ethanol systems

This section and those following shall explore the profiles and performances of different bioenergy systems, ranging from electricity production to liquid fuels production. While it is appreciated that the study presented in this research is the production of ethanol for potable use, the results from a diverse range of bio-energy systems is deemed to be relevant in establishing the methodological approach and typical results and concerns raised on bio-systems, and this sets a relevant platform for the analysis of this particular research.

2.2.1 Background

Renewable energy sources make up one-fifth of the world's energy supplies, with 13 - 14% originating from biomass, and 6% from hydro-power. It is estimated, however, that in developing countries, biomass can account to up to 90% of all energy used, while in some developed countries such as Sweden and Finland, its use is in the range of 16 – 18% (Hall & Scrase, 1998). A study by Chum and Overend (2001) also revealed that in the United States alone, biomass (43%) is only second to hydropower (51%) as a primary renewable energy source.

Despite its apparent abundance, biomass still remains the least efficiently exploited renewable energy source, overshadowed by the dominance of hydro-power, solar and wind energy (Sims, 2001). Biomass is most commonly used as fuel, by incinerating it to generate heat. Other routes of conversion to retrieve biomass energy in other forms are yet to be fully utilised.

Owing to its climate, Africa has an abundance of biomass, and hence the exploration of energy options which offer its efficient use and maximisation is imperative (Karakezi & Mackenzie, 1993).

2.2.2 Sources of bioenergy

Bioenergy sources can be classified into three main categories:

(i) residues and wastes from agricultural production
(ii) purpose-grown energy crops, and
(iii) natural vegetation.

2.2.2.1 Residues and wastes

This refers to trash from agricultural processing such as rice-husks, corncobs, bagasse and cane tops from sugarcane. Other crops that produce residue which can be used for bio-energy are barley (straw), coconut (shell), groundnuts (shell), and maize (husks, stalks).

These are an essential source of bio-energy, particularly in regions where most of the land is used for food production (Kartha & Larson, 2000).

2.2.2.2 Purpose-grown energy crops

These are the crops that are specifically grown for energy conversion, and typical examples are sugarcane, sugar beet, rapeseed, wheat, maize, sorghum and potatoes (Kaltschmitt et al., 1996). -- Perrenial grasses, such as switchgrass, big bluestem, reed canary grass and alfalfa have also been successfully grown for the purpose of energy harvest (Hallam et al., 2001).

2.2.3 Conversion routes to bio-energy from biomass

Biomass can be converted to bio-energy in the form of heat, power and transport/machinery fuels. The diagram below illustrates the different forms of bio-energy, as well as the processing routes used for their production:

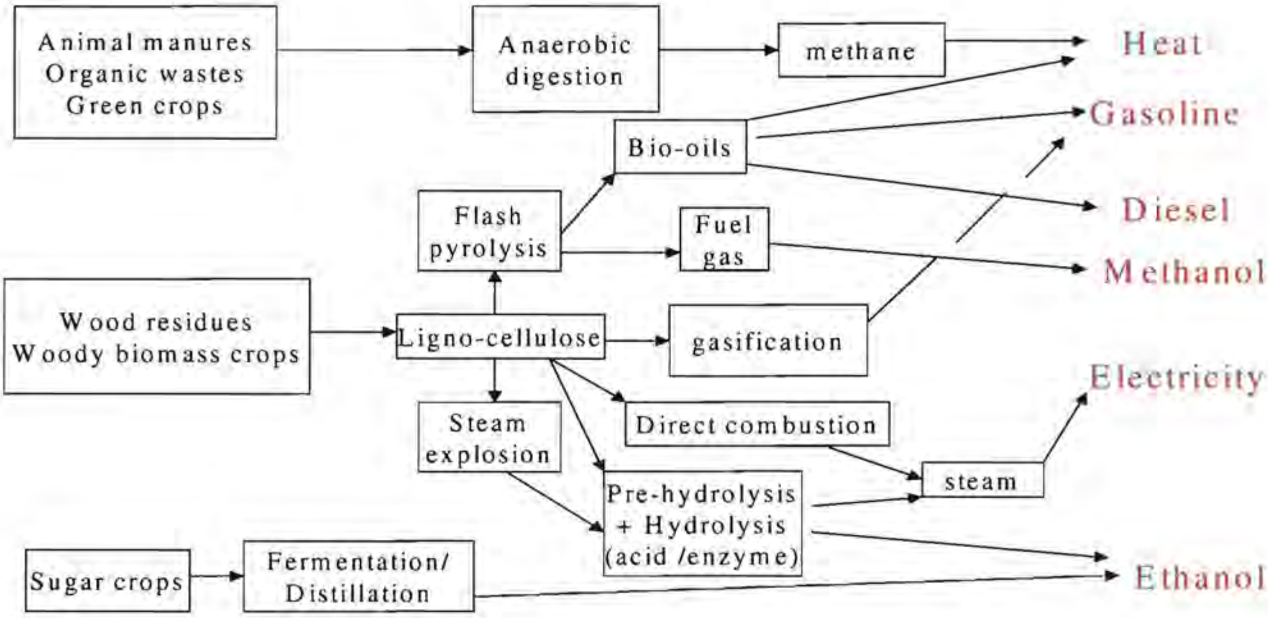


Figure 2.2 Biomass to bio-energy routes (Sims, 2001)

Brief discussions on some of the technologies illustrated in the figure above (with the exception of ethanol from sugar crops which is discussed in detail in section 2.2.4) shall follow here to develop an understanding of the technical diversity in the conversion of the different energy carriers.

2.2.3.1 Gasification

Combustible gas is produced through high-temperature (thermochemical) and low-temperature (biological) processes. In thermochemical gasification, the biomass is essentially burnt with just enough air (incomplete combustion) to convert it to gaseous fuel. Updraft and downdraft fixed-bed gasifiers are used, and the product gas can be used for heating, cooking or for internal combustion engines to produce electricity or shaft power generation.

2.2.3.2 Anaerobic digestion

In this process, the organic matter is degraded by three kinds of bacteria: fermentative bacteria, acetogens and methanogens. The fist two break down complex organic compounds into simpler intermediates, which are then converted to methane and carbon dioxide by methanogens.

2.2.3.3 Steam turbine combined heat and power

Pressurised water is boiled, and the resulting steam is expanded to drive a turbine generator, then condensed back to water for partial or full recycling to the boiler. A heat exchanger can be used to recover heat from flue gases and use this to preheat combustion air, and a de-aerator is required to remove dissolved oxygen from the water before boiling it. The boiler fuel is biomass, preferably dried to improve the boiler efficiency.

2.3 Bio-ethanol from biomass: process routes and technology

2.3.1 Production of bio-ethanol

2.3.1.1 Main liquid bio-fuels

The key liquid bio-fuels that have been researched as potential replacements for fossil fuel are bio-diesel (from vegetable oil ester), bio-ethanol (from fermentation of sugars in crops) and its derivative Ethyl Tertiary Butyl Ether (ETBE). Other liquid biofuels such as bio-methanol and its derivative MTBE (Methyl Tertiary Butyl Ether) from lignocellulosic material have been researched, but have not gained the commercial potential and market share of the first two (ATLAS web site, 2001).

2.3.1.2 Comparison of bio-diesel and bio-ethanol

Biodiesel had a worldwide production capacity of 1 263 000 metric tons in 1996, with Germany and France as the leading producers. In the European Union (EU) alone, production is estimated at 907 000 metric tons.

The main feedstock for bio-diesel production in Europe is oil from rapeseed, although other vegetable oils may be used. Its capital use has been in the blending with petroleum diesel for use in urban-public-bus and truck fleets, but also for fuelling farm equipment, and as a heating fuel, solvent, hydraulic oil, and lubricant (Raneses et al., 1999). In the United States, bio-diesel is produced mainly from soybeans.

Until recently, however, Brazil and North America were the only two regions which produced fuel ethanol from sugarcane and maize, respectively, on a significant commercial scale. Table 2.1 below illustrates the distribution of ethanol production as of 1999, identifying key players in the industry.

Table 2.1 World production of bio-ethanol

Country	Production (billion litres)	Raw materials
Brazil	14.0	Sugarcane, beets
United States	5.3	Cereal grains (mostly corn)
Europe	4.3	Cereal grains, beets
Russia	2.5	Cereal grains, beets
Total world production	28.0	

Berg, 1999, cited by Lyons, 1999

2.3.1.3 Blending ethanol with gasoline

(a) Background

Octane rating is a measure of the tendency of the air and fuel mixture to resist spontaneous combustion as it is heated during the compression stroke in the engine cylinder of a four-stroke engine. This pre-ignition, or knock effect, as is commonly known, would otherwise decrease the efficiency of the engine and increase wear. At high temperatures and pressures during compression of fuel in the engine, the fuel molecules break down to free radicals, which can then build up the chain reaction to cause pre-ignition. The role of an additive like tetra-ethyl lead is to "scavenge" these free radicals, reacting with them before they can cause the said chain reaction. Changing its composition can, however, increase the octane value of gasoline. By blending with ethanol, which is a low bond order hydrocarbon, the probability of forming free radicals at high temperatures and pressures can be reduced (Thomas & Kwong, 2001)

(b) Status and prospects of ethanol as fuel

Brazil's Proalcool Program introduced in 1975, following the energy crisis of the period, set the pace for the country's leading alcohol programme, which grew from 1 billion litres in 1976 to 12.6 billion litres in 1995 of ethanol from sugarcane. In the Unites States, ethanol is produced from corn (maize), and is more expensive than the sugarcane based ethanol. As a result, it relies on a government subsidy of \$0.14/l to make it competitive with gasoline.

In sub-Saharan Africa, South Africa, Zimbabwe, Malawi and Zambia are viewed as having great potential for fuel ethanol production, based on their current sugar production capacities. Each of these countries is estimated to have a potential cane-to-ethanol production capacity greater than 100 million litres per annum, and a molasses-to-ethanol potential capacity of above 10 million litres per annum (Thomas & Kwong, 2001)

This forms strong basis for the motivation for the replacement of gasoline additives with ethanol, but also provides an incentive for the weak economies of these African countries, which could be boosted by reduced dependency of crude oil imports.

2.3.1.4 Feedstock for ethanol production

There are several feedstock used for ethanol production, as discussed previously. The different sources shall be discussed here, with attention given to their content and processing techniques.

(a) Maize (grain crops)

Grain crops can be used to produce bio-ethanol by fermentation of the sugars found in them. Typical grain crops used are maize and wheat.

Processing maize and other grain crops involves wet or dry milling. In wet milling, the grain is soaked in water with sulphur dioxide for up to 40h, followed by grinding and separation of starch and co-products. For wheat, the valuable bran and germ are removed first by dry processing in a flour mill, then soaked in water. The starch fraction is then cooked at low temperatures to encourage gelatinisation, followed by the addition of α-amylase, which yields dextrin oligosaccharides.

The final stage of processing is saccharification, where glyco-amylase converts the starch to glucose, which can then be fermented to alcohol (Wheals et al., 1999).

(b) Sugarcane

Sugarcane (*Saccharum officinarum*) contains 12 – 17% sugars on a wet basis, and 68 – 72% moisture. The sugar composition is 90% sucrose and 10% glucose or fructose. Up to 95% efficiency can be achieved in the extraction of juice from the cane, and the remaining solid residue is cane fibre, or bagasse.

For an ethanol-only producing process, the cane juice is typically heated to reduce microbial contamination, then concentrated by evaporation, and then fermented. A sugar-ethanol process, however, centrifuges the sucrose crystals formed during evaporation, and syrup (molasses) remains, containing up to 65% w/w sugars.

Both the cane juice and molasses contain sucrose and other sugars which can be fermented to produce ethanol (Wheals et al, 1999).

2.3.1.5 Ethanol from molasses

Molasses is the feedstock used for the production of the bio-ethanol being studied here, hence considerable detail of the processing shall be illustrated to establish an understanding of the process. A more specific description of the particular process for this research will follow in Chapter 3.

(a) Chemistry of molasses fermentation

The sugars in molasses are mainly in the form of glucose. Sucrose is broken down to glucose via hydrolysis:

$$C_{12}H_{22}O_{11} + H_2O \rightarrow 2C_6H_{12}O_6$$

The glucose in turn is fermented to ethanol via the Gay-Lussac equation for ethanol production from glucose via fermentation:

$$C_6H_{12}O_6 + YEAST \rightarrow 2CO_2 + 2C_2H_5OH$$

The process involves dilution of the molasses to 25° Brix required to allow for fermentation to begin, due to the high osmotic pressure exerted by the sugars and salts. (Brix is the sum of the dissolved (or dissolvable) matter in a substance expressed as a percentage by mass or as an actual mass).

Fermentation then takes place at 32 – 37°C, but the maximum temperature may be lowered to achieve high final alcohol volumes because alcohol inhibition of yeast growth is intensified at higher temperatures (Mutargh, 1999).

(b) Alcohol recovery

The fermentation product is called beer, and a stripping column is used to separate the dunder from the liquid alcohol product. The final stage of the alcohol recovery process is distillation. The ethanol-water mixture, however, forms an azeotrope at 95.4% ethanol purity, and this causes a high energy requirement for the distillation stage.

2.3.2 The future of biomass processing technology

A prediction for future energy scenarios is presented by Shell International Petroleum Company, cited by Hall and Scrase (1996). In this prediction, biomass becomes a major energy supplier after 2020, supplying up to 14% of energy demands, while solar and wind contribute 17% and 11% respectively. The biomass percentage contribution is projected to rise even further to 25 – 46% by the year 2100.

In the light of these visions, extensive research is being carried out to explore efficient methods of energy retrieval from biomass sources.

An enzyme hydrolysis-based biomass-to-ethanol processing scheme has been proposed, where the biomass is milled, then treated with steam and dilute sulphuric acid, to open up the ligno-cellulose pore structure and make it more susceptible to enzyme attack. The ligno-cellulosic solids are then converted to ethanol in a simultaneous saccharification and fermentation bio-reactor. The advantage of this technology is that it reduces end-product inhibition of the cellulases by glucose through continuous fermentative conversion, but it also reduces capital costs by reducing the number of vessels required to separately carry out hydrolysis and fermentation (McMillan, 1997).

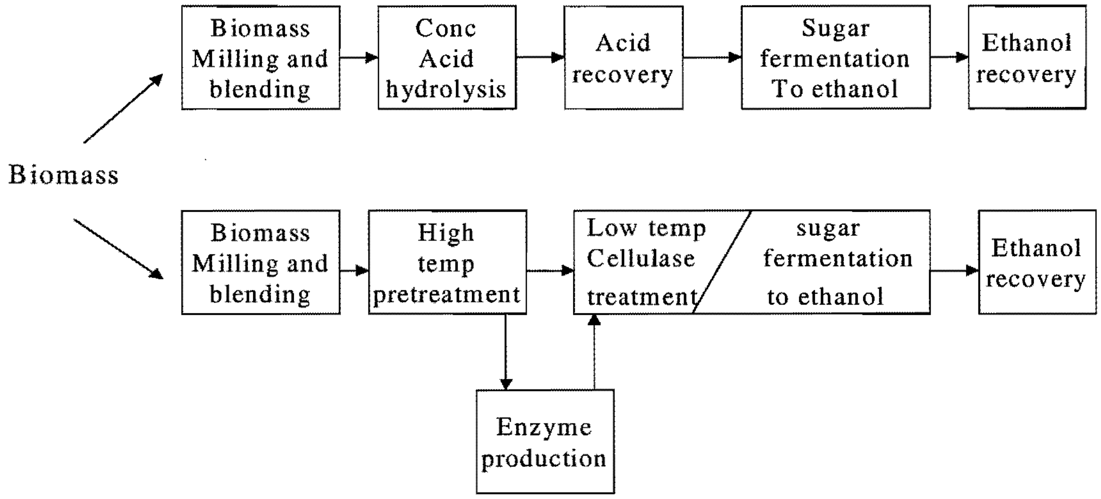


Figure 2.3 Possible process routes for ethanol production(from Mielenz, 2001)

The diagram above illustrates this route, parallel to an alternative route which requires the pre-treatment of biomass for both ethanol fermentation and ethanol production. This involves simultaneous saccharification and (co-) fermentation, depending on the ability of the fermentation organism to use pentose sugars along with glucose.

Another significant breakthrough is the development of improved fermentative micro-organisms capable of fermenting pentose and hexose sugars to ethanol at high yield, among other specific research findings specific to process components (Ingram and Conway, 1988; Ingram et al,.1990; Zhang et al., 1995; cited by McMillan, 1997).

2.4 Describing the environmental performance of bio-fuels from a life-cycle perspective

Different approaches to measuring the sustainability and renewability of bio-fuels shall now be explored in sub-sections to follow. They all stem from a life-cycle approach, and this serves as a basis for their compatibility. The diagram below illustrates a generic life-cycle scheme; it shows the main sub-processes involved in the life-cycle of a bio-energy system, and identifies the flows of value for describing environmental performance:

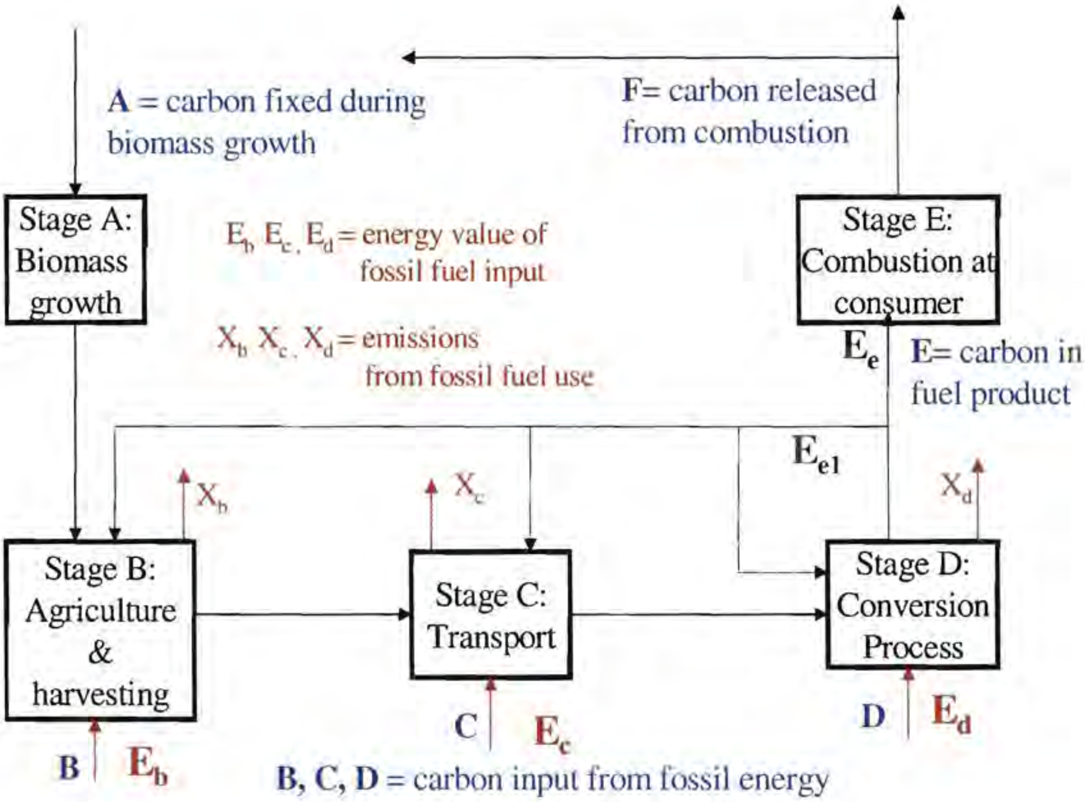


Figure 2.4 The stages involved in the analysis of a bioenergy system

The main stages A to E in the diagram above constitute the aspects of a bio-energy system which are studied in order to determine its renewability. Focus is paid to the carbon and energy inputs and outputs to the various stages, as well as the gaseous emissions which result from the fossil energy use in them. The carbon and energy value of the fuel product are tracked through the life-cycle stages, and compared against the total input values involved.

2.4.1 *How is the renewability of a bio-fuel assessed?*

The following general points are, amongst others, of concern in determining the extent of renewability of a biomass fuel:

(i) the fuel should provide more energy than that required for its production.

(ii) its CO_2 release in to the environment should be lower than that of an energy equivalent amount of fossil fuel.

(iii) land requirement should not be too high, in competition with food production (Bastianoni & Marchettini, 1996).

However, more specific approaches to determining these points shall be discussed in this section.

2.4.1.1 Carbon balances

Carbon dioxide is the key greenhouse gas responsible for environmental issues of climate change. The production and use of agro-based fuels, however, mitigates the presence of carbon dioxide in the atmosphere, because this carbon dioxide is used by the crops in photosynthesis, converting the carbon released back to biomass, in a complete carbon cycle.

Mann & Spath (1997) define a concept of **carbon closure,** to account for carbon flows involved in biomass cultivation, production, and end use. This analysis is determined as follows:

$$CarbonClosure = 100(1-\frac{Net}{Abs}) = 100(1-\frac{Feed+Trans+PP}{Abs})$$

where :

Net = net amount of CO_2 released from the system after credit is taken for the amount absorbed by the biomass during growth

Abs = the CO_2 absorbed by the biomass during growth

Feed = the CO_2 released from the feedstock subsystem, not including the credit taken for the amount absorbed by the biomass growth

Trans = the CO_2 released from the transportation subsystem

PP = the CO_2 released from the power plant subsystem, not including the CO_2 emitted from gasification and combustion of biomass

This analysis hence shows the relationship between fossil carbon dioxide and the carbon fixed during biomass growth in a life cycle, and can be used to show the overall impact of fossil fuel use in the life of a bio-fuel or related product from a biomass source.

A related approach analyses **avoided emissions**, where the use of biomass used as fuel replaces a quantity of fossil fuel that may have been used, or improved efficiency in energy utilisation results in a reduction in fossil fuel use. The CO_2 that may have resulted from its combustion is classified as "avoided emissions", and these figures would vary depending on the energy savings calculated, as well as the measure of relativity on which they are based (e.g. per annum, per kWh electricity produced, per hectare of land, etc) (Macedo, 1998)

2.4.1.2 Energy balancing: input versus output

The energy analysis approach evaluates all the fossil fuel inputs in upstream processing steps like agriculture, transportation and processing, and these are compared against the deliverable energy of the product bio-fuel.

Referring again to the figure 2.4, the net energy available from a fuel, E_e, is equal to (E_G-E_{e1}), where E_G is the gross energy produced by the fuel during combustion and E_{e1} is the total feedback energy in the fuel production process.

A combination of the net energy yield and gross CO_2 emissions can be assessed in a single **figure of merit**, determined as follows:.

$$\text{Net energy yielded from 1 kg fuel (MJ) / Gross } CO_2 \text{ emission from 1 kg fuel (kg)}$$

Other useful figures of analysis are **energy yield ratios**, which are the ratio of gross energy output to energy input (E_G/E_{e1}), as defined above (Prakash et al., 1998).

Similiarly, a **fossil energy ratio** is proposed by Sheehan et al. (1998) ,defined as

$$E_e / (E_b + E_c + E_d)$$

This relates the energy retrieved from a product bio-fuel, weighed against the fossil energy input involved in its life cycle, particularly in its production and conversion, and the related upstream processes.

For fossil energy ratios greater than 1, the system approaches renewability, which is theoretically only feasible for no fossil energy requirements (ratio of infinity).

2.4.2 *Other life-cycle based approaches for evaluating biofuel renewability*

Some researchers have criticised the above indicators in addressing sustainability and renewability, and their arguments are presented below, in recognition of their argument.

2.4.2.1 Exergy analysis

It is argued that measuring the renewability of an energy source using energy accounting methodology is questionable because they are based on the first law of thermodynamics, which encompasses the principle of energy conservation. As a result it is deemed impossible to calculate an "energy yield" since energy is conserved.

An ecosystem may be considered as a succession of devices forming a natural thermochemical cycle where, overall, the work (exergy) necessary to sustain life is acquired through energy exchanges between the sun and space. Exergy is accumulated in matter through photosynthesis, and then released during fuel production and combustion.

Exergy accounting is used to evaluate the departure from ideal behaviour caused by non-renewable resource consumption through the concept of restoration work.

A *renewability indicator* is hence proposed, which relates the work produced from a renewable cycle (W_P), to the difference between it and the work needed to restore the non-renewable resources consumed in the cycle (W_R):

$$\frac{W_P - W_R}{W_P}$$

This method is hence believed to account better for the resource input involved in the biofuel production ((Berthiaume et al, 2001).

2.4.2.2 Emergy analysis

Bastianoni and Marchettini (1996) propose a similar concept to the one discussed above, where **emergy** is defined as a measure of the overall convergence of energy, time and space required for the availability of a given resource. Emergy analysis considers different inputs such as energy from renewable and non-renewable sources, but also the goods, labour and materials involved in a process, on the same basis, this being the solar equivalent energy (emergy) concentrated to provide each input.

It is believed that emergy analysis can be used to establish a longer-term stability and measure environmental stress by including environmental inputs otherwise regarded as "free" in typical energy analyses. Inputs are evaluated not only in terms of their energy content, but also their transformities, hence their overall input value is accordingly weighted.

2.5 Key results from previously studied bio-systems

This section shall present the key studies isolated from literature which have relevant results to the research to be presented here.

The different studies that assessed the utilisation of biomass from sugarcane processing are discussed first, and their results are presented. Each study has reported their results differently, so the figures are then re-calculated to present them on a comparative basis, in terms of the indicators discussed under section 2.4.1.

The section is concluded with discussions on the sustainability concerns which have been raised over the production and use of bio-fuels.

2.5.1 Biomass utilisation from sugarcane processing

2.5.1.1 Bio-ethanol production from bagasse as a gasoline additive

A study by Kadam (2002) investigated the environmental benefits of blending bio-ethanol from the excess bagasse from sugarcane milling, versus its conventional incineration and the current use of gasoline in India.

The two scenarios compared were as follows:

1. Bagasse disposal by open field burning, and current gasoline use.
2. Bagasse conversion to produce ethanol, and excess electricity production, followed by use of gasoline with the ethanol blended in it.

This analysis was tackled from a modelling perspective, and the technology for conversion of bagasse to ethanol was assumed to be that proposed in section 2.3.2 for the conversion of cellulosic and hemicellulosic biomass by saccharification and co-fermentation.

Using life-cycle analysis, for a functional unit "disposal of 1 ton bagasse", the following comparative results were obtained in favour of scenario 2 which produces ethanol for gasoline blending:

- Over 100% reductions (except for natural gas which showed 30% increase) in the use of the resources coal, lignite, oil and water for the ethanol production scenario.
- Reductions in all key air emissions (CO_2, CO, nitrogen oxides and sulphur oxides), except for hydrocarbon emissions and nitrous oxide (N_2O).
- The total primary energy on a life-cycle basis was 30% lower for the ethanol production scenario (Kadam, 2002).

These results are highly in favour of both the production and use of bio-ethanol for fuel blending, and strengthen the proposed motion for this use.

2.5.1.2 Electricity generation

Bagasse from sugarcane is generally used as fuel for the process, and it sufficiently meets the energy requirements of the operating sites, often with excess bagasse incinerated as a disposal method.

Mauritius has a prominent sugar industry, and several studies have progressed to analyse the use of the bagasse for extended purposes. One such study analyses the generation of electricity from the excess bagasse, including the use of other biomass residue classified as cane tops and leaves, and trash (dead, dry leaves). It was concluded that up to 565kg of sugarcane biomass can be potentially made available for the generation of exportable electricity per ton of millable cane, representing between 60 and 678 kWh/ton millable cane, depending on the technology used (Beeharry, 1996).

In a related study, Beeharry (1999) also investigated the option of composting the excess bagasse to be used as manure for the cane fields to increase the cane yield, while producing exportable electricity from the excess bagasse from the cane milling. This investigation was made from a cradle-to-gate life-cycle perspective, comparing current practice in Mauritius where excess bagasse generates electricity. A second option where the excess bagasse is composted and used as manure, and a third option which incorporates compost bagasse application with improved steam management on the processing sites were compared.

This study concluded that composting bagasse increased cane yield by 30%, but at the expense of a deficit in electricity production even for the process' own needs. The third option, however, showed that up to 58 kWh exportable electricity per ton millable cane could be realised while increasing the cane yield.

This result hence highlights the importance of process efficiency of the processing stages in determining the output of bio-energy systems.

2.5.2 Carbon balances of bioenergy systems

In evaluating the impact of bio-energy systems, their greenhouse gas mitigation potential is identified as an important criterion. With carbon dioxide identified as the main greenhouse gas, carbon balancing is an imperative approach to determining the performance of bio-energy systems.

Different studies on bio-energy systems have investigated their carbon balances, and (avoided) carbon dioxide emissions, and these shall be presented here. The figures are first discussed as they are reported in their corresponding studies, followed by a comparative assessment based on the re-calculation of these figures

2.5.2.1 Carbon closure analysis

A life-cycle overview of the Brazilian bio-ethanol production from sugarcane programme by Macedo (1998) analysed the carbon dioxide emissions for the entire process, paying attention to the emissions from combustion of the fossil fuel input and reported emissions of up to 17.2 kg CO_2 per ton cane processed.

The bio-energy system options for bagasse utilisation that are presented in the study by Beeharry (1996, 1999) in section 2.5.1.2 above were revisited by the same author, Beeharry (2001), to analyse their carbon balance figures and avoided emissions. Here, the analysed scenarios were as follows:

1. Current practice where excess bagasse is used for electricity generation.
2. Composting excess bagasse, together with improved steam management (also previously analysed).
3. Use of cane tops and leaves in addition to bagasse for electricity generation.
4. Composting of cane tops and leaves in addition to excess bagasse; a modification of scenario 2.

Carbon closures (see section 2.4.1.1) of above 96% were realised for all four systems options presented above.

Another study on bio-diesel produced from soybean oil also reported that for every 169g of carbon converted to fat and oil in soybean during photosynthesis, 148 g report back to the atmosphere as CO_2 during fuel combustion (Sheehan et al., 1998).

The figures from these studies described above were re-worked and synthesised to generate the necessary parameters for a carbon closure analysis (see section 2.4.1.1). A comparative assessment has been illustrated below in figure 2.5

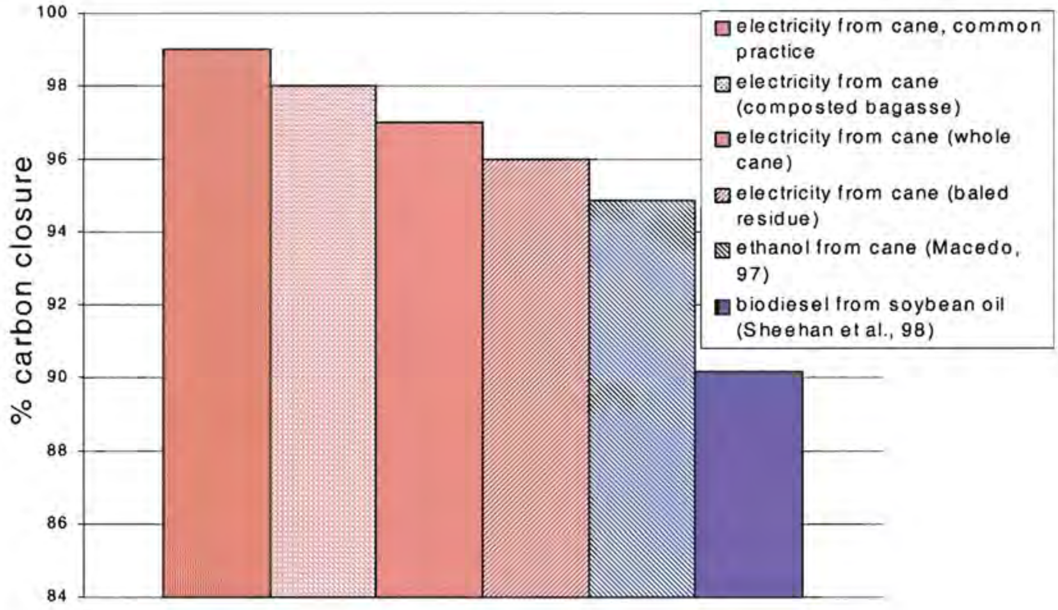


Figure 2.5 Carbon closures for different bioenergy systems

A 100% carbon closure would indicate that no or negligible amounts of carbon from fossil fuel use are released, in comparison to that absorbed during biomass growth. It can be seen that carbon closures above 90% and up to 100% are achieved for different bio-energy routes, and this means that the carbon released from use of fossil fuel in the life cycle is almost completely re-absorbed in the biomass growth phase.

2.5.2.2 Avoided emissions from bio-energy systems

The concept behind determining avoided emissions has also been discussed previously in section 2.4.1.1, and the results of this analysis are presented here.

- The Brazilian ethanol production overview study by Macedo (1998), which revealed net savings of 12.74 x 10^6 t C per year or 46.7 x 10^6 t CO_2 per year.
- Kaltschmitt et al. (1996), studying the production of biodiesel from rapeseed (RME), where it was shown that up to 70 kg of carbon dioxide equivalent emissions per GJ of substituted finite primary energy in its production life-cycle.
- A summary of energy efficiencies (presented in section 2.4.3 below) and gaseous emissions presented by Bastianoni and Marchettini (1996) for production of bio-ethanol from different sugarcane and grapes, as produced in different parts of the world (see appendix B1)

Another comparative analysis has been made to relate the avoided emissions from the different studies mentioned above. The figures have again been re-calculated here, to compare the results on a similar basis. The comparability of these figures needs careful understanding: avoided emissions are calculated based on an amount of fossil energy which is expected, or has been, physically replaced by the use of a biofuel, or by efficient processing leading to the "saving" of fossil fuel use. These figures are typically calculated relative to a crop yield (tons per hectare per year). The units used below, however, are kg CO_2 per GJ finite primary energy (Kaltschmitt, 1996), which is a useful analysis in the way that it relates to the fossil primary energy input to the process. The results are shown in figure 2.6 below.

Carbon closures, as discussed above, are a self-examination of a bio-energy system, while avoided emissions are a cross-comparison of the emissions in the absolute context, with a fixed parameter as shown in the paragraph above.

The study by Kaltschmitt is represented by the purple bar (biodiesel), while those of and Macedo and Bastianoni & Marchettini are analysing bio-fuels (blue bars). Beeharry's studies (red bars) examine electricity production from various uses of bagasse.

A range from 20 to 840 kg CO_2 equivalents per GJ finite primary energy is seen here, and this illustrates the range in potential saving in CO_2 emissions from the different processes.

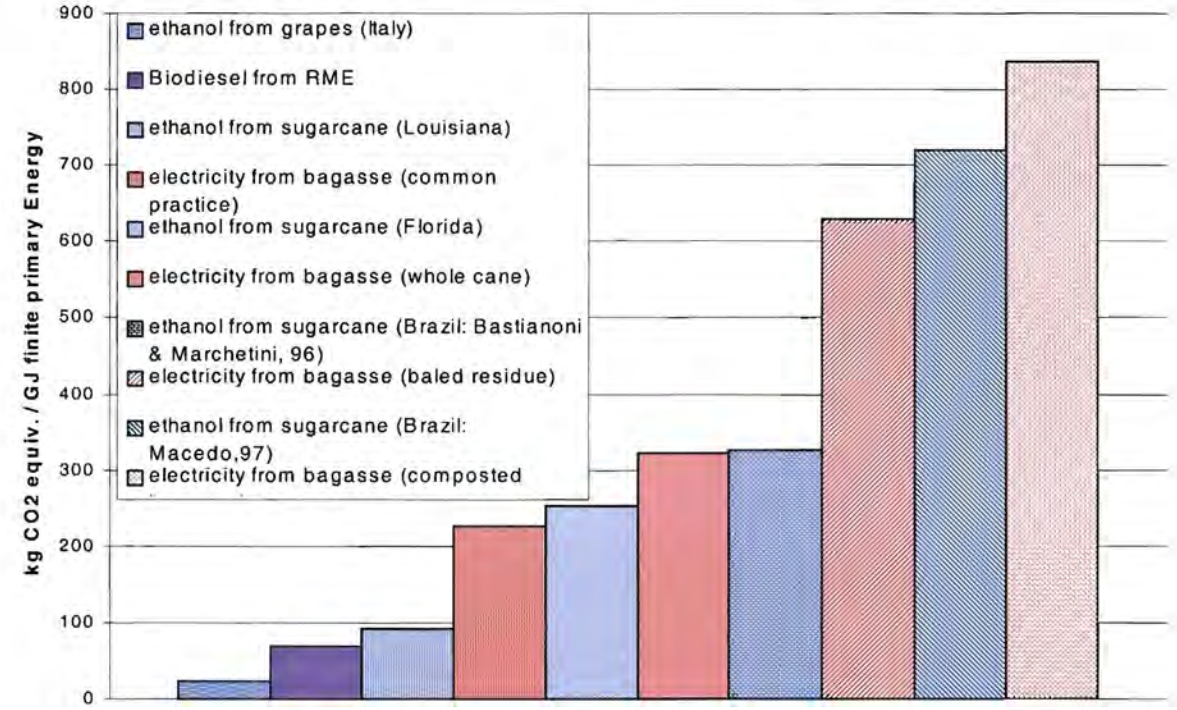


Figure 2.6 Avoided emissions for different bioenergy systems

2.5.3 Energy efficiencies of bioenergy systems

The ratios relating energy output of the resultant bio-fuel to the fossil energy input into its production are also key in determining the sensibility of making a particular product. The data from the key studies in the previous discussions of this chapter again provides an excellent comparison basis here, and the figure below shows the range of energy ratios realised in the different systems. The figures reported in this chart have been sourced from the following references: Ethanol from sugarcane for Florida and Louisiana, and from grapes in Italy – ref. Bastianoni & Marchettini, 96; Biodiesel from soybean, and petroleum – ref. Sheehan et al., 98; Ethanol from maize in North America – ref. Berthiaume et al., 01.

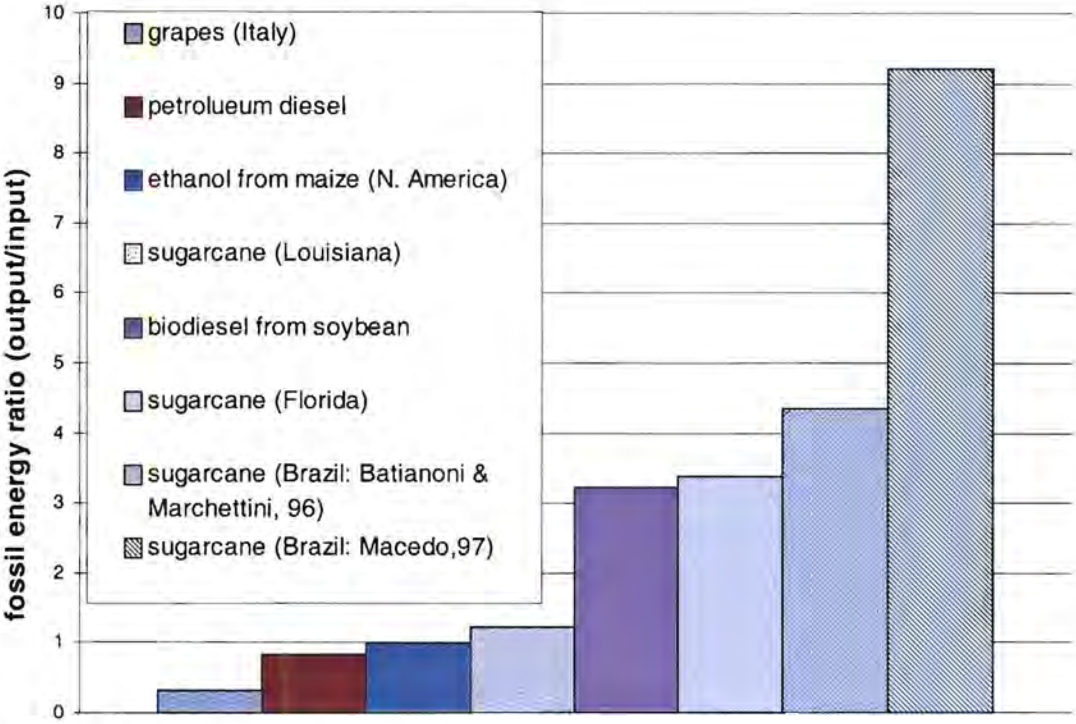


Figure 2.7 Fossil energy ratios

Fossil energy ratios below and in the region of 1 indicate no or low energy profit.

Only one of the bioenergy systems illustrated above (bioethanol from grapes) reports a fossil energy ratio below than one, indicating no benefit in its production. The rest of the systems show ratios of up to 9, indicating that encouragingly high energy yields are attainable in biofuel production. The figure for petroleum diesel has been included here as a comparative measure.

2.5.4 Concerns raised about bio-fuels

There are several environmental issues, however, in the production and processing of bio-fuels, and these need to be highlighted and addressed before large-scale production of these fuels can be advocated.

2.5.4.1 Land use

Key concerns in bioenergy production have been identified as its competition with food and fibre production for land use and the removal of nutrients from the soil (Sims, 1999).

In support of this, the *emergy* analysis by Bastianoni and Marchettini (1996) to assess the feasibility of bioethanol production (see section 2.4.2) found that that one of the major constraints on the feasibility of commercial cultivation of biomass for ethanol production was its competition for arable land with food production. This is related to regional population and per capita consumption.

A study by Marrison and Larson (1996), however, evaluated the potential biomass energy production in Africa by 2025, in competition with land needs for food production. It was concluded here that, with improved yield efficiencies for food cropping, even with only 10% of land that is not forest, wilderness or cropland used for biomass energy crops, up to 18 EJ per annum of bioenergy could be harvested, while meeting the needs of the population in terms of food crops.

2.5.4.2 Gaseous emissions from use of biofuels

Although biofuels illustrate a general reduction in toxic emissions release, the analysis by Kaltschmitt et al. (1996) identified poor results for nitrous oxide emissions in the use of bio-diesel from rapeseed methyl ester. This result is confirmed by the findings of Sheehan et al. (1998), where biodiesel nitrous oxide emissions reported a 13% increase in comparison to petroleum diesel.

In the modelling by Kadam (2002) of the use of an ethanol-gasoline blend (see section 2.5.1.1), it was also shown that the blended gasoline has reduced comparative air emissions, with the exception of nitrous oxide.

All hydrocarbons, with the exception of methane, were grouped together to investigate the comparative severity of these emissions in the ethanol-gasoline blend, compared against normal gasoline use. These hydrocarbons included volatile organic hydrocarbons (VOCs), ethanol, furfural, hydroxymethyl furfural (HMF), aldehydes, and benzene. Here it was seen that the fuel blend scenario produced 17% more hydrocarbon emissions compared to pure gasoline use.

2.5.4.3 Transportation

Another concern which is raised at times is the high energy requirement and environmental burden of transportation of large volumes of low energy density of biomass fuels (Sims, 1999). A relevant study was carried out for the exportation of bio-electricity from Scandanavia to Holland.

The scenarios explored were the transportation of the solid biomass via different transportation options (including road and sea), exportation of grid electricity after it is produced locally, and domestic use of the electricity, without exportation. The results, however, showed no large differences in environmental loads between any of the scenarios. Transportation of large volumes of processed biomass fuel may thus have less significance in terms of comparative environmental burden. The analysis here, however, involved combinations of road and sea transportation options (Forsberg, 2000).

2.6 Conclusion of relevant literature

The following conclusions can be drawn from the discussions presented in this chapter:

- The renewability of biofuels can be assessed using carbon balances, energy yield calculations and measures of fossil energy use in its life-cycle. Land use for crop production in competition with its use for growing food crops is also a key assessment parameter for determining the sustainability of the production cycle.

- Ethanol can be produced from a wide range of bioenergy sources, and various novel and existing technologies are available for the different conversion routes.

- Carbon closures of above 90%, and up to 100% percent have been achieved for sugarcane bio-energy systems. Energy yields of above 1, and up to 9 are also achievable, in the context of bio-ethanol produced for sugar crops.
  However, this range of results for different bio-energy systems, and in particular for bio-ethanol, indicates that significant differences exist in the production schemes. This affirms the hypothesis and approach taken for this study, in stating that there is need to assess the specific dynamics of the production of bio-ethanol from sugarcane molasses as it is currently done.

- The production and use of bio-ethanol as a gasoline additive replacement is potentially feasible, and is superior to current gasoline use from an environmental perspective, in the categories of resource and primary energy use, and some gaseous emissions. There is concern, however, over the nitrous and sulphur oxide emissions from the gasoline blended with ethanol.

- Although past studies show that bio-systems achieve overall energy and greenhouse gas emission benefits, no studies have been done for South Africa, particularly for the production of ethanol from sugarcane molasses.

3. GOAL AND SCOPE OF THE LIFE CYCLE ASSESSMENT

As laid out in the introductory chapter, this thesis centres on a cradle-to-gate life cycle assessment of the production of bio-ethanol from sugarcane molasses in an industrial African setting, aiming to compile a comprehensive inventory of all material and energy resource needs and its environmental outputs. The details of this inventory are to be used to provide an indication of the sustainability of providing this product, by determining the environmental impacts of the collective of industrial processes harnessed.

The chapters to follow hereon are structured in line with the ISO 14040 standards on life-cycle assessment methodology, where the following stages of a study are defined:

- Goal and scope definition
- Inventory Analysis
- Impact Assessment
- Interpretation

This chapter addresses the first of these stages, where the goals of the research into the life-cycle assessment of ethanol produced from molasses are presented. The limitations on the scope of the study, as well as details on the data quality and other parameters involved at the onset of the study are also described.

However, before formally stating the goals and scope of the LCA, the thesis hypothesis shall be revisited, as it is the main aim of the LCA to gather and interpret the necessary data to either substantiate or refute this hypothesis.

3.1 Statement of hypothesis of study

The following hypothesis is re-stated for the production of bio-ethanol from sugarcane molasses:

The production of bio-ethanol from sugarcane molasses is principally a sustainable process, based on the renewable nature of the sugarcane raw material. Life-cycle assessment can be used to profile the environmental burdens of the production, and identify areas of concern that are the focus of possible improvement.

Building on the conclusions of the literature review, this hypothesis can now be expanded. Specifically, it is expected that the analysis of the bioethanol production life-cycle can show the following technical points:

- A high carbon closure illustrating the sequestration of fossil carbon dioxide released during conversion and use by that absorbed during biomass growth.

- A high fossil energy ratio, based on its self-sufficiency in energy requirement provided by bagasse incineration and potential electricity generation.

- Competitive land use, allowing for simultaneous food and energy crop production.

- Concern over the emissions of noxious gases, such as nitrous and sulphur oxides, and volatile hydrocarbons, which need to be acted on to reduce adverse local and regional impacts.

3.2 Goal of study

The primary goals of this study were:

- to generate a life cycle profile of ethanol as produced by the fermentation of molasses, a by-product in the South African sugar industry, and

- to develop an understanding of the sustainability of the overall process and product, and classify the extent of "environmental friendliness" of the product ethanol by determining:

    (a) the carbon closure of the bioethanol product system,
    (b) the fossil energy requirement for the cradle to gate life cycle,
    (c) the environmental impacts of the resource use and emissions from the process.

Secondary objectives were to carry out this study so that it can complement other environmental decision-making at the producer level, particularly:

- to record data at the distillery in such a way that it is of use in the design and implementation of an environmental management system envisaged for the production site; and

- to structure the data gathering at the molasses to ethanol process site so that it supports a current project to design and implement an adequate waste management strategy for the liquid effluent generated there.

Target Audience

This research was undertaken in fulfilment of the Master of Science in Chemical Engineering degree awarded by the University of Cape Town. The initial target audience is hence an academic one, including staff and post-graduate researchers in the field of Environmental Engineering and Life Cycle Assessment. Researchers working on the bio-product are also part of the targeted audience.

Secondly, the results of this study are intended for the use of technical management of the sponsoring sugar company to aid their full understanding of the environmental issues associated with their products, both existing and new. Subsequently, this information shall assist in decision and policy making in the implementation of environmental management.

Finally, the data gathered in the study is to aid in assessing the environmental desirability of using such bio-ethanol as a gasoline additive. Hence, this information also targets policy-making bodies as well as commercial investors, as it may provide a basis for understanding the implications of the production and use of the product as fuel.

3.3 Scope

The following scope was proposed for the LCA at its outset:

3.3.1 System definition and boundary

The system to be studied is the production of ethanol by a sugar company. From the life-cycle perspective, the system essentially involves the conversion of carbon dioxide and water into glucose in biomass, most of which is extracted into the sugar process, with the remainder being subsequently fermented to produce ethanol as the product of interest. The cradle of the study is hence the growth of the sugarcane, and the gate end is the ethanol product from the distillation process of the molasses-to-ethanol process.

The system to be studied is thus explicitly defined as a *process* system, and the relevant sub-systems consist of cane growing, cane processing (to separate molasses), fermentation (to produce ethanol), and finally distilling of the ethanol-water mixture.

The following assessment shall hence be made, with regards to the system boundary:

- Sugar cane shall be traced back to its cultivation,
- The product ethanol out of the distillery shall be the final life cycle stage analysed, excluding product use,
- Imported utilities and materials, such as electricity, coal, lime, sulphuric acid, fertiliser and diesel shall be added into the study as closed loop flows, their production being analysed using a relevant database profile.

The sub-processes for the life cycle shall hence be labelled as follows:

- Agricultural Process (cane growing)
- Road transport 1 (from cane fields to sugar mill)
- Sugarcane to molasses processing
- Road transport 2 (from sugar mill to distillery)
- Molasses to ethanol process

Smaller process flows (not shown in the diagram) such as fertiliser for the Agricultural Processing stage, and other process chemicals shall be evaluated for their contribution to the overall life cycle. If deemed to be insignificant (less than 0.2% of functional unit, on a comparative basis) to the overall analysis they shall be left as open loop flows, and hence not included quantitatively in the life cycle.

It is acknowledged that the sugarcane to molasses process exists predominantly for the production of sugar. A formal allocation procedure (see section4.1) will be developed to account for its share of the environmental burdens.

The diagram below illustrates the system boundary chosen for this study, in line with the objectives defined and the goals:

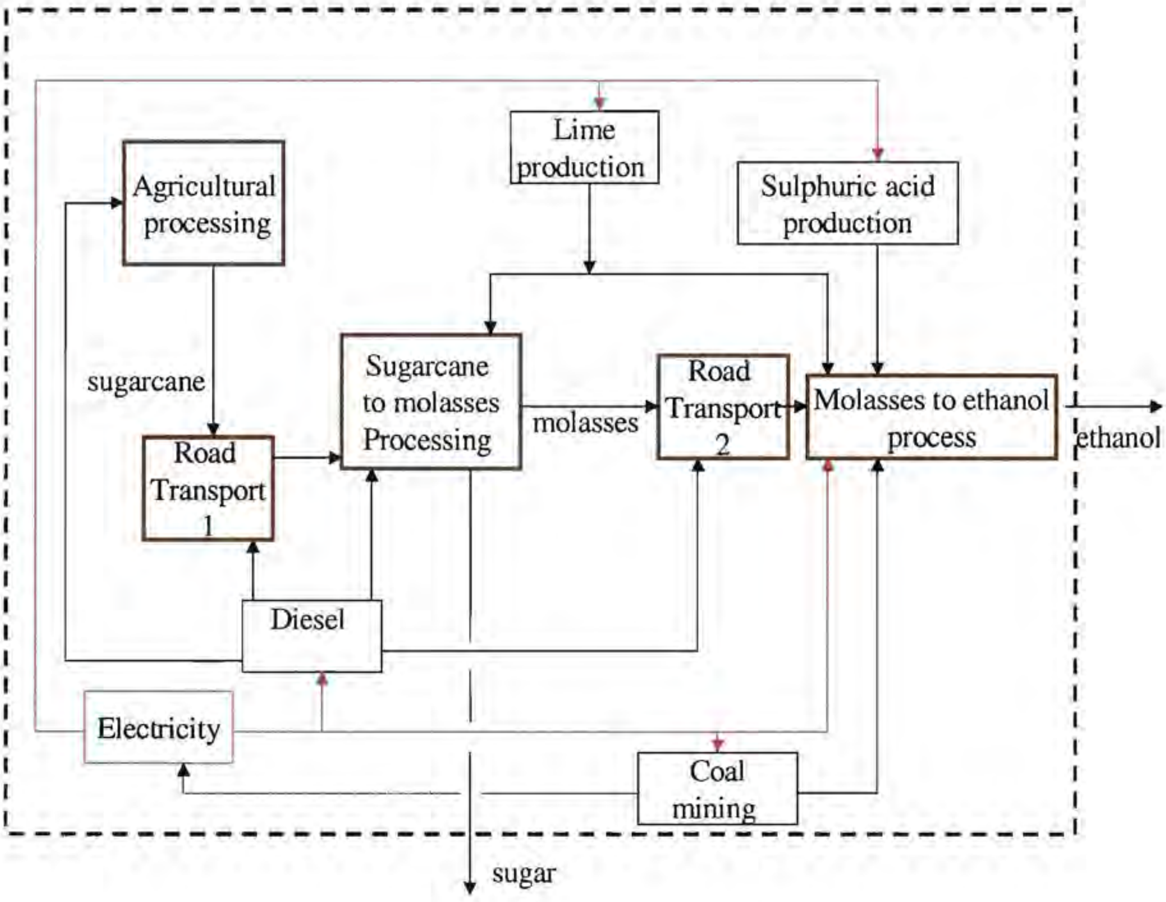


Figure 3.1 System boundary for the life-cycle study

The dotted line illustrates the system boundary for the life-cycle study.

3.3.2 Impact categories to be studied

The following impact categories have been selected to be relevant to the analysis of the environmental burdens of this product's life-cycle, and shall be investigated. For those impact categories that are global in nature, emissions occurring outside the geographical area of the production sites as a result of activities occurring within the system boundary will also be studied.

1. Global warming
2. Acidification
3. Nutrient enrichment
4. Impacts of land use
5. Photochemical ozone creation potential
6. Human toxicity
7. Ozone depletion
8. Resource depletion

The relevance of each of the impact categories listed above shall be made in the relevant chapter (Chapter 6), with reference to the flows of interest, once the inventory has been completed and presented. Their selection at this point is based on literature indications of the aspects of bio-energy systems that are of environmental concern.

3.3.3 Functional unit

The functions of the product are multiple, each being specific to the particular market to which it is supplied. The producer's interest lies primarily in the product's capacity for value generation. The primary market to which the product is sold is the potable alcohol market, but in view of the goals of the study, the product's recipient environment is variable. The function of the process system can thus be defined as *to produce ethanol product for use in its different target markets.*

An amount of 1000 litres (1 kl) of ethanol shall be used as the functional unit for the study. All data for mass and energy balances shall hence be normalised for this functional unit.

3.3.4 Data quality

The quality of the data to be used in the study shall be based on the sugar company's current production profiles. Average data values over a seasonal ethanol production period, and its corresponding sugar processing season's data shall be considered sufficient to meet the goals of the study.

An average scenario approach shall be used for the initial consideration of the variability of process parameters used in the analysis.

A further approach shall then be employed in context of a sensitivity analysis, to determine the response of the system in different cases of input and production variations, and with respect to the allocation methods employed.

3.4 Concluding remarks

The goals and scope of this life-cycle assessment have been presented in this chapter, and the sub-processes that constitute the life-cycle of bio-ethanol have been grouped. These process units shall now be described in more detail in chapter 4.

4. Unit descriptions and inventory preparation

Proceeding from the goal definition for and the delimitation of the scope of the LCA presented in chapter 3, this chapter now describes the important sub-processes making up the cradle to gate life cycle, and discusses the methods used in acquiring and compiling the inventory data.
From a general identification and grouping of the sub-systems of the cradle to gate life-cycle, the chapter proceeds to examine the allocation of environmental burdens between sugar and molasses production. Each of the sub-processes of the life cycle shall then be described with respect to its function, and the approach used to gather the relevant data is also outlined under each sub-section.
The compilation of the data to produce a model of the process, and the use of software database information is also discussed, and finally the quality of the data compiled is commented on.

In line with the definition of the system, its boundary and its sub-systems in section 3.3.1, it was considered useful to group the sub-processes into those over which the company has a significant degree of control (termed "foreground" processes, and those over which the company has little control ("background" processes). Figure 4.1 shows the former in bold at the centre of the system, and the latter supporting this primary production chain.

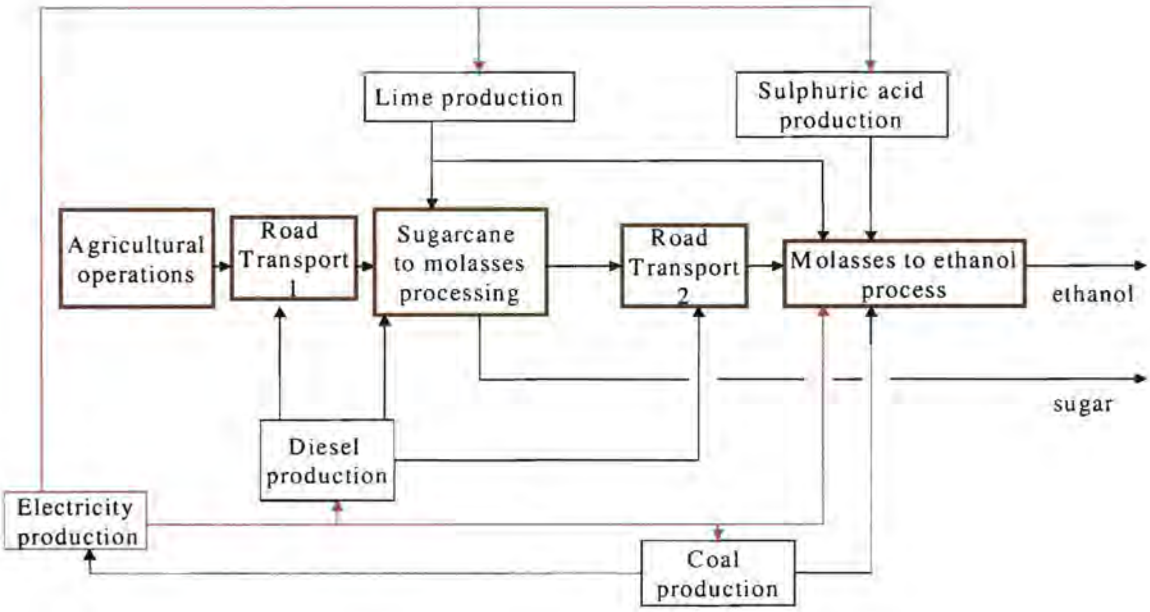


Figure 4.1 Foreground and background sub-systems for the LCA

(a) Foreground sub-processes

These are the sub-processes related directly to the sites of production of the bio-ethanol, and are directly associated with the processing of the product. These are:

- Agricultural Processing
- Sugarcane to Molasses Processing (Sugar Milling)
- Molasses to Ethanol Processing
- Road Transportation

Primary data, relating specifically to the production pattern and practices of the company in the study, was compiled for these sub-processes (except Road Transportation).

Agricultural Processing is, strictly speaking, not under direct supervision of the Company, but their exclusiveness as a cane buyer in the vicinity of the region puts them in considerable control over the quality of the cane produced. It is hence deemed that they are both directly and indirectly in control of the agricultural process.

Road transportation is classified as a foreground process, and is deemed to be partly under the Company's supervision by virtue of the choice of transportation alternatives (e.g. rail) that the producer would have, if it were found that this step had severe impacts on the environmental profile of the bio-ethanol production.

(b) Background sub-processes

These are the sub-processes that involve the production of the ancillary flows of utilities and reagents that are used in the foreground sub-process. It was considered sufficient to model these processes using relevant published or software database information, due to the inaccessibility of local primary data relating to them and the low degree of influence the company has over their environmental profiles.

These background sub-processes are:

- Coal production
- Electricity production
- Lime production
- Sulphuric acid production
- Diesel production
- Fertiliser production
- Water extraction

It can be seen that the influence of the company on background processes would be minimal, compared to that over the foreground processes. Medium influence on background processes would imply that, by simply changing the source of the flow, the company could influence the environmental burdens attached to the particular service it delivers. This is applicable only in the event where the environmental burdens associated with the process were found to affect the overall life cycle profile of the product under study in a detrimental manner.

The details of each sub-process will be illustrated in full in the subsections to follow, leading to the data specifics gathered from each of the sites. Before this, however, it is necessary to resolve the complications arising from the nature of the product (ethanol), as a by-product from another production system, being that of sugar production.

4.1 Allocation

A methodological allocation problem arises when a multifunctional process has more than one function for the product life-cycle under investigation, or a different function for other products. In this case, it is a production process with two products, these being sugar and molasses.

The main product of the sugarcane to molasses sub-process is cane sugar, and molasses is classified as a by-product of this process. The molasses is often treated as a waste stream, but the value addition of utilising this to produce ethanol is such that it can be considered as a by-product stream. The problem is to decide what share of the environmental burdens of the specific activity and its consequences should be allocated to the by-product investigated.

The system for which allocation is to be effected is the first section of the study as illustrated in Figure 4.1 previously, isolated below for clarity:

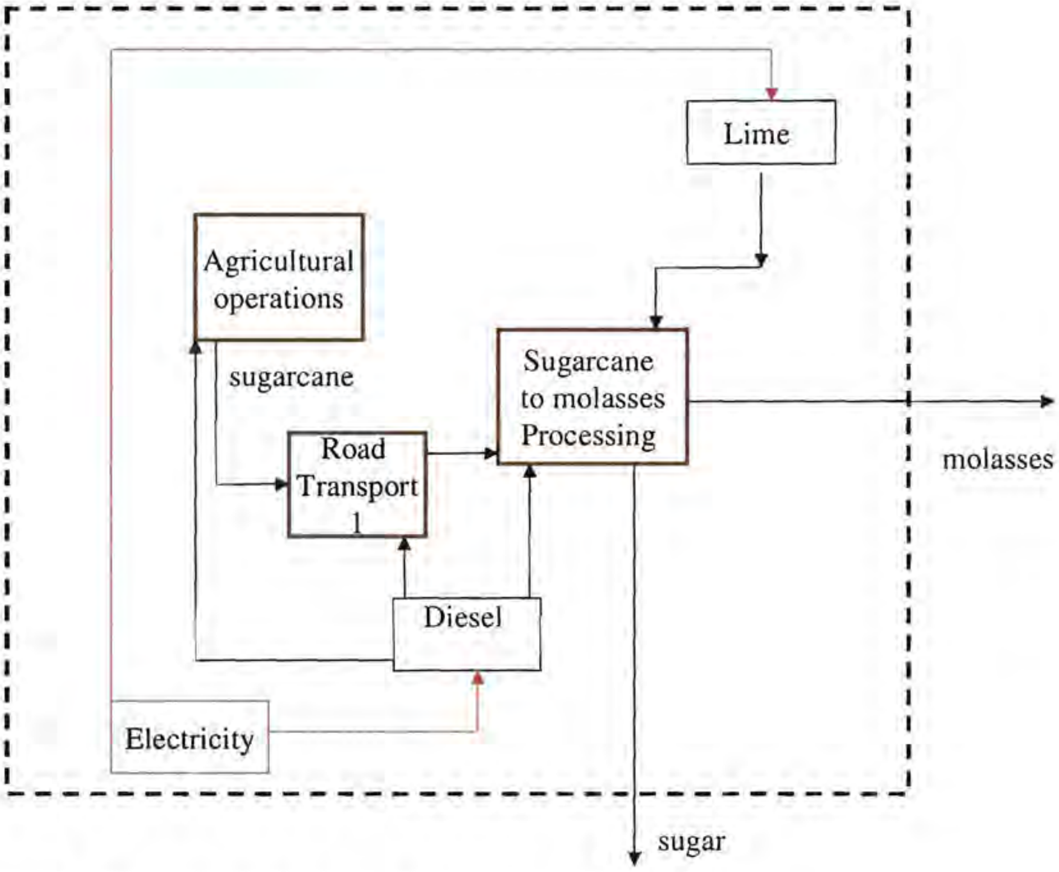


Figure 4.2 The sugar-molasses co-production system

The environmental burdens associated with all the input flows to this sub-process (electricity, lime, diesel) and their associated inventory flows, up to the production of the two products (sugar and molasses) shall be affected by the allocation procedure to be adopted.

Allocation should ideally be avoided where possible either by expanding the system under consideration, or by subdivision of the process to isolate the process routes which result in the production of each of the individual products. However, in the event where the products are made from the same process route, different approaches may be used to partition the associated input and output burdens between them. Two criteria may be used to allocate between products, these are technical and economic criteria (Ekvall & Finnveden, 2001).
Technical criteria relates to quantity and material grade of products, where as economic criteria relates to the utility value of the products, and relative price becomes the partitioning key. Allocation proportional to quantity and material grade can be used for co-products which arise from the same material, as in this case (Hauschild & Wentzel, 1998).

Accordingly, a mass-based allocation shall hence be used to attribute fractions of the standard input and output flows of this sub-process and of those preceding it, to the production of molasses. A mass ratio of sugar product to molasses shall be used as the allocation factor for all inventory inputs, outputs and calculations to be presented in the overall inventory.
Typically, a mass ratio of sugar to molasses of 3:1 is expected, representing an allocation factor of 0.33 (Pillay, publication date unknown).

An alternative scenario to this is one where all inputs and outputs for the production of molasses are attributed to sugar processing alone, on the basis that molasses is a waste product, and not a by-product. This perspective is in accordance with the company's mission statement, which states that the objective of their operations is predominantly for the production of sugar.
On this basis, the allocation to molasses has a factor of zero (0), hence molasses are regarded as a "free" input with no environmental burdens. This assumption has, however, complications in the defining of a carbon balance for the bio-ethanol life cycle, since the source of the molasses now appears "untraceable".
The effect of this allocation shall be explored further in the context of a sensitivity analysis in sections 5.7.1 and 6.2.10.

4.2 Major sub-processes

The unit processes involved in each subsystem shall be described in this section, together with the details of the approach used to gather and compile the data relevant to each unit. Where bound by confidentiality of the processing details, a generic description of the technology shall be employed. The corresponding flows that are also of sensitive nature shall remain "masked" in the inventory, but their associated environmental burdens shall be accounted for, in full.

4.2.1 Agricultural Processing Data

This is the sub-process in which the growing of the sugarcane is modelled, through to the cane product as the key output from this stage. The different cane fields which supply the sugar processing mill are all within an average distance of 30 km from the mill itself, which is situated in the southern Kwa Zulu-Natal province of South Africa.

Based on the issues highlighted in literature concerning the cultivation of biomass for energy production, and the goals and scope of this study, it was deemed sufficient to model the South African cane processing profile based on the following key figures:

(i) Average cane yield per hectare (area-specific)
(ii) Fertiliser use per hectare (Nitrogen and Phosphorous fertilisers)
(iii) Water use for irrigation (where applicable)
(iv) Fossil energy use for machinery (predominantly diesel)
(v) Pesticides usage

Due to time constraints and unavailability of data, however, figures for pesticide use and water for irrigation were excluded from the compilation of agricultural processing data. This is considered as a significant discrepancy, because water is among the resources of concern in South Africa, and the use of pesticides is also of note in the categories of toxicity (human and aquatic). In general, however, the sugarcane growing practice in the southern region of Kwa Zulu-Natal in South Africa does not involve irrigation, unlike the northern region where irrigation is common, and the region reports very high water usage figures from the agricultural sector. Consequently, the crop yields are higher for the northern regions than in the south.

The information used here was gathered from The South African Sugar Association via personal communication (P. Govender), and the table below summarises the gathered estimates:

Table 4.1 Agricultural processing data

Input / Output	**Units**	**Quantity**
Cane yield	ton per ha	75
N fertiliser	kg per ha	60 -120
P fertilizer	kg per ha	20-50
Diesel fuel	litres per ha	88

4.2.2 Sugarcane to Molasses Process: Sugar milling data

This is the process where the sugarcane milling, and sugar and molasses production takes place. The sugar mill studied processes sugarcane using conventional methods of cane crushing, juice separation and concentration, and sugar crystallisation. There is a downstream process on site, however, which utilises some of the bagasse to produce higher-value derivatives. The depleted bagasse then returns to the sugar mill, where it is used as fuel for the boilers to produce process energy.

The sugar milling operation can conveniently be grouped into 5 main process blocks:

- Milling & Extraction (cane crushing and extraction of cane juice)
- Sugar Production (evaporation and crystallisation)
- Power Generation (electricity and steam generation)
- Effluent Processing & Handling
- Downstream Process (production of value-addition chemical)

The downstream process that uses bagasse to produce value-added products is run as a separate business operation, and hence it as relatively straightforward to allocate environmental burdens. Figure 4.3 illustrates the site boundary described above, and indicates in general, the flows of concern. The dotted line indicates the boundary of the study, and the flows shown to cross this boundary are essentially the flows that are recorded in the inventory of this site.

Internal flows, such as the water and steam exchanges between the sub-processes are shown (in blue), as well as the bagasse and fines flows (in brown).

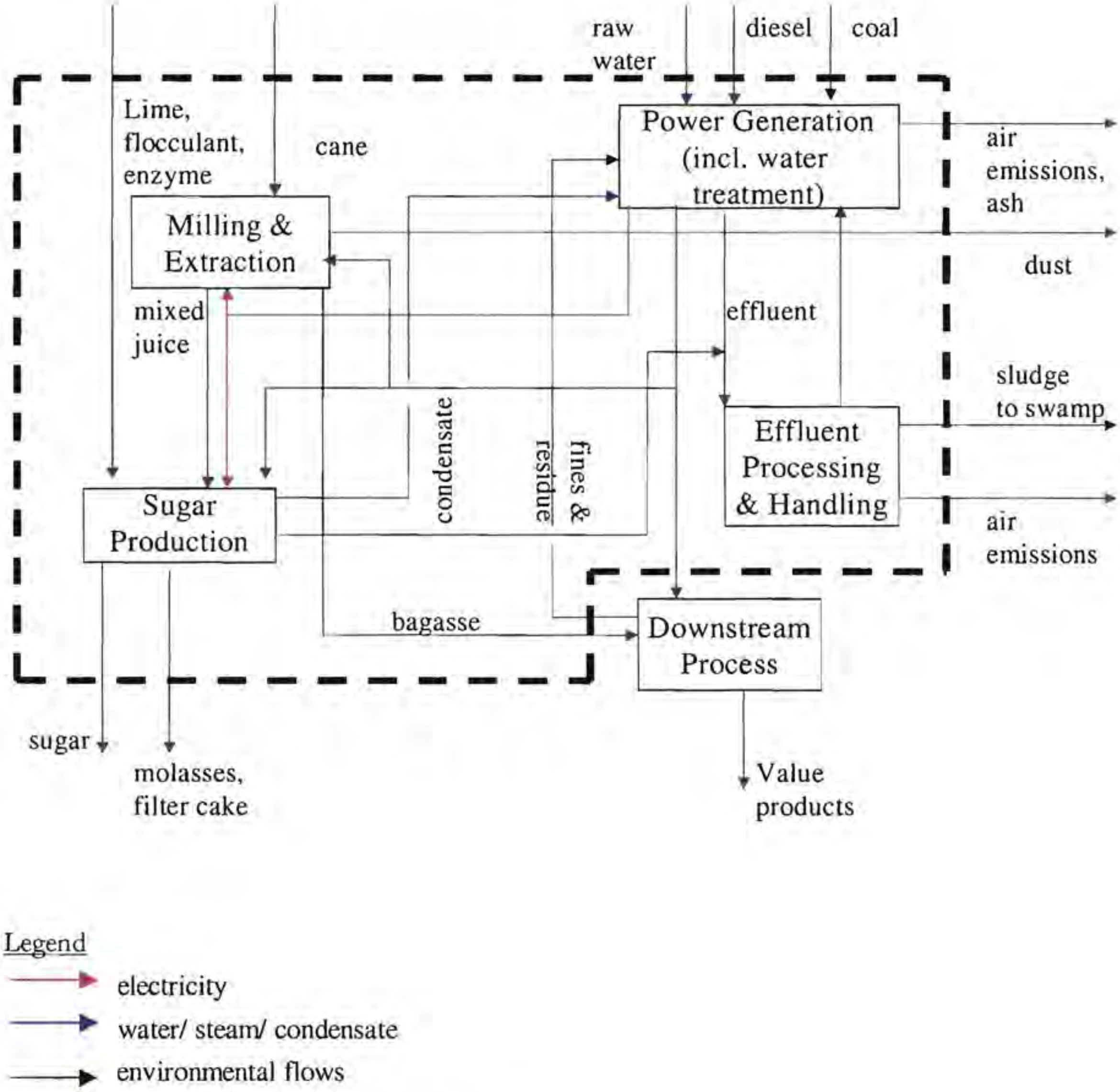


Figure 4.3 Sugarcane to molasses process

The sections below briefly discuss the processes involved in the blocks illustrated in the diagram above.

4.2.2.1 Milling & Extraction

This process step involves the crushing and shredding of raw cane, to separate the cane juice from the fibre.

Inputs into this process block are cane, imbibition water, and steam, used to drive the shredders and the cane knives. Imbibition water is an internal flow, its source being treated process water from the clean water dam, a recycle stream.

The output inter-unit flows are the mixed juice, to the Main Process, and bagasse, which is an internal flow to the downstream process, but returns as residue to the Power Generation to be used as boiler fuel. An environmental flow of concern here is dust, composed of bagasse fines, from the cane handling, shredding and crushing. It is not normally monitored by the site operation and thus could not be quantified in this inventory. It is a flow of concern, because it can be harmful to human health and can cause a bronchial condition.

4.2.2.2 Sugar Production

This encompasses the boiler house operations of cane juice concentration by evaporation, followed by crystallisation. The cane juice is heated to accelerate inversion, and the subsequent evaporation procedures encourage crystallisation of the sugar crystals. Molasses are the concentrate from a series of concentration processes. Notable inputs are lime, process flocculant and enzyme. The main economic flows out of this process block are sugar, molasses and filter cake.

The simplified figure below (figure 4.4) shows the sequence from which sugarcane and molasses are produced in this process block.

Steam is used for heating to initiate evaporation, and then returns to the power generation sub-process as condensate.

An important trade-off concept is observed here: the sugar processing aims to reduce the sucrose content in its molasses to its minimum, to recover the most sucrose in its sugar product. However, the molasses-to-ethanol process (to be discussed later) strives to attain the highest sucrose content in its molasses to recover higher yields of ethanol product from its fermentation process. There is hence the potential for the company as a whole to control and vary which of their products, sugar or ethanol, is produced, and in what quantities.

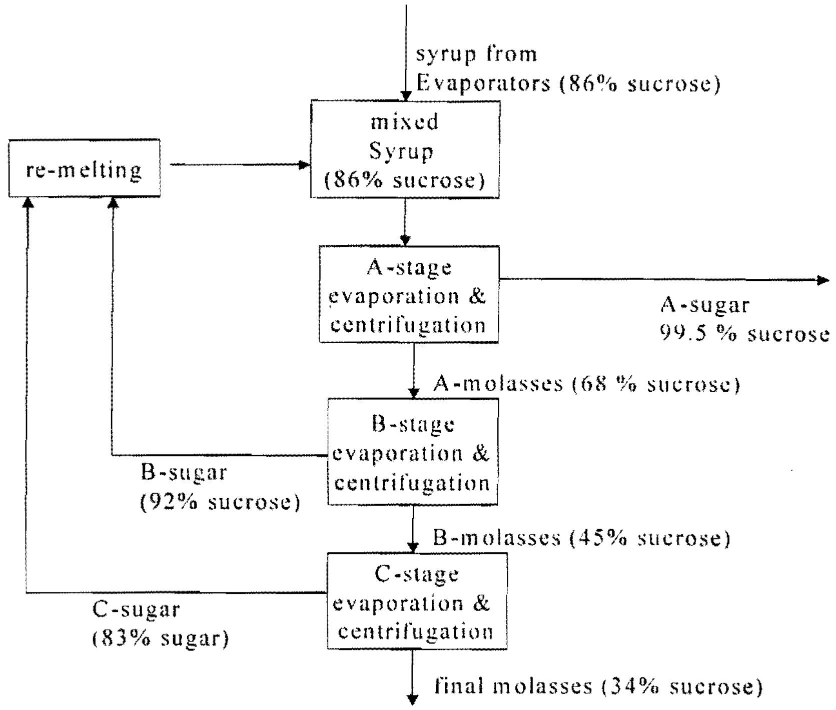


Figure 4.4 Production of molasses and sugar: final stages

4.2.2.3 Power Generation

In this process block, high and low pressure steam is generated from the combustion of bagasse in boilers. It is used to drive machinery, as well as turbo alternators to produce electricity, and to provide process heat to the process and downstream sections. Other utilities, such as water and wastewater management, as well as cooling, were considered part of this process block. Diesel, coal and bagasse are the main economic inputs, while steam and electricity are the economic outputs from this process. The environmental flows here are ash and air emissions arising from the combustion of bagasse in the furnaces, as well as raw water intake and effluent discharges.

Bagasse from sugar milling is produced in enough quantities to meet all energy requirements of a sugar processing mill (Beeharry, 1999), hence it is assumed that the coal used in the boilers is for the extra energy requirement of the downstream process. None of the coal used on site was therefore allocated to sugar processing.

4.2.2.4 Sugar mill data compilation

The records for the 2000 production season of 44 weeks were compiled and aggregated, on a weekly basis, to record the input and output values for the flows indicated in the discussions above (See appendix C1).

A simple combustion model calculation using a typical bagasse composition from literature was used to estimate the gaseous emissions from the combustion of bagasse from the boilers. Finally, average figures, as well as minima and maxima figures, representing the production profile over the 44-week season were recorded.

4.2.3 Molasses to ethanol Process: Distillery Data

This sub-process and its associated background processes constitute the second half of the overall LCA study, to form the complete cradle-to-gate picture of the process. This is shown in the figure below:

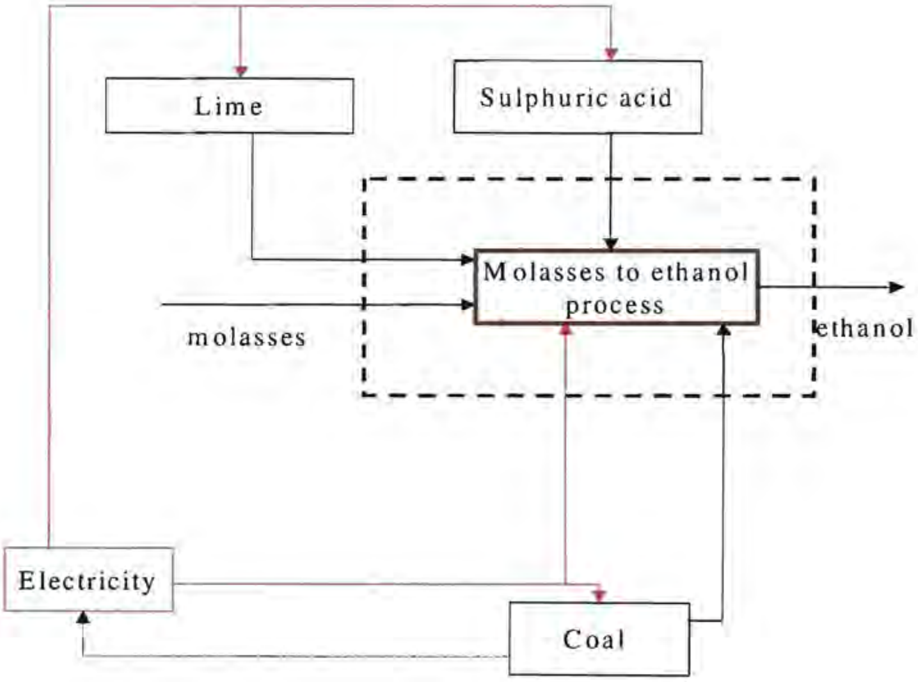


Figure 4.5 Gate-to-gate profile of molasses-to-ethanol process

An assessment of the molasses-to-ethanol process block shall now be made to identify the key processes, and the origins of the input and output flows recorded in the inventory for this site process.

The molasses-to-ethanol process comprises of two main conceptual processes:

- **fermentation** of the sugars present in molasses to alcohol
- **distillation**, to separate the ethanol-water mixture

Similar to the sugar mill analysis, the site processes were grouped into sub-processes, depending on their functionality, as follows:

- Molasses storage & handling
- Pre-fermentation
- Fermentation
- Distillation
- Steam & Electricity Generation

The figure below shows the site boundary for this process:

:

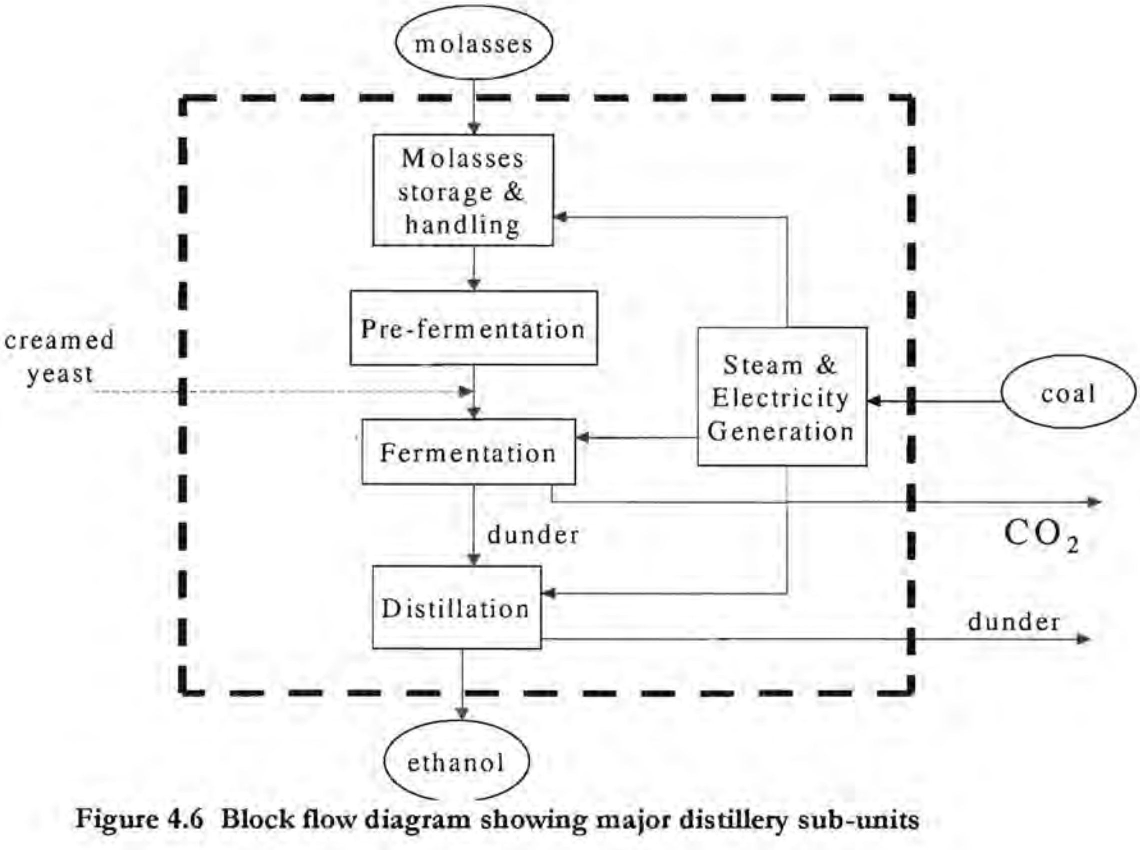


Figure 4.6 Block flow diagram showing major distillery sub-units

4.2.3.1 Process description

This process follows conventional methods of ethanol production, as described in the literature (section 2.3.1.5).

Molasses are stored in cone roof tanks, and are prevented from contact with moisture, to avoid premature fermentation before they are introduced into fermentation tanks.

The use of cream yeast, however, is alternative to the pre-fermentation process which prepares the yeast locally onsite, but this system was not operational during the period of observation.

The molasses are then introduced into the fermentation tanks where a batch fermentation process takes place. They are first diluted with water to 25° brix because the sugars and salts exert a very high osmotic pressure which would otherwise hinder the fermentation process. The molasses originally have about 45% sugar content, which is reduced to about 14% after dilution. The fermentation then takes place over approximately 30 hours, and some of the carbon dioxide released is captured and sold as a separate product.

The "beer" from the fermentation process then undergoes a stripping process, where the dunder is separated from the alcohol water mixture. The dunder is sent to waste tanks where sedimentation of the solid particles takes place, while the liquid effluent is sent to sewage.

The ethanol-water mixture then undergoes a series of distillation processes, with a final ethanol product of 95.4% purity (azeotropic point). Some absolute alcohol production may take place, depending on requirement, and this is done by dehydrating the 95.4% ethanol product with cyclo-hexane.

In the steam and electricity generation process, coal is used to generate 31 and 21 bar steam for the distillation processes and other site requirements. Electricity can be generated using the high pressure steam from the boilers to drive a turbine. In the period studied, however, there was no electricity generation for the mills' internal use.

4.2.3.2 Data compilation procedures

An ethanol production period of 12 months, corresponding to the sugar production season for which the sugarcane-to-molasses process data was compiled, was chosen for data gathering on this process site.

Production figures over the studied period were obtained from the distillery operational records to quantify the main economic flows, while the standard (environmental) flows were calculated based on these flows, using results of sampling of wastes and emissions, which are recorded periodically. The flows recorded were corrected to reflect the operation of the distillery only, factoring out other commercial operations on site (a related independent production process exists on site, and shares the utility requirements of the process studied here).

The approach used here was to compile month-by-month "black-box" mass balances over the defined sub-units of the distillery, creating inventory lists of all inputs and outputs. The sub-units were then inter-linked in sequence of the production line, to produce overall process profiles, which were then aggregated to arrive at the one-year data inventory, and an average monthly one. The collected data was compiled in a series of identical inter-linked Excel spreadsheets, one for each sub-unit process, with a worksheet for each month. This matrix was summed to give an overall profile of the process for each of the 12 months of the period of study, reflecting the sums of all "economic" (purchased/sold) and "standard" (to or from the environment) inputs and outputs for the studied system (see appendix C2).

4.2.4 Transportation Data

There are several transport steps involved in this life-cycle study. In principal, all transportation of services and imported flows to the process should be included in the assessment. However, the two steps of transportation directly involved with the manufacture of the product are the following:

- Transportation of sugarcane from cane fields to the sugar mill (Road transport 1)
- Transportation of molasses from the sugar mill to the distillery (Road Transport 2)

Based on the distance and load capacities involved with each of these, it was assumed that they are the most intensive of the transport steps involved and would hence be the ones of most significance.

Log book records of cane and molasses deliveries to each of the sites were used to determine the average loads and truck capacities for deliveries, as well as the geographical locations of the origins of each of the loads.

The transportation steps were modelled using LCI transportation databases, and the trucks used are 40 ton and 30 ton diesel trucks, for the sugarcane and molasses transportation, respectively. The return trip for the trucks is inclusive in the assessment.

The information gathered is summarised in the table below:

Table 4.2 Summary of transportation data

Destination	average load (tons)	average distance (km)	truck capacity (tons)	other detail
from cane field to sugar mill	30	30	40	diesel truck
from sugar mill to distillery	30	70	30	diesel truck

4.3 Ancillary units and model compilation

To incorporate the associated production inventories of other flows into the inventory of the cradle-to-gate study, and for the evaluation of an environmental impact assessment, environmental processing evaluation software was used.

The TEAM™ software by Ecobilan / Pricewaterhouse Coopers (PWC) was used to model the entire cradle-to-gate life cycle process. Besides its availability, this software was determined to be ideal for its ease of use, its extensive database for the production of several inputs that are relevant to this study, and good impact assessment and valuation methods.

4.3.1 Interlinking of software modules and process data to produce overall inventory

The following software database modules were used, in addition to the compiled process data described in the sections above:

- Coal Production
- Electricity Production
- Lime Production
- Diesel Production
- Sulphuric Acid Production
- Road Transportation

The inventories associated with each of these modules constitute cradle-to-gate life-cycle analyses. However, there is need for precaution in using database information to model life cycles of products, because the information on the software may pertain to production patterns in Europe and America, but may not necessarily reflect local production in South Africa.

With the exception of Electricity Production, whose database information has specifically been modified to reflect the 1996 South African electricity production, the rest (coal, diesel and lime) are generic production profiles. It is expected that a major discrepancy would be with respect to energy use in such production steps, because European industrial production often has natural gas as a key energy source, whereas in South Africa, coal is the key energy source due to its abundance and low cost.

Another possible discrepancy is the old technology used in industry in Africa, compared to the technology on which these production modules are based.

A fertiliser production module was not available, and the approach below is proposed for the determination of the relevance of its inclusion in the life cycle study.

4.3.2 Dealing with Fertilizer Production in the life-cycle inventory

In the LCA modelling package used, no databases were available for Nitrogen and Phosphorous fertilisers used in the agricultural processing stage. The basic calculation approach shown below proposes how to determine the significance of including this module in the overall inventory.

Assuming that Nitrogen fertilisers can be represented by Ammonium Nitrate (NH_4NO_3), and Phosphorous fertilisers are Ammonium Phosphate $(NH_4)_3PO_4$), the equations for the production of ammonia, subsequently the production of the fertilisers, are represented by the following formulae:

Ammonia Production:

$$N_2 + 3H_2 \Leftrightarrow 2NH_3 \qquad (1)$$

Ammonium Nitrate Production:

$$NH_3 + HNO_3 \rightarrow NH_4NO_3 \qquad (2)$$

Ammonium Phosphate production:

$$3NH_3 + H_3PO_4 \Leftrightarrow (NH_4)_3PO_4 \qquad (3)$$

Based on these equations, and the fertiliser requirements for the agricultural stage, the corresponding amount of ammonia required can be calculated.

Domene and Ayres (2001) have published emissions from the production of ammonia using natural gas obtained from an Aspen simulation of the process (see table 4.3 below). An adaptation for the production of the ammonia required for the fertilisers can be made to simulate those emissions corresponding to the production of the required amount of ammonia.

The CO_2 emissions can then be used as an indication of the energy intensity of the process, using the a rough estimation that the fertiliser production step is as energy intensive as the modelled ammonia production.

This figure can then be compared to the fossil CO_2 reporting in the final inventory, and the significance of this production step can hence be deduced. This analysis is applied in section 5.7.2.2 to follow.

Table 4.3 Emissions from ammonia production

	value
	per 1000kg NH3
Inputs	
Air	15109
CH4	615
H20	11000
Outputs	
CO2	1500
N2	10900
H2S	13

(Domene and Ayres, 2001)

4.4 Overall data quality evaluation

Evaluation of data quality is important for understanding the reliability of the data gathered, and also for the correct interpretation and use of the results. The section above has already described the adaptability of software data for use in this life-cycle analysis.

4.4.1 Temporal and technological representation

The use of primary data from specific sites means that the production profile resulting from the analysis is specific to the analysed site. However, both the sugar milling and molasses-to-ethanol processes are generic, and follow conventional production methods. It is hence deemed that the results of this life-cycle analysis can be confidently used as an indication of current procedures and methodology in this industry, for the specific region.

The gathered data are for the production season for the year 2000 - 2001.

4.4.2 Data consistency

The methods of data aggregation for each of the site processes have been described in their respective sub-sections previously. Weighted averaging was used to arrive at the aggregates recorded for the overall production profiles, over the 44 weeks of production for the sugarcane-to-molasses process, and over 12 months production, for the molasses-to-ethanol process. Data checks on unreasonably high or low numbers were made, and extreme outliers were excluded in the averaging procedure.

The periods of operation studied for the sugarcane-to-molasses and molasses-to-ethanol processes were consistent with each other, to avoid seasonal variations in crop yield and sucrose content, which would otherwise off-set the material balances on which the inter-linking of the processes is based.

The figures for the agricultural operations, however, are not very accurate, and can be considered as first-order estimates to create an understanding of the associated key input and output values.

4.5 Conclusion

Each of the sub-processes involved in the life cycle has been described, and the key flows into and out of them have been highlighted. The corresponding data aggregation procedures have also been described, and the raw data for these can be found in appendix B. The augmented inventories for the ancillary flows which have been obtained from a software database have also been listed, and together these make up the cradle-to-gate inventory, which shall now be presented and discussed in the chapter to follow.

5. RESULTS AND INTERPRETATION OF INVENTORY

5.1 Introduction

Using the methods of compilation and modelling described in chapter 4, the full LCI was compiled, and is shown in appendix A.

In this chapter, the basic material balances for each of the site processes analysed are first shown, leading to the presentation of a brief summary of the appendix A. Some key input and output flows are highlighted here, leading to their discussion.

An interpretation of the inventory is then presented, starting with a comparison of the foreground and background process, from an energy and material perspective, and leading onto the determination of life-cycle performance measures similar to those found in the literature. Finally, an analysis of different factors which affect the inventory is made, referring to the system allocation, as well as other flow and modular changes to the system.

5.2 Material balances for the main processes

The details of each of the site processes have already been discussed in section 4.2, under the approach used for data gathering. The diagrammatic representations of the processes illustrate the key inputs and outputs to each process, to create an overall picture of the material flows involved on the production of the final ethanol product.

5.2.1 Agricultural Operations process data summary

The diagram below summarises the economic flows for data gathered at the process level for the Agricultural operations, normalised for the production of 1 ton sugarcane:

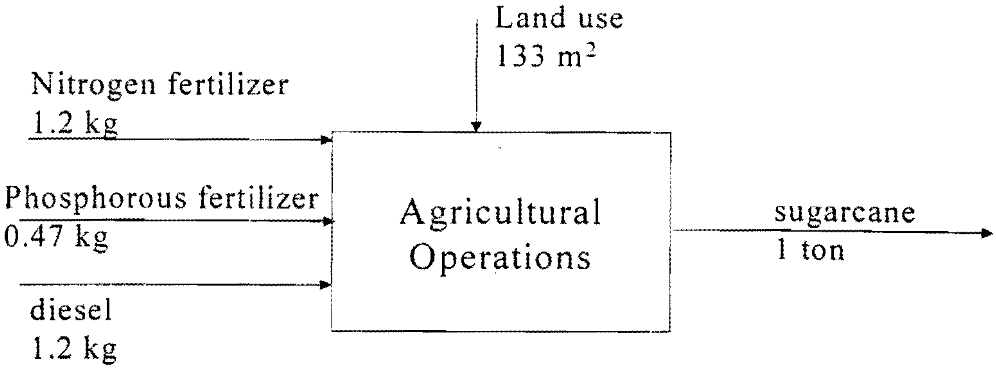


Figure 5.1 Material inputs and outputs for Agricultural operations

This cane now feeds into the Sugarcane to Molasses process, as discussed under section 4.2.

5.2.2 Sugarcane to molasses Process data summary

For this process, there are two different material balances, one for the combined sugar and ethanol system, and the other corresponding to a mass allocation of the burdens of sugar processing to the production of molasses alone.

In the first analysis (figure 5.2a), the material balance of the overall process is shown, where sugar and molasses are the main products, and the relative inputs and pertaining to their production are shown. Figure 5.2b shows the allocated figures for the production of molasses only, the sugar output is hence considered to be zero in this scenario.

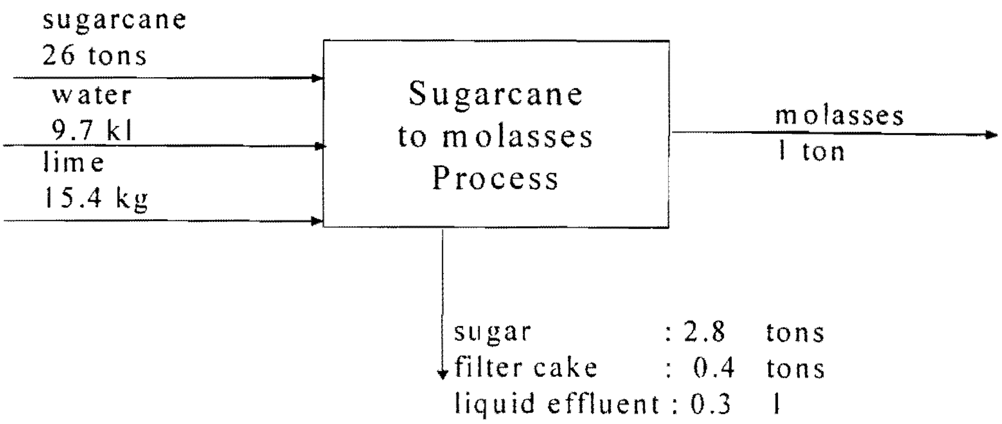


Figure 5.2a Sugarcane to molasses Process data (without partition between products)

Bagasse is an internal flow, consumed in the process stage, and hence does not appear as an output from this process. This illustrates the performance of the overall bio-energy system; sugarcane is converted to molasses and sugar. The process flows have been normalised for the production of 1 ton of molasses.

The effect of the partitioning between these two products can now be seen in figure 5.2b to follow.

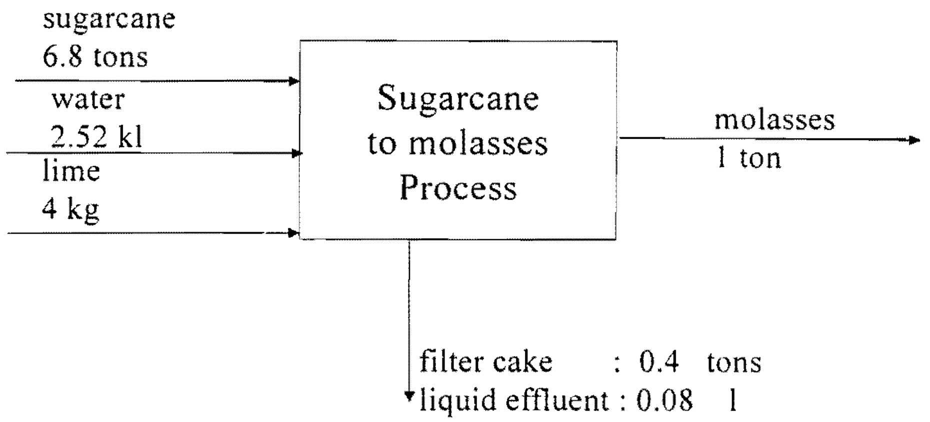


Figure 5.2b Sugarcane to molasses Process data (with allocation to molasses production)

For every ton of molasses produced, 2.8 tons of sugar are also produced. Based on the discussion in section 4.1 on allocation, the allocation factor for partitioning between sugar and molasses production thus becomes $\frac{1}{(1+2.8)}$ equals to 0.26. This means that 26% of the sugar processing burdens is allocated to the production of molasses alone.

The comparison of these two figure 5.2a and 5.2b clearly shows the effect of allocation; in figure 5.2b appropriated values for inputs and output values for the production of molasses alone are shown, as though the process was solely for the synthesis of this product. The significance of this allocation on the carbon balance becomes evident here; 1 ton of molasses is produced from 26 tons of sugarcane in the overall process, yet only 6.8 tons of this cane is appropriated to the production of the molasses alone.

The alternative zero allocation of burdens to molasses production would mean that no inputs and outputs are assigned to this flow, hence the molasses flow becomes the cradle of the study. The effects of this shall be explored further in section 5.6.1.

5.2.3 Molasses to ethanol Process data summary

The molasses produced from the previous process stage are now processed at the distillery to produce ethanol.

Similar to the previous analysis, figure 5.3 below summarises the operation of the distillery. Here the flows are normalised for the production of 1 kl of ethanol product

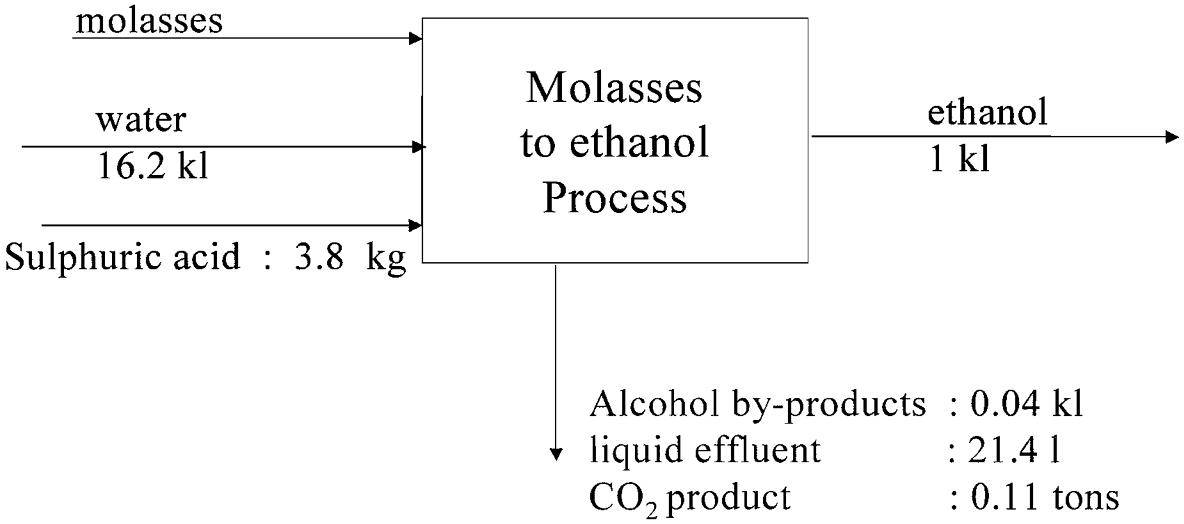


Figure 5.3 Material inputs and outputs for Molasses to ethanol Process

These three sub-processes and the associated background processes previously described form the overall bio-ethanol production life cycle, which is now presented in Table 5.1 to follow. This table is an abridged form of appendix A1, and only shows the flows for the 26% allocation system, highlighting the flows of interest which are discussed in the sections to follow. The reader is referred to appendix A for a full perusal of the complete inventory.

TABLE 5.1 : ABRIDGED INVENTORY FOR BIOETHANOL PRODUCTION SYSTEM,
WITH 26% ALLOCATION TO MOLASSES PRODUCTION

	Flow	Units	TOTAL	Coal Production	Diesel Production	Sulphuric Acid Production	Lime Production	Electricity Production	Road Transport	Agricultural Processing	Molasses to ethanol process	Sugarcane to molasses process
Inputs:	(r) Coal (in ground)	kg	1.46E+03	1.31E+03	5.07E-03	1.42E-02	1.07E-02	1.46E+02	-	-	-	-
	(r) Limestone (CaCO3, in ground)	kg	6.00E+01	1.23E+00	1.03E-02	-	3.46E+01	2.41E+01	-	-	-	-
	(r) Natural Gas (in ground)	kg	1.56E+01	9.43E+00	1.07E+00	1.52E-01	2.45E+00	2.50E+00	-	-	-	-
	(r) Oil (in ground)	kg	4.92E+01	2.35E+00	4.63E+01	3.77E-02	1.07E-01	4.22E-01	-	-	-	-
	(s) Nitrogen (N)	g	1.07E+04	-	-	-	-	-	-	1.07E+04	-	-
	(s) Phosphorus (P)	g	2.39E+03	-	-	-	-	-	-	2.39E+03	-	-
	Land Use (II -> III)	m2a	5.59E+00	5.59E+00	6.90E-05	-	1.49E-07	-	-	-	-	-
	Land Use (II -> IV)	m2a	7.48E-01	7.48E-01	8.40E-05	-	1.81E-07	-	-	-	-	-
	Land Use (III -> IV)	m2a	3.84E+03	2.65E-01	9.52E-08	-	2.05E-10	-	-	3.84E+03	-	-
	Water Used (total)	litre	2.96E+04	2.19E+03	1.90E+02	9.56E+00	6.88E+00	3.09E+02	-	-	1.62E+04	1.07E+04
Outputs	(a) Aromatic Hydrocarbons (unspecified)	g	1.79E-04	6.10E-05	3.79E-07	-	8.16E-10	1.18E-04	-	-	-	-
	(a) Carbon Dioxide (CO2, biomass)	g	7.86E+06	-	-	-	-	-	-	-	7.50E+05	7.11E+06
	(a) Carbon Dioxide (CO2, fossil)	g	2.26E+06	6.83E+04	1.29E+04	5.10E+02	2.15E+04	2.40E+05	4.99E+04	-	1.87E+06	-
	(a) Carbon Monoxide (CO)	g	7.85E+03	6.35E+02	8.10E+00	7.16E-02	3.41E+00	3.10E+02	1.36E+02	-	6.76E+03	-
	(a) Ethanol (C2H5OH)	g	8.00E+03	9.21E-05	4.61E-06	-	1.14E-05	2.09E-04	-	-	8.00E+03	-
	(a) Hydrocarbons (except methane)	g	5.29E+02	1.09E+02	3.09E+02	-	2.61E+00	4.17E+01	6.68E+01	-	-	-
	(a) Hydrocarbons (unspecified)	g	1.55E+01	9.10E+00	2.85E-02	5.25E+00	1.31E-03	1.10E+00	-	-	-	-
	(a) Lead (Pb)	g	2.67E-01	6.30E-02	3.05E-03	-	9.89E-05	1.98E-01	3.51E-03	-	-	-
	(a) Methane (CH4)	g	8.46E+03	7.36E+03	2.23E+02	-	9.49E+00	8.66E+02	2.04E+00	-	-	-
	(a) Nitrogen Oxides (NOx as NO2)	g	3.75E+04	6.24E+02	3.14E+01	2.96E+00	7.08E+00	5.54E+02	6.39E+02	-	1.50E+03	3.41E+04
	(a) Nitrous Oxide (N2O)	g	1.04E+01	4.64E-01	1.42E-01	-	2.34E-02	2.74E+00	6.99E+00	-	-	-
	(a) Organic Matter (unspecified)	g	2.74E-02	1.75E-02	7.36E-04	-	1.59E-06	9.21E-03	-	-	-	-
	(a) Particulates (unspecified)	g	3.41E+03	1.21E+03	6.63E+00	6.81E+00	2.96E+02	1.86E+03	3.47E+01	-	-	-
	(a) Sulphur Oxides (SOx as SO2)	g	1.48E+04	3.16E+02	6.51E+01	7.75E+01	1.80E+00	1.23E+03	7.97E+00	-	4.62E+03	8.52E+03
	(w) Acids (H+)	g	2.74E+01	3.59E-01	7.63E-04	2.66E+01	2.24E-05	4.34E-02	-	-	3.70E-01	1.07E-05
	(w) AOX (Adsorbable Organic Halogens)	g	1.02E-02	4.59E-04	9.66E-03	-	2.28E-05	5.78E-05	-	-	-	-
	(w) BOD5 (Biochemical Oxygen Demand)	g	9.96E-01	2.20E-02	2.07E-01	7.60E-01	3.49E-03	3.79E-03	-	-	-	-
	(w) Chlorides (Cl-)	g	1.47E+04	1.11E+04	2.35E+03	-	5.78E+00	1.25E+03	-	-	-	-
	(w) COD (Chemical Oxygen Demand)	g	1.39E+06	3.49E-01	6.84E+00	5.45E-05	5.11E-02	5.07E-02	-	-	1.39E+06	5.90E+00
	(w) Dissolved Matter (unspecified)	g	2.70E+05	8.17E+02	1.58E-01	4.58E-02	9.31E-03	9.18E+01	-	-	2.69E+05	5.34E+02
	(w) Dissolved Organic Carbon (DOC)	g	5.67E-02	1.76E-03	1.42E-02	-	4.05E-02	2.95E-04	-	-	-	-
	(w) Nitrates (NO3-)	g	7.23E+00	3.24E-01	6.83E+00	-	1.52E-02	6.06E-02	-	-	-	-
	(w) Nitrites (NO2-)	g	1.28E-05	3.96E-07	3.21E-06	-	9.14E-06	6.64E-08	-	-	-	-
	(w) Phosphates (PO4 3-, HPO4--, H2PO4-, H3PO4, as P)	g	6.22E-04	5.19E-05	1.03E-04	-	2.95E-04	1.72E-04	-	-	-	-
	(w) Phosphorus (P)	g	2.00E-02	9.00E-04	1.89E-02	-	5.49E-05	1.14E-04	-	-	-	-
	(w) Sulphates (SO4--)	g	1.14E+05	4.49E+02	3.79E+01	-	3.77E-01	7.83E+01	-	-	1.13E+05	-
	(w) Suspended Matter (unspecified)	g	8.30E+05	1.38E+01	1.08E+00	2.28E+00	2.53E+00	2.63E+00	-	-	8.30E+05	5.05E+00
	(w) VOC (Volatile Organic Compounds)	g	1.68E+00	7.56E-02	1.59E+00	-	3.43E-03	9.59E-03	-	-	-	-
	(w) Water (unspecified)	litre	1.26E+03	1.11E+03	2.70E-03	-	5.83E-06	1.42E+02	-	-	-	-
	(w) Water: Chemically Polluted	litre	2.14E+04	1.20E+01	7.79E+00	-	1.68E-02	1.62E+00	-	-	2.14E+04	-
	sugar product	**tons**	**1.19E+01**	-	-	-	-	-	-	-	-	**1.19E+01**
	ethanol product	**kl**	**1.00E+00**	-	-	-	-	-	-	-	**1.00E+00**	-
	Waste (total)	kg	4.98E+02	4.17E+02	1.93E-01	1.82E-02	2.45E-03	8.00E+01	-	-	-	3.41E-01
Reminders:	E Feedstock Energy	MJ	2.34E+04	2.09E+04	1.88E+03	1.20E+01	2.93E-02	1.28E+03	-6.80E+02	-	-	-
	E Fuel Energy	MJ	4.32E+03	2.81E+03	9.08E+01	-1.16E+01	1.05E+02	6.50E+02	6.80E+02	-	-	-
	E Non Renewable Energy	MJ	2.77E+04	2.37E+04	1.97E+03	3.85E+00	1.05E+02	1.92E+03	-	-	-	-
	E Renewable Energy	MJ	1.28E+01	9.34E-01	8.41E-03	5.17E-04	1.74E-02	1.19E+01	-	-	-	-
	E Total Primary Energy	MJ	2.78E+04	2.38E+04	1.97E+03	3.85E+00	1.05E+02	1.93E+03	-	-	-	-

5.3 Discussion of key inputs and outputs

5.3.1 Resource inputs

Coal and oil represent the key primary energy inputs into the life cycle. The mass of each resource input per kl of product made is shown here, but a more effective scrutiny of primary energy input can be made with respect to the particular background sub-processes from which each of the resource uses originate, as shown in Table 5.2 below:

Table 5.2 Energy values of resource inputs

Flow	Units	TOTAL	Coal	Diesel	Sulphuric acid	Lime	Electricity	Sugarcane to
			Production	Production	Production	Production	Production	Molasses Process
(r) Coal (in ground)	kg	1455.6	1309.8	0	0	0	145.8	0
(r) Oil (in ground)	kg	49.2	2.4	46.3	0	0.1	0.4	0
(r) Natural Gas (in ground)	kg	15.6	9.4	1.1	0.2	2.5	2.5	0
Bagasse	kg	4320	0	0	0	0	0	4320
E Total Primary Energy (fossil)	MJ	27758	23751.6	1966.9	3.9	105.2	1930.2	0
E Total Primary Energy (biomass)	MJ	31622	0	0	0	0	0	31622

The natural gas recorded here refers to coal bed methane; the table above shows that 9.4 kg of the reported 15.6 kg total for natural gas (in ground) originates from the Coal Production sub-process, confirming this.

It is interesting to note the comparative energy value of bagasse. This value is not reported in the overall inventory, since it is an internal flow, but has been shown here to illustrate the energy contribution that the biomass plays in the overall process. Based on the LHV (lower heating value) of bagasse, it has a 1.1 times higher primary energy value (31,600 MJ) than the total fossil energy input (27,800 MJ), and this is for the allocated scenario. This illustrates the magnitude of biomass energy available from the sugar process, and justifies the assumption that all energy requirements of the process can be satisfied, in excess, by the use of bagasse.

For the fossil energy inputs, the following points are noted:

- The overall fossil primary energy distribution is dominantly attributed to coal production (86%), while Electricity (7%) and diesel (7%) production share the remainder fraction.

It can be seen here that lime and sulphuric acid production are relatively insignificant to the overall life-cycle, on an energy basis.
This enforces the point raised previously that coal usage is the key fossil energy contributor.

- Of the non-energy inputs (Table 5.1), water use is 29,600 litres for every 1000 litres of ethanol product, and this is without accounting for cane irrigation.

5.3.2 *Gaseous emissions*

Biomass carbon dioxide (7.9 tons) and fossil carbon dioxide (2.3 tons) are the main gaseous emissions, while nitrogen oxides, sulphur oxides, carbon monoxide, methane and ethanol vapour contribute 37kg, 15 kg, 8kg, 8kg and 8kg respectively. The dominance is clearly on the part of carbon dioxide emissions. These flows are the key to several of the impact categories to follow in the subsequent chapter.
Particulate emissions are also significant under the human toxicity impact category; here the key particulate emissions (3.4 kg) originate from the Coal and Electricity production sub-processes. However, the particulate emissions from the primary processing sites (particularly bagasse from sugarcane to molasses process) were unquantified and hence this figure represents an underestimation of the particulates emitted in this life-cycle.

5.3.3 *Water emissions*

The following water emissions immediately stand out as significant, from the life cycle: sulphates (SO_2^-) (116 kg), chlorides (Cl^-) (16 kg), dissolved matter (270 kg) and suspended matter (830 kg). The effluent also reports a chemical oxygen demand (COD) of 1390 kg, and together these flows are of significant impact depending on their recipient environment. This effect shall be described further under the relevant impact categories in the chapter to follow (Chapter 6).

It should also be noted that scenarios such as accidental pipe failure, leading to leakage of water emissions into aquatic ecosystems, have not been assessed. The impact of these emissions largely depends on whether they are emitted to a waste treatment plant, or directly to aquatic eco-systems.

The subsections to follow shall now present different interpretation aspects of the results which have been presented in sections 5.2 and 5.3.

5.4 Comparing foreground and background sub-process

An analysis of the relative intensities of the foreground and background processes on the inventory is made here. This is done to determine how much influence the producer can have on the overall environmental profile of the bio-ethanol life-cycle.
Isolating which flows, and subsequently which environmental impacts are a result of the primary process of production, and those which are secondary from the inventories associated with the imported flows does this.

The list in Table 5.3 focuses on those flows which have a contribution from both the two mentioned classes of sub-process, and a percentage analysis is used here to determine the emphasis of the foreground sub-process on the totals for these flows reported in the inventory.

The following overall assessment can be made for the relative impacts of the foreground and background process:

- Foreground processes dominate the use of land, due to agricultural processing land use for cane growing.
- Water usage is largely (90%) attributed to foreground processes, without the values for irrigation water.
- Gaseous emissions of carbon dioxide (fossil and renewable), carbon monoxide, ethanol vapour, nitrogen oxides, nitrous oxides, and sulphur oxides are dominantly from the foreground processes.

  Particulate emissions are however noted as being dominantly from background process, and this is because those from foreground process were unquantified (section 5.3.2 above). The total shown here is clearly an underestimation; foreground processes would be expected to dominate the emission of particulates as they do with gaseous emissions.
- Emissions to water of COD, dissolved and suspended matter, and sulphates are fully attributed to foreground process, and in particular to the molasses to ethanol process.
- The total waste (solid waste) reported here (500 kg) is chiefly mining tailings from Coal Production. However, there is a large amount of ash from the molasses to the ethanol

process which was not quantified, which would affect the balance of contribution between foreground and background processes, for a mass of 0.75 tons of coal consumed.

The background processes hence account for the majority of the input and output flows by fraction of mass, but the few flows which are dominated by foreground process are actually of key value to the several impact categories, to be discussed in the chapter to follow.

This is important information, because these emissions are very significant for several impact categories to follow in the subsequent chapter, and this shows that the company can have direct influence on these angles of the overall environmental profile (see discussion in section 4.3).

It should be noted again here that air emissions mainly originate from the combustion of coal and bagasse in the foreground processes producing molasses and ethanol, respectively.
Water and land use were also isolated as significant resource inputs into the life cycle, and the analysis here confirms that these are also within the company's influence to reduce their impact.

Table 5.3 Comparing foreground and background sub-processes

	Flow	Units	Life Cycle Total	Background	Foreground	% contribution of
				Processes	Processes	foreground processes
Inputs	Land Use (III -> IV)	m2a	3.84E+03	2.65E-01	3.84E+03	100.0
	Water Used (total)	litre	2.96E+04	2.71E+03	2.69E+04	90.9
Outputs	(a) Benzene (C6H6)	g	7.54E+00	7.53E+00	1.59E-02	0.2
	(a) Benzo(a)pyrene (C20H12)	g	4.02E-02	4.01E-02	7.94E-05	0.2
	(a) Cadmium (Cd)	g	8.86E-03	8.07E-03	7.92E-04	8.9
	(a) Carbon Dioxide (CO2, biomass)	g	7.86E+06	0.00E+00	7.86E+06	100.0
	(a) Carbon Dioxide (CO2, fossil)	g	2.26E+06	3.43E+05	1.92E+06	85.0
	(a) Carbon Monoxide (CO)	g	7.85E+03	9.57E+02	6.90E+03	87.8
	(a) Ethanol (C2H5OH)	g	8.00E+03	3.17E-04	8.00E+03	100.0
	(a) Hydrocarbons (except methane)	g	5.29E+02	4.62E+02	6.68E+01	12.6
	(a) Lead (Pb)	g	2.67E-01	2.64E-01	3.51E-03	1.3
	(a) Methane (CH4)	g	8.46E+03	8.46E+03	2.04E+00	-
	(a) Nitrogen Oxides (NOx as NO2)	g	3.75E+04	1.22E+03	3.63E+04	96.7
	(a) Nitrous Oxide (N2O)	g	1.04E+01	3.37E+00	6.99E+00	67.5
	(a) Particulates (unspecified)	g	3.41E+03	3.38E+03	3.47E+01	1.0
	(a) Sulphur Oxides (SOx as SO2)	g	1.48E+04	1.69E+03	1.31E+04	88.6
	(a) Zinc (Zn)	g	2.35E+00	1.91E-01	2.16E+00	91.9
	(w) Acids (H+)	g	2.74E+01	2.70E+01	3.70E-01	1.4
	(w) COD (Chemical Oxygen Demand)	g	1.39E+06	7.29E+00	1.39E+06	100.0
	(w) Dissolved Matter (unspecified)	g	2.70E+05	9.09E+02	2.70E+05	99.7
	(w) Sulphates (SO4--)	g	1.14E+05	5.66E+02	1.13E+05	99.5
	(w) Suspended Matter (unspecified)	g	8.30E+05	2.24E+01	8.30E+05	100.0
	(w) Water: Chemically Polluted	litre	2.14E+04	2.14E+01	2.14E+04	99.9
	Waste (total)	kg	4.98E+02	4.98E+02	3.41E-01	0.1

5.5 Environmental performance indicators for the Molasses to Ethanol Process

A specific focus of this assessment is the molasses to ethanol process. This is revisited here in line with the classification made in the introduction to Chapter 4, where this process is classified as one on which the company would have the high influence, with respect to altering its environmental performance for improvement.

To characterise the environmental profile of the distillery, the use of average indicators for each of the nine key inventory flows is proposed, calculated from the inventory. These indicators represent four input parameters (molasses, coal, water and electric power), one internal one (steam use) and four representing outputs to the environment (fossil and renewable carbon dioxide, sulphur dioxide and liquid effluent).

Table 5.4 lists the values calculated to be the average load during the 1-year study period.

Table 5.4 Eco-indicators (Flows per kilolitre of product alcohol)

Indicator	Units	Value
Coal	ton/kl	0.75
Water	kl/kl	16.4
Power	kWh/kl	251
Steam	GJ/kl	16.2
CO_2 (fossil)	ton/kl	1.89
CO_2 (renewable)	ton/kl	0.75
SO_2	kg/kl	4.4
Effluent	kl/kl	22.3

It is seen that approximately 2.65 tons of carbon dioxide (total) are produced, and three quarters of a ton of coal consumed for every kilolitre of product.

Water use (16.4 kl/kl) also appears to be high, for a fermentation-distillation process. Further, there is an obvious imbalance here, of water input versus total effluent (22.3 kl/kl). During the data gathering exercise, it was reported that water input flowmeters were faulty. It is therefore recommended that further observation of water use be made for this site process to determine a more accurate input figure.

Electricity is imported onto site. It is interesting to compare this to the analysis by Beeharry (1999), which showed that up to 58 kWh per ton millable cane can be produced at sugar mills. Since110 tons are processed per kl of product, this means that up to 6.4 GWh/kl electricity is potentially available for export from sugarcane processing. This is greater than the reported 251 kWh/ kl requirement for this site, and prompts the possibility of the use of "green" electricity, produced elsewhere by the same company, from residual biomass.

5.6 Life cycle performance measures based on inventory data

In this sub-section, some of the life-cycle calculations described in section 2.4.1 of the literature review are performed on the inventory data, and a comparative analysis of the figures attained here is made with those found in the literature. The focus here is on carbon flows and energy inputs and outputs associated with each of the sub-processes.

5.6.1 Carbon analyses of the bio-system

In the analysis of bio-energy systems, it is imperative to track all the key carbon flows associated with the biomass, to determine the efficiency of the conversion process, overall. Figures 5.4a and 5.4b illustrate this, the biomass carbon flows are shown in green, while additional carbon flows (fossil fuel use) to the system are shown in brown. The overall bio-energy system's performance from a carbon perspective is made, paying attention to the accounting of carbon over each of the sub-processes. The carbon closures of the allocated and unallocated systems are then compared and the parallels between the two scenarios are drawn.

5.6.1.1 Process carbon balances

Figure 5.4a shows the bioenergy system without partition of process inputs and outputs, where the system represents the simultaneous production of both sugar and molasses, corresponding to the production profile shown previously in section 5.2.2 and figure 5.2a.

In this overall bio-energy system analysis, the following carbon balances are observed over individual sub-processes:

- Over the sugarcane-to-molasses process, sugarcane is converted to molasses, bagasse and sugar product. A carbon balance over this process achieves a closure of 98%.

- The molasses-to ethanol process, however, shows a carbon balance closure of 84% only, for the flows recorded here. This discrepancy here is seen for the following main reason:

  Dunder (waste from the fermentation process) is rich in carbon, which may not have been fermented to ethanol. This accounts for most of the carbon which is lost to waste here, the high readings of suspended (830 kg) and dissolved matter (270 kg) from the molasses to ethanol process illustrates this. Assuming a 10% carbon content in the combined suspended and dissolved matter represents 0.11 tons of the unaccounted 0.12 tons of carbon here.

  Other possible carbon losses may be from other alcohol products (pure ethanol, and low grade (industrial), which are not tracked in this analysis, and product vapour losses from the distillation process, which were estimated at 1% of the final product. These, however, are insignificant in comparison to carbon losses in dunder.

5.6.1.2 Carbon closures for the bio- energy system scenarios

The concept of *carbon closure* has been discussed previously in section 2.4.1 and is now revisited here. Carbon closure is defined by the formula

$$100[1-\frac{(B+C+D)}{A}]$$

where B,C and D refer to the carbon in CO_2 emissions from fossil energy use in the agriculture and harvesting, transportation, and conversion stages of the biofuel production respectively, and A refers to the carbon fixed in the biomass during photosynthesis (growth). It is essentially an indicator for the extent of fossil CO_2 mitigation which a system is allowed by the fixing of carbon into biomass during growth.

The numbers denoted "B", "C"$_{(1,2)}$ and "D"$_{(1,2)}$ refer to the fossil carbon inputs to the different stages in the life cycle. An assumption shall be made here, that all the carbon in these fuels shall be converted to CO_2 during combustion. This is an assumption; in practice the efficiency of combustion would be such that less carbon would be released as CO_2, hence the carbon closure calculated here represents the minimum value attainable.

"A" denotes the carbon in the biomass (sucrose and fibre), while "E" is the carbon in the final ethanol product.

Applying the formula above to the figures shown in the combined sugar-ethanol system shown in figure 5.4a, a carbon closure of 94% is achieved. This means that, as an overall operational system, the off-set caused by fossil carbon dioxide release to the atmosphere, to the carbon fixed in biomass during its growth is only 6%, and this represents a relatively good performance of the system.

Figure 5.4b is the corresponding carbon analysis for the illustration in the previously shown figure 5.2b, where 26% allocation to the production of molasses only is made. Only the inputs and outputs to the cane growing and sugarcane to molasses processes are affected by this allocation procedure, as can be seen in the figures on this diagram. The carbon closure achieved for the bio-ethanol system is now only **79 %**. The difference between the carbon closure of the combined sugarcane-ethanol system (94%) and this figure is significant; this is a clear indication that the production of molasses only to produce bio-ethanol in the current context of the sugar manufacturing process has poor performance in terms of fossil carbon emissions.

5.6.2 Fossil energy ratio

This analysis now relates the fossil energy inputs to the energy value of the final output product, as opposed to the carbon closure, which related fossil carbon emissions to the carbon input.

With reference to figures 5.4a and 5.4b again, the fossil energy ratio is then the energy value of the ethanol E, weighed against the energy value of all the fossil energy inputs together ("B", "C"$_{(1,2)}$ and "D"$_{(1,2)}$) (see section 2.4.1.2) The formula is repeated here for clarity:

Fossil energy ratio = $E_E / (E_B + E_C + E_D)$, (accounting for fossil energy inputs only)

where E_X is the energy value of the flow in the diagram.

Fossil energy ratios of 1.06 for the combined sugar-ethanol system, 1.13 for the 26% allocation to molasses production and 1.14 for the zero allocation to molasses production scenario are realised (see appendix B2).

The combined sugar-ethanol system ratio is calculated here simply for comparison, of importance is the figure corresponding to the 26% allocation scenario. This ratio (1.13) indicates that the renewable energy harvested in the ethanol is marginally higher the total fossil energy requirement for its retrieval.

This figure remains relatively the same for the zero allocation scenario (1.14) because the coal input alone is equivalent to 86% of the energy recovered in the fuel product, and is unaffected by the allocation between the two products (sugarcane and molasses). This shows that the fossil energy intensity of the molasses-to-ethanol process is the key determining factor for the overall yield outlook for the entire system.

Application of the discussion in section 2.4.1.2 is made here; this figure illustrates how the energy benefit of the product bio-fuel matches the fossil energy input into its production. In this context then, the process appears not sustainable.

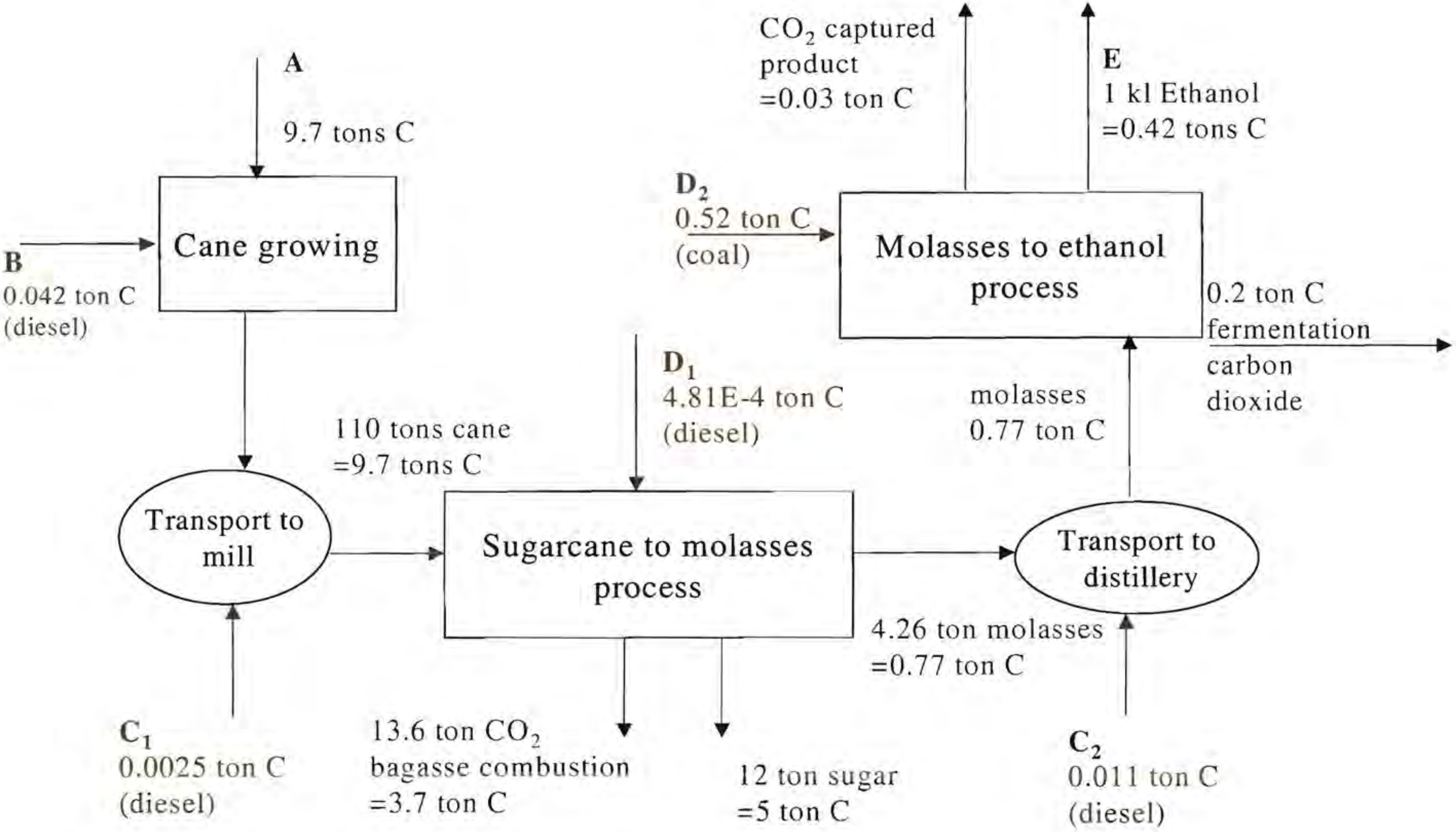


Figure 5.4a A carbon analysis of the combined sugar-ethanol bio-system

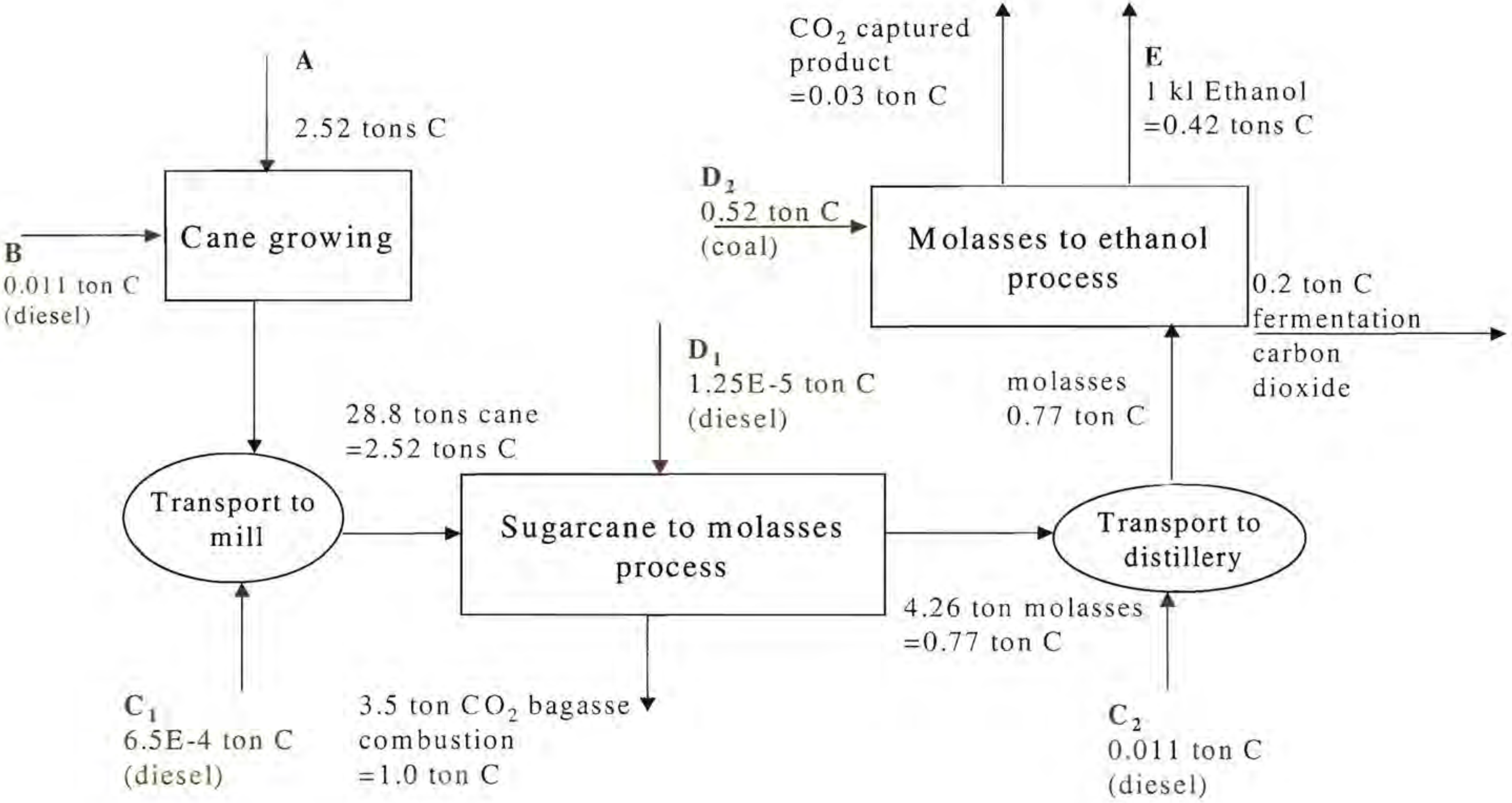


Figure 5.4b A carbon analysis of the bio-energy system with 26% allocation to molasses

5.7 Analysis of factors which influence the bio-ethanol inventory

There are several factors which affect the inventory, and subsequently the environmental profile of the study.In this section, the effects of allocation on the inventory shall first be explored, followed by an analysis of the sensitivity of the inventory to other variations such as the influence of including a fertiliser production module and a coal transportation module. Finally, a discussion on the use of toxic substances in the processing of the alcohol is presented.

5.7.1 Effect of allocation on bio-ethanol inventory

As described in section 3.3.1, a mass-based allocation has been used to accordingly attribute the resources and burdens of molasses production in parallel with sugar production.

In the alternative scenario, an allocation factor of zero is made with respect to molasses production, which effectively implies that molasses are a "burden-free" input into the life-cycle. The argument here is that the essence of the sugar milling process is to produce sugar, as informed by the company's mission statement, and molasses are simply a waste product stream which may not be allocated for. The molasses flow becomes the "cradle" of the study, and the ethanol product out of the distillery is the "gate" end of the study.

This excludes the Agricultural processing and Sugarcane to Molasses sub-processes, and road transport (to sugar mill). The figure below shows this modified system:

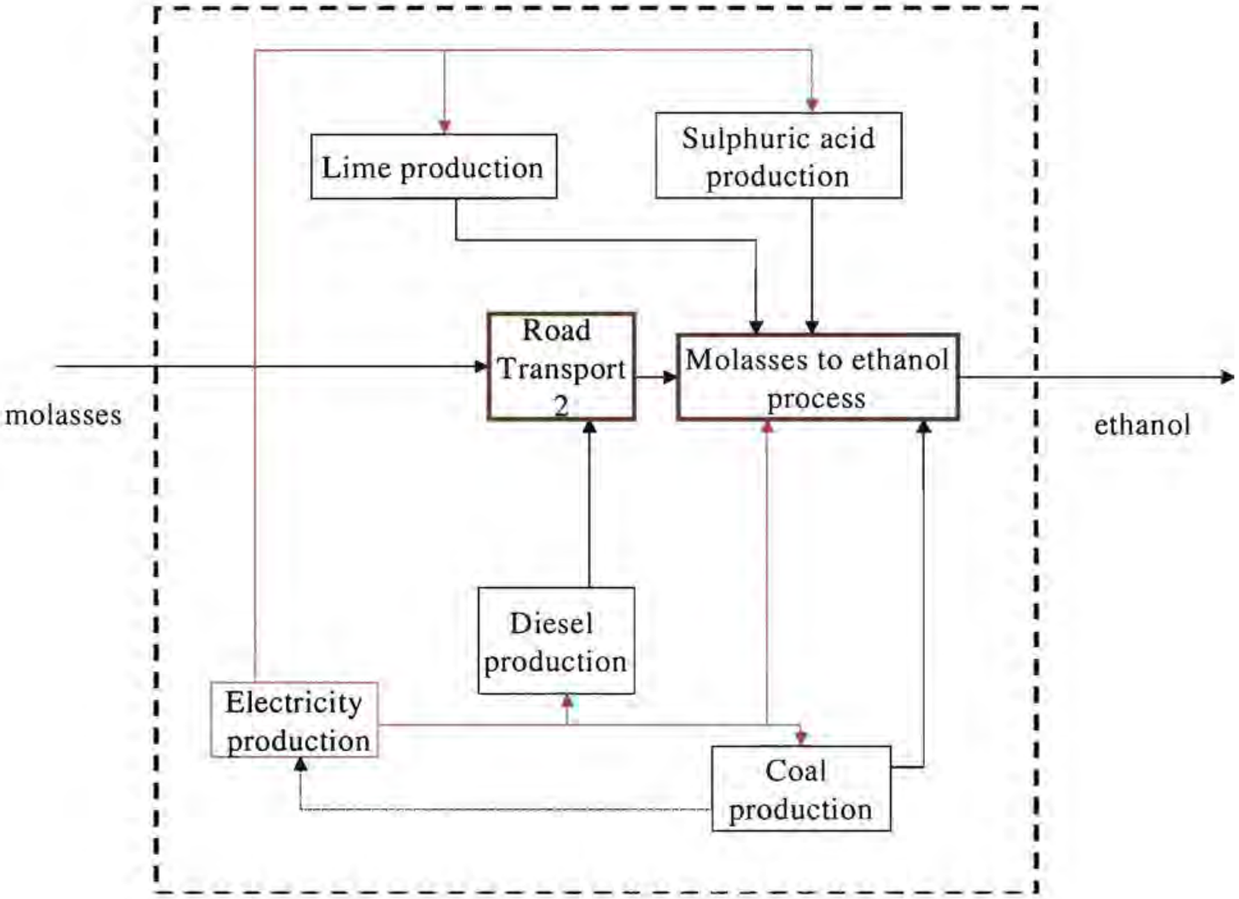


Figure 5.5 Modified system with zero allocation to molasses

5.7.1.1 Effect of allocation on primary energy requirements

From an energy perspective, the effect of attributing none of the sugar processing burdens to the production of molasses can be shown by comparison to the original scenario where 26% of the burdens have been allocated. The table below shows these figures, and the discussion follows below:

Table 5.5 Energy analysis for unallocated life cycle

Flow	Units	TOTAL	Coal	Diesel	Sulphuric acid	Lime	Electricity
			Production	Production	Production	Production	Production
E Total Primary Energy (zero allocation)	MJ	26275	23752	575	4	27	1917
E Total Primary Energy (26% allocation)	MJ	27758	23752	1967	4	105	1930

The following observations are made:

- The total primary energy remains relatively unchanged (5% change), and this confirms that the energy intensity of the life cycle is focused on the Molasses to Ethanol process, and its related background processes.
- Coal and sulphuric acid production figures remain unchanged, as these pertain specifically to the molasses to ethanol process. Electricity production is slightly reduced, to correspond with the exclusion of the lime and diesel for the detached sugarcane to molasses process, and the related transport step.
- Diesel Production shows the biggest reduction for the scenario with no allocation to molasses production, since the upstream agricultural, transport and sugarcane to molasses processes have the higher requirement for this utility.

It should be noted here that these changes may have more significant impacts than identified here, and shall therefore be re-investigated under the impact assessment sections in the following chapter.

The resulting inventory with zero allocation to molasses can be seen in Appendix A2.

5.7.1.2 Other notable flows affected by allocation

From the analysis above, it can be seen that the standard flows associated with diesel, lime and electricity production are changed accordingly due to the effect of the allocation. In particular, noxious gas emissions associated with diesel and electricity production will be significantly reduced in the scenario with zero allocation to molasses. However, the significance of these changes can be seen best in the context of the impact assessment which follows in the next chapter.

Other significant flows affected by the allocation are the following:

- land use is now excluded (see Appendix A2) from the life-cycle.
- water use is reduced by 37%.

5.7.2 Sensitivity of the bio-ethanol study to the inclusion of other sub-processes

5.7.2.1 Influence of the transportation steps

The two transport steps, which have been analysed in this bio-ethanol study, are the transportation of sugarcane from agricultural fields to the sugar milling site, and that of molasses to the distillery site. Table 5.6 below shows the energy intensities of each of these steps:

Table 5.6 Relative intensities of the two transport steps of the study

Step	**Energy (MJ)**	**Capacity (tons)**	**Distance (km)**
sugarcane transportation to sugar mill	549	40	30
molasses transportatio to distillery	131	30	70

It can be seen here, that for a zero allocation to molasses, the first transportation step becomes excluded, and the combined energy intensity of the transport step is decreased by 80%.

The overall intensity of the transport step (680 MJ) is relatively insignificant, compared to the combined energy intensity of the other sub-processes (27 758 MJ) in the analysis of the subsections above, and this shows that this may have no significant impact on the inventory.

However, the largest imported flow is coal to the molasses-to-ethanol process; 0.75 tons of coal are consumed per kl of ethanol produced. This coal is mined in an area approximately 300 km from the production site, and is shipped by rail transport. This step has not been added to the analysis of the overall process.

A separate model of this transportation step was made, in comparison with the transport steps which have been discussed above, and the following results were found:

The coal transportation step has an energy intensity of 47.5 MJ fuel energy, compared to the total value of 678 MJ fuel energy for the two transport steps currently included in the study.

This would represent a 7% increase in the energy intensity of the life-cycle transport step overall, should it be included in the analysis. But the analysis above also showed that the existing transportation sub-system has a primary energy value of only 2% of the combined energy intensities of the other sub-processes.

It appears then, that the omission of the coal transportation step may not have an impact on the overall transport energy requirement for the process and other associated flows. Nevertheless it remains a recommendation that an update of the process model should include all transportation steps of imported process flows, as these may collectively have significant bearing on the environmental profile of the study.

5.7.2.2 Effect of including fertiliser production data

As pointed out in section 4.3.2, the unavailability of data for the production of fertilisers resulted in its exclusion as a sub-process module. However, the section proposed an analysis method to determine the extent of influence that this sub-process may have on the overall inventory. The basic approach is repeated here for clarity, and the following results were found:

Assuming that Nitrogen fertilisers are represented by Ammonium Nitrate (NH_4NO_3), and Phosphorous fertilisers are Ammonium Phosphate ($(NH_4)_3PO_4$), the following calculation can be made:

Ammonia Production:

$$N_2 + 3H_2 \Leftrightarrow 2NH_3 \qquad (1)$$

Ammonium Nitrate Production:

$$NH_3 + HNO_3 \rightarrow NH_4NO_3 \qquad (2)$$

Ammonium Phosphate production:

$$3NH_3 + H_3PO_4 \Leftrightarrow (NH_4)_3PO_4 \qquad (3)$$

Now, usage figures are 90 kg/ha and 35 kg/ha for the Nitrogen and Phosphorous fertilisers respectively (see section 4.2.1). For a cane yield of 75 tons/ha, and an allocated production figure of 28.8 tons cane per functional unit, using equations 1, 2, and 3 above:

Allocated fertiliser input

Ammonium Nitrate (NH_4NO_3): $\frac{90}{75}(28.8) = 34.6kg$

From equation (2), using molecular ratios, the amount of ammonia required is:

$$\frac{17}{80}(34.6) = 7.3kgNH_3$$

Ammonium Phosphate ($(NH_4)_3PO_4$: $\frac{35}{75}(28.8) = 11.5kg$

Using equation (3), this amounts to

$$\frac{51}{149}(11.5) = 4kgNH_3$$

The total amount of ammonia required to produce these fertilisers is **11.3 kg NH_3 per f.u.** (functional unit).

Domene and Ayres (2001) have published emissions from the production of ammonia using natural gas which were obtained from an Aspen simulation of the process. These are adapted for the production of the 11.3 kg ammonia required per functional unit as follows:

Table 5.7 Emissions from ammonia production (adapted for calculation)

	value per 1000kg NH_3	**kg per f.u**
Inputs		
Air	15109	170.9
CH4	615	6.9
H20	11000	124.3
Outputs		
CO2	1500	17.0
N2	10900	123.2
H2S	13	0.1

Focusing on CO_2 emissions alone to determine energy intensity of the process, an estimated factor of 2 was applied to account for the energy intensity of the actual fertiliser production process of equations 2 and 3. The figure for CO_2 emissions becomes **34 kg per f.u.**

The inventory reports a CO_2 (fossil) total of 2320 kg per f.u. 34 kg hence represents about **1.4% of total emissions**, when included in the total.

At this level of contribution it would be more appropriate to include the fertiliser production steps into the bioethanol life cycle, especially as emissions of some pollutants (e.g. nitrous oxides) might be higher in relative terms. However, given the lack of access to a suitable appropriate database, fertiliser production has been excluded here.

5.7.2.3 Use of toxic chemicals for alcohol production

Cyclo-hexane is used as a dehydrating agent to produce absolute alcohol (100% ethanol) from the azeotropic mixture of the final distillation product (see section 4.2.3). However, it was not recorded in the inventory, hence an investigation into the extent of its use was launched.

It was found that only 0.36 l cyclo-hexane per kl of ethanol product is used in the production life-cycle, representing 0.04% of the functional unit. On the basis of the rule used to exclude associated primary processing flows, which excludes all flows that represent less than 0.2 % of the functional unit, the exclusion of cycle-hexane and its production in the life-cycle study is hence justified.

Nevertheless, the material safety data sheet (MSDS) for this substance indicates that it flammable, as well as toxic to humans in the event of ingestion. It should therefore be handled with extreme care and sensitivity, especially when using for processing alcohol for potable use.

The exercise of this caution is also extended to the use of sulphuric acid, which is highly corrosive, and is fatal if ingested into the body.

5.8 Concluding remarks for the inventory interpretation

From the interpretation of the inventory figures discussed here, it can be seen that:

- Coal Production accounts for 86% of the fossil primary energy input into the life cycle, and Electricity and Diesel Production each contribute 7%. The solar energy endowment, invested in the bagasse, is 1.1 times greater than the fossil energy input.

- Foreground processes dominate the emission of many of the key environmental flows.

- The overall ethanol-sugarcane production system has a carbon closure of 94%, but the allocated production system shows a carbon closure of 79%.
  The 26 % allocated system shows a fossil energy ratio of 1.13.

- A zero allocation to molasses only induces a 5% decrease in the fossil primary energy requirement, compared to the 26% allocation scenario. Diesel requirement shows the greatest change in resource use, when allocation is effected.

- Transportation, as a life-cycle sub-process, has only a 2% contribution to the energy intensity of the overall process. The inclusion of Coal Transportation in the inventory was shown to have little effect on the overall energy input requirement.

- The exclusion of Fertiliser Production as a module in the life cycle was also determined to be allowable if not optimal, based on an order of magnitutde carbon analysis.

This chapter has presented the results of the life-cycle inventory, and has analysed several of the indicators for the performance of the overall system. The analysis here, however, is largely on a mass and energy basis; it is important to determine the significance of each of the flows with respect to impact categories. The chapter to follow (Chapter 6) does this, and the analysis is also used to identify if the changes in the inventory discussed here have any significant impacts in terms of the effects caused in the relevant categories.

6. LIFE CYCLE IMPACT ASSESSMENT

6.1 Introduction

This chapter discusses the different impact assessment categories used to evaluate the results of the inventory.

One of the goals of this study is to determine a measure of the sustainability of the production process. An indication of the sustainability of a production process can be seen from the impacts that it has on the environment from which it draws its resources, and to which it emits its environmental outputs.

There are also several scenarios presented in the previous chapter, which may have shown insignificant changes in the mass and energy flows reported in the inventory, but may have notable changes in the context of the impacts which they cause.

The impact categories that are studied here were presented previously, in section 3.3.2. The impact assessment results were generated from the TEAM™ tool for impact assessment, using the following methodologies for impact categories:

CML - Centre of Environmental Science, Leiden University
IPCC - International Panel on Climate Change
USES – Uniform System for the Evaluation of Substances
WMO - World Meteorological Organisation
CST - Critical Surface-Time, Ecole Polytechnique Fédérale de Lausanne

The results have been presented in graphical form, showing the contributing flows for the particular impact categories, corresponding to the different sub-processes from which the particular flows originate.

6.2 Results from impact categories used to assess inventory data

The subsections to follow shall then discuss the individual impact categories and their contributing sub-processes. All the results in this section are for the 26% allocation scenario.

6.2.1 Climate Change

The sun's short-wave radiation (UV and visible light) is reflected directly or re-emitted from the atmosphere, or the surface of the earth as longer wave infrared (IR) radiation. A "natural" greenhouse effect is created due to the presence of water vapour in the atmosphere, where the re-emitted radiation is absorbed in the atmosphere, maintaining the earth's temperature. However, the emission of gases by man-made activities increases the absorption of this re-emitted radiation, and is additionally increasing the earth's temperature in a detrimental manner. The key pollutant gases in this respect are CO_2 (carbon dioxide), CH_4 (methane), N_2O (nitrous oxide), and halocarbons (Hauschild & Wenzel, 1998).

Figure 6.1 shows the results of the greenhouse effect potential of the overall life-cycle, illustrating the contributions from each of the sub-processes, in units of g equivalent CO_2. The effect over 20 years is the category shown in the analysis here.
It can be seen here that the key contributors are CO_2 and CH_4. As foreseen, the molasses to ethanol process' coal combustion releases the most CO_2 over the entire life-cycle, creating a greenhouse effect potential of 1870 kg equivalent CO_2.
Coal Production is then the second key contributing process to this impact category, releasing 540 kg equivalent CO_2. The contribution of methane here is from coal bed methane.
Electricity Production is the third key contributing process in this category.

6.2.2 Acidification

Soil, or aquatic ecosystems acidification is an impact which leads to the reduction in the system's acid neutralising capacity, directly caused by the addition of hydrogen ions which displace other cations which are in turn leached out of the system.

For a substance to be classified as acidifying, it should therefore be responsible for an addition or release of hydrogen ions in the recipient system, where the accompanying anions become leached from the system (Hauschild & Wenzel, 1998).

SO_2, NO_2 and NH_3 are dominant in the inventory, and are the chief cause of this effect, hence classifying this category as relevant to the study.

Figure 6.2 shows the results of this analysis. The combustion of bagasse in the sugarcane to molasses process releases the most SO_2 and NO_2, followed by the coal use of the molasses to ethanol process.

The location of the Sugarcane to Molasses Process is such that the recipient environment for air acidification would be the agricultural sector that produces sugarcane; the leaching of soils as a result of acidification would possibly reduce the land fertility and marginalise crop yields, or else require lime addition.

The Molasses to ethanol Process is located in an urban industrial area, and corrosion of metal structural degradation would similarly become an issue of concern.

These results are in line with the predictions made from the literature survey, which highlighted the emissions of SO_2 and NO_2 as key in the life-cycle of bio-energy systems (section 2.5.4.2). The analysis there was based on the use of the product fuel, whereas here the cause is due to the incineration of the biomass during processing. Nevertheless, the combustion of the bagasse is in the interest of energy recovery, hence it becomes a relevant issue.

Another aspect of agricultural practice not analysed in this study is the practice of cane-burning before harvest. This would also have significant implications for the environmental profile of the Agricultural Process, producing effects similar to those caused by the bagasse incineration of the Sugarcane to molasses Process as shown.

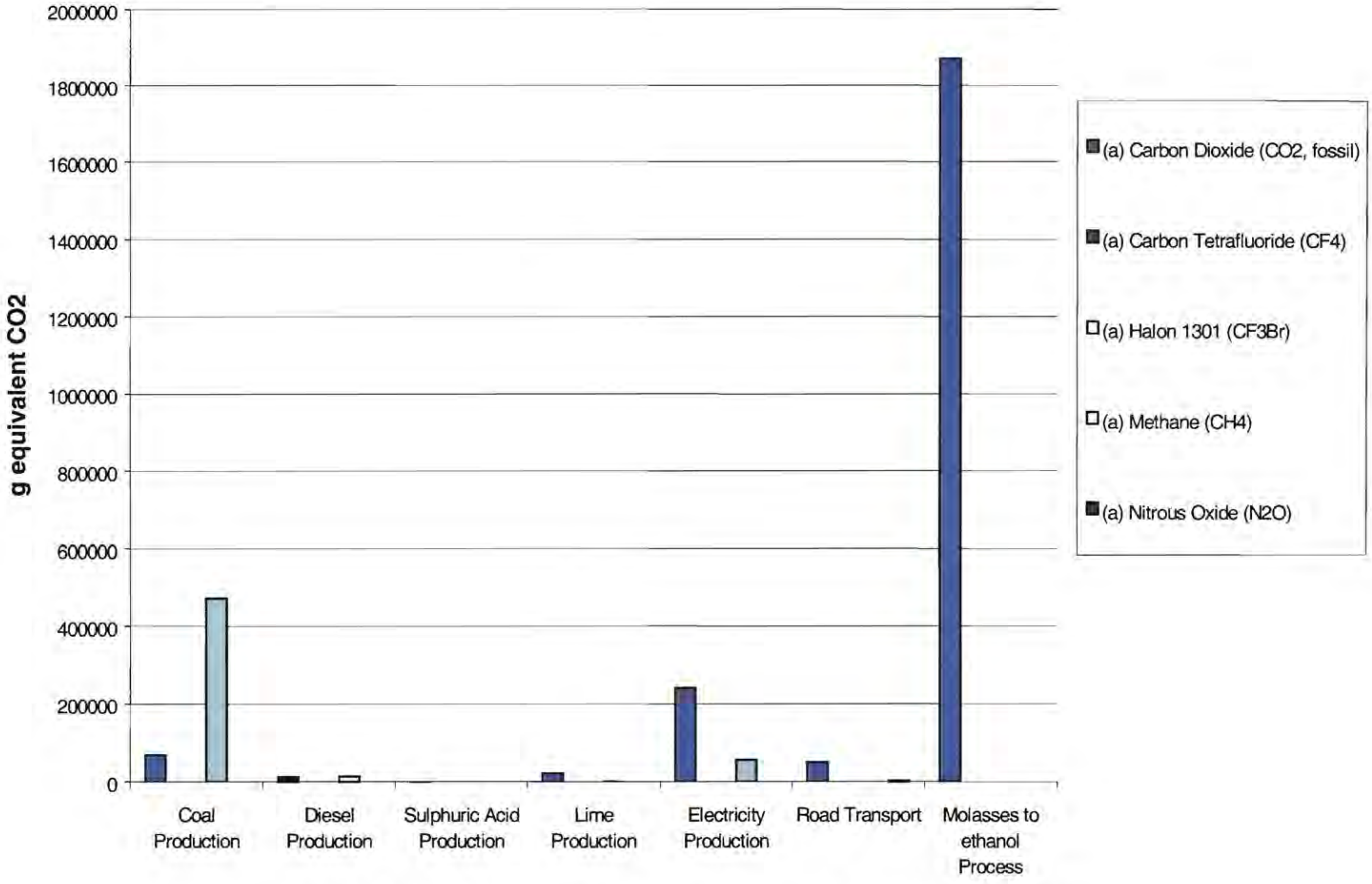


Figure 6.1 IPPC-Greenhouse effect (direct, 20 years) for bio-ethanol life cycle

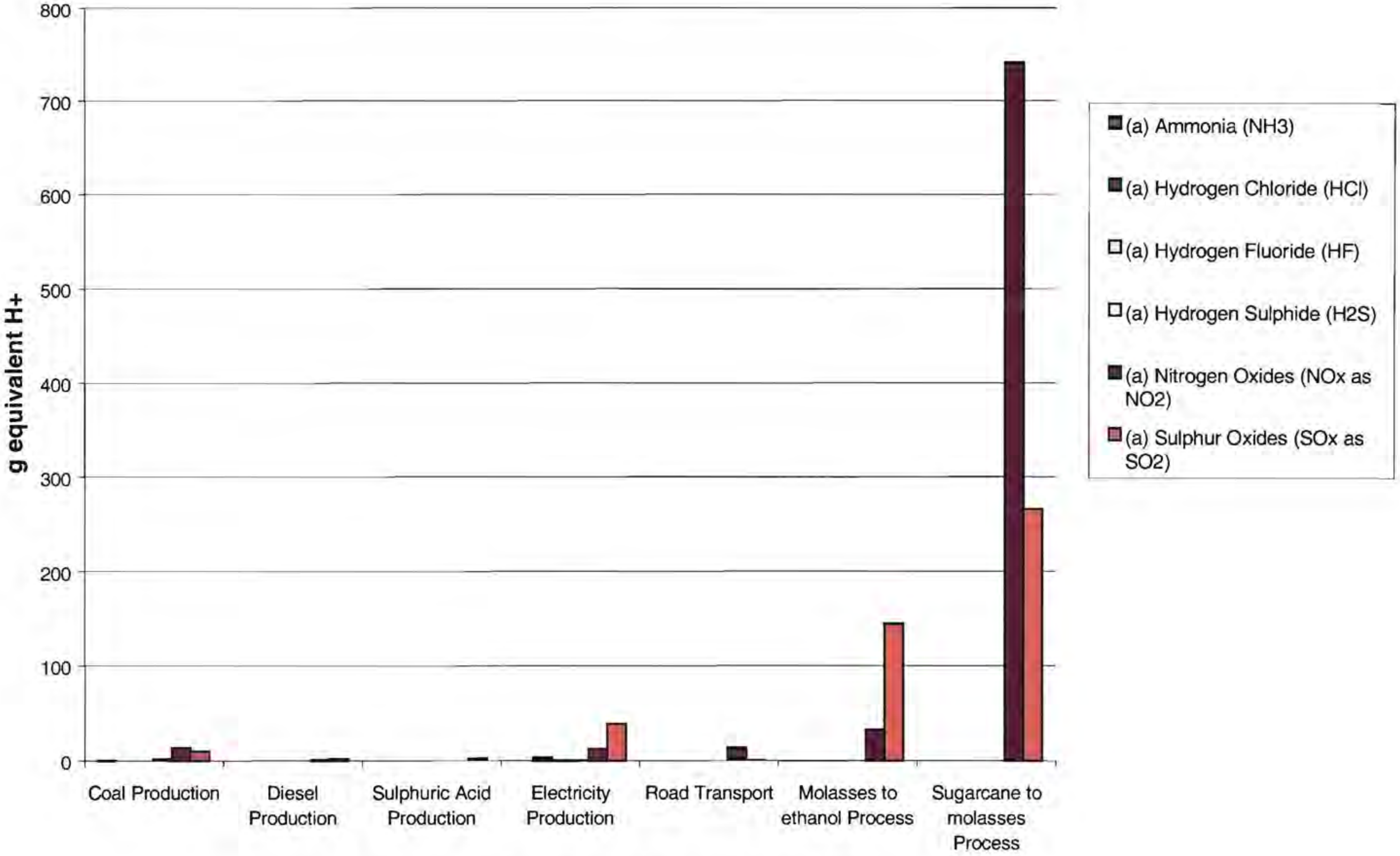


Figure 6.2 CML-Air Acidification potentials for bio-ethanol life cycle

6.2.3 Nutrient Enrichment

The depletion of oxygen at the bottom of lakes and coastal waters is called **eutrophication.** This is caused by the excess enrichment of the aquatic environment with nutrient salts, particularly those of nitrogen and phosphorous, which leads to excessive growth of algae and other plant life, which in turn consumes oxygen when they are broken down. Subsequently, all aquatic life suffers the lack or reduction of oxygen levels, leading to death (Hauschild & Wenzel, 1998).

In the agriculture subsystem of the process, N&P (nitrogen and Phosphorous) fertiliser is applied to the fields and it is a reasonable assumption that a significant amount of the fertiliser is run off into water streams, causing eutrophication. An estimation of this was, however, omitted due to information limitations.

Similarly, the Sugarcane to molasses Process is located along a coastal margin, and inevitably some effluent from the effluent lagoon seeps into the sea, but a figure of this quantity is also not available. This is a significant shortfall in the inventory.

Of the recorded information, the COD (chemical oxygen demand) of the Molasses to ethanol Process effluent is the most significant contributor to this effect (Figure 6.3). A comparative assessment can only be commented on with the contribution of the lacking areas discussed above, and so the results in this category can be classified incomplete and require further analysis for meaningful interpretation.

6.2.4 Photochemical oxidant formation potential

Depending on climate conditions, air emissions from industry and transportation can be trapped at ground level. Here they react with sunlight to produce photochemical smog, which contains ozone, produced from the interactions of volatile organic compounds (VOCs) and NO_X in the following sequence:

1. VOCs, CO and OH react in sunlight to form peroxy radicals.
2. The peroxy radicals oxidise NO to NO_2.
3. NO_2 is split by sunlight with formation of NO and release of oxygen atoms.
4. Oxygen atoms react with molecular oxygen (O_2), to form ozone, O_3.

The hydrocarbons responsible for this phenomenon are the following, ranked in order of decreasing potential:

Alkenes, aldehydes, ketones, alkanes and hydrocarbons (Hauschild & Wenzel, 1998).

A significant source of contribution to this category is the alcohol vapour emissions from the distillation process of the Molasses to ethanol Process. An estimation of 1% of ethanol product lost to fugitive emissions was made, and this results in a higher contribution than all other aspects of the life cycle (figure 6.4). Should the fugitive emissions be found to be in the region of 0.1% of the functional unit, this would represent a value of 32 grams equivalent ethylene, which would still be among the higher values of those identified from the other sub-processes.

It is interesting to note the insignificance of the road transport sector in this life-cycle, with respect to hydrocarbon emissions here.

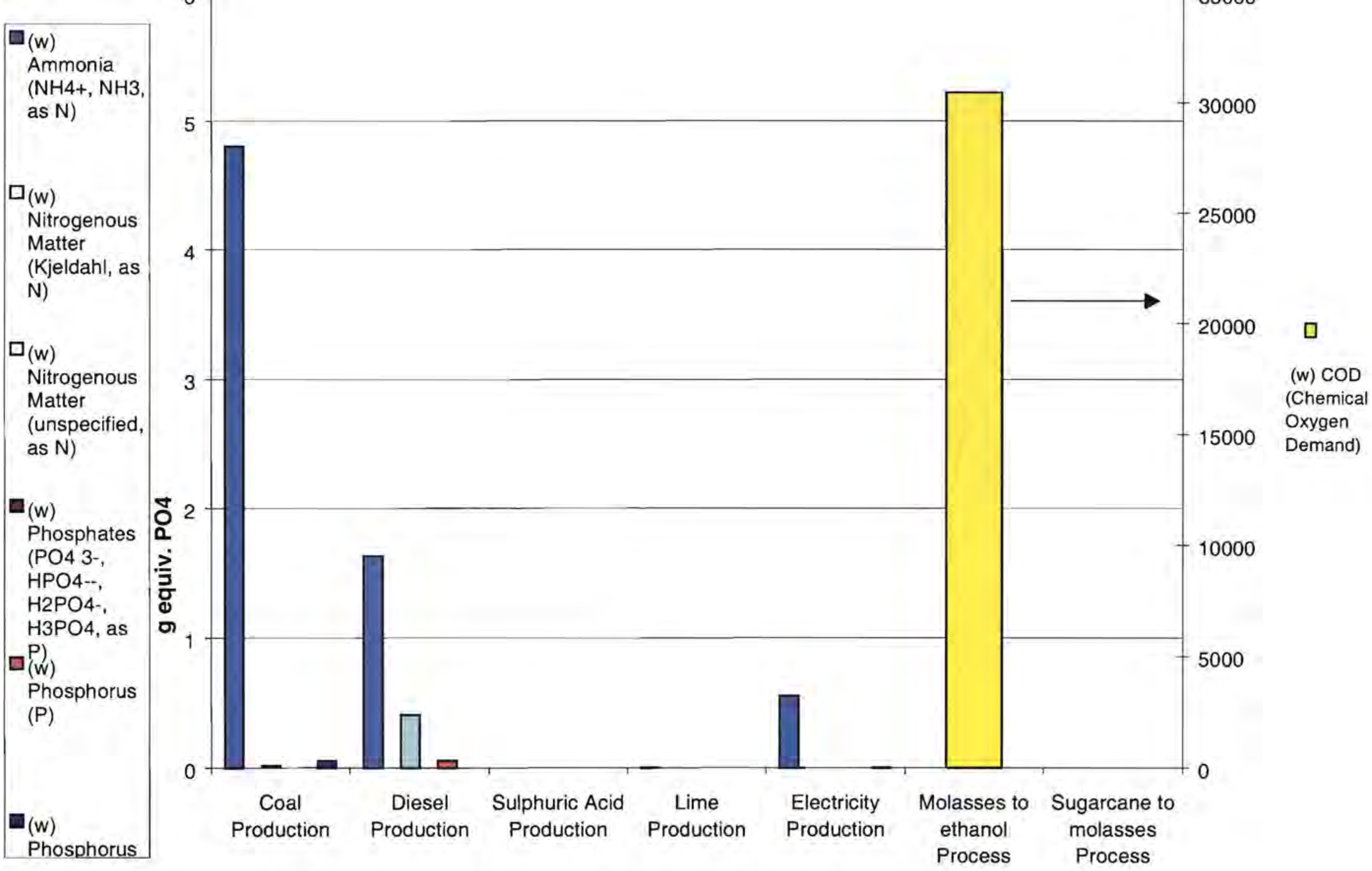


Figure 6.3 CML-Eutrophication potentials for bio-ethanol life cycle

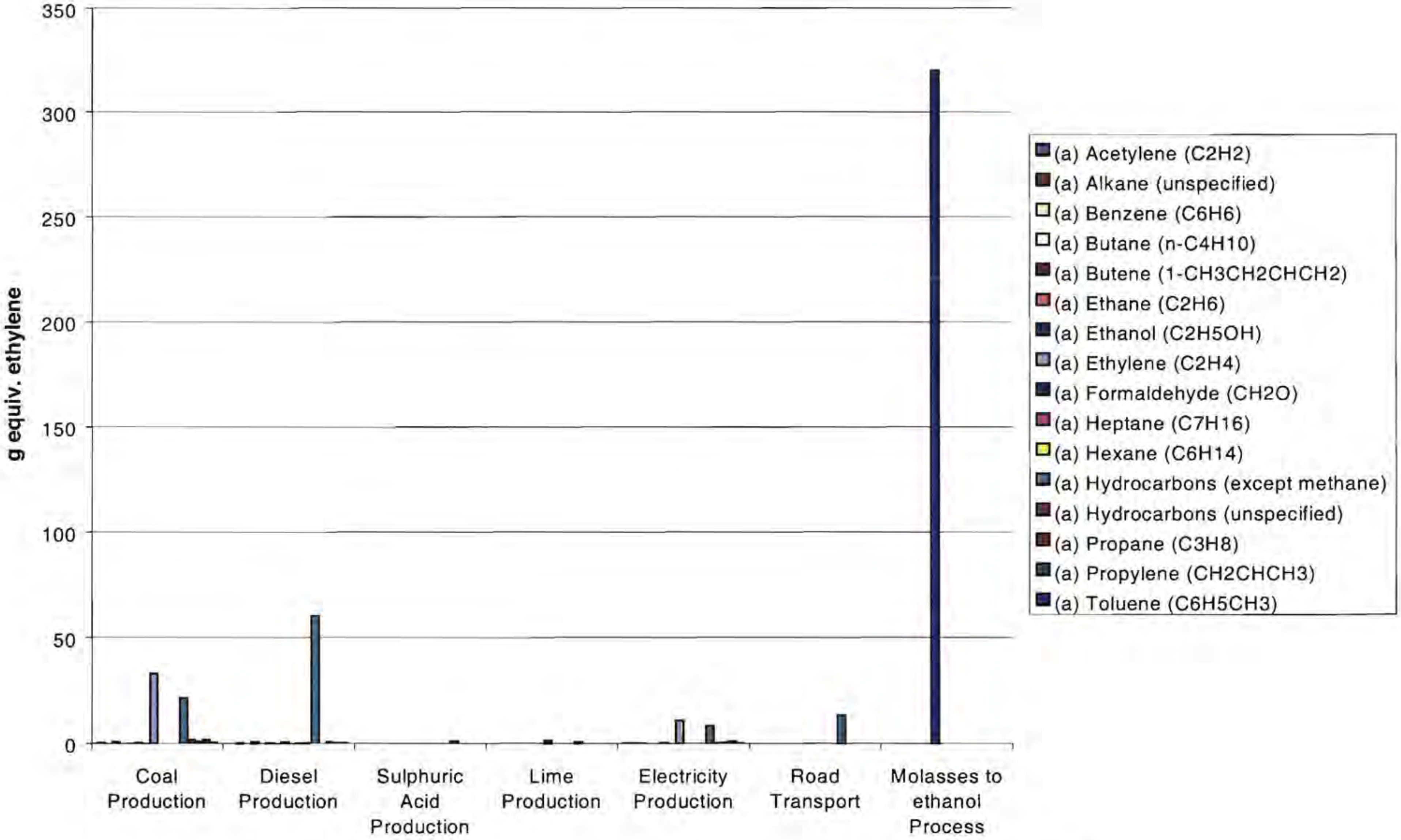


Figure 6.4 WMO-Photo-oxidant formation potentials for bio-ethanol life-cycle

6.2.5 *Ozone depletion*

This impact category is classically included in life-cycle assessment; however the processes in this study do not release the responsible emissions for its cause, and hence its relevance is suspected to be minimal.

The stratosphere is the region 15-50 km above the troposphere, which is the part of the atmosphere above the earth for up to 10 km upwards. Here, the presence of ozone, O_3, is significantly higher than in other regions for the following reasons:

- Photolytic formation of ozone from oxygen under the influence of UV radiation,
- The relatively high stability of ozone in the bottom stratum of the stratosphere

A naturally occurring ozone depletion process occurs in this region in the presence of methane, nitrous oxide, water vapour, and chlorine and bromine compounds. Man-made activities have increased the release of chlorine and bromine-containing componds: CFCs, tetrachloromethane, 1,1,1 – trichloroethane, HCFCs, halons and methyl bromide. Resultantly this has increased the natural ozone depletion process, exposing the earth to the harmful UV B-radiation from the sun, otherwise filtered by the ozone layer.

The assumption that this effect is insignificant is confirmed by the result shown in figure 6.5. All the contributing process have emissions under 0.12 g equivalent CFC-11 over the life-cycle, with Diesel Production having the highest contribution of 0.11 g equivalent CFC-11 per kl of ethanol produced. Normalised, this contributes 2.14E-10 of the global impact, which is relatively insignificant, as shall be seen under the normalisation discussion (section 6.3) to follow.

6.2.6 *Human toxicity*

This impact category is a complex one for evaluation because the number of substances which contribute to it is very large, and there are different basic toxicity mechanisms such as damage to DNA, induction of allergy or inhibition of specific enzymes. As a result, there is no unanimity on any coherent and operational method for a quantitative assessment of toxic substances, within the environmental assessment of products.

The following classification of toxins which affect human health is made:

- metals e.g. lead, cadmium, mercury, emitted from processes, causing various acute and chronic effects.
- Persistent (low degradability) substances e.g. PCBs (polychlorinated biphenyls), PAHs (polycyclic aromatic hydrocarbons) and dioxins, which accumulate in adipose tissue.
- Organic substances which emulate the female sex hormone oestrogen on sensitive receptors in humans and animals.
- Volatile organic compounds, sulphur and nitrogen oxides, as well as particulate matter.

Direct exposure occurs via inhalation and ingestion, while indirect exposure can be through ingestion of plants which have been exposed to pollution, or ingestion of consumers of their products (e.g. herbivores) (Hauschild & Wenzel, 1998).

Several different methods of evaluation have been used to analyse this impact category, to illustrate a range of concerns that arise from the different approaches. Firstly, the assessment of two methods, USES and CST, are compared. The results are shown in figures 6.6a and 6.6b.

The USES method (figure 6.6a), in units of grams equivalent 1-4 dichlorobenzene, highlights the lead (Pb) emissions from Electricity Production (13.2 kg equivalent) and Coal Production (4.2 kg equivalent), but also the nitrogen oxides from the Sugarcane to molasses Process (8.9 kg equivalent).

The CST method, in figure 6.6b. focuses on the emissions from Electricity Production, with Selenium as the chief pollutant. In figure 6.6c (CML method) the sulphur oxide and nitrogen oxide emissions from the Molasses to ethanol and Sugarcane to molasses Processes are highlighted as the key emissions of human health concern.

Overall, trace elements from coal fired power stations, nitrogen oxides and sulphur oxides appear to be the key health issues arising from the life-cycle, in agreement with the focus laid out in the opening paragraph of this sub-section.

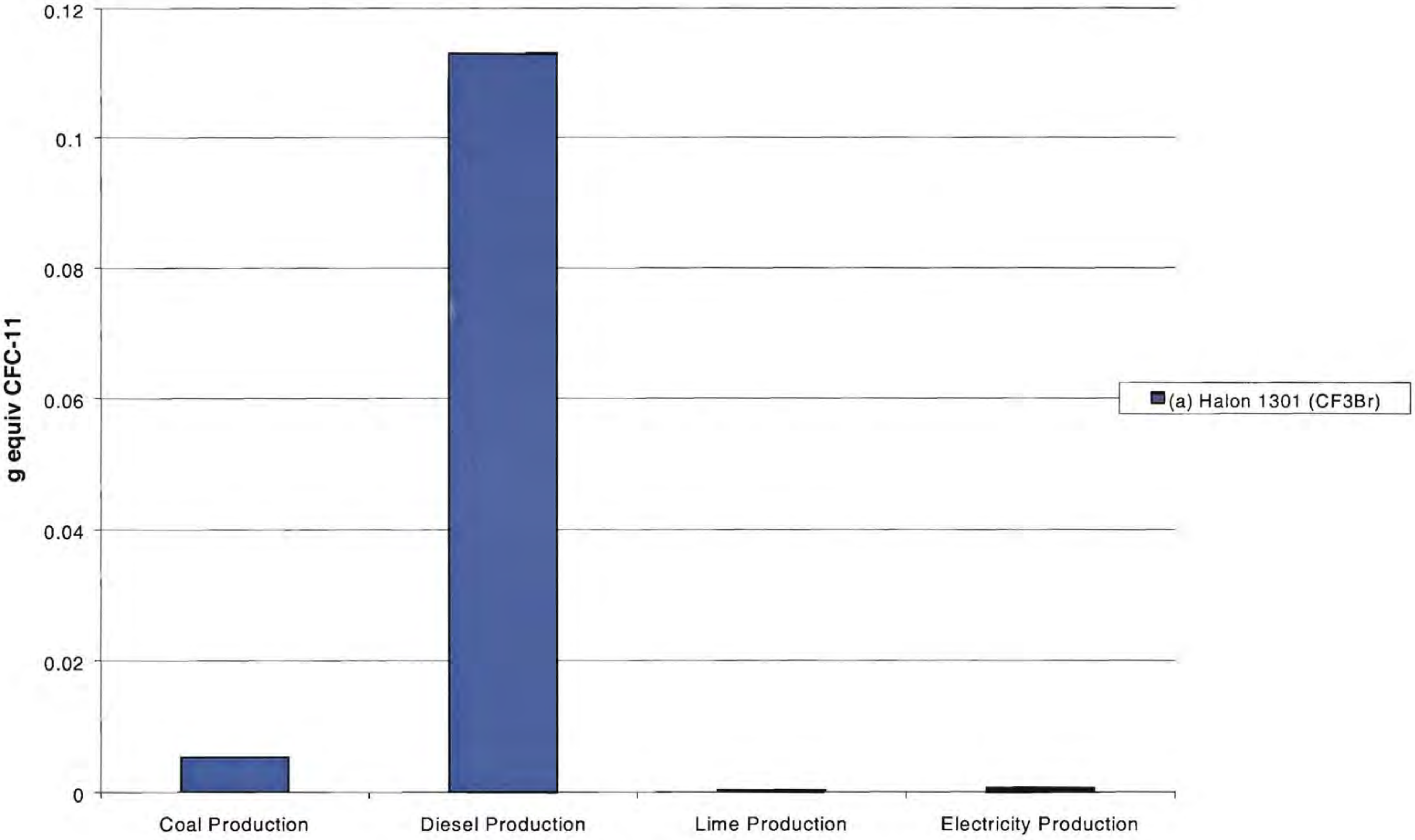


Figure 6.5 WMO-Ozone depletion potentials for bio-ethanol life cycle

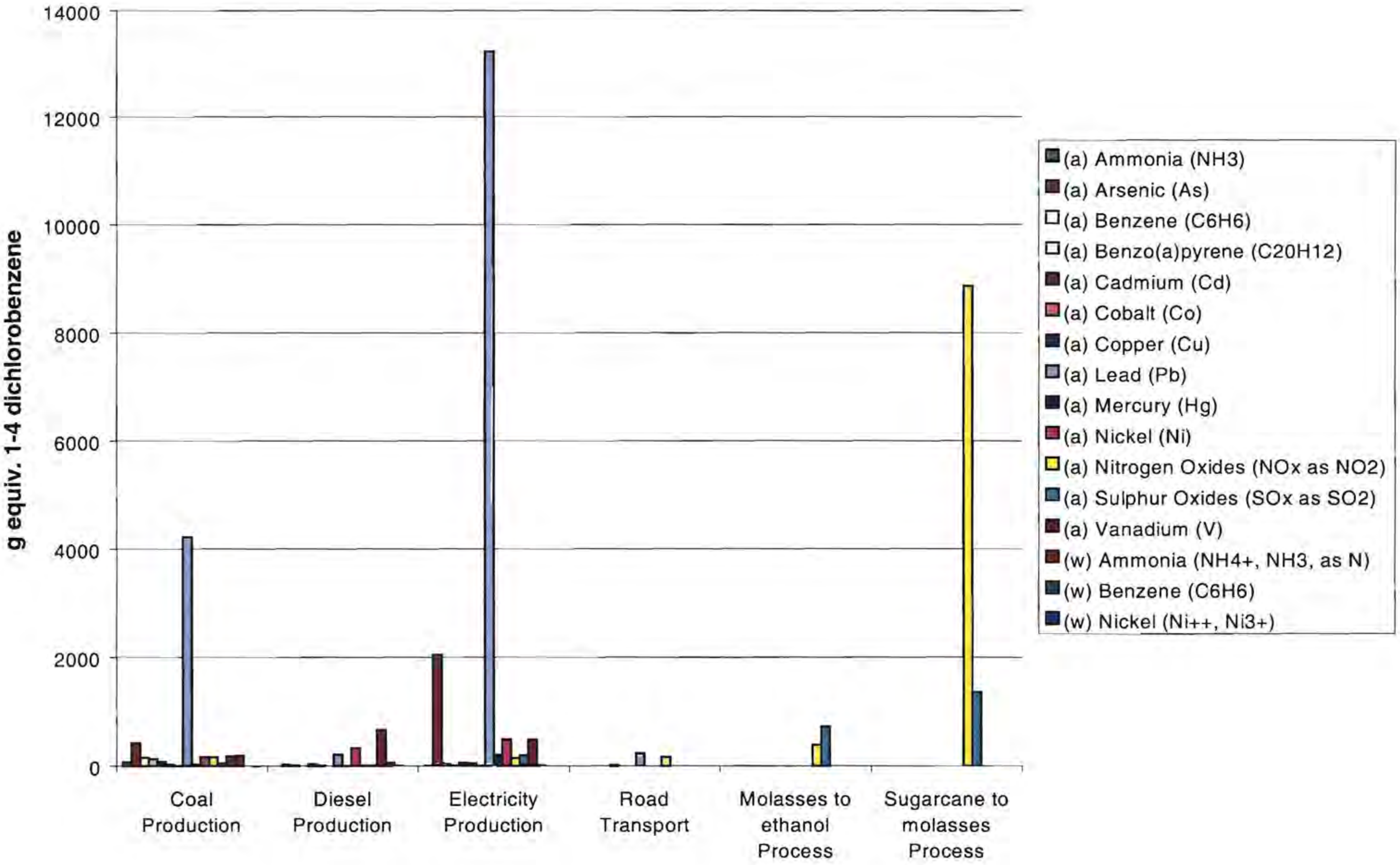


Figure 6.6a USES-Human toxicity potentials for bio-ethanol life cycle

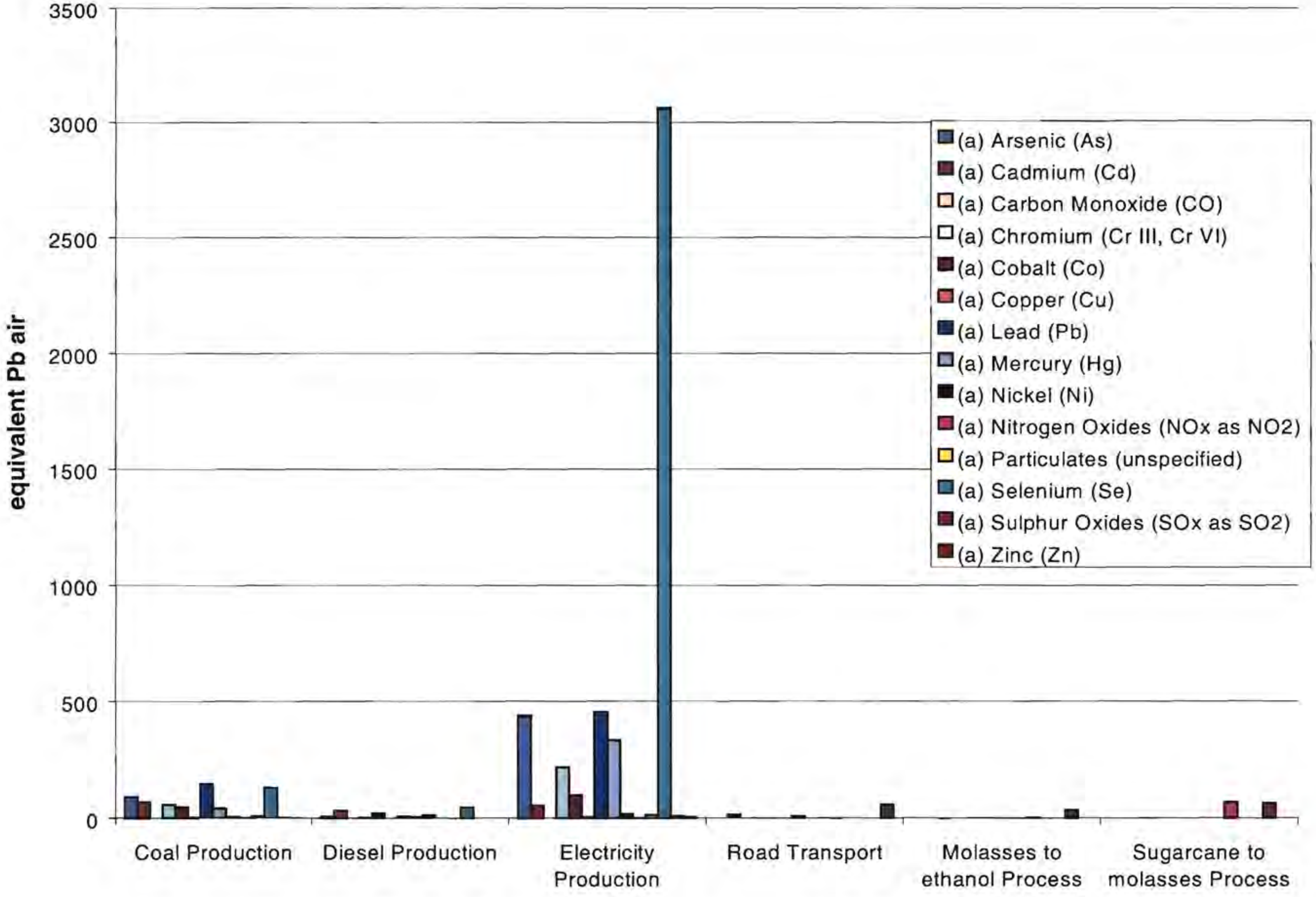


Figure 6.6b CST-Human toxicity potentials for bio-ethanol life-cycle

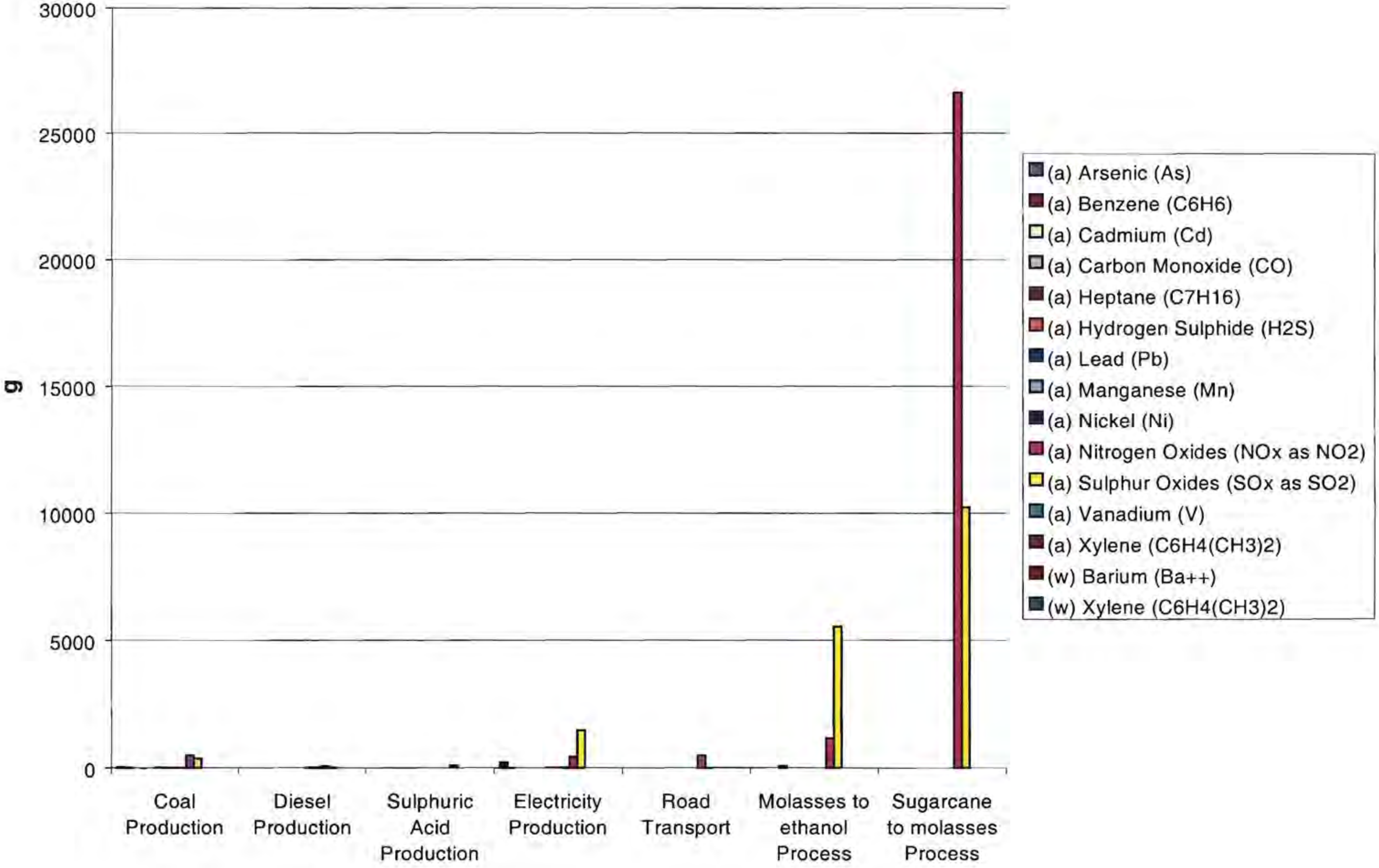


Figure 6.6c CML-Human toxicity potentials for bio-ethanol life cycle

6.2.7 Resource depletion

This impact category is of interest in evaluation; while the classification of the use of metal ore as being non-renewable is questionable, based on our capability to recover and recycle metals, the consumption of other resources such as crude oil, coal and natural gas is definitely an irreversible process. The unit of measurement is "fraction of reserve", and the results require careful evaluation, because where the fraction used may appear insignificant, it is the rate of consumption which is of concern.

Figure 6.7 shows coal and oil as the key resources consumed in the production life cycle of bio-ethanol. This is in support of the analysis shown in section 5.3.1 on resource inputs. The consumption of metals does not appear to be of comparable magnitude on the scale of the other resources discussed above.

6.2.8 Impacts of land use

As discussed in section 2.5.4, a key concern arising from biomass fuels production is its competition for land use with food production. In this impact category, however, issues of scrutiny include the loss of bio-diversity from the harvesting of natural resources and the destruction or alteration of the land. Due to the lack of an LCA methodology to deal directly with impacts of land use, a qualitative discussion shall be made here.

The land requirement for the growing of the cane required for the production of 1 kl of bio-ethanol has been determined as 0.38 hectares (3800 m^2). This is a significant area, especially since the production capacity of the ethanol process is approximately 40 000 kl/yr, meaning that 15 200 hectares (152 million m^2) of land per production season is reserved for cane growing for bio-ethanol production. This figure would double if only one crop per two years is harvested; it is therefore sensitive to agricultural practice.

It is noted, however, that there is no significant cane growing expansion in the region, hence the issue of loss of biodiversity becomes inapplicable. The loss in variety of species as a result of the growth of mono-cultural crops may have long been affected, but the issue of soil erosion arises from the continued use of the land:

Soil erosion, caused by the continuous ploughing and planting cycles; this leads to the nutrients from the soil, which would consequently contribute to eutrophication in aquatic ecosystems.

A more detailed investigation into the agricultural practices of cane growing is required, to give both a qualitative and quantitative assessment of the intensity of land use.

6.2.9 Overall contributions to impact categories

A percentage contribution analysis is made here to show which sub-processes contribute significantly to each of the impact categories described above. The aim of this analysis is to direct the focus of action to individual steps in the life-cycle which contribute in a detrimental manner to the overall environmental profile, and a dominant contributor is taken as one which contributes over two-thirds of the score for the particular impact category. Figure 6.8 shows this assessment, and the following summary can be made:

Impact category	Dominant contributors
CST-Human toxicity	Electricity Production (83%)
CML-Human Toxicity	Sugarcane to molasses Process (77%)
Photochemical oxidant formation	Molasses to ethanol Process (67%)
Depletion of the ozone layer	Diesel Production (95%)
Greenhouse effect	Molasses to ethanol Process (67%)
Aquatic Ecotoxicity	Diesel Production (75%)
Eutrophication (water)	Molasses to ethanol Process (100%)
Depletion of non-renewable resources	Coal Production
Air Acidification	Sugarcane to molasses Process (79%)

From this analysis it is seen that the Molasses to ethanol and sugarcane to molasses sub-process are significant contributors in several impact categories of the life-cycle. These have been classified as foreground sub-processes (see section 5.3)

It is interesting to note that although the majority of the flows in the inventory originate from background sub-processes, it is the particular flows from the foreground sub-process which are the cause of several of the impact categories discussed here.

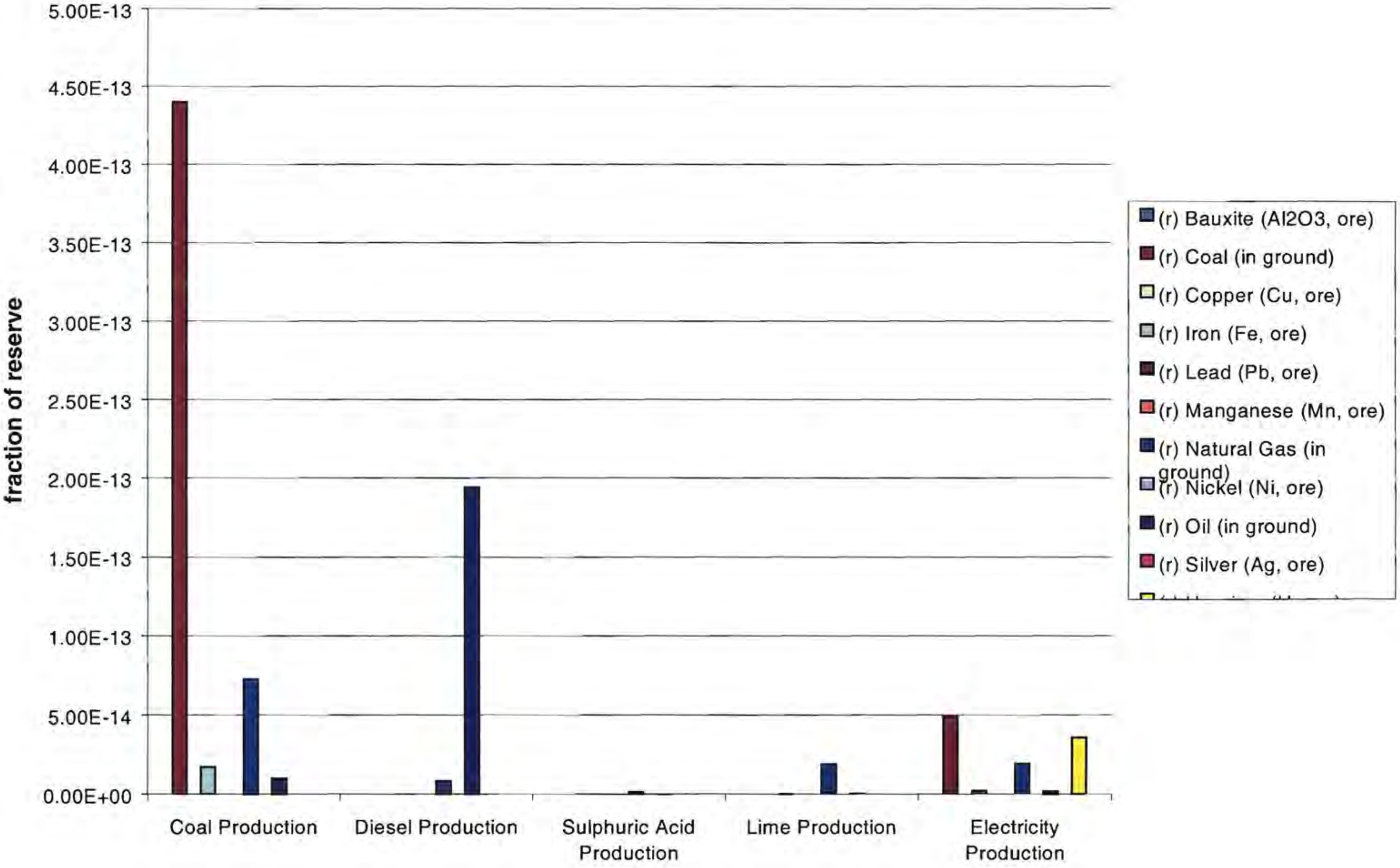


Figure 6.7 CML-Resource depletion for bio-ethanol life cycle

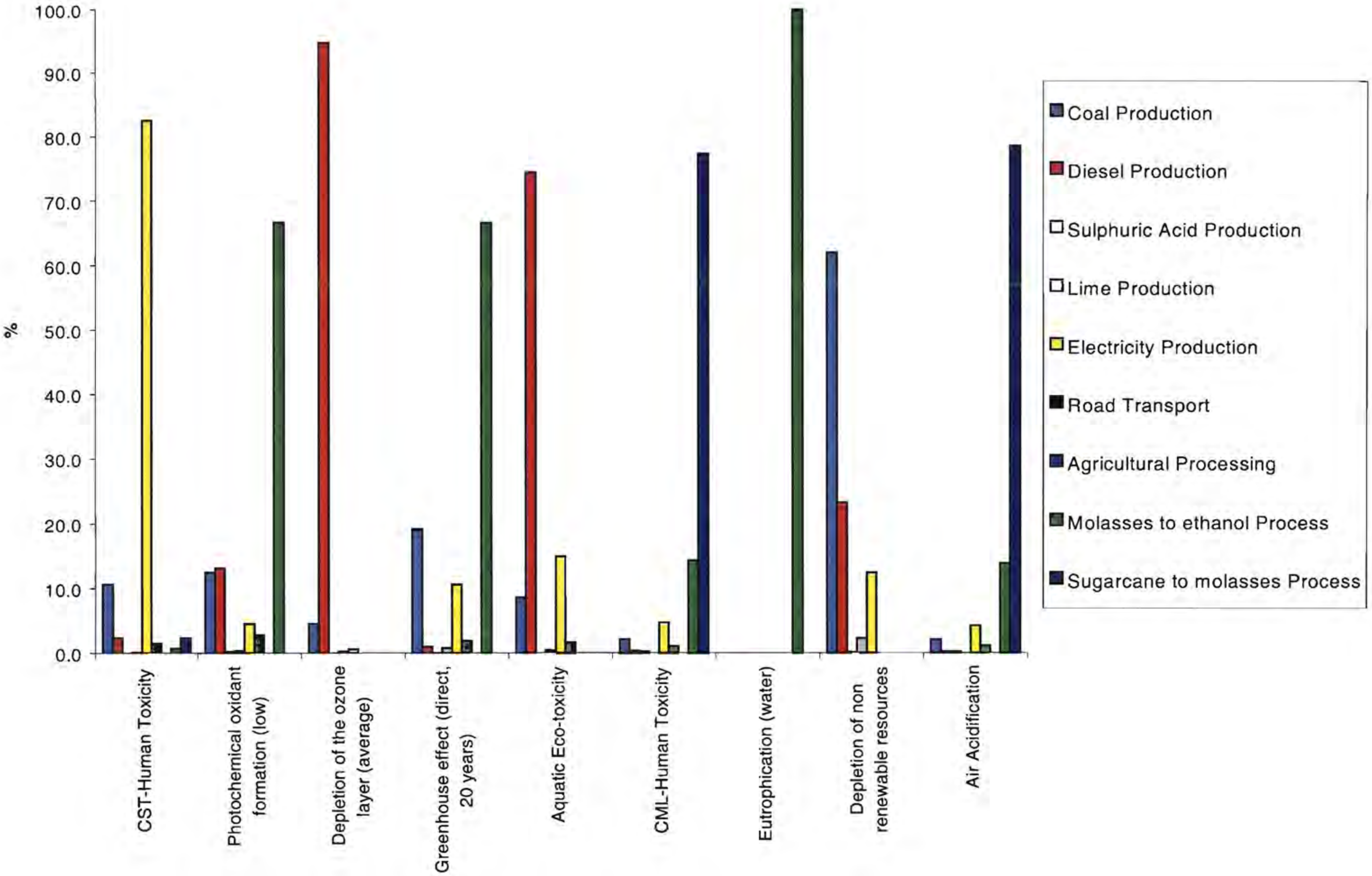


Figure 6.8 Relative contributions of sub-processes to each of he impact categories

6.2.10 Effect of zero allocation to molasses on impact categories

The impact assessment illustrated in the subsections above was applied to the scenario where molasses are allocated no burdens of the sugarcane processing. As previously explained, the aim of this analysis is to identify whether allocation has other significant impacts from in the relevant categories, which may otherwise not be noticeable from a quantitative analysis.

All impact categories showed a decrease in the impacts, for the zero allocation to molasses scenario. This is expected since all the associated flows are reduced. The table below shows the scores for the impact categories, for the two allocation scenarios, and the resulting percentage reduction.

The results were found as follows:

Table 6.1 Effect of allocation on impact categories

Impact Category	Units	26% allocation	zero allocation	% reduction
CML-Air Acidification	g eq. H^+	1284	271	78.9
CST-Human Toxicity	eq. Pb air	5,707	5,427	4.9
CML-Human Toxicity	g	47,611	10,548	77.8
USES 1.0-Human Toxicity	g eq. 1-4-dichlorobenzene	36,169	24,733	31.6
CST-Aquatic Eco-toxicity	eq. Zn water	14	7	53.4
WMO-Photochemical oxidant formation (low)	g eq. ethylene	480	432	10.1
WMO-Depletion of the ozone layer (average)	g eq. CFC-11	0.12	0.04	67.2
IPCC-Greenhouse effect (direct, 20 years)	g eq. CO2	2,808,031	2,760,123	1.7
CML-Eutrophication (water)	g eq. PO4	30,500	30,498	0.0
CML-Depletion of non renewable resources	frac. of reserve	8.70E-13	7.12E-13	18.2

The air acidification and human toxicity impact categories show the highest reductions for the zero allocation scenario. This is because there is no contribution of SO_2 and NO_2 from the combustion of bagasse, from the sugarcane to molasses scenario; molasses are regarded as "free" or environmental burden.

The impact on aquatic eco-toxicity is also halved; the phenol in water from Diesel Production, and air-borne Mercury from Electricity Production, which are the key contributing substances to this category, are accordingly reduced with the reduction of these flows.

The ozone layer depletion score is also reduced, in proportion with the reduction of the diesel usage in the zero allocation scenario.

This analysis has added quality and perspective to the observations made in section 5.7.1. It shows that the exclusion of the sugarcane-to-molasses sub-process may have insignificant bearing in the life-cycle of bio-ethanol, from an energy requirement perspective, but has notable implications in the specific categories of impact assessment in which the associated flows dominate (see section 6.2.9 above).

6.3 Normalisation of impact category scores

In order to gain a better understanding of the relative size of an effect, a normalisation step is required. Each effect calculated for the life cycle is benchmarked against the known total effect for this class. This total effect may be regional, or global, and may also have a temporal dimension (e.g. total emission per year).

Normalisation enables the assessment the relative contribution from the material production to each already existing effect. Normalisation factors were found for all impact categories except for land use and aquatic ecotoxicity. The depletion of resources was previously reported as a fraction of the reserve, hence did not require normalisation. These are based on 1995 world impact figures (Guinée et al., 2001). These values are shown in the table below:

Table 6.2 Normalisation factors for impact categories

Impact Category	Units	Normalisation factors
Air Acidification	kg (SO_2 eq.).yr^{-1}	2.99E+11
Human Toxicity	kg (1,4-DCB eq.).yr^{-1}	4.98E+13
Photochemical oxidant formation (low)	kg (C_2H_4 eq.).yr^{-1}	4.55E+10
Depletion of the ozone layer (average)	kg (CFC-11 eq.).yr^{-1}	5.15E+08
Greenhouse effect (direct, 20 years)	kg (CO2 eq.).yr^{-1}	3.86E+13
Eutrophication (water)	kg (PO_4^{3-} eq.).yr^{-1}	1.29E+11

Using these factors, the normalised profile was obtained for the 26% and zero molasses allocation bio-ethanol production scenarios, shown in the Table 6.2, and illustrated in figure 6.9, below:

Table 6.3 Normalised scores for the impact categories studied

Impact Category	units	26% allocation	zero allocation
Air Acidification	fraction of impact	4.29E-12	8.27E-11
Human Toxicity	fraction of impact	7.26E-13	1.33E-16
Photochemical oxidant formation (low)	fraction of impact	1.06E-11	9.49E-12
Depletion of the ozone layer (average)	fraction of impact	2.32E-13	7.61E-14
Greenhouse effect (direct, 20 years)	fraction of impact	7.27E-11	7.15E-11
Eutrophication (water)	fraction of impact	2.36E-10	2.36E-10
Depletion of non renewable resources	fraction of impact	8.70E-13	7.12E-13

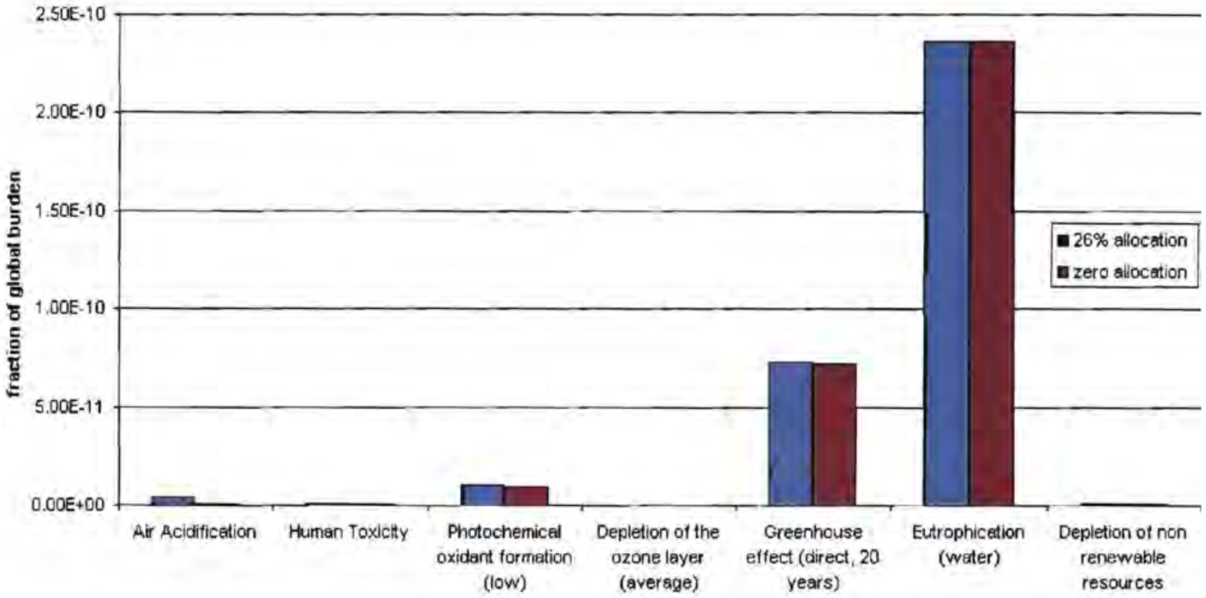


Figure 6.9 Normalised scores for the impact categories studied

It is interesting to note here that eutrophication in water systems is the impact category of greatest concern, on a relative scale. It should be noted, however, that the water emissions which contribute to this impact originate from the molasses to ethanol process, and are treated at a wastewater plant after leaving the processing site; and so the recipient environment is not necessarily exposed to the level of impact indicated here. Nevertheless, this is an indication of the severity of its impact, should the effluent not be treated, and end up in aquatic bio-systems.

The second significant impact is climate change, and this originates from the fossil carbon dioxide emissions from the coal use. This is as expected, there is need to minimise on the utilisation of fossil energy for the molasses to ethanol process, for the impact caused by it.

The cause of photochemical oxidant formation is the approximated ethanol vapour emissions from the distillation process; as discussed in section 6.2.4. There is need, as this analysis confirms, to determine a more accurate figure for volatile organic carbons, as this also appears to be an impact category of concern.

From the analysis of section 6.2.8, the molasses to ethanol process is the key contributor to all three of the impact categories discussed above. This is a clear indication that this is the process dominating the environmental impact of the life cycle

Air acidification is also an impact category of some concern, but not on the scale of the first two mentioned above. Human toxicity, depletion of the ozone layer, and depletion of renewable resources are the impact categories of the least concern for this life cycle.

6.4 Summary of the life cycle impact assessment

The impact assessment has quantified the emissions of the inventory in context of the particular global impacts to which they contribute. The following observations have been made:

- A zero allocation to molasses significantly reduces the air acidification, human toxicity and ozone depletion impact potentials of the overall life cycle.

- The emissions from the sugarcane to molasses and molasses to ethanol processes dominate in the contributions to most of the impact categories assessed for this bio-system.

- Eutrophication of aquatic eco-systems is the life cycle impact of the highest relative concern, seconded by climate change. The molasses to ethanol process is the dominant contributor to these, making it the most relevant sub-process of the life-cycle with respect to environmental impact.

7. CONCLUSIONS AND RECOMMENDATIONS

The production of bio-ethanol from sugarcane molasses was assessed from a life-cycle perspective, in a cradle to gate study. The study was specific to the production in one South African company, where the bio-ethanol production is a sub-process of an established sugar manufacturing industry, and is an example of several value addition processes which are associated with sugarcane production, utilising molasses and bagasse. The key sub-process in the life-cycle study which were analysed are the following:

- Agricultural Processing (sugarcane growing),
- Sugarcane to Molasses Process (sugar production process, with molasses as by-product),
- Molasses to Ethanol Process (fermentation of molasses sugars to ethanol, and distillation),
- Road Transportation (of sugarcane, and molasses)

The associated process flows, whose production life-cycles were also analysed, included the following processes:

- Coal Mining
- Electricity Generation
- Sulphuric Acid Production
- Lime Production
- Diesel Production

The results generated from this study can be used to inform both processing management and research audiences on the environmental implications of producing bio-ethanol from sugarcane, and identify the opportunities of improvement in the life-cycle of its production.

The discussion that follows now concludes the findings of this study, and the recommendations made set the platform for future work in terms of refining the analysis of the process. The way forward for the producing company and others fitting this production profile, to monitor and improve their environmental performance, is also advised.

The primary goal of using life-cycle assessment to build an inventory for the production of bio-ethanol from sugarcane has been successfully achieved, within the scope and limitations laid out for this study.

The literature survey revealed that a compilation of the carbon balance and of the cumulative energy demand could be used to assess the degree of renewability of bio-energy systems. It was found that carbon closures of above 90% and up to 100%, and fossil energy ratios above 1 and up to 9 have been achieved for other sugarcane bio-energy systems.

Based on these observations, the hypothesis was then put forward that the production of bio-ethanol from sugarcane molasses is principally a sustainable process, based on the renewable nature of the sugarcane raw material. It was also hypothesised that life-cycle assessment can be used to profile the environmental burdens of the production, and identify areas of concern that are the focus of possible improvement.

It was expected that the bio-energy system would show a high carbon closure illustrating the sequestration of fossil carbon dioxide released during conversion and use by that absorbed during biomass growth, and a high fossil energy ratio, based on its self-sufficiency in energy requirement provided by bagasse incineration and potential electricity generation.

The following results were found from the analysis:

A carbon closure of 94% was determined for the joint sugar-ethanol production system. For the preferred scenario, in which 26% of environmental burdens are allocated to molasses, this carbon closure is reduced to 79%. This is an indication that the overall bio-energy system performs well, but the isolated bio-ethanol production route as a sub-process of the sugar production industry, upsets this balance, because of its particular fossil energy requirement.

Fossil energy ratios of 1.13 and 1.14 were realised for the 26% and zero allocation systems, confirming that the molasses-to-ethanol process dominates the fossil energy requirement of the overall process.

These figures might appear marginal; for the production of ethanol as alternative fuel it would not appear sensible to invest an amount of fossil energy close to that retrieved in the renewable product. However, it should be borne in mind that the bulk of this fossil energy is supplied in the form of coal, and that one third of South Africa's liquid fuels are also produced from coal, at energy yields probably in the range of 30 to 40%.

For the current production pattern the impact categories of highest concern are eutrophication of aquatic eco-systems, climate change, photochemical oxidant formation and air acidification, in order of decreasing significance. Eutrophication concerns arise mainly from the COD of the effluent of the molasses-to-ethanol process, and this is without the added effect of Nitrogen and Phosphorous salts from agricultural processing, which were unquantified.

The photo-oxidant formation effect also arises from volatile hydrocarbon emissions, which have only been estimated, and could potentially be higher, causing a more significant effect. Climate change is initiated by the fossil carbon dioxide from the coal combustion. All these three effects are therefore directly arising from the molasses to ethanol process, making it the focus for improvement of the overall environmental profile of the bio-ethanol production system.

Other observations arising from the analysis of the current production profile are the following:

- The overall influence of the transportation step on the system profile is insignificant (contributes 2% to primary energy requirement), from an energy intensity perspective. The inclusion of coal transportation to the processing site was found to be of no influence to this contribution.
- The production of fertilisers as a sub-process module was also determined as small, from an energy and emissions perspective.
- A zero allocation to molasses was found to have minimal influence (5% reduction) on the fossil energy requirements of the production system. However, in terms of impact assessment, significant differences (> 65%) were noted for air acidification, human toxicity and ozone depletion potentials.

There are aspects of this study that would require further attention for a full understanding of the implications of bio-ethanol production from sugarcane:

1. The agricultural sector is the highest water consumer in South Africa. Therefore a scrutiny of agricultural practices for sugarcane growing is still outstanding, to

quantify the water usage for irrigation, as well as quantify and assess the impacts of pesticide and fertiliser usage in terms of seepage into water streams.

2. The impacts of land use need to be assessed from a socio-economic perspective, in order to project the feasibility of mass cane production for energy provision, besides the competition for food crops cultivation. This analysis needs evaluation from a regional perspective, as land requirements and availability may be area-specific.

3. An accurate estimation of the volatile hydrocarbons emitted from the distillation process of the molasses-to-ethanol process is required to understand the potential impact on photochemical oxidant formation.

There are several scenarios of the process, however, which can potentially alter the environmental profile of the process.
An integration of the two process sites (sugar milling, and conversion to ethanol) would allow for the more efficient use of bagasse-derived process heat available from milling process, and utilise this to supplement the fossil energy requirement for the distillation process. This would have a significant effect on the energy profile, and by reduction of coal use, the subsequent impacts would also be reduced. There is also the potential to produce electricity from the incineration of the excess bagasse from the milling process, which could be used internally by both the sugar production and ethanol production processes.

Secondly, allowing for a higher sucrose content in the residual molasses from the sugarcane-to-molasses production could significantly reduce upstream flows in the system per functional unit. A higher ethanol content in the fermentation product may also reduce the distillation energy requirement, although the water-ethanol azeotropic mixture plays a distinct role in the energy requirement for this process.

The following **recommendations** can now be made, based on the conclusions drawn from the analysis presented in this research:

- An energy efficiency analysis of the molasses-to-ethanol process should be made to identify areas of possible improvement to reduce the fossil energy requirement.

- The possibility of electricity generation from excess bagasse for own use by the company, at physically distinct sites, could be explored. This would add credit to the sustainability of the overall process. Exportation of this electricity for commercial benefit is a possible route, but may be restricted by other trading factors, also worth exploring.

- Figures for agricultural water requirement and pesticide usage should be compiled and added to this analysis for a comprehensive understanding of impacts of the agricultural processing stage of the life cycle.

It is also recommended that further work based on this study to compare the performance of ethanol produced from alternative feedstocks such as corn and cellulosic biomass should be carried out, as this would provide insight in to the preferrential feedstocks, from an environmental perspective, for large-scale ethanol production.

As final remark on this study, the possibility of production of bio-ethanol directly from sugarcane has future potential, depending on the projections in the markets for both sugar and ethanol. Whole cane can be crushed and the sugars fermented to produce ethanol, yielding higher volumes of fuel product, similar to the Brazilian ethanol programme (Macedo, 1997). Alternative technologies, as well as adaptation of current ones, would require application to assist this transformation, and an economic evaluation as well as an application of the LCA approach used here could be used to evaluate the feasibility.

This is an aspect worth exploration by companies and research teams in the sugar industry to maximise on the alternative utilisation routes of sugarcane as a biomass energy source.

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Appendix A

Life- cycle inventories for the production of bio-ethanol from sugarcane molasses

INVENTORY FOR BIOETHANOL PRODUCTION LIFE CYCLE, WITH 26% ALLOCATION TO MOLASSES PRODUCTION

	Flow	Units	TOTAL	Coal Production	Diesel Production	Sulphuric Acid Production	Lime Production	Electricity Production	Road Transport	Agricultural Processing	Molasses to ethanol process	Sugarcane to molasses process
Inputs:	(r) Barium Sulphate (BaSO4, in ground)	kg	5.57E-03	1.72E-04	1.39E-03	0.00E+00	3.98E-03	2.89E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Bauxite (Al2O3, ore)	kg	1.50E-03	1.17E-04	1.35E-03	0.00E+00	1.59E-05	2.10E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Bentonite (Al2O3 4SiO2.H2O, in ground)	kg	5.26E-04	1.63E-05	1.32E-04	0.00E+00	3.76E-04	2.73E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Calcium Sulphate (CaSO4, ore)	kg	3.76E-02	3.74E-02	2.45E-04	0.00E+00	5.29E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Chromium (Cr, ore)	kg	1.07E-06	3.31E-08	2.68E-07	0.00E+00	7.65E-07	5.55E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Clay (in ground)	kg	2.39E-01	2.09E-01	1.63E-03	0.00E+00	7.45E-04	2.71E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Coal (in ground)	kg	1.46E+03	1.31E+03	5.07E-03	1.42E-02	1.07E-02	1.46E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Copper (Cu, ore)	kg	5.45E-06	1.69E-07	1.36E-06	0.00E+00	3.89E-06	2.82E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Gravel (unspecified)	kg	5.15E+00	5.11E+00	3.35E-02	0.00E+00	7.22E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Iron (Fe, ore)	kg	1.94E+00	1.73E+00	4.11E-03	0.00E+00	1.17E-02	1.97E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Iron Sulphate (FeSO4, ore)	kg	4.71E-02	4.24E-02	1.52E-08	0.00E+00	3.28E-11	4.72E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Lead (Pb, ore)	kg	1.70E-06	5.26E-08	4.26E-07	0.00E+00	1.21E-06	8.82E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Lignite (in ground)	kg	8.85E-03	2.75E-04	2.21E-03	0.00E+00	6.30E-03	6.22E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Limestone (CaCO3, in ground)	kg	6.00E+01	1.23E+00	1.03E-02	0.00E+00	3.46E+01	2.41E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Manganese (Mn, ore)	kg	6.24E-07	1.93E-08	1.56E-07	0.00E+00	4.45E-07	3.23E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Natural Gas (in ground)	kg	1.56E+01	9.43E+00	1.07E+00	1.52E-01	2.45E+00	2.50E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Nickel (Ni, ore)	kg	3.63E-07	1.12E-08	9.08E-08	0.00E+00	2.59E-07	1.88E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Oil (in ground)	kg	4.92E+01	2.35E+00	4.63E+01	3.77E-02	1.07E-01	4.22E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Pyrite (FeS2, ore)	kg	8.93E-03	2.76E-04	2.23E-03	0.00E+00	6.37E-03	4.63E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Sand (in ground)	kg	1.28E-01	1.15E-01	5.88E-04	0.00E+00	1.18E-04	1.28E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Silver (Ag, ore)	kg	2.70E-08	8.36E-10	6.76E-09	0.00E+00	1.93E-08	1.40E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Sodium Chloride (NaCl, in ground or in sea)	kg	8.04E-01	7.07E-01	6.13E-03	0.00E+00	4.12E-05	9.09E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Uranium (U, ore)	kg	4.80E-04	2.52E-07	7.95E-08	5.77E-08	2.27E-07	4.80E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Zinc (Zn, ore)	kg	3.96E-08	1.23E-09	9.91E-09	0.00E+00	2.83E-08	2.05E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(s) Nitrogen (N)	g	1.07E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.07E+04	0.00E+00	0.00E+00
	(s) Phosphorus (P)	g	2.39E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.39E+03	0.00E+00	0.00E+00
	Explosive (unspecified)	kg	4.89E-01	4.89E-01	1.78E-07	0.00E+00	3.84E-10	1.34E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Iron Scrap	kg	3.14E-01	2.47E-01	3.82E-02	0.00E+00	8.24E-05	2.83E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Land Use (II -> III)	m2a	5.59E+00	5.59E+00	6.90E-05	0.00E+00	1.49E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Land Use (II -> IV)	m2a	7.48E-01	7.48E-01	8.40E-05	0.00E+00	1.81E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Land Use (III -> IV)	m2a	3.84E+03	2.65E-01	9.52E-08	0.00E+00	2.05E-10	0.00E+00	0.00E+00	3.84E+03	0.00E+00	0.00E+00
	Raw Materials (unspecified)	kg	6.85E+00	7.89E-02	3.46E-02	0.00E+00	7.46E-05	6.74E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Water Used (total)	litre	2.96E+04	2.19E+03	1.90E+02	9.56E+00	6.88E+00	3.09E+02	0.00E+00	0.00E+00	1.62E+04	1.07E+04
	Water: Unspecified Origin	litre	2.71E+03	2.19E+03	1.90E+02	9.56E+00	6.88E+00	3.09E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Wood	kg	7.64E+00	6.88E+00	5.14E-05	0.00E+00	1.40E-04	7.66E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Outputs:	(a) Acetaldehyde (CH3CHO)	g	2.95E-04	5.03E-05	3.65E-05	0.00E+00	1.04E-04	1.05E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Acetic Acid (CH3COOH)	g	2.12E-02	8.20E-04	5.14E-03	0.00E+00	1.47E-02	5.03E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Acetone (CH3COCH3)	g	1.75E-04	4.65E-05	6.43E-06	0.00E+00	1.75E-05	1.04E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Acetylene (C2H2)	g	2.41E+00	1.09E+00	4.23E-06	0.00E+00	9.12E-09	1.31E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Aldehyde (unspecified)	g	1.32E-02	8.86E-03	5.08E-04	0.00E+00	5.32E-05	3.79E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Alkane (unspecified)	g	2.55E+00	8.71E-02	9.65E-01	0.00E+00	2.85E-01	1.21E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Alkene (unspecified)	g	2.41E+00	1.09E+00	2.19E-04	0.00E+00	6.13E-04	1.31E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Alkyne (unspecified)	g	9.09E-06	2.81E-07	2.27E-06	0.00E+00	6.49E-06	4.71E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Aluminium (Al)	g	3.77E+01	1.25E+01	1.76E-04	0.00E+00	2.71E-04	2.52E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Ammonia (NH3)	g	4.84E+00	4.35E+00	9.91E-04	0.00E+00	1.07E-04	4.92E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Antimony (Sb)	g	5.76E-03	8.95E-04	1.57E-08	0.00E+00	3.38E-11	4.86E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) AOX (Adsorbable Organic Halogens)	g	2.10E-10	1.89E-10	6.78E-17	0.00E+00	1.46E-19	2.10E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Aromatic Hydrocarbons (unspecified)	g	1.79E-04	6.10E-05	3.79E-07	0.00E+00	8.16E-10	1.18E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Arsenic (As)	g	5.95E-02	1.01E-02	6.82E-04	0.00E+00	4.40E-06	4.87E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Barium (Ba)	g	4.50E-01	1.48E-01	2.30E-06	0.00E+00	3.77E-06	3.02E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Benzaldehyde (C6H5CHO)	g	1.64E-09	5.08E-11	4.11E-10	0.00E+00	1.17E-09	8.50E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Benzene (C6H6)	g	7.54E+00	5.35E+00	3.46E-01	0.00E+00	4.01E-02	1.79E+00	1.59E-02	0.00E+00	0.00E+00	0.00E+00
	(a) Benzo(a)pyrene (C20H12)	g	4.02E-02	3.61E-02	2.61E-06	0.00E+00	1.95E-06	4.04E-03	7.94E-05	0.00E+00	0.00E+00	0.00E+00
	(a) Berylium (Be)	g	6.63E-03	1.68E-03	2.16E-08	0.00E+00	1.62E-08	4.95E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Boron (B)	g	2.50E+00	1.04E-01	5.37E-05	0.00E+00	1.31E-04	2.39E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Bromium (Br)	g	4.99E-01	2.08E-02	5.96E-06	0.00E+00	1.26E-05	4.78E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Butane (n-C4H10)	g	3.73E+00	1.66E-01	3.42E+00	0.00E+00	9.53E-02	4.34E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Flow	Units	TOTAL	Coal Production	Diesel Production	Sulphuric Acid Production	Lime Production	Electricity Production	Road Transport	Agricultural Processing	Molasses to ethanol process	Sugarcane to molasses process
(a) Butene (1-CH3CH2CHCH2)	g	8.77E-02	3.95E-03	8.30E-02	0.00E+00	2.06E-04	5.01E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Cadmium (Cd)	g	8.86E-03	3.55E-03	1.70E-03	0.00E+00	8.10E-06	2.80E-03	7.92E-04	0.00E+00	0.00E+00	0.00E+00
(a) Calcium (Ca)	g	4.51E+00	1.48E+00	6.19E-03	0.00E+00	6.55E-04	3.02E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Carbon Dioxide (CO2, biomass)	g	7.86E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.50E+05	7.11E+06
(a) Carbon Dioxide (CO2, fossil)	g	2.26E+06	6.83E+04	1.29E+04	5.10E+02	2.15E+04	2.40E+05	4.99E+04	0.00E+00	1.87E+06	0.00E+00
(a) Carbon Monoxide (CO)	g	7.85E+03	6.35E+02	8.10E+00	7.16E-02	3.41E+00	3.10E+02	1.36E+02	0.00E+00	6.76E+03	0.00E+00
(a) Carbon Tetrafluoride (CF4)	g	1.32E-06	4.08E-08	3.30E-07	0.00E+00	9.41E-07	6.84E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Chlorine (Cl2)	g	1.69E-05	0.00E+00	0.00E+00	4.65E-06	0.00E+00	1.23E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Chromium (Cr III, Cr VI)	g	7.55E-02	1.57E-02	8.57E-04	0.00E+00	1.73E-05	5.89E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Cobalt (Co)	g	1.30E-02	3.68E-03	1.70E-03	0.00E+00	6.98E-06	7.57E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Copper (Cu)	g	5.11E-02	1.15E-02	2.56E-03	0.00E+00	2.89E-05	3.70E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Cyanide (CN-)	g	6.60E-02	5.94E-02	1.11E-06	0.00E+00	3.10E-06	6.61E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Dioxins (unspecified)	g	4.93E-08	1.44E-09	1.63E-11	0.00E+00	4.39E-11	4.78E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Ethane (C2H6)	g	2.84E+01	1.13E+01	1.16E+01	0.00E+00	4.17E-01	5.13E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Ethanol (C2H5OH)	g	8.00E+03	9.21E-05	4.61E-06	0.00E+00	1.14E-05	2.09E-04	0.00E+00	0.00E+00	8.00E+03	0.00E+00
(a) Ethylbenzene (C8H10)	g	8.77E-02	3.95E-03	8.30E-02	0.00E+00	2.05E-04	5.01E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Ethylene (C2H4)	g	4.55E+01	3.29E+01	5.84E-01	0.00E+00	1.19E+00	1.08E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Fluorides (F-)	g	3.75E-05	5.59E-07	9.34E-06	4.65E-06	2.01E-08	2.29E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Fluorine (F2)	g	6.65E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.65E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Formaldehyde (CH2O)	g	2.11E-01	6.19E-03	3.44E-03	0.00E+00	9.84E-03	1.91E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Halogenated Matter (unspecified)	g	2.76E-12	2.48E-12	8.90E-19	0.00E+00	1.92E-21	2.76E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Halon 1301 (CF3Br)	g	9.95E-03	4.48E-04	9.42E-03	0.00E+00	2.30E-05	5.69E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Heptane (C7H16)	g	8.76E-01	3.95E-02	8.30E-01	0.00E+00	1.91E-03	5.01E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Hexane (C6H14)	g	1.75E+00	7.86E-02	1.66E+00	0.00E+00	3.84E-03	9.98E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Hydrocarbons (except methane)	g	5.29E+02	1.09E+02	3.09E+02	0.00E+00	2.61E+00	4.17E+01	6.68E+01	0.00E+00	0.00E+00	0.00E+00
(a) Hydrocarbons (unspecified)	g	1.55E+01	9.10E+00	2.85E-02	5.25E+00	1.31E-03	1.10E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Hydrogen (H2)	g	5.66E-05	5.09E-05	1.83E-11	0.00E+00	3.94E-14	5.67E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Hydrogen Chloride (HCl)	g	1.23E+02	3.48E+00	7.84E-02	1.80E-04	2.66E-03	1.19E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Hydrogen Fluoride (HF)	g	4.43E+00	1.21E-01	7.80E-03	9.43E-06	3.69E-04	4.30E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Hydrogen Sulphide (H2S)	g	3.30E+01	2.97E+01	1.32E-02	0.00E+00	3.77E-02	3.30E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Iodine (I)	g	1.24E-01	4.69E-03	2.54E-06	0.00E+00	6.16E-06	1.20E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Iron (Fe)	g	1.52E+01	5.14E+00	8.84E-03	0.00E+00	8.69E-04	1.01E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) lanthanum (La)	g	1.51E-02	7.20E-03	2.56E-08	0.00E+00	5.52E-11	7.94E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Lead (Pb)	g	2.67E-01	6.30E-02	3.05E-03	0.00E+00	9.89E-05	1.98E-01	3.51E-03	0.00E+00	0.00E+00	0.00E+00
(a) Magnesium (Mg)	g	1.33E+01	4.47E+00	7.10E-05	0.00E+00	1.21E-04	8.83E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Manganese (Mn)	g	1.04E-01	5.01E-02	1.92E-04	0.00E+00	5.47E-04	5.32E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Mercury (Hg)	g	8.27E-03	9.25E-04	8.60E-05	0.00E+00	1.95E-05	7.24E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Metals (unspecified)	g	2.74E-03	2.42E-03	5.81E-06	6.16E-06	1.25E-08	3.00E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Methane (CH4)	g	8.46E+03	7.36E+03	2.23E+02	0.00E+00	9.49E+00	8.66E+02	2.04E+00	0.00E+00	0.00E+00	0.00E+00
(a) Methanol (CH3OH)	g	5.29E-04	1.56E-04	5.41E-06	0.00E+00	1.25E-05	3.54E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Molybdenum (Mo)	g	1.30E-02	2.39E-03	8.51E-04	0.00E+00	1.84E-06	9.80E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Nickel (Ni)	g	1.01E-01	1.72E-02	3.41E-02	0.00E+00	1.73E-04	5.00E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Nitrogen Oxides (NOx as NO2)	g	3.75E+04	6.24E+02	3.14E+01	2.96E+00	7.08E+00	5.54E+02	6.39E+02	0.00E+00	1.50E+03	3.41E+04
(a) Nitrous Oxide (N2O)	g	1.04E+01	4.64E-01	1.42E-01	0.00E+00	2.34E-02	2.74E+00	6.99E+00	0.00E+00	0.00E+00	0.00E+00
(a) Organic Matter (unspecified)	g	2.74E-02	1.75E-02	7.36E-04	0.00E+00	1.59E-06	9.21E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Particulates (unspecified)	g	3.41E+03	1.21E+03	6.63E+00	6.81E+00	2.96E+02	1.86E+03	3.47E+01	0.00E+00	0.00E+00	0.00E+00
(a) Pentane (C5H12)	g	4.55E+00	2.03E-01	4.19E+00	0.00E+00	1.27E-01	2.57E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Phenol (C6H5OH)	g	1.26E-08	3.90E-10	3.15E-09	0.00E+00	8.98E-09	6.52E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Phosphorus (P)	g	2.99E-01	7.59E-02	2.16E-06	0.00E+00	4.03E-06	2.23E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Phosphorus Pentoxide (P2O5)	g	1.51E-03	1.36E-03	4.87E-10	0.00E+00	1.05E-12	1.51E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Polycyclic Aromatic Hydrocarbons (PAH, unspecified)	g	1.38E-03	4.31E-05	3.44E-04	0.00E+00	9.85E-04	6.12E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Potassium (K)	g	4.50E+00	1.48E+00	7.23E-04	0.00E+00	2.04E-03	3.02E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Propane (C3H8)	g	1.23E+01	5.54E+00	3.57E+00	0.00E+00	1.18E-01	3.07E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Propionaldehyde (CH3CH2CHO)	g	4.52E-09	1.40E-10	1.13E-09	0.00E+00	3.22E-09	2.34E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Propionic Acid (CH3CH2COOH)	g	5.92E-06	1.84E-07	1.49E-06	0.00E+00	4.25E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Propylene (CH2CHCH3)	g	3.76E+00	2.16E+00	1.66E-01	0.00E+00	3.97E-04	1.43E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Scandium (Sc)	g	5.52E-03	2.82E-03	8.69E-09	0.00E+00	1.87E-11	2.69E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Selenium (Se)	g	5.06E-02	2.05E-03	6.93E-04	0.00E+00	3.62E-05	4.78E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Silicon (Si)	g	5.61E+01	1.84E+01	3.83E-04	0.00E+00	7.45E-04	3.78E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Flow	Units	TOTAL	Coal Production	Diesel Production	Sulphuric Acid Production	Lime Production	Electricity Production	Road Transport	Agricultural Processing	Molasses to ethanol process	Sugarcane to molasses process
(a) Sodium (Na)	g	2.29E+00	7.41E-01	3.92E-02	0.00E+00	1.37E-04	1.51E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Strontium (Sr)	g	6.46E-01	1.53E-01	1.94E-06	0.00E+00	9.85E-07	4.93E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Sulphur Oxides (SOx as SO2)	g	1.48E+04	3.16E+02	6.51E+01	7.75E+01	1.80E+00	1.23E+03	7.97E+00	0.00E+00	4.62E+03	8.52E+03
(a) Tars (unspecified)	g	2.81E-05	1.26E-06	2.66E-05	0.00E+00	5.75E-08	1.50E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Thallium (Tl)	g	3.23E-03	7.66E-04	7.95E-09	0.00E+00	1.71E-11	2.47E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Thorium (Th)	g	7.97E-03	2.89E-03	1.64E-08	0.00E+00	3.53E-11	5.08E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Tin (Sn)	g	3.03E-03	1.44E-03	5.12E-09	0.00E+00	1.10E-11	1.59E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Titanium (Ti)	g	1.33E+00	4.47E-01	3.73E-06	0.00E+00	2.53E-06	8.83E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Toluene (C6H5CH3)	g	1.99E+00	1.09E+00	5.14E-01	0.00E+00	2.08E-02	3.60E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Uranium (U)	g	6.46E-03	1.53E-03	1.59E-08	0.00E+00	3.43E-11	4.93E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Vanadium (V)	g	2.75E-01	3.75E-02	1.36E-01	0.00E+00	3.80E-04	1.01E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Xylene (C6H4(CH3)2)	g	5.96E-01	2.24E-02	3.32E-01	0.00E+00	8.29E-04	2.41E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Zinc (Zn)	g	2.35E+00	3.96E-02	2.25E-03	0.00E+00	3.26E-04	1.49E-01	2.16E+00	0.00E+00	0.00E+00	0.00E+00
(a) Zirconium (Zr)	g	3.77E-02	3.39E-02	1.22E-08	0.00E+00	2.63E-11	3.78E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(ar) Lead (Pb210)	kBq	1.16E-01	3.09E-03	3.62E-07	0.00E+00	7.81E-10	1.13E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(ar) Polonium (Po210)	kBq	5.60E-03	5.60E-03	6.55E-07	0.00E+00	1.41E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(ar) Potassium (K40)	kBq	8.56E-04	8.56E-04	1.00E-07	0.00E+00	2.16E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(ar) Radioactive Substance (unspecified)	kBq	9.16E-03	8.24E-03	2.96E-09	0.00E+00	6.38E-12	9.17E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(ar) Radium (Ra226)	kBq	3.78E-02	7.90E-04	9.24E-08	0.00E+00	1.99E-10	3.70E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(ar) Radium (Ra228)	kBq	4.28E-04	4.28E-04	5.01E-08	0.00E+00	1.08E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(ar) Radon (Rn220)	kBq	1.32E-02	1.32E-02	1.54E-06	0.00E+00	3.32E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(ar) Radon (Rn222)	kBq	1.09E+01	9.82E+00	2.54E-02	0.00E+00	5.48E-05	1.09E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(ar) Thorium (Th228)	kBq	3.62E-04	3.62E-04	4.24E-08	0.00E+00	9.13E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(ar) Thorium (Th232)	kBq	2.30E-04	2.30E-04	2.70E-08	0.00E+00	5.81E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(ar) Uranium (U238)	kBq	6.59E-04	6.58E-04	7.70E-08	0.00E+00	1.66E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Aluminium (Al)	g	7.11E-02	2.20E-03	1.78E-02	0.00E+00	5.08E-02	3.69E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Arsenic (As)	g	2.84E-05	8.79E-07	7.11E-06	0.00E+00	2.03E-05	1.47E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Cadmium (Cd)	g	1.29E-08	3.98E-10	3.22E-09	0.00E+00	9.17E-09	6.66E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Calcium (Ca)	g	2.84E-01	8.79E-03	7.11E-02	0.00E+00	2.03E-01	1.47E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Carbon (C)	g	2.13E-01	6.60E-03	5.34E-02	0.00E+00	1.52E-01	1.11E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Chromium (Cr III, Cr VI)	g	3.56E-04	1.10E-05	8.90E-05	0.00E+00	2.54E-04	1.84E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Cobalt (Co)	g	1.30E-08	4.03E-10	3.26E-09	0.00E+00	9.30E-09	6.76E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Copper (Cu)	g	6.53E-08	2.02E-09	1.63E-08	0.00E+00	4.66E-08	3.38E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Iron (Fe)	g	1.42E-01	4.40E-03	3.55E-02	0.00E+00	1.01E-01	7.36E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Lead (Pb)	g	2.98E-07	9.23E-09	7.47E-08	0.00E+00	2.13E-07	1.55E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Manganese (Mn)	g	2.84E-03	8.79E-05	7.11E-04	0.00E+00	2.03E-03	1.47E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Mercury (Hg)	g	2.37E-09	7.33E-11	5.93E-10	0.00E+00	1.69E-09	1.23E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Nickel (Ni)	g	9.80E-08	3.03E-09	2.45E-08	0.00E+00	6.99E-08	5.08E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Nitrogen (N)	g	1.11E-06	3.45E-08	2.79E-07	0.00E+00	7.95E-07	5.77E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Oils (unspecified)	g	4.22E-04	1.31E-05	1.06E-04	0.00E+00	3.01E-04	2.19E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Phosphorus (P)	g	3.56E-03	1.10E-04	8.90E-04	0.00E+00	2.54E-03	1.84E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Sulphur (S)	g	4.26E-02	1.32E-03	1.07E-02	0.00E+00	3.04E-02	2.21E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Zinc (Zn)	g	1.07E-03	3.30E-05	2.67E-04	0.00E+00	7.62E-04	5.53E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Acids (H+)	g	2.74E+01	3.59E-01	7.63E-04	2.66E+01	2.24E-05	4.34E-02	0.00E+00	0.00E+00	3.70E-01	1.07E-05
(w) Aldehyde (unspecified)	g	3.03E-05	9.41E-07	7.61E-06	0.00E+00	2.17E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Alkane (unspecified)	g	6.25E-01	2.82E-02	5.92E-01	0.00E+00	1.84E-03	3.57E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Alkene (unspecified)	g	5.77E-02	2.60E-03	5.46E-02	0.00E+00	1.69E-04	3.30E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Aluminium (Al3+)	g	3.39E+00	2.88E+00	1.83E-02	0.00E+00	2.46E-02	4.76E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Ammonia (NH4+, NH3, as N)	g	1.66E+01	1.14E+01	3.88E+00	0.00E+00	9.02E-03	1.32E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) AOX (Adsorbable Organic Halogens)	g	1.02E-02	4.59E-04	9.66E-03	0.00E+00	2.28E-05	5.78E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Aromatic Hydrocarbons (unspecified)	g	2.55E+00	1.55E-01	2.37E+00	0.00E+00	9.11E-03	1.90E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Arsenic (As3+, As5+)	g	2.27E-03	9.23E-05	1.91E-03	0.00E+00	5.26E-05	2.22E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Barium (Ba++)	g	1.20E+01	5.42E-01	1.14E+01	0.00E+00	2.83E-02	6.96E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Barytes	g	1.01E+00	3.12E-02	2.52E-01	0.00E+00	7.19E-01	5.22E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Benzene (C6H6)	g	6.25E-01	2.82E-02	5.92E-01	0.00E+00	1.84E-03	3.57E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) BOD5 (Biochemical Oxygen Demand)	g	9.96E-01	2.20E-02	2.07E-01	7.60E-01	3.49E-03	3.79E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Boron (B III)	g	7.80E-02	3.51E-03	7.38E-02	0.00E+00	2.30E-04	4.46E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Cadmium (Cd++)	g	3.41E-03	1.51E-04	3.19E-03	0.00E+00	9.96E-06	5.69E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Calcium (Ca++)	g	1.55E+02	6.96E+00	1.46E+02	0.00E+00	5.35E-01	9.16E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Flow	Units	TOTAL	Coal Production	Diesel Production	Sulphuric Acid Production	Lime Production	Electricity Production	Road Transport	Agricultural Processing	Molasses to ethanol process	Sugarcane to molasses process
(w) Cerium (Ce++)	g	4.76E-03	2.16E-04	4.54E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Cesium (Cs++)	g	3.72E-05	0.00E+00	0.00E+00	0.00E+00	9.79E-06	2.74E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Chlorides (Cl-)	g	1.47E+04	1.11E+04	2.35E+03	0.00E+00	5.78E+00	1.25E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Chlorinated Matter (unspecified, as Cl)	g	1.60E-01	4.96E-03	4.01E-02	0.00E+00	1.14E-01	8.31E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Chloroform (CHCl3)	g	1.72E-07	5.32E-09	4.30E-08	0.00E+00	1.23E-07	8.91E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Chromium (Cr III)	g	7.47E-04	2.31E-05	1.87E-04	0.00E+00	5.33E-04	3.87E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Chromium (Cr III, Cr VI)	g	1.20E-02	5.24E-04	1.10E-02	0.00E+00	2.37E-05	5.04E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Chromium (Cr VI)	g	1.40E-08	4.34E-10	3.51E-09	0.00E+00	1.00E-08	7.27E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Cobalt (Co I, Co II, Co III)	g	4.61E-05	1.43E-06	1.15E-05	0.00E+00	3.29E-05	2.39E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) COD (Chemical Oxygen Demand)	g	1.39E+06	3.49E-01	6.84E+00	5.45E-05	5.11E-02	5.07E-02	0.00E+00	0.00E+00	1.39E+06	5.90E+00
(w) Copper (Cu+, Cu++)	g	7.06E-03	3.12E-04	6.48E-03	0.00E+00	1.31E-04	1.40E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Cyanides (CN-)	g	1.90E+00	1.70E+00	9.70E-03	0.00E+00	7.13E-05	1.89E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Dissolved Matter (unspecified)	g	2.70E+05	8.17E+02	1.58E-01	4.58E-02	9.31E-03	9.18E+01	0.00E+00	0.00E+00	2.69E+05	5.34E+02
(w) Dissolved Organic Carbon (DOC)	g	5.67E-02	1.76E-03	1.42E-02	0.00E+00	4.05E-02	2.95E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Ethylbenzene (C6H5C2H5)	g	1.15E-01	5.20E-03	1.09E-01	0.00E+00	2.44E-04	6.59E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Fluorides (F-)	g	2.84E+00	2.50E+00	4.77E-02	4.65E-06	6.49E-03	2.81E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Formaldehyde (CH2O)	g	2.18E-09	6.74E-11	5.45E-10	0.00E+00	1.55E-09	1.13E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Hexachloroethane (C2Cl6)	g	3.03E-13	9.38E-15	7.59E-14	0.00E+00	2.16E-13	1.57E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Hydrocarbons (unspecified)	g	1.30E-03	1.08E-03	1.20E-05	5.04E-07	1.39E-05	2.00E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Hypochlorite (ClO-)	g	5.14E-05	1.60E-06	1.29E-05	0.00E+00	3.69E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Hypochlorous Acid (HClO)	g	5.14E-05	1.60E-06	1.29E-05	0.00E+00	3.69E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Inorganic Dissolved Matter (unspecified)	g	8.46E-02	7.52E-02	3.72E-04	0.00E+00	7.73E-06	9.02E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Iode (I-)	g	4.80E-01	2.16E-02	4.55E-01	0.00E+00	9.84E-04	2.75E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Iron (Fe++, Fe3+)	g	2.62E+00	1.66E+00	5.60E-01	0.00E+00	2.51E-02	3.75E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Lead (Pb++, Pb4+)	g	1.16E-02	1.05E-04	2.01E-03	0.00E+00	3.33E-04	9.20E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Magnesium (Mg++)	g	4.08E+00	1.81E-01	3.79E+00	0.00E+00	2.89E-02	7.76E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Manganese (Mn II, Mn IV, Mn VII)	g	1.17E+00	8.27E-01	2.20E-01	0.00E+00	1.06E-03	1.19E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Mercury (Hg+, Hg++)	g	2.00E-05	9.01E-07	1.89E-05	0.00E+00	4.08E-08	1.90E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Metals (unspecified)	g	1.04E-01	9.24E-02	2.82E-04	1.72E-05	4.07E-06	1.11E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Methylene Chloride (CH2Cl2)	g	4.93E-04	1.52E-05	1.23E-04	0.00E+00	3.52E-04	2.55E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Molybdenum (Mo II, Mo III, Mo IV, Mo V, Mo VI)	g	2.99E-03	9.00E-05	1.89E-03	0.00E+00	4.08E-06	1.01E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Nickel (Ni++, Ni3+)	g	1.03E-01	8.22E-02	1.10E-02	0.00E+00	1.49E-04	9.37E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Nitrates (NO3-)	g	7.23E+00	3.24E-01	6.83E+00	0.00E+00	1.52E-02	6.06E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Nitrites (NO2-)	g	1.28E-05	3.96E-07	3.21E-06	0.00E+00	9.14E-06	6.64E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Nitrogenous Matter (Kjeldahl, as N)	g	5.21E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.21E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Nitrogenous Matter (unspecified, as N)	g	1.03E+00	4.79E-02	9.70E-01	0.00E+00	2.89E-03	6.68E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Oils (unspecified)	g	4.25E+00	1.97E-01	3.85E+00	4.65E-06	1.11E-01	8.62E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Organic Dissolved Matter (unspecified)	g	1.87E-03	8.09E-04	4.98E-06	0.00E+00	1.39E-05	1.04E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Phenol (C6H5OH)	g	5.57E-01	2.55E-02	5.26E-01	4.74E-06	1.71E-03	3.26E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Phosphates (PO4 3-, HPO4--, H2PO4-, H3PO4, as P)	g	6.22E-04	5.19E-05	1.03E-04	0.00E+00	2.95E-04	1.72E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Phosphorus (P)	g	2.00E-02	9.00E-04	1.89E-02	0.00E+00	5.49E-05	1.14E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Phosphorus Pentoxide (P2O5)	g	4.50E-02	4.05E-02	1.45E-08	0.00E+00	3.13E-11	4.50E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Polycyclic Aromatic Hydrocarbons (PAH, unspecified)	g	7.66E-02	1.55E-02	5.91E-02	0.00E+00	1.32E-04	1.77E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Potassium (K+)	g	2.12E+01	9.57E-01	2.01E+01	0.00E+00	5.84E-02	1.21E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Rubidium (Rb+)	g	4.80E-02	2.16E-03	4.55E-02	0.00E+00	9.81E-05	2.75E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Salts (unspecified)	g	2.59E+01	2.33E+01	4.86E-03	0.00E+00	1.38E-02	2.60E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Saponifiable Oils and Fats	g	2.34E+01	1.06E+00	2.22E+01	0.00E+00	4.79E-02	1.34E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Selenium (Se II, Se IV, Se VI)	g	2.86E-03	9.00E-05	1.89E-03	0.00E+00	4.08E-06	8.78E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Silicon Dioxide (SiO2)	g	1.77E-04	5.47E-06	4.42E-05	0.00E+00	1.26E-04	9.16E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Silver (Ag+)	g	2.88E-03	1.30E-04	2.73E-03	0.00E+00	5.88E-06	1.65E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Sodium (Na+)	g	2.10E+03	6.03E+02	1.42E+03	0.00E+00	3.30E+00	7.25E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Strontium (Sr II)	g	3.34E+01	5.39E+00	2.74E+01	0.00E+00	6.15E-02	6.20E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Sulphates (SO4--)	g	1.14E+05	4.49E+02	3.79E+01	0.00E+00	3.77E-01	7.83E+01	0.00E+00	0.00E+00	1.13E+05	0.00E+00
(w) Sulphides (S--)	g	7.82E-02	3.77E-03	7.38E-02	0.00E+00	1.71E-04	4.83E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Sulphites (SO3--)	g	3.39E-05	2.63E-08	2.12E-07	0.00E+00	6.06E-07	3.30E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Sulphurated Matter (unspecified, as S)	g	5.40E-05	4.78E-05	8.58E-07	0.00E+00	1.85E-09	5.33E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Suspended Matter (unspecified)	g	8.30E+05	1.38E+01	1.08E+00	2.28E+00	2.53E+00	2.63E+00	0.00E+00	0.00E+00	8.30E+05	5.05E+00
(w) Tars (unspecified)	g	4.02E-07	1.80E-08	3.81E-07	0.00E+00	8.21E-10	2.14E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Tetrachloroethylene (C2Cl4)	g	7.41E-10	2.29E-11	1.85E-10	0.00E+00	5.29E-10	3.84E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00

	Flow	Units	TOTAL	Coal Production	Diesel Production	Sulphuric Acid Production	Lime Production	Electricity Production	Road Transport	Agricultural Processing	Molasses to ethanol process	Sugarcane to molasses process
	(w) Tin (Sn++, Sn4+)	g	3.06E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.06E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(w) Titanium (Ti3+, Ti4+)	g	2.39E-03	5.74E-05	4.64E-04	0.00E+00	1.32E-03	5.43E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(w) TOC (Total Organic Carbon)	g	3.59E+01	1.61E+00	3.34E+01	0.00E+00	6.50E-01	2.03E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(w) Toluene (C6H5CH3)	g	5.20E-01	2.34E-02	4.92E-01	0.00E+00	1.57E-03	2.97E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(w) Trichlorethane (1,1,1-CH3CCl3)	g	1.67E-09	5.17E-11	4.18E-10	0.00E+00	1.19E-09	8.66E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(w) Trichloroethylene (C2HCl3)	g	4.60E-08	1.42E-09	1.15E-08	0.00E+00	3.28E-08	2.38E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(w) Triethylene Glycol (C6H14O4)	g	5.67E-02	1.75E-03	1.42E-02	0.00E+00	4.05E-02	2.94E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(w) Vanadium (V3+, V5+)	g	5.38E-03	9.00E-05	1.89E-03	0.00E+00	4.08E-06	3.40E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(w) VOC (Volatile Organic Compounds)	g	1.68E+00	7.56E-02	1.59E+00	0.00E+00	3.43E-03	9.59E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(w) Water (unspecified)	litre	1.26E+03	1.11E+03	2.70E-03	0.00E+00	5.83E-06	1.42E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(w) Water: Chemically Polluted	litre	2.14E+04	1.20E+01	7.79E+00	0.00E+00	1.68E-02	1.62E+00	0.00E+00	0.00E+00	2.14E+04	0.00E+00
	(w) Xylene (C6H4(CH3)2)	g	4.51E+00	2.04E-01	4.28E+00	0.00E+00	9.63E-03	2.58E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(w) Zinc (Zn++)	g	1.13E-01	8.26E-02	1.92E-02	0.00E+00	9.69E-04	1.00E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(wr) Radioactive Substance (unspecified)	kBq	8.43E-05	7.58E-05	2.72E-11	0.00E+00	5.87E-14	8.44E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(wr) Radium (Ra224)	kBq	2.40E-01	1.08E-02	2.27E-01	0.00E+00	4.90E-04	1.37E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(wr) Radium (Ra226)	kBq	4.73E+00	2.16E-02	4.55E-01	0.00E+00	9.81E-04	4.25E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(wr) Radium (Ra228)	kBq	4.80E-01	2.16E-02	4.55E-01	0.00E+00	9.81E-04	2.75E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(wr) Thorium (Th228)	kBq	9.60E-01	4.33E-02	9.10E-01	0.00E+00	1.96E-03	5.49E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	ethanol product	kl	1.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+00	0.00E+00
	Recovered Matter (total)	kg	9.23E-01	6.67E-01	5.44E-04	0.00E+00	1.17E-06	2.56E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Recovered Matter (unspecified)	kg	9.23E-01	6.67E-01	5.44E-04	0.00E+00	1.17E-06	2.56E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Recovered Matter: Iron Scrap	kg	2.61E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.61E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	sugar product	tons	1.19E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.19E+01
	Waste (hazardous)	kg	2.02E-01	1.41E-01	4.53E-02	0.00E+00	9.78E-05	1.58E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste (incineration)	kg	7.67E-02	4.46E-02	2.51E-02	0.00E+00	2.09E-03	4.98E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste (municipal and industrial)	kg	2.16E-01	1.94E-01	4.89E-06	0.00E+00	4.52E-08	2.18E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste (total)	kg	4.98E+02	4.17E+02	1.93E-01	1.82E-02	2.45E-03	8.00E+01	0.00E+00	0.00E+00	0.00E+00	3.41E-01
	Waste (unspecified)	kg	2.76E+01	8.78E-01	6.15E-03	1.82E-02	1.35E-05	2.67E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste: Highly Radioactive (class C)	kg	6.43E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.43E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste: Low Radioactive (class A)	kg	3.15E-02	1.32E-03	2.77E-02	0.00E+00	5.98E-05	2.35E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste: Mineral (inert)	kg	4.62E+02	4.16E+02	7.79E-02	0.00E+00	1.69E-04	4.63E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste: Mining	kg	3.34E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.34E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste: Non Mineral (inert)	kg	1.29E-02	8.54E-03	3.30E-03	0.00E+00	7.11E-06	1.10E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste. Non Toxic Chemicals (unspecified)	kg	4.61E-05	4.07E-05	2.03E-07	0.00E+00	4.37E-10	5.20E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste: Radioactive	kg	4.64E-03	2.11E-04	4.43E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste: Radioactive (unspecified)	kg	3.63E-05	0.00E+00	0.00E+00	0.00E+00	9.54E-06	2.67E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste: Slags and Ash (unspecified)	kg	7.13E+00	2.04E-01	2.64E-03	0.00E+00	5.71E-06	6.93E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Reminders:	E Feedstock Energy	MJ	2.34E+04	2.09E+04	1.88E+03	1.20E+01	2.93E-02	1.28E+03	-6.80E+02	0.00E+00	0.00E+00	0.00E+00
	E Fuel Energy	MJ	4.32E+03	2.81E+03	9.08E+01	-1.16E+01	1.05E+02	6.50E+02	6.80E+02	0.00E+00	0.00E+00	0.00E+00
	E Non Renewable Energy	MJ	2.77E+04	2.37E+04	1.97E+03	3.85E+00	1.05E+02	1.92E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	E Renewable Energy	MJ	1.28E+01	9.34E-01	8.41E-03	5.17E-04	1.74E-02	1.19E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	E Total Primary Energy	MJ	2.78E+04	2.38E+04	1.97E+03	3.85E+00	1.05E+02	1.93E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Electricity	MJ elec	1.09E+03	3.07E+02	5.00E+00	3.79E-01	3.70E+00	1.48E+02	0.00E+00	6.26E+02	0.00E+00	

INVENTORY FOR BIOETHANOL PRODUCTION LIFE CYCLE, WITH ZERO ALLOCATION TO MOLASSES

	Flow	Units	TOTAL	Coal Production	Diesel Production	Sulphuric Acid Production	Lime Production	Electricity Production	Road Transport	Agricultural Processing	Molasses to ethanol process	Sugarcane to molasses process
Inputs:	(r) Barium Sulphate (BaSO4, in ground)	kg	1.63E-03	1.72E-04	4.08E-04	0.00E+00	1.02E-03	2.87E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Bauxite (Al2O3, ore)	kg	5.37E-04	1.17E-04	3.95E-04	0.00E+00	4.06E-06	2.09E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Bentonite (Al2O3.4SiO2.H2O, in ground)	kg	1.54E-04	1.63E-05	3.85E-05	0.00E+00	9.60E-05	2.71E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Calcium Sulphate (CaSO4, ore)	kg	3.75E-02	3.74E-02	7.17E-05	0.00E+00	1.35E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Chromium (Cr, ore)	kg	3.13E-07	3.31E-08	7.84E-08	0.00E+00	1.95E-07	5.51E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Clay (in ground)	kg	2.37E-01	2.09E-01	4.78E-04	0.00E+00	1.90E-04	2.69E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Coal (in ground)	kg	1.45E+03	1.31E+03	1.48E-03	1.42E-02	2.75E-03	1.45E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Copper (Cu, ore)	kg	1.59E-06	1.69E-07	3.99E-07	0.00E+00	9.94E-07	2.81E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Gravel (unspecified)	kg	5.12E+00	5.11E+00	9.80E-03	0.00E+00	1.85E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Iron (Fe, ore)	kg	1.93E+00	1.73E+00	1.20E-03	0.00E+00	2.99E-03	1.96E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Iron Sulphate (FeSO4, ore)	kg	4.71E-02	4.24E-02	4.45E-09	0.00E+00	8.39E-12	4.69E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Lead (Pb, ore)	kg	4.96E-07	5.26E-08	1.25E-07	0.00E+00	3.10E-07	8.76E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Lignite (in ground)	kg	2.59E-03	2.75E-04	6.46E-04	0.00E+00	1.61E-03	6.18E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Limestone (CaCO3, in ground)	kg	3.41E+01	1.23E+00	3.01E-03	0.00E+00	8.86E+00	2.40E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Manganese (Mn, ore)	kg	1.82E-07	1.93E-08	4.57E-08	0.00E+00	1.14E-07	3.21E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Natural Gas (in ground)	kg	1.30E+01	9.43E+00	3.13E-01	1.52E-01	6.26E-01	2.48E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Nickel (Ni, ore)	kg	1.06E-07	1.12E-08	2.66E-08	0.00E+00	6.62E-08	1.87E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Oil (in ground)	kg	1.64E+01	2.35E+00	1.35E+01	3.77E-02	2.75E-02	4.19E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Pyrite (FeS2, ore)	kg	2.61E-03	2.76E-04	6.54E-04	0.00E+00	1.63E-03	4.60E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Sand (in ground)	kg	1.28E-01	1.15E-01	1.72E-04	0.00E+00	3.03E-05	1.27E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Silver (Ag, ore)	kg	7.88E-09	8.36E-10	1.98E-09	0.00E+00	4.93E-09	1.39E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Sodium Chloride (NaCl, in ground or in sea)	kg	7.99E-01	7.07E-01	1.79E-03	0.00E+00	1.05E-05	9.02E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Uranium (U, ore)	kg	4.77E-04	2.52E-07	2.33E-08	5.77E-08	5.80E-08	4.76E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(r) Zinc (Zn, ore)	kg	1.16E-08	1.23E-09	2.90E-09	0.00E+00	7.23E-09	2.04E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(s) Nitrogen (N)	g	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(s) Phosphorus (P)	g	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Explosive (unspecified)	kg	4.89E-01	4.89E-01	5.20E-08	0.00E+00	9.80E-11	1.33E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Iron Scrap	kg	2.87E-01	2.47E-01	1.12E-02	0.00E+00	2.11E-05	2.81E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Land Use (II -> III)	m2a	5.59E+00	5.59E+00	2.02E-05	0.00E+00	3.80E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Land Use (II -> IV)	m2a	7.48E-01	7.48E-01	2.46E-05	0.00E+00	4.63E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Land Use (III -> IV)	m2a	2.65E-01	2.65E-01	2.79E-08	0.00E+00	5.25E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Raw Materials (unspecified)	kg	6.78E+00	7.89E-02	1.01E-02	0.00E+00	1.91E-05	6.69E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Water Used (total)	litre	1.88E+04	2.19E+03	5.54E+01	9.56E+00	1.76E+00	3.07E+02	0.00E+00	0.00E+00	1.62E+04	0.00E+00
	Water: Unspecified Origin	litre	2.56E+03	2.19E+03	5.54E+01	9.56E+00	1.76E+00	3.07E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Wood	kg	7.64E+00	6.88E+00	1.50E-05	0.00E+00	3.57E-05	7.60E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Outputs:	(a) Acetaldehyde (CH3CHO)	g	1.92E-04	5.03E-05	1.07E-05	0.00E+00	2.65E-05	1.04E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Acetic Acid (CH3COOH)	g	6.59E-03	8.20E-04	1.50E-03	0.00E+00	3.77E-03	4.99E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Acetone (CH3COCH3)	g	1.57E-04	4.65E-05	1.88E-06	0.00E+00	4.47E-06	1.04E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Acetylene (C2H2)	g	2.40E+00	1.09E+00	1.24E-06	0.00E+00	2.33E-09	1.30E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Aldehyde (unspecified)	g	1.28E-02	8.86E-03	1.49E-04	0.00E+00	1.36E-05	3.77E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Alkane (unspecified)	g	1.65E+00	8.71E-02	2.82E-01	0.00E+00	7.29E-02	1.20E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Alkene (unspecified)	g	2.40E+00	1.09E+00	6.42E-05	0.00E+00	1.57E-04	1.30E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Alkyne (unspecified)	g	2.65E-06	2.81E-07	6.65E-07	0.00E+00	1.66E-06	4.68E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Aluminium (Al)	g	3.76E+01	1.25E+01	5.16E-05	0.00E+00	6.93E-05	2.50E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Ammonia (NH3)	g	4.84E+00	4.35E+00	2.90E-04	0.00E+00	2.75E-05	4.89E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Antimony (Sb)	g	5.72E-03	8.95E-04	4.59E-09	0.00E+00	8.64E-12	4.83E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) AOX (Adsorbable Organic Halogens)	g	2.10E-10	1.89E-10	1.98E-17	0.00E+00	3.74E-20	2.09E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Aromatic Hydrocarbons (unspecified)	g	1.78E-04	6.10E-05	1.11E-07	0.00E+00	2.09E-10	1.17E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Arsenic (As)	g	5.87E-02	1.01E-02	2.00E-04	0.00E+00	1.12E-06	4.84E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Barium (Ba)	g	4.48E-01	1.48E-01	6.71E-07	0.00E+00	9.64E-07	3.00E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Benzaldehyde (C6H5CHO)	g	4.79E-10	5.08E-11	1.20E-10	0.00E+00	2.99E-10	8.45E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Benzene (C6H6)	g	7.25E+00	5.35E+00	1.01E-01	0.00E+00	1.03E-02	1.77E+00	1.28E-02	0.00E+00	0.00E+00	0.00E+00
	(a) Benzo(a)pyrene (C20H12)	g	4.01E-02	3.61E-02	7.63E-07	0.00E+00	4.98E-07	4.01E-03	6.41E-05	0.00E+00	0.00E+00	0.00E+00
	(a) Berylium (Be)	g	6.59E-03	1.68E-03	6.33E-09	0.00E+00	4.14E-09	4.91E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Boron (B)	g	2.48E+00	1.04E-01	1.57E-05	0.00E+00	3.35E-05	2.38E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Bromium (Br)	g	4.96E-01	2.08E-02	1.74E-06	0.00E+00	3.22E-06	4.75E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Butane (n-C4H10)	g	1.23E+00	1.66E-01	1.00E+00	0.00E+00	2.44E-02	4.31E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Butene (1-CH3CH2CHCH2)	g	2.88E-02	3.95E-03	2.43E-02	0.00E+00	5.25E-05	4.98E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(a) Cadmium (Cd)	g	7.46E-03	3.55E-03	4.98E-04	0.00E+00	2.07E-06	2.78E-03	6.26E-04	0.00E+00	0.00E+00	0.00E+00

Flow	Units	TOTAL	Coal Production	Diesel Production	Sulphuric Acid Production	Lime Production	Electricity Production	Road Transport	Agricultural Processing	Molasses to ethanol process	Sugarcane to molasses process
(a) Calcium (Ca)	g	4.48E+00	1.48E+00	1.81E-03	0.00E+00	1.67E-04	3.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Carbon Dioxide (CO2, biomass)	g	7.50E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.50E+05	0.00E+00
(a) Carbon Dioxide (CO2, fossil)	g	2.23E+06	6.83E+04	3.77E+03	5.10E+02	5.50E+03	2.38E+05	4.03E+04	0.00E+00	1.87E+06	0.00E+00
(a) Carbon Monoxide (CO)	g	7.82E+03	6.35E+02	2.37E+00	7.16E-02	8.73E-01	3.08E+02	1.12E+02	0.00E+00	6.76E+03	0.00E+00
(a) Carbon Tetrafluoride (CF4)	g	3.85E-07	4.08E-08	9.65E-08	0.00E+00	2.41E-07	6.79E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Chlorine (Cl2)	g	1.69E-05	0.00E+00	0.00E+00	4.65E-06	0.00E+00	1.22E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Chromium (Cr III, Cr VI)	g	7.44E-02	1.57E-02	2.51E-04	0.00E+00	4.43E-06	5.85E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Cobalt (Co)	g	1.17E-02	3.68E-03	4.98E-04	0.00E+00	1.78E-06	7.52E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Copper (Cu)	g	4.90E-02	1.15E-02	7.49E-04	0.00E+00	7.38E-06	3.68E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Cyanide (CN-)	g	6.59E-02	5.94E-02	3.24E-07	0.00E+00	7.93E-07	6.57E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Dioxins (unspecified)	g	4.89E-08	1.44E-09	4.78E-12	0.00E+00	1.12E-11	4.74E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Ethane (C2H6)	g	1.99E+01	1.13E+01	3.39E+00	0.00E+00	1.07E-01	5.09E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Ethanol (C2H5OH)	g	8.00E+03	9.21E-05	1.35E-06	0.00E+00	2.92E-06	2.07E-04	0.00E+00	0.00E+00	8.00E+03	0.00E+00
(a) Ethylbenzene (C8H10)	g	2.88E-02	3.95E-03	2.43E-02	0.00E+00	5.25E-05	4.98E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Ethylene (C2H4)	g	4.41E+01	3.29E+01	1.71E-01	0.00E+00	3.05E-01	1.07E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Fluorides (F-)	g	3.07E-05	5.59E-07	2.73E-06	4.65E-06	5.15E-09	2.27E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Fluorine (F2)	g	6.61E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.61E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Formaldehyde (CH2O)	g	2.00E-01	6.19E-03	1.01E-03	0.00E+00	2.52E-03	1.90E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Halogenated Matter (unspecified)	g	2.75E-12	2.48E-12	2.60E-19	0.00E+00	4.91E-22	2.74E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Halon 1301 (CF3Br)	g	3.27E-03	4.48E-04	2.75E-03	0.00E+00	5.87E-06	5.65E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Heptane (C7H16)	g	2.88E-01	3.95E-02	2.43E-01	0.00E+00	4.89E-04	4.98E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Hexane (C6H14)	g	5.75E-01	7.86E-02	4.86E-01	0.00E+00	9.81E-04	9.91E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Hydrocarbons (except methane)	g	2.97E+02	1.09E+02	9.04E+01	0.00E+00	6.68E-01	4.14E+01	5.52E+01	0.00E+00	0.00E+00	0.00E+00
(a) Hydrocarbons (unspecified)	g	1.54E+01	9.10E+00	8.32E-03	5.25E+00	3.34E-04	1.09E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Hydrogen (H2)	g	5.65E-05	5.09E-05	5.35E-12	0.00E+00	1.01E-14	5.63E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Hydrogen Chloride (HCl)	g	1.22E+02	3.48E+00	2.29E-02	1.80E-04	6.79E-04	1.19E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Hydrogen Fluoride (HF)	g	4.39E+00	1.21E-01	2.28E-03	9.43E-06	9.43E-05	4.27E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Hydrogen Sulphide (H2S)	g	3.30E+01	2.97E+01	3.87E-03	0.00E+00	9.63E-03	3.28E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Iodine (I)	g	1.23E-01	4.69E-03	7.44E-07	0.00E+00	1.57E-06	1.19E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Iron (Fe)	g	1.52E+01	5.14E+00	2.59E-03	0.00E+00	2.22E-04	1.00E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) lanthanum (La)	g	1.51E-02	7.20E-03	7.49E-09	0.00E+00	1.41E-11	7.89E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Lead (Pb)	g	2.63E-01	6.30E-02	8.93E-04	0.00E+00	2.53E-05	1.96E-01	2.77E-03	0.00E+00	0.00E+00	0.00E+00
(a) Magnesium (Mg)	g	1.32E+01	4.47E+00	2.08E-05	0.00E+00	3.10E-05	8.77E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Manganese (Mn)	g	1.03E-01	5.01E-02	5.61E-05	0.00E+00	1.40E-04	5.28E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Mercury (Hg)	g	8.15E-03	9.25E-04	2.51E-05	0.00E+00	4.97E-06	7.20E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Metals (unspecified)	g	2.73E-03	2.42E-03	1.70E-06	6.16E-06	3.20E-09	2.98E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Methane (CH4)	g	8.29E+03	7.36E+03	6.54E+01	0.00E+00	2.43E+00	8.60E+02	1.67E+00	0.00E+00	0.00E+00	0.00E+00
(a) Methanol (CH3OH)	g	5.13E-04	1.56E-04	1.58E-06	0.00E+00	3.20E-06	3.52E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Molybdenum (Mo)	g	1.24E-02	2.39E-03	2.49E-04	0.00E+00	4.69E-07	9.73E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Nickel (Ni)	g	7.69E-02	1.72E-02	9.97E-03	0.00E+00	4.43E-05	4.97E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Nitrogen Oxides (NOx as NO2)	g	3.20E+03	6.24E+02	9.18E+00	2.96E+00	1.81E+00	5.51E+02	5.13E+02	0.00E+00	1.50E+03	0.00E+00
(a) Nitrous Oxide (N2O)	g	8.87E+00	4.64E-01	4.16E-02	0.00E+00	5.97E-03	2.72E+00	5.64E+00	0.00E+00	0.00E+00	0.00E+00
(a) Organic Matter (unspecified)	g	2.68E-02	1.75E-02	2.15E-04	0.00E+00	4.06E-07	9.15E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Particulates (unspecified)	g	3.17E+03	1.21E+03	1.94E+00	6.81E+00	7.56E+01	1.85E+03	2.82E+01	0.00E+00	0.00E+00	0.00E+00
(a) Pentane (C5H12)	g	1.49E+00	2.03E-01	1.23E+00	0.00E+00	3.25E-02	2.56E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Phenol (C6H5OH)	g	3.67E-09	3.90E-10	9.22E-10	0.00E+00	2.30E-09	6.48E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Phosphorus (P)	g	2.97E-01	7.59E-02	6.32E-07	0.00E+00	1.03E-06	2.21E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Phosphorus Pentoxide (P2O5)	g	1.51E-03	1.36E-03	1.43E-10	0.00E+00	2.69E-13	1.50E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Polycyclic Aromatic Hydrocarbons (PAH, unspecified)	g	4.02E-04	4.31E-05	1.01E-04	0.00E+00	2.52E-04	6.08E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Potassium (K)	g	4.48E+00	1.48E+00	2.12E-04	0.00E+00	5.20E-04	3.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Propane (C3H8)	g	9.66E+00	5.54E+00	1.04E+00	0.00E+00	3.01E-02	3.05E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Propionaldehyde (CH3CH2CHO)	g	1.32E-09	1.40E-10	3.31E-10	0.00E+00	8.24E-10	2.32E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Propionic Acid (CH3CH2COOH)	g	1.71E-06	1.84E-07	4.35E-07	0.00E+00	1.09E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Propylene (CH2CHCH3)	g	3.63E+00	2.16E+00	4.86E-02	0.00E+00	1.01E-04	1.42E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Scandium (Sc)	g	5.50E-03	2.82E-03	2.54E-09	0.00E+00	4.79E-12	2.68E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Selenium (Se)	g	4.98E-02	2.05E-03	2.03E-04	0.00E+00	9.25E-06	4.75E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Silicon (Si)	g	5.59E+01	1.84E+01	1.12E-04	0.00E+00	1.90E-04	3.75E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Sodium (Na)	g	2.25E+00	7.41E-01	1.15E-02	0.00E+00	3.49E-05	1.50E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Strontium (Sr)	g	6.43E-01	1.53E-01	5.66E-07	0.00E+00	2.52E-07	4.90E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Sulphur Oxides (SOx as SO2)	g	6.25E+03	3.16E+02	1.90E+01	7.75E+01	4.61E-01	1.22E+03	0.00E+00	0.00E+00	4.62E+03	0.00E+00
(a) Tars (unspecified)	g	9.22E-06	1.26E-06	7.79E-06	0.00E+00	1.47E-08	1.49E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Flow	Units	TOTAL	Coal Production	Diesel Production	Sulphuric Acid Production	Lime Production	Electricity Production	Road Transport	Agricultural Processing	Molasses to ethanol process	Sugarcane to molasses process
(a) Thallium (Tl)	g	3.21E-03	7.66E-04	2.33E-09	0.00E+00	4.38E-12	2.45E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Thorium (Th)	g	7.94E-03	2.89E-03	4.80E-09	0.00E+00	9.04E-12	5.05E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Tin (Sn)	g	3.02E-03	1.44E-03	1.50E-09	0.00E+00	2.82E-12	1.58E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Titanium (Ti)	g	1.32E+00	4.47E-01	1.09E-06	0.00E+00	6.46E-07	8.77E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Toluene (C6H5CH3)	g	1.61E+00	1.09E+00	1.50E-01	0.00E+00	5.32E-03	3.58E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Uranium (U)	g	6.43E-03	1.53E-03	4.65E-09	0.00E+00	8.77E-12	4.90E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Vanadium (V)	g	1.78E-01	3.75E-02	3.98E-02	0.00E+00	9.71E-05	1.01E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Xylene (C6H4(CH3)2)	g	3.59E-01	2.24E-02	9.71E-02	0.00E+00	2.12E-04	2.39E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(a) Zinc (Zn)	g	1.89E+00	3.96E-02	6.60E-04	0.00E+00	8.34E-05	1.48E-01	1.70E+00	0.00E+00	0.00E+00	0.00E+00
(a) Zirconium (Zr)	g	3.77E-02	3.39E-02	3.56E-09	0.00E+00	6.71E-12	3.75E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(ar) Lead (Pb210)	kBq	1.15E-01	3.09E-03	1.06E-07	0.00E+00	2.00E-10	1.12E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(ar) Polonium (Po210)	kBq	5.60E-03	5.60E-03	1.92E-07	0.00E+00	3.61E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(ar) Potassium (K40)	kBq	8.56E-04	8.56E-04	2.93E-08	0.00E+00	5.52E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(ar) Radioactive Substance (unspecified)	kBq	9.15E-03	8.24E-03	8.65E-10	0.00E+00	1.63E-12	9.11E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(ar) Radium (Ra226)	kBq	3.75E-02	7.90E-04	2.70E-08	0.00E+00	5.09E-11	3.68E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(ar) Radium (Ra228)	kBq	4.28E-04	4.28E-04	1.46E-08	0.00E+00	2.76E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(ar) Radon (Rn220)	kBq	1.32E-02	1.32E-02	4.51E-07	0.00E+00	8.49E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(ar) Radon (Rn222)	kBq	1.09E+01	9.82E+00	7.44E-03	0.00E+00	1.40E-05	1.08E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(ar) Thorium (Th228)	kBq	3.62E-04	3.62E-04	1.24E-08	0.00E+00	2.33E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(ar) Thorium (Th232)	kBq	2.30E-04	2.30E-04	7.89E-09	0.00E+00	1.49E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(ar) Uranium (U238)	kBq	6.58E-04	6.58E-04	2.25E-08	0.00E+00	4.25E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Aluminium (Al)	g	2.07E-02	2.20E-03	5.21E-03	0.00E+00	1.30E-02	3.66E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Arsenic (As)	g	8.29E-06	8.79E-07	2.08E-06	0.00E+00	5.18E-06	1.46E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Cadmium (Cd)	g	3.75E-09	3.98E-10	9.41E-10	0.00E+00	2.35E-09	6.62E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Calcium (Ca)	g	8.29E-02	8.79E-03	2.08E-02	0.00E+00	5.18E-02	1.46E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Carbon (C)	g	6.22E-02	6.60E-03	1.56E-02	0.00E+00	3.89E-02	1.10E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Chromium (Cr III, Cr VI)	g	1.04E-04	1.10E-05	2.60E-05	0.00E+00	6.49E-05	1.83E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Cobalt (Co)	g	3.80E-09	4.03E-10	9.54E-10	0.00E+00	2.38E-09	6.71E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Copper (Cu)	g	1.90E-08	2.02E-09	4.78E-09	0.00E+00	1.19E-08	3.36E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Iron (Fe)	g	4.14E-02	4.40E-03	1.04E-02	0.00E+00	2.59E-02	7.31E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Lead (Pb)	g	8.71E-08	9.23E-09	2.18E-08	0.00E+00	5.44E-08	1.54E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Manganese (Mn)	g	8.29E-04	8.79E-05	2.08E-04	0.00E+00	5.18E-04	1.46E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Mercury (Hg)	g	6.91E-10	7.33E-11	1.73E-10	0.00E+00	4.32E-10	1.22E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Nickel (Ni)	g	2.86E-08	3.03E-09	7.17E-09	0.00E+00	1.79E-08	5.04E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Nitrogen (N)	g	3.25E-07	3.45E-08	8.15E-08	0.00E+00	2.03E-07	5.73E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Oils (unspecified)	g	1.23E-04	1.31E-05	3.09E-05	0.00E+00	7.70E-05	2.17E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Phosphorus (P)	g	1.04E-03	1.10E-04	2.60E-04	0.00E+00	6.49E-04	1.83E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Sulphur (S)	g	1.24E-02	1.32E-03	3.12E-03	0.00E+00	7.78E-03	2.19E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(s) Zinc (Zn)	g	3.12E-04	3.30E-05	7.82E-05	0.00E+00	1.95E-04	5.50E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Acids (H+)	g	2.74E+01	3.59E-01	2.23E-04	2.66E+01	5.73E-06	4.31E-02	0.00E+00	0.00E+00	3.70E-01	0.00E+00
(w) Aldehyde (unspecified)	g	8.72E-06	9.41E-07	2.23E-06	0.00E+00	5.55E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Alkane (unspecified)	g	2.05E-01	2.82E-02	1.73E-01	0.00E+00	4.69E-04	3.55E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Alkene (unspecified)	g	1.89E-02	2.60E-03	1.60E-02	0.00E+00	4.32E-05	3.28E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Aluminium (Al3+)	g	3.36E+00	2.88E+00	5.35E-03	0.00E+00	6.29E-03	4.73E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Ammonia (NH4+, NH3, as N)	g	1.39E+01	1.14E+01	1.13E+00	0.00E+00	2.31E-03	1.31E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) AOX (Adsorbable Organic Halogens)	g	3.35E-03	4.59E-04	2.82E-03	0.00E+00	5.83E-06	5.74E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Aromatic Hydrocarbons (unspecified)	g	8.69E-01	1.55E-01	6.92E-01	0.00E+00	2.33E-03	1.89E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Arsenic (As3+, As5+)	g	8.85E-04	9.23E-05	5.58E-04	0.00E+00	1.35E-05	2.21E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Barium (Ba++)	g	3.95E+00	5.42E-01	3.33E+00	0.00E+00	7.23E-03	6.91E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Barytes	g	2.94E-01	3.12E-02	7.38E-02	0.00E+00	1.84E-01	5.19E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Benzene (C6H6)	g	2.05E-01	2.82E-02	1.73E-01	0.00E+00	4.70E-04	3.55E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) BOD5 (Biochemical Oxygen Demand)	g	8.47E-01	2.20E-02	6.05E-02	7.60E-01	8.92E-04	3.76E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Boron (B III)	g	2.56E-02	3.51E-03	2.16E-02	0.00E+00	5.88E-05	4.43E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Cadmium (Cd++)	g	1.14E-03	1.51E-04	9.32E-04	0.00E+00	2.55E-06	5.65E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Calcium (Ca++)	g	5.08E+01	6.96E+00	4.28E+01	0.00E+00	1.37E-01	9.10E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Cerium (Ce++)	g	1.54E-03	2.16E-04	1.33E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Cesium (Cs++)	g	2.97E-05	0.00E+00	0.00E+00	0.00E+00	2.50E-06	2.72E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Chlorides (Cl-)	g	1.30E+04	1.11E+04	6.87E+02	0.00E+00	1.48E+00	1.24E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Chlorinated Matter (unspecified, as Cl)	g	4.68E-02	4.96E-03	1.17E-02	0.00E+00	2.92E-02	8.25E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Chloroform (CHCl3)	g	5.01E-08	5.32E-09	1.26E-08	0.00E+00	3.14E-08	8.85E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Chromium (Cr III)	g	2.18E-04	2.31E-05	5.47E-05	0.00E+00	1.36E-04	3.84E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Flow	Units	TOTAL	Coal Production	Diesel Production	Sulphuric Acid Production	Lime Production	Electricity Production	Road Transport	Agricultural Processing	Molasses to ethanol process	Sugarcane to molasses process
(w) Chromium (Cr III, Cr VI)	g	4.25E-03	5.24E-04	3.21E-03	0.00E+00	6.06E-06	5.01E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Chromium (Cr VI)	g	4.09E-09	4.34E-10	1.03E-09	0.00E+00	2.56E-09	7.22E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Cobalt (Co I, Co II, Co III)	g	1.35E-05	1.43E-06	3.38E-06	0.00E+00	8.41E-06	2.37E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) COD (Chemical Oxygen Demand)	g	1.39E+06	3.49E-01	2.00E+00	5.45E-05	1.31E-02	5.03E-02	0.00E+00	0.00E+00	1.39E+06	0.00E+00
(w) Copper (Cu+, Cu++)	g	2.38E-03	3.12E-04	1.90E-03	0.00E+00	3.34E-05	1.39E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Cyanides (CN-)	g	1.89E+00	1.70E+00	2.84E-03	0.00E+00	1.82E-05	1.88E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Dissolved Matter (unspecified)	g	2.70E+05	8.17E+02	4.61E-02	4.58E-02	2.38E-03	9.12E+01	0.00E+00	0.00E+00	2.69E+05	0.00E+00
(w) Dissolved Organic Carbon (DOC)	g	1.66E-02	1.76E-03	4.15E-03	0.00E+00	1.03E-02	2.93E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Ethylbenzene (C6H5C2H5)	g	3.79E-02	5.20E-03	3.19E-02	0.00E+00	6.23E-05	6.55E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Fluorides (F-)	g	2.80E+00	2.50E+00	1.40E-02	4.65E-06	1.66E-03	2.79E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Formaldehyde (CH2O)	g	6.35E-10	6.74E-11	1.59E-10	0.00E+00	3.97E-10	1.12E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Hexachloroethane (C2Cl6)	g	8.84E-14	9.38E-15	2.22E-14	0.00E+00	5.53E-14	1.56E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Hydrocarbons (unspecified)	g	1.28E-03	1.08E-03	3.51E-06	5.04E-07	3.55E-06	1.99E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Hypochlorite (ClO-)	g	1.48E-05	1.60E-06	3.78E-06	0.00E+00	9.42E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Hypochlorous Acid (HClO)	g	1.48E-05	1.60E-06	3.78E-06	0.00E+00	9.42E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Inorganic Dissolved Matter (unspecified)	g	8.42E-02	7.52E-02	1.09E-04	0.00E+00	1.98E-06	8.96E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Iode (I-)	g	1.58E-01	2.16E-02	1.33E-01	0.00E+00	2.52E-04	2.73E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Iron (Fe++, Fe3+)	g	2.20E+00	1.66E+00	1.64E-01	0.00E+00	6.41E-03	3.73E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Lead (Pb++, Pb4+)	g	9.92E-03	1.05E-04	5.87E-04	0.00E+00	8.52E-05	9.14E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Magnesium (Mg++)	g	1.37E+00	1.81E-01	1.11E+00	0.00E+00	7.38E-03	7.71E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Manganese (Mn II, Mn IV, Mn VII)	g	1.01E+00	8.27E-01	6.42E-02	0.00E+00	2.71E-04	1.18E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Mercury (Hg+, Hg++)	g	6.63E-06	9.01E-07	5.53E-06	0.00E+00	1.04E-08	1.88E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Metals (unspecified)	g	1.04E-01	9.24E-02	8.24E-05	1.72E-05	1.04E-06	1.11E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Methylene Chloride (CH2Cl2)	g	1.44E-04	1.52E-05	3.61E-05	0.00E+00	8.99E-05	2.54E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Molybdenum (Mo II, Mo III, Mo IV, Mo V, Mo VI)	g	1.64E-03	9.00E-05	5.53E-04	0.00E+00	1.04E-06	9.99E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Nickel (Ni++, Ni3+)	g	9.48E-02	8.22E-02	3.23E-03	0.00E+00	3.82E-05	9.31E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Nitrates (NO3-)	g	2.39E+00	3.24E-01	2.00E+00	0.00E+00	3.88E-03	6.02E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Nitrites (NO2-)	g	3.74E-06	3.96E-07	9.38E-07	0.00E+00	2.34E-06	6.60E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Nitrogenous Matter (Kjeldahl, as N)	g	5.18E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.18E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Nitrogenous Matter (unspecified, as N)	g	3.39E-01	4.79E-02	2.84E-01	0.00E+00	7.39E-04	6.63E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Oils (unspecified)	g	1.44E+00	1.97E-01	1.13E+00	4.65E-06	2.84E-02	8.56E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Organic Dissolved Matter (unspecified)	g	1.85E-03	8.09E-04	1.46E-06	0.00E+00	3.54E-06	1.03E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Phenol (C6H5OH)	g	1.83E-01	2.55E-02	1.54E-01	4.74E-06	4.37E-04	3.24E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Phosphates (PO4 3-, HPO4--, H2PO4-, H3PO4, as P)	g	3.28E-04	5.19E-05	3.02E-05	0.00E+00	7.53E-05	1.71E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Phosphorus (P)	g	6.56E-03	9.00E-04	5.53E-03	0.00E+00	1.40E-05	1.13E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Phosphorus Pentoxide (P2O5)	g	4.49E-02	4.05E-02	4.25E-09	0.00E+00	8.01E-12	4.47E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Polycyclic Aromatic Hydrocarbons (PAH, unspecified)	g	3.46E-02	1.55E-02	1.73E-02	0.00E+00	3.38E-05	1.76E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Potassium (K+)	g	6.97E+00	9.57E-01	5.88E+00	0.00E+00	1.49E-02	1.21E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Rubidium (Rb+)	g	1.58E-02	2.16E-03	1.33E-02	0.00E+00	2.51E-05	2.73E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Salts (unspecified)	g	2.59E+01	2.33E+01	1.42E-03	0.00E+00	3.54E-03	2.58E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Saponifiable Oils and Fats	g	7.69E+00	1.06E+00	6.49E+00	0.00E+00	1.22E-02	1.33E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Selenium (Se II, Se IV, Se VI)	g	1.52E-03	9.00E-05	5.53E-04	0.00E+00	1.04E-06	8.72E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Silicon Dioxide (SiO2)	g	5.15E-05	5.47E-06	1.29E-05	0.00E+00	3.22E-05	9.10E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Silver (Ag+)	g	9.46E-04	1.30E-04	7.98E-04	0.00E+00	1.50E-06	1.64E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Sodium (Na+)	g	1.09E+03	6.03E+02	4.15E+02	0.00E+00	8.43E-01	7.20E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Strontium (Sr II)	g	1.40E+01	5.39E+00	8.01E+00	0.00E+00	1.57E-02	6.16E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Sulphates (SO4--)	g	1.14E+05	4.49E+02	1.11E+01	0.00E+00	9.65E-02	7.78E+01	0.00E+00	0.00E+00	1.13E+05	0.00E+00
(w) Sulphides (S--)	g	2.59E-02	3.77E-03	2.16E-02	0.00E+00	4.38E-05	4.79E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Sulphites (SO3--)	g	3.31E-05	2.63E-08	6.21E-08	0.00E+00	1.55E-07	3.28E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Sulphurated Matter (unspecified, as S)	g	5.33E-05	4.78E-05	2.51E-07	0.00E+00	4.73E-10	5.29E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Suspended Matter (unspecified)	g	8.30E+05	1.38E+01	3.17E-01	2.28E+00	6.46E-01	2.61E+00	0.00E+00	0.00E+00	8.30E+05	0.00E+00
(w) Tars (unspecified)	g	1.32E-07	1.80E-08	1.11E-07	0.00E+00	2.10E-10	2.13E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Tetrachloroethylene (C2Cl4)	g	2.16E-10	2.29E-11	5.42E-11	0.00E+00	1.35E-10	3.82E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Tin (Sn++, Sn4+)	g	3.04E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.04E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Titanium (Ti3+, Ti4+)	g	1.07E-03	5.74E-05	1.36E-04	0.00E+00	3.38E-04	5.39E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) TOC (Total Organic Carbon)	g	1.18E+01	1.61E+00	9.78E+00	0.00E+00	1.66E-01	2.02E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Toluene (C6H5CH3)	g	1.71E-01	2.34E-02	1.44E-01	0.00E+00	4.01E-04	2.95E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Trichlorethane (1,1,1-CH3CCl3)	g	4.88E-10	5.17E-11	1.22E-10	0.00E+00	3.05E-10	8.60E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Trichloroethylene (C2HCl3)	g	1.34E-08	1.42E-09	3.36E-09	0.00E+00	8.39E-09	2.37E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Triethylene Glycol (C6H14O4)	g	1.65E-02	1.75E-03	4.15E-03	0.00E+00	1.03E-02	2.92E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(w) Vanadium (V3+, V5+)	g	4.02E-03	9.00E-05	5.53E-04	0.00E+00	1.04E-06	3.37E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00

	Flow	Units	TOTAL	Coal Production	Diesel Production	Sulphuric Acid Production	Lime Production	Electricity Production	Road Transport	Agricultural Processing	Molasses to ethanol process	Sugarcane to molasses process
	(w) VOC (Volatile Organic Compounds)	g	5.51E-01	7.56E-02	4.65E-01	0.00E+00	8.76E-04	9.53E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(w) Water (unspecified)	litre	1.26E+03	1.11E+03	7.90E-04	0.00E+00	1.49E-06	1.41E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(w) Water: Chemically Polluted	litre	2.14E+04	1.20E+01	2.28E+00	0.00E+00	4.29E-03	1.61E+00	0.00E+00	0.00E+00	2.14E+04	0.00E+00
	(w) Xylene (C6H4(CH3)2)	g	1.48E+00	2.04E-01	1.25E+00	0.00E+00	2.46E-03	2.56E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(w) Zinc (Zn++)	g	9.84E-02	8.26E-02	5.62E-03	0.00E+00	2.48E-04	9.93E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(wr) Radioactive Substance (unspecified)	kBq	8.42E-05	7.58E-05	7.96E-12	0.00E+00	1.50E-14	8.38E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(wr) Radium (Ra224)	kBq	7.88E-02	1.08E-02	6.65E-02	0.00E+00	1.25E-04	1.36E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(wr) Radium (Ra226)	kBq	4.38E+00	2.16E-02	1.33E-01	0.00E+00	2.51E-04	4.22E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(wr) Radium (Ra228)	kBq	1.58E-01	2.16E-02	1.33E-01	0.00E+00	2.51E-04	2.73E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	(wr) Thorium (Th228)	kBq	3.15E-01	4.33E-02	2.66E-01	0.00E+00	5.01E-04	5.45E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	ethanol product	kl	1.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+00	0.00E+00
	Recovered Matter (total)	kg	9.21E-01	6.67E-01	1.59E-04	0.00E+00	3.00E-07	2.54E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Recovered Matter (unspecified)	kg	9.21E-01	6.67E-01	1.59E-04	0.00E+00	3.00E-07	2.54E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Recovered Matter: Iron Scrap	kg	2.59E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.59E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	sugar product	tons	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste (hazardous)	kg	1.70E-01	1.41E-01	1.33E-02	0.00E+00	2.50E-05	1.57E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste (incineration)	kg	5.74E-02	4.46E-02	7.33E-03	0.00E+00	5.33E-04	4.94E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste (municipal and industrial)	kg	2.16E-01	1.94E-01	1.43E-06	0.00E+00	1.15E-08	2.17E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste (total)	kg	4.97E+02	4.17E+02	5.63E-02	1.82E-02	6.26E-04	7.95E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste (unspecified)	kg	2.74E+01	8.78E-01	1.80E-03	1.82E-02	3.44E-06	2.66E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste: Highly Radioactive (class C)	kg	6.39E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.39E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste: Low Radioactive (class A)	kg	1.18E-02	1.32E-03	8.12E-03	0.00E+00	1.53E-05	2.34E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste: Mineral (inert)	kg	4.62E+02	4.16E+02	2.28E-02	0.00E+00	4.32E-05	4.60E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste: Mining	kg	3.31E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.31E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste: Non Mineral (inert)	kg	1.06E-02	8.54E-03	9.64E-04	0.00E+00	1.82E-06	1.09E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste: Non Toxic Chemicals (unspecified)	kg	4.59E-05	4.07E-05	5.93E-08	0.00E+00	1.12E-10	5.17E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste: Radioactive	kg	1.51E-03	2.11E-04	1.29E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste: Radioactive (unspecified)	kg	2.90E-05	0.00E+00	0.00E+00	0.00E+00	2.44E-06	2.65E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste: Slags and Ash (unspecified)	kg	7.08E+00	2.04E-01	7.73E-04	0.00E+00	1.46E-06	6.88E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Reminders:	E Feedstock Energy	MJ	2.22E+04	2.09E+04	5.49E+02	1.20E+01	7.48E-03	1.27E+03	-5.49E+02	0.00E+00	0.00E+00	0.00E+00
	E Fuel Energy	MJ	4.04E+03	2.81E+03	2.66E+01	-1.16E+01	2.69E+01	6.45E+02	5.49E+02	0.00E+00	0.00E+00	0.00E+00
	E Non Renewable Energy	MJ	2.63E+04	2.37E+04	5.75E+02	3.85E+00	2.69E+01	1.91E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	E Renewable Energy	MJ	1.27E+01	9.34E-01	2.46E-03	5.17E-04	4.46E-03	1.18E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	E Total Primary Energy	MJ	2.63E+04	2.38E+04	5.75E+02	3.85E+00	2.69E+01	1.92E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Appendix B1

Readings summary and re-calculated data for life – cycle calculations from literature

B1a : LITERATURE READINGS SUMMARY

Author	Study	System, and its boundaries	functional unit
Kadam, 1996	bagasse to ethanol for use as gasoline oxgenate, vs bagasse inceneration. Comparative LCA	Gasoline production inclusive; Scenario 1 involves gasoline use and bagasse open-field burning. Scenario 2 assesses bagasse conversion to ethanol and excess electricity production, plus reformulated gasoline use	1 tonne bagasse
Sims, 2001	Potential contribution of biomass in the energy forum;examples of projects in Australasia	N/A	N/A
Beeharry, 1996	Electricity generation from excess biomass of the sugar industry	Bagasse conversion to electricity is studied use of cane tops & leaves, and trash(excess boimass) is investigated	1 ton cane
Kaltschmitt, 1996	Several biofuels compared against their fossil fuel counterparts, a life-cycle analysis perspective	raw material cultivation, production and utilisation phases, compared against those of fossil fuels	1 ha agric-area for comparison of biofuels, useful energy (MJ) for comparison with fossil fuel
Macedo, 1997	CO2 and energy balance for bio-ethanol production & utilisation in Brazil 96/97 harvest yr life-cycle approach	cradle -to-gate analysis for energy accounting, and cradle-to-grave assessment for CO2 balance	1 ton cane
Bastianoni & Marchettini,1996	Bioethanol production from biomass is examined examined from a carbon balance, process efficiency and land requirement perspective to give an *emergy* analysis	US and Brazilian sugarcane to ethanol processes inclusive of agricultural processing, and italian grapes-to-ethanol processes	1 ha arable land, studied over a year
Prakash et al., 1998	Energy and CO2 analysis for ethanol from molasses process in India, a life-cycle approach	Cultivation process not included, only process energy analysis and referenced combusiton detail	1 l ethanol

B1a : LITERATURE READINGS SUMMARY

Author	Assessment criteria	Key Results	Commentary
Kadam, 1996	emmisions, COD	CO, SOx(30%), NOx(50%) are lower for scenario 2. Particulate emissions lower by factor of 30 COD higher for scenario 2 (ethanol process)	N/A
Sims, 2001		Source-to-product digrammatic illustration of biomass routes. Limitations similar to those of Bastianoni & Marchettini, 1996: land use competition, removal of nutrients from soil, transport of biomass to the conversion plant	N/A
Beeharry, 1996	Energy per t cane	Use of residue amounts to 565 kg of baggase equivalent per ton millable cane available for electricity generation. This corresponds to an equiv electricity output of 678 kWh/ t milable cane	N/A
Kaltschmitt, 1996	avoided emissions	70 kg CO2 equvalents can be avoided per gigajoule of substituted finite primary energy N2O and SO2 nitrogen oxides emissions are poor for all bioenergy carriers,compared to fossil fuels RME is the least favourable energy carrier wrt energy yield, but has most favourable emissions except fror nitrous oxides (worst)	N/A
Macedo, 1997	energy ratio avoided emissions CO2 balance	236 MJ/t cane fossil energy input into agric & industry phases, = 17.2 kg CO2/t cane Energy ratio (output/input) 9.2 avg, 11.2 top value 1.7 kg N20/ha/yr from fertiliser use=3.17 kg CO2/ t cane Net savings in CO2 emissions: 12.74E06 t C/yr	N/A
Bastianoni & Marchettini,1996	output/input energy ratio, fossil energy input per unit are, CO2 balance land required per unit energy delivered	Sugarcane: Brazil / Florida / Louisiana; Grapes: Italy energy ratio: 4.35 / 3.38 / 1.23; 0.31 fossil E J.ha/yr: 1.36E10 / 4.58E10 / 1.1E11; 7.71E10 CO2 av. G/ha/yr: 4.44E6 / 1.16E7 / 1.01E7; 1.87E6 Land (toe): 0.92 / 0.38 / 1.67	toe = ton of oil equivalent emergy analysis shows the processes are not sustainable due to land constraints
Prakash et al., 1998	energy ratio, figure of merit gross CO2 emissions	energy ratio: 2.15 net energy in bioethanol : 14.4 MJ/ nil kg carbon figure of merit : 14.4 MJ/kg Process energy requirement : 21.1 MJ/ l	figure of merit is net energy yielded from 1kg fuel (MJ)/gross CO2 emission from 1 kg fuel (kg)

B1a : LITERATURE READINGS SUMMARY

Author	Study	System, and its boundaries	functional unit
Ofoli & Stout, Goldemberg, Gieseler et al, cited by Prakash	energy yields for ethanol production	N/A	
Mohee & Beeharry, 1999	Life-cycle analysis of incorporated sugarcane bioenergy systems in Mauritius	Sugarcane plantation, harvesting, transportation and sugarcane processing steps included in system boundary Composting bagasse to use as manure on the cane fields(System B) vs normal practice (System A), both with electricity production is investigated. Incorporated steam management with composting is explored (System C)	kWh exportable electricity
Beeharry, 2000	A carbon balance analysis of bioenergy systems for electricity production compared to coal-based power generation systems	LCA-adapted methodology, full analysis of cultivation to conversion for the boimass, vs the equivalent for coal production and use Different system options for maximising biomass use are explored, see ref. For detail	1 kWh electricity
Sheehan et al., 1998 (NREL)	An overview of biodiesel and petroleum diesel life cycles	Biodiesel from soybean oil is investigated, agricultural processing through to combusition in an engine is analysed; similiarly for petroleum diesel	1 brake-horsepower hour(bhp-h)

B1a : LITERATURE READINGS SUMMARY

Author	Assessment criteria	Key Results	Commentary
Ofoli & Stout, Goldemberg, Gieseler et al, cited by Prakash	energy yield ratios (output/input)	source ratio irrigated corn 1.08 dryland corn 1.16 sugarcane 2.40 cassava 1.45 sorghum 1.92 sugarbeet 1.1 grain 1.4	N/A
Mohee & Beeharry, 1999	cane & sugar yeild / ha exportable electricity potential per t cane resource consumption (machine energy input)	Indicators A B C Cane yeild (t cane/ha) 66 85.8(+30%) 85.8(+30%) Elect. Export (kWh.t cane) 20 deficit of 12.4 58 (+190%) E for machinery(kWh/t sugar) 32 43 (+34%) 43 (+34%) Fertilisers (kg N/ t sugar) 21 16(-23) 16(-23%) air emmisions (t / t sugar) 16 17 (+6%) 17(+6%)	N/A
Beeharry, 2000	avoided emission, carbon closure	Indicator ref. Whole cane baled residue compost Elec(kWh.t cane) 41 158 276 58 Avoided CO2(kg/kWh) 1.137 1.082 1.081 1.087 Carbon closure 99 98 97 96	Carbon closure defined by Mann & Spath 1997, Beeharry's interpretation is wrong! But the figures are correct
Sheehan et al., 1998 (NREL)	energy efficiency, fossil energy ratio carbon balance	biodiesel energy eff: 80.55%; petroleum diesel energy eff: 83.28% Fossil energy ratio : 3.22 Of 169 g absorbed in agriculture, 148.39 end up in biodiesel; and then 148 g end up as tailpipe emission CO2 Net CO2 emissions reduced by 78.5% NOx emissions are 13% higher than those of petroleum diesel	efficiency defined as fuel product energy/ total primary energy fossil energy ratio= fuel energy / fossil energy inputs

B1b : ORIGINAL AND RECALCULATED LITERATURE FIGURES

Assessment criteria	study	reference fuel / output	figures	units	recalculated	units
	Bastianoni & Marchettini, 96	ethanol from grapes (Italy)			23.087	kg CO2 equiv/GJ finite primary E
avoided emissions	Kaltschmitt, 96		70	kg CO2 equiv/GJ finite primary E	70	kg CO2 equiv/GJ finite primary E
	Bastianoni & Marchettini, 96	ethanol from sugarcane (Louisiana)			91.818	kg CO2 equiv/GJ finite primary E
	Beeharry, 00	electrcity from bagasse (reference)	1.137	kg/kWh	227	kg CO2 equiv/GJ finite primary E
	Bastianoni & Marchettini, 96	ethanol from sugarcane (Florida)			253.275	kg CO2 equiv/GJ finite primary E
	Beeharry, 00	electrcity from bagasse (whole cane)	1.08E+00	kg/kWh	322	kg CO2 equiv/GJ finite primary E
	Bastianoni & Marchettini, 96	ethanol from sugarcane (Brazil)			326.471	kg CO2 equiv/GJ finite primary E
	Beeharry, 00	electrcity from bagasse (baled residue)	1.08E+00	kg/kWh	630	kg CO2 equiv/GJ finite primary E
	Macedo,97	ethanol	4.67E+07	t CO2/ yr	720	kg CO2 equiv/GJ finite primary E
	Beeharry, 00	electrcity from bagasse (composted bagasse)	1.09E+00	kg/kWh	837	kg CO2 equiv/GJ finite primary E
Fossil energy ratios	Bastianoni & Marchettini, 96	ethanol	0.31	grapes (Italy)		
	Berthiaume et al.,	ethanol from corn	0.98	maize, N. America		
	Bastianoni & Marchettini, 96	ethanol	1.23	sugarcane (Louisiana)		
	Bastianoni & Marchettini, 96	ethanol	3.38	sugarcane (Florida)		
	Bastianoni & Marchettini, 96	ethanol	4.35	Sugarcane (Brazil ,96)		
	Sheehan et al, 99	petroleum diesel	0.83	petroleum diesel		
	Sheehan et al, 99	soybean	3.22	biodiesel	0.81	energy efficiency ratio
	Macedo,97	ethanol	9.2	sugarcane (Brazil ,97)		
other energy ratios	Prakash, 98 cited	ethanol	1.08	irrigated corn	N/A	NA
	Prakash. 98 cited	ethanol	1.1	sugarbeet		
	Prakash, 98 cited	ethanol	1.16			
	Hovelius & Hansson, 99	RME	12.8			
	Hovelius & Hansson, 99	RME	7.5	winter cultivation		
	Hovelius & Hansson, 99	RME	2.4			
	Prakash, 98 cited	ethanol	1.4	grain		
	Prakash, 98 cited	ethanol	1.45	cassava		
	Prakash, 98 cited	ethanol	1.92	sorghum		
	Prakash, 98	ethanol	2.15	molasses		
Carbon closure	Beeharry, 01	electricity from sugarcane (normal practice)	99	%	N/A	N/A
		electricity from sugarcane (composted bagasse)	98	%		
		electricity from sugarcane (whole cane)	97	%		
		electricity from sugarcane (baled residue)	96	%		
	Macedo,97	ethanol	94.9	%		
	Sheehan et al, 99	biodiesel from soybean oil	90.2	%		

Appendix B2

Life cycle calculations for bio-ethanol production system

Carbon closure calculation (overall system)

Formula	**$100(1-(B+C+D)/A)$**
B,C,D =	carbon input from fossil energy input in all stages of the LC (agric & harvest, transport, conversion)
A=	carbon fixed in biomass during growth

Overall sugarcane-ethanol system

Mass cane	110.00 ton		
Consisting of:			
13% mass sucrose	14.30 ton		
15% fibre	16.50 ton		

Carbon input:

Sucrose	6.02 ton		(using molar mass ratio of 144/342)
Fibre/Bagasse	3.63 ton		(22% carbon in fibre)
TOTAL	**9.65 ton**	**=A**	

Fossil carbon input:

Coal	0.74 ton		
Diesel	0.067 ton		
% carbon in coal	70		
% carbon in diesel	83.62		calculated using the formula % C =76.99+(10.9*specific gravity) +(-0.76*sulphur content)
Carbon in coal	0.52 ton		
Carbon in oil	0.056 ton		assume s.g. =0.8, sulphur content = 2%
Total fossil Carbon	0.57 **ton**	**=B+C+D**	

applying the formula above,

Carbon closure = **94** %

Carbon closure calculation (26% allocation to molasses production)

Formula	**100(1-(B+C+D)/A)**
B,C,D =	carbon input from fossil energy input in all stages of the LC (agric & harvest, transport, conversion)
A=	carbon fixed in biomass during growth

Overall sugarcane-ethanol system

Mass cane	28.80 ton
Consisting of:	
13% mass sucrose	3.74 ton
15% fibre	4.32 ton

Carbon input:

Sucrose	1.58 ton		(using molar mass ratio of 144/342)
Fibre/Bagasse	0.95 ton		(22% carbon in fibre)
TOTAL	**2.53 ton**	**=A**	

Fossil carbon input:

Coal	0.74 ton	
Diesel	0.028 ton	
% carbon in coal	70	
% carbon in diesel	83.62	calculated using the formula % C =76.99+(10.9*specific gravity) +(-0.76*sulphur content)
Carbon in coal	0.52 ton	
Carbon in oil	0.023 ton	assume s.g. =0.8, sulphur content = 2%
Total fossil Carbon	0.54 **ton =B+C+D**	

applying the formula above,

Carbon closure = 79 %

Calculation of fossil energy ratio

Formula : Energy output (in fuel) / Fotal fossil energy input

Energy in 1 kl ethanol **24000 MJ**

Calorific values		
ethanol	MJ/kg	30
Coal	MJ/kg	28
diesel	MJ/kg	45

	overall bioenergy system		26% allocation to molasses		zero allocation to molasses	
Diesel input						
agriculture	30.06 kg		7.82 kg		0 kg	
sugarcane to molasses process						
molasses to ethanol process	0.54 kg		0.54 kg		0.54 kg	
transport	12.82 kg		5 kg		5 kg	
TOTAL	43.42 kg	1953.9 MJ	13.3556 kg	601.0 MJ	5.54 kg	249.3 MJ
Coal input						
molasses to ethanol process coal	0.74 ton	20720 MJ	0.74 ton	20720 MJ	0.74 ton	20720 MJ
Total Fossil E Input		**22673.9 MJ/kl**		**21321 MJ/kl**		**20969.3 MJ/kl**
Fossil energy ratio	1.06			1.13		1.14

Appendix C1

Primary data for the sugarcane to molasses process

RAW DATA FOR THE SUGARCANE TO MOLASSES PROCESS

	Input			Process Chemicals			Products & by-products
WEEK NO.	Cane	Water	water / cane	lime	flocculant	enzyme	Sugar
	tons		ratio	tons	kg	kg	tons
1	41683	24578	0.59	38	950	30	2420
2	54692	32562	0.60	29	625	90	3826
3	52431	26205	0.50	37	1300	60	3842
4	45460	21586	0.47	31	1250	15	3448
5	41767	21847	0.52	30	775	45	3481
6	56485	23349	0.41	39	500	0	4740
7	67744	21407	0.32	47	1000	0	6280
8	49892	20957	0.42	27	525	0	4703
9	65733	29899	0.45	46	600	0	6504
10	67043	33165	0.49	37	275	10	6918
11	67167	27354	0.41	47	650	0	6967
12	68518	29408	0.43	38	525	15	7344
13	65626	27240	0.42	33	625	60	7255
14	67585	19494	0.29	33	500	45	7453
15	71932	25002	0.35	35	375	0	8223
16	72694	23009	0.32	35	400	210	8483
17	73146	19823	0.27	37	550	0	8710
18	70800	19867	0.28	35	450	15	8479
19	60637	16985	0.28	30	500	90	7310
20	64158	21929	0.34	42	450	75	7991
21	70612	18960	0.27	35	650	0	8641
22	68654	22100	0.32	42	875	15	8630
23	68826	28085	0.41	49	1025	0	8951
24	67925	29127	0.43	46	750	0	8870
25	41825	19658	0.47	26	525	75	4830
26	67160	31097	0.46	44	675	225	8314
27	69620	32194	0.46	45	675	105	8655
28	63049	30693	0.49	37	750	165	7637
29	58892	30913	0.52	29	800	315	7181
30	54997	37737	0.69	33	650	180	6333
31	54359.5	33278	0.52	40	450	30	7457
32	59082	32524	0.55	35	675	225	6803
33	58474	36891	0.63	35	525	210	6797
34	50945	29880	0.59	26	700	45	5773
35	60195	24457	0.41	37	1025	360	6997
36	35348	23724	0.67	20	550	120	3874
37	51078	22704	0.44	24	575	480	5342
38	34853	22558	0.65	25	525	90	3512
39	17778	19187	1.08	13	575	180	1714
40	33730	22399	0.66	24	525	390	3529
41	51821	37881	0.73	26	825	120	5444
42	51505	33315	0.65	36	625	360	5399
43	45528	26027	0.57	23	725	45	4606
44	18682	25133	1.35	12	125	60	1755
TOTAL	2490132	1156188	22	1488	28625	4555	271422
AVERAGE	56594	26277	0.50	33.82	650.57	103.52	6168.68
MIN	17778	16985	0.27	12.00	125.00	0.00	1714.00
MAX	73146	37881	1.35	49.00	1300.00	480.00	8951.00

RAW DATA FOR THE SUGARCANE TO MOLASSES PROCESS (CONTINUED)

								Effluent	**Internal Flows**
WEEK					Fuel	moisture		Effluent	21 bar steam
NO.	Molasses	Bagasse	Filter cake	chemical	Coal	in bagasse	cane fibre	produced	to downstream
	tons	tons	tons	tons	tons	%	tons	m3	tons
1	2069	14453	656	293	3334	52	6997	9088	11739
2	3284	17326	469	478	2012	50	8734	5689	18658
3	2591	16356	629	481	1835	49	8350	594	18773
4	1874	13900	546	381	2069	49	7157		15062
5	1625	12834	501	353	1900	47	6829	9556	14704
6	2070	18293	678	490	1827	49	9275	9219	19536
7	2525	20956	813	577	1563	49	10755	6725	21984
8	1850	15032	599	400	1810	47	7955	13851	17009
9	2535	20275	789	577	1668	49	10375	16227	23182
10	2516	20182	805	596	1638	49	10293	6331	21693
11	2582	20150	806	581	1596	49	10321	5444	22872
12	2428	19877	822	614	1588	48	10330	12587	23346
13	2469	19023	788	588	1650	48	9843	10847	21741
14	2473	19264	811	588	1318	48	10067	16092	20360
15	2548	20753	863	663	1575	47	10904	12664	22982
16	2811	20753	872	608	1519	48	10800	9535	22513
17	2821	21116	878	652	1567	48	11001	8852	22693
18	2608	21179	850	633	1454	48	10990	9156	23113
19	2369	17832	728	480	1511	48	9253	7690	18171
20	2456	19599	770	553	1453	48	10127	8233	20885
21	2742	21710	847	614	1314	48	11261	7532	22502
22	2696	20875	824	568	1382	49	10680	8137	21212
23	2542	20308	826	620	1343	48	10499	8525	22379
24	2654	20248	815	618	1472	48	10614	8129	23228
25	1559	13749	502	302	1316	47	7276	8780	12889
26	2700	21474	806	584	1094	48	11102	4632	22784
27	2728	21288	835	628	1154	48	11155	6243	23043
28	2257	20337	757	536	1367	48	10508	7090	21026
29	2298	18526	707	513	1400	48	9693	6239	21671
30	1908	17956	660	484	1796	47	9544	6490	19355
31	2203	21678	773	519	1334	48	11236	6586	19618
32	2092	19865	709	493	1483	48	10347	4682	20940
33	2207	19690	702	506	1396	48	10268	28217	21652
34	1944	17177	611	430	1188	49	8803	2895	16034
35	2287	19876	722	561	1637	48	10375	14188	22918
36	1344	12199	424	331	1479	48	6345	9823	15021
37	1867	16979	613	431	1833	47	8994	8648	16777
38	1448	12115	418	307	1459	48	6357	14307	13801
39	883	6053	213	122	921	46	3246	12219	4928
40	1171	11572	405	300	1275	48	6073	8403	10279
41	2115	17026	621	489	1728	47	9041	9113	20068
42	1969	17002	618	492	1742	47	8951	0	20859
43	1940	14759	546	439	1750	48	7705	172	17619
44	924	6373	224	200	2009	49	3260	1259	10698
TOTAL	96982	777985	29851	21673	69759		403686	370689	842317
AVERAGE	2204.14	17681.48	678.43	492.57	1585	48	9175	8621	19144
MIN	883.00	6053.44	213.00	122.00	921	46.38	3245.854528	0	4928
MAX	3284.00	21710.00	878.00	663.00	3334	51.59	11260.977	28217	23346

RAW DATA FOR THE SUGARCANE TO MOLASSES PROCESS (CONTINUED)

	Internal Flows (continued)		**High Pressure Steam**		**Low Pressure Steam**		**Electricity**
WEEK	LP steam to		Boiler 1	Boiler 4	Boiler 2	Boiler 3	
NO.	mill	LP condensate	31 bar steam	31 bar steam	21 bar	21 bar	
	tons	tons	tons	tons	tons	tons	MWh
1	5451	5426	6225	28105	6979	6536	1299
2	8858	8284	16438	17125	6544	6754	1463
3	9323	7758	14721	16736	6184	6522	1347
4	7897	5193	10119	17219	6403	6437	1222
5	6681	5065	8206	17764	6484	6380	1285
6	9967	7542	14483	18117	7339	7590	1426
7	11750	9417	19174	18361	7308	7819	1518
8	8388	6815	15101	17244	5250	6122	1333
9	12686	9763	18137	18252	7710	7529	1497
10	12961	9701	20134	18079	6487	7601	1480
11	13351	10048	21067	17555	5603	7567	1469
12	12489	10201	21283	16992	7087	7282	1507
13	12700	9488	19672	17861	6636	7173	1466
14	11922	9339	19547	17014	6734	7003	1421
15	13211	10819	22305	17939	6417	7150	1513
16	13065	11091	22944	18523	7654	4671	1536
17	12764	10734	22711	16844	7364	8095	1551
18	13120	10998	22158	18128	7822	7582	1531
19	10086	8718	13497	18610	6865	7841	1361
20	11676	10469	19109	18505	6735	6828	1501
21	12497	11028	19994	18465	7011	7264	2302
22	11582	10730	20664	18842	5384	7636	1566
23	12785	10614	18648	18701	6781	7361	1470
24	13144	10660	19540	19203	7227	7395	1526
25	7069	6129	10016	15440	5495	4827	1122
26	12819	14286	21188	18221	6609	6887	1502
27	12884	12941	21599	18428	5756	7429	1582
28	12005	12121	18307	18623	6849	7206	1517
29	12544	13017	18245	17142	6688	6105	1490
30	10892	10187	15916	17909	5963	6513	1455
31	11589	9674	19322	19083	5618	5697	1520
32	13068	11707	17942	17168	6626	6667	1502
33	13329	12029	17793	17219	6731	7031	1457
34	9487	10056	14613	15523	5456	5267	1173
35	13669	13470	17459	18826	6529	6764	1496
36	8899	7402	7549	14889	5054	5384	1098
37	9689	9603	15103	17861	4465	6129	1310
38	7686	7231	8533	14130	4797	4701	1000
39	2298	2978	1645	10119	2937	3749	619
40	5051	6296	6658	12179	4473	4481	926
41	11298	9623	17742	17562	4423	6874	1449
42	11953	11338	15297	18265	6527	6892	1311
43	9289	10422	11534	17852	6614	6764	1243
44	4883	5220	3175	11221	5105	5841	851
TOTAL	468755	415631	705513	767844	274723	291346	61213
AVERAGE	10654	9446	16034	17451	6244	6622	1391
MIN	2298	2978	1645	10119	2937	3749	619
MAX	13669	14286	22944	28105	7822	8095	2302

Appendix C2

Primary data for the molasses to ethanol process

RAW DATA FOR MOLASSES TO ETHANOL PROCESS

	Distillation products				**Utilities and raw material consumption**				
Month	potable	industrial	absolute	feints heads	coal	power	water	steam	steam
	kl	kl	kl	kl	tons	kWh	kl	tons	GJ
Apr-00	2,914	64	628	60	2,730	681,308	65,065	23,045	65,432
May-00	2,074	64	501	51	1,858	516,339	49,051	17,569	49,351
Jun-00	2,098	107	391	51	1,841	535,728	47,087	15,937	44,677
Jul-00	1,823	107	411	72	2,277	539,015	53,277	15,139	42,051
Aug-00	2,915	8	598	102	2,422	607,283	53,660	18,604	51,730
Sep-00	1,776	44	306	52	1,554	390,631	29,203	12,042	33,761
Oct-00	3,676	85	633	79	2,857	575,988	62,815	19,963	57,026
Nov-00	3,038	23	561	71	2,407	578,481	58,853	18,546	52,738
Dec-00	2,215	90	335	54	2,025	484,717	44,767	14,875	41,863
Jan-01	3,146	18	546	68	2,648	496,571	43,574	18,750	53,292
Feb-01	2,984	114	398	69	2,623	594,525	54,506	19,153	53,601
Mar-01	2,107	37	362	46	1,574	330,972	27,085	12,615	35,023
Average	2,564	63	472	65	2,235	527,630	49,079	17,187	48,379
Minimum	1,776	8	306	46	1,554	330,972	27,085	12,042	33,761
Maximum	3,676	114	633	102	2,857	681,308	65,065	23,045	65,432

RAW DATA FOR MOLASSES TO ETHANOL PROCESS (2)

	Process chemicals						
Month	Caustic Soda 47%	Caustic Soda 100%	Formalin	MgSO4	CuSO4	Urea	cyclohexane
	tons	tons	tons	tons	tons	tons	l
Apr-00	18.44	12.87	0	1.18	0	6.00	972
May-00	16.64	11.61	0.004	0.73	0	6.50	1458
Jun-00	17.85	12.46	0.002	0.40	0	4.50	1458
Jul-00	5.64	3.94	0	0.58	0	5.50	2430
Aug-00	20.59	14.37	1.335	0.85	0	7.00	486
Sep-00	8.67	6.05	0.45	0.30	0	4.00	967
Oct-00	17.49	12.21	2.67	0.98	0	11.35	952
Nov-00	16.28	11.36	1.335	0.80	0	11.70	1428
Dec-00	17.75	12.39	1.335	0.80	0	8.00	1190
Jan-01	15.21	10.62	1.56	0.43	0	6.00	185
Feb-01	13.97	9.75	1.11	0.15	0	3.75	740
Mar-01	12.21	8.52	1.335	0.00	0	2.00	800
Average	15	11	1	1	-	6	1089
Minimum	6	4	-	-	-	2	185
Maximum	21	14	3	1	-	12	2430

RAW DATA FOR MOLASSES TO ETHANOL PROCESS (3)

	Gaseous emissions					Effluent
Month	CO2(fossil)	CO2 (renewable)	CO	NOx	SO2	total effluent
	tons	tons	tons	tons	tons	kl
Apr-00	6,745	2,549	32	5	13	60736
May-00	4,591	2,025	18	3	8	66994
Jun-00	4,548	1,800	24	-	9	66384
Jul-00	5,820	1,933	13	4	7	68942
Aug-00	6,190	2,567	18	5	17	71288
Sep-00	3,971	1,479	8	3	14	57589
Oct-00	7,337	3,443	8	6	20	72839
Nov-00	6,180	2,735	42	5	24	74844
Dec-00	5,200	1,936		4	12	66420
Jan-01	6,800	2,680		6	18	59516
Feb-01	6,736	2,413		6	18	64815
Mar-01	4,043	1,859		2	8	47835
Average	5,680	2,285	21	5	14	64850
Minimum	3,971	1,479	8	2	7	47835
Maximum	7,337	3,443	42	6	24	74844