A Life Cycle Assessment into energy recovery from organic waste: A case study of the Water Treatment Facility of SABMiller Newlands Brewery.

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Jonathan Cohen

Abstract

This thesis aims to assess the avoided environmental burdens of waste water treatment by additional on-site anaerobic waste water treatment prior to municipal treatment and disposal to river. It investigates the opportunity for further burden reduction by way of energy capture from generated biogas and re-integration within a plant-wide environment. The Life Cycle Assessment (LCA) was the analytical tool used to quantify burdens attributable to additional on-site effluent treatment, and further quantify the burdens avoided due to energy capture and re-integration.

This thesis was born from the opportunity for energy reclamation from biogas, generated by the SABMiller Newlands Brewery anaerobic digester. Western Cape power failures prompted the search for alternate energy sources, focusing SABMiller attention to the currently flared biogas emitted from the SABMiller Newlands effluent treatment facility.

The thesis investigates the environmental benefits of on-site effluent treatment prior to disposal to sewer. Environmental impact comparisons are made across 3 treatment configurations (involving combinations of SABMiller treatment and municipal treatment), and the added benefit of on-site effluent treatment is quantified. In addition, the burden profile of releasing effluent to river without treatment is also established as a benchmark for comparison.

Results from the LCA highlight the importance of adequate effluent treatment prior to disposal, including satisfactory effluent waste water stabilisation as well as the effective handling of gaseous emissions, found to be a key contributor to the burden profile of the municipal treatment facility. Power consumption was also found be a highly influential variable when comparing the burden profile of treatment alternatives. Particularly, the power consumed in moving effluent to the municipal treatment facility adds significantly to the power requirement of the treatment process. Power consumed from pumping effluent to Athlone constitutes approximately 19% of total power draw of the process. With improved on-site effluent treatment, opportunity presents itself for the direct disposal of effluent to river or local re-use, facilitating a significant reduction in power consumed.

The thesis reviews combined heat and power technologies in an effort to determine the most suitable energy reclamation technology applicable to the Newlands Brewery. In terms of SABMiller system requirements, a CHP system, utilising a gas engine as the prime mover was found to be the most suitable technology based on biogas flow-rates and compositions. However, this conclusion needs to be considered in light of the results of the 2nd LCA, which indicated that thermal use for steam generation results in comparatively lower environmental burdens system-wide. In extending the methodology presented by this thesis to other waste-water treatment facilities, refinement through the application of LCA to allow for predictions concerning the impact of context in addition to incorporating the expectations of a purely 1st principles thermodynamic approach is recommended. The waste water management system was found to generate a net surplus of power of 10 times the energy needed for the treatment process, allowing for a significant reduction in grid power consumption. With energy capture and re-integration, the burdens avoided extend beyond the boundaries of the waste water management system, as power consumption from the national grid can be reduced beyond the power requirement of the water management system.

The thesis maintains a generic approach in an effort to remain relevant across industry sectors. Energy generating technologies were reviewed in the context of fuel type (biogas) as opposed to industry or sector. The mass balance (and methodology) used to quantify and characterise biogas flow-rate and composition was developed to serve as a generic tool that can be used in light of limited process information. Ultimately, the thesis presents itself as a framework for assessment in pursuit of reduced environmental harm.

Dedication

I dedicate this work to my parents, Josy and Gillian Cohen, for their continued support and motivation throughout the completion of my degree.

Acknowledgements

I would like to thank all the people who assisted me in completing this research

A special thanks goes to my supervisor, Professor Sue Harrison, for her invaluable input and sustained commitment throughout the duration of this project. Also, a special thanks to my co-supervisor Dr. Harro von Blottnitz for lending me his extensive expertise in the area of Life Cycle Analysis and for his continued encouragement.

In addition, I would like to thank the all the staff with whom I interacted at SABMiller Newlands Brewery and at the Athlone Municipal Treatment Facility for their support and willingness in assisting me with the collection of data and information I required to complete this thesis.

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1. CHP: Combined Heat and Power
2. CI: Compression Ignition
3. COD: Chemical Oxygen Demand
4. EIA: Environmental Impact Assessment
5. GWP: Global Warming Potential
6. HHV: Higher Heating Value
7. HRSG: Heat Recovery Steam Generator
8. IPCC: International Panel on Climate Change
9. LCA: Life Cycle Assessment
10. LCI: Life Cycle Inventory
11. LHV: Lower heating value
12. SAB: South African Breweries
13. SHP: Single Heat and Power
14. SI: Spark Ignition
15. SS: Suspended Solids
16. VFA: Volatile Fatty Acids
17. VOC: Volatile Organic Carbon
18. WTF: Water Treatment Facility
19. WWT: Waste Water Treatment

Chapter 1: Introduction

1.1 Background

Awareness of the need for cleaner production in the process industries is becoming ever more apparent in today's world. Numerous approaches to alleviating the burdens placed on the environment by industrial processes are being considered and implemented across a range of industrial sectors to achieve the target of sustainable development (Penker, 2004). Sustainable development endorses the responsible use of renewable resources. Water and energy are the two most pivotal resources for human survival (Penker, 2004). Efforts to limit water and energy wastage have wide-spread benefits in the social, economic and environmental sectors of society.

Technology plays a large role in minimising environmental damage as a result of economic activity (Goodland and Daly, 1996). Many industrial companies are implementing sustainable strategies that maintain production rates whilst simultaneously limiting environmental burdens and waste production.

Renewable energy technologies are recognised through investment incentives for both government and private sectors. In May 2004, the South African Department of Minerals and Energy Department completed the first strategy document on energy efficiency and renewables, aimed at identifying sources capable of financially assisting the implementation of these technologies in industry. Furthermore, a target was set to produce 4% of the country's electricity from renewable sources by 2013 (www.eia.doe.gov/emeu/cabs/safrenv.html).

Figure 1.1 puts this requirement for "renewable" electricity into context by showing the trend of South Africa's consumption of energy from 2001 to 2004. (Statistics SA P. 4141, April 2004). As illustrated in Figure 1.2, the majority (71%) of energy consumed in South Africa is generated from the combustion of coal (well over 90% for electricity generation), containing 0.5-1.2% sulphur and up to 45% ash. Coal fired power stations are not required to scrub the sulphur-containing off gas, leading to acid rain and further environmental degradation (www.eia.doe.gov/emeu/cabs/safrenv.html).

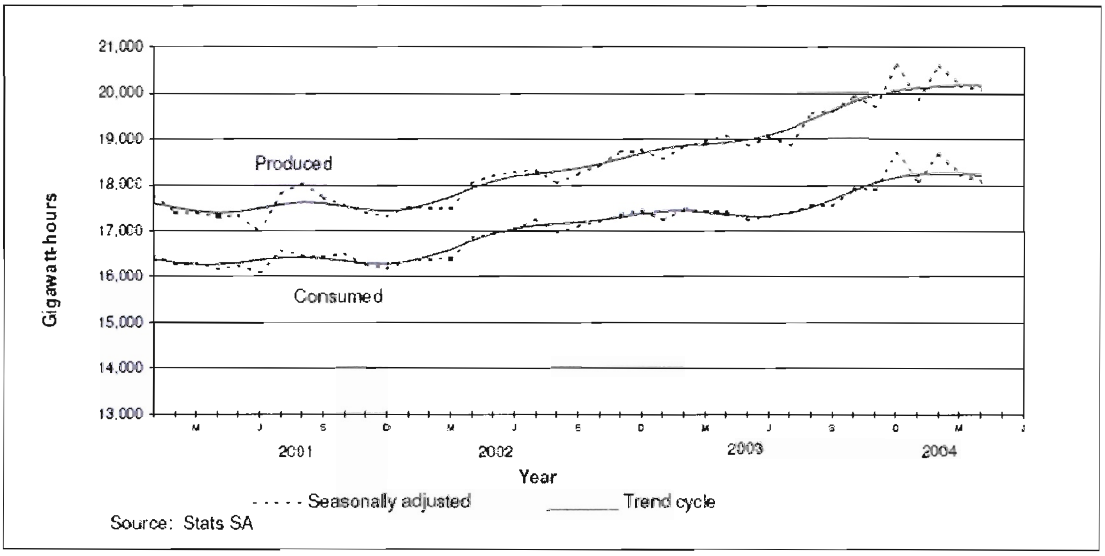


Figure 1.1: Increase in South African energy production and consumption (Statistics South Africa, Statistical release P4141, April 2004)

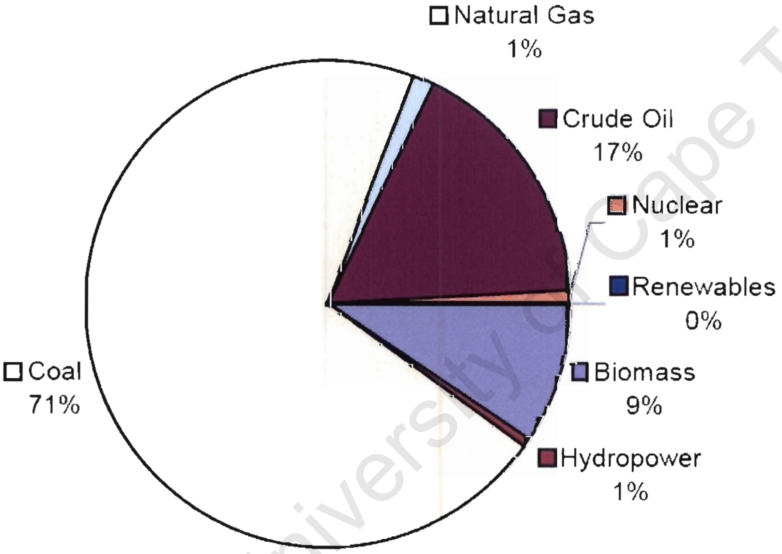


Figure 1.2: Primary energy sources utilized in South Africa (Department of Minerals and Energy, 2002)

With reference to water, South Africa is a water scarce country. At only 500 mm per annum, its average national rainfall is less than half of the world average. Current trends indicate that availability will not be able to match demand by the year 2030 (www.dwaf.gov.za).

Organic wastes in effluent streams from industrial activities are a major source of water pollution. Table 1.1 presents organic water pollution data resulting from anthropogenic activity in South Africa. The majority (41.3%) of South Africa's industrial contribution to organic waste is as a result of food and beverage production.

In light of this, environmental awareness, specifically in the brewing industry, has grown significantly in the last 20 years (Driessen and Vereijken, 2003). With the implementation of ISO 14001, the brewing industry has begun to invest extensively in biological effluent treatment (Driessen and Vereijken, 2003).

Table 1.1: Contribution by sector to organic water pollution in South Africa (www.worldbank.org/nipr/wdi98/table3.6.pdf)

Primary metals	**Pulp and Paper**	**Chemicals**	**Food and Beverages**	**Stone, Ceramics and Glass**	**Textiles**	**Wood**	**Other**
%	%	%	%	%	%	%	%
12.7	16.7	9.5	41.3	0.2	11	2.7	5.9

Knowledge about environmental emissions, including effluent quality and quantity, has become used in industry to improve the efficiency of brewing processes and minimization of waste as reported by Vereijken et al (1999), cited by Driessen and Vereijken, (2003). Other drivers in recent years for effluent treatment investment have included more stringent environmental legislation and discharge levies.

1.2 Current Situation

In addressing the need for efficient utilization of South Africa's natural resources in light of sustainable process operations, and in an effort to enhance environmental integrity, by minimizing burdens produced from their site, SABMiller Newlands Brewery commissioned an anaerobic effluent plant in July 2004 with the capacity of treating up to 18000 kg COD/day. The plant successfully reduces volatile fatty acid concentrations by up to 99%, and suspended solid concentrations by up to 50%, prior to being processed to sewer.

The biogas produced has the inherent potential of being utilized for its energy content. SABMiller has recognised this opportunity and has commissioned a study forming part of this thesis, into the viable options for energy capture.

1.3 Objectives and Rationale

This project aims to investigate the potential for value creation through burden reduction. Specifically, it addresses whether this is possible through the effective handling of brewery effluent. Opportunities for energy recovery through applicable technologies present a viable option in industry for value creation and waste minimization. This work aims to assess and incorporate the possibility of energy recovery through waste water treatment and biogas reclamation, and reflect upon the reduction in burdens as a result thereof. This facilitates a 'cradle-to-grave' assessment of the burdens attributable to brewery effluent treatment, the potential for burden reduction and the resulting benefit of energy capture, concerning both energy provision and burden reduction.

This thesis centres on studying the water treatment facility (WTF) at SABMiller Newlands Brewery as a case study to inform the general case of water treatment, burden reduction and potential energy generation from waste. It aims to characterise the burden profile of the SABMiller effluent plant, quantifying its impact on the environment in order to provide focus to assess opportunity for reducing the burdens of product streams (around the WTF) on the environment. Through this, it aims to result in implementable solutions to use the flared methane by re-integration within the plant.

The SABMiller Newlands Brewery provided an adequate environment with which to investigate this issue, quantifying the environmental impact of the SABMiller effluent plant relative to the subsequent reduction in burdens emitted with the re-integration of flared methane.

This assessment has far-reaching applications across industry sectors, where opportunity exists for enhancing energy efficiencies, specifically from effluent management and biogas reclamation. Better understanding of the environmental implications of energy reclamation within the framework of waste water treatment enables process optimisation in terms of avoided burdens.

1.4 Thesis Structure

The thesis presents a generic approach to understanding the flows and emissions originating from the SABMiller on-site effluent treatment facility. The approach was developed to have applicability outside the investigated case study. Having quantified effluent plant material flows and utility consumption, the environmental impact of on-site effluent treatment is investigated in the context of several alterative water management systems. Energy recovery technologies, applicable to the SABMiller Newlands WTF, are investigated, with recommendations made based on the characterised biogas generated and Newlands Brewery utility requirements. A final assessment is then made, quantifying the environmental burdens avoided due to energy reclamation from the biogas emitted.

Having placed the study in context, a review of the literature to be used in this study follows in **Chapter 2**. **Chapter 3** presents the effluent treatment facility mass balance. A detailed description of the goals, scope and system boundaries of the Life Cycle Assessment are presented in **Chapter 4**. This provides a framework within which the environmental burdens attributable to the effluent process are evaluated. The thesis positions the environmental impact of the plant in **Chapter 4**. Energy recovery technologies applicable to the SABMiller Newlands Brewery are then analysed in **Chapter 5** and compared in **Chapter 6** by making use of a generic decision-making framework. A re-assessment of the environmental impact of the plant, post energy re-integration is presented in **Chapter 7** and conclusions and recommendations are presented in **Chapter 8**.

Chapter 2: Literature Review

Chapter 2 aims to organise the relevant literature in a progressive manner such that the theory behind the investigative study is understood. The concept of industrial ecology is first reviewed with reference to sustainable development and the primary engineering tool used to measure and improve process sustainability, specifically Life Cycle Assessment, is presented. A brief overview of Western Cape waste water infrastructure is then presented followed by a review of anaerobic digestion and biogas utilization. Biogas scrubbing techniques are also reviewed, while utilization options are only reviewed in Chapter 6.

2.1 Industrial Ecology

2.1.1 Introduction

Industrial Ecology is a conceptual development of a framework with the holistic aim of reducing the burdens placed on the environment whilst addressing the question of sustainable development (Garner and Keoleian, 1995). Industrial ecology is defined as the study of the physical, chemical and biological interactions and interrelationships both within and between industrial and ecological systems. Industrial ecology is a focus within the field of sustainable development. A system to be studied is defined as an industrial ecosystem; industrial ecology aims to study the entire system, not just individual components (Korhene and Snakin, 2005).

2.1.2 The Industrial model and potential for its revision

The current industrial model can generally be considered a linear system (Korhene and Snakin, 2005). Raw materials are used in the manufacture of goods and services. These products are consumed and wastes are generated. Industrial ecology aims to re-arrange this system into a cascading arrangement, where the wastes from one process are utilized as the raw materials for another (Gibbs and Deutz, 2004). To achieve this, industrial ecology aims to view systems as interacting and co-depending. It provides a framework with which to interlink processes, plants and industries producing wastes, into an operating network, minimizing the industrial effluent material that is absorbed by natural sinks (Gibbs and Deutz, 2004) while maximizing resource productivity.

The nature of environmental problems is that they are not limited in their influence on any one particular area of an ecosystem but may impact throughout the ecosystem (Garner and Keoleian, 1995). Industrial ecology presents a shift in focus from waste reduction at a particular site (i.e. pollution prevention) to waste minimization from the larger system as a whole (Gibbs and Deutz, 2004). It offers a holistic approach, focused not so much on localised environmental impacts but rather on a significant systematic change required to eliminate environmental damage (Gibbs and Deutz, 2004). Through this, it establishes industrial ecosystems, as reported by den Hond, (2000) and referenced by Gibbs and Deutz (2004), between waste producing processes by closing material flows in loops of reuse.

Industrial metabolism requires the tracing of material and energy flows, as well as emissions and wastes between industrial and ecological systems (Garner and Keoleian, 1995). This helps to identify starting points for burden reduction. Potential improvements in resource utilization efficiencies can be identified by quantifying process inputs and generation of by-products and waste streams. Negative environmental implications can thus be reduced by increasing process efficiency within industrial systems (Garner and Keoleian, 1995).

Frosch and Gallopoulos (1989), cited by Garner and Keoleian (1995), defined the ideal industrial system as an analogue of its biological counterpart. In an ideal industrial ecosystem, the wastes produced by one process are consumed completely by other processes. No material would cross the industrial ecosystem-natural system boundary and neither system would impinge on the other. While this represents the ideal, industrial ecologists seek to work towards the concept.

2.1.3 Sustainable Development as a goal

The principal aim of industrial ecology is the promotion of ecologically sustainable development at the global, regional and local level (Garner and Keoleian, 1995). Sustainable development was defined by the Brundtland Commission as "meeting the needs of the present generation without sacrificing the needs of future generations" (WCED, 1987).

Sustainable development is comprised of three components: social, environmental and economic sustainability. This review will focus on the environmental aspect of sustainable development. However, the interlinking of the three components is key in the overall process assessment.

Environmental sustainability, a subset of sustainable development, can be directly dissociated into three guiding principles (Goodland and Daly, 1996):

1. Waste disposal should be kept within the assimilative capacity of the environment.
2. Raw material utilization should be kept within the regenerative capacity of the ecosystem, preventing depletion of non-renewable resources.
3. The rate of depletion of non-renewable resources should not exceed the rate at which renewable substitutes are developed.

The constituent components of environmental sustainability can be categorized broadly amongst three main principles, representing the pillars of environmental sustainability:

a. Sustainable Use of Resources:

Resources can be largely divided into two categories, renewable sources and non-renewable sources. Industrial ecology favours the use of renewable resources preventing the exhaustion of non-renewables and ensuring a sustainable future. One cannot assume that, because substitutes to non-renewable resources have been found in the past, that alternatives will be found in the future (Garner and Keoleian, 1995).

b. Ecological and Human Health

It is necessary to monitor the effect that industrial processes have on the surrounding environment and ecosystems. Human health is directly related to the condition of the planet on both local and global scales. In order to preserve and maintain an acceptable standard of human health, ecological systems need be maintained (Garner and Keoleian, 1995).

c. Environmental Equity

The third primary focus of sustainable development is in achieving an inter-generational and inter-societal equity.

a. *__Inter-generational equity:__* Depleting today's resources in an effort to meet short term objectives jeopardizes future generations and their ability to meet their needs. Industrial ecology alerts us to the potential of degrading non-renewable resources, negatively influencing ecological balance and health. (Garner and Keoleian, 1995).

b. *Inter-societal equity*: Developed countries, with fairly modest populations consume a disproportionate amount of resources in comparison to developing countries, indicating an inefficient utilization of raw material world wide. (Garner and Keoleian, 1995).

Sustainable development is an integral aspect of industrial ecology. The two concepts complement each other and support an approach to maintaining environmental integrity into the future, whilst accommodating the industrial needs of the present.

At the company level, sustainable development aims to establish a balance between economic, environmental and social elements (Harrison and Dennis, 2005). Balancing the creation of capital by the provision of products or services, limiting the impact of that provision on the finite resources available and limiting the impact on the needs and quality of life, is referred to as achieving the triple bottom line. The incentive for achieving the triple bottom line lies in the recognition by industry of the added benefit in profits that can be achieved by operating sustainably in all three categories.

2.1.4 Tools used in Industrial Ecology

Systems analysis forms the centre of an analytical basis for an industrial ecology study. Life Cycle Assessment (LCA) is a useful tool in this approach (Seager and Theis 2002). A systems analysis intrinsically incorporates a holistic approach to environmental analysis.

The common denominator of all investigative tools is that they are a function of the system boundaries defined. Inherent to the industrial ecology definition is the concept that, with a continual expansion in system boundaries, "supraoptimal" solutions may be found (Seager and Theis 2002). By co-ordinating the activities of all components into a larger, more intricate system, as opposed to combining the individual best options for each subsystem, an outcome more in line with the basic intrinsic concept of industrial ecology will emerge.

LCA is a method for assessment of the environmental impact of products, processes or services from raw materials to waste products. This assessment method can be used not only as a comparative tool for alternate production routes but also to highlight aspects such as parts of the product or process life cycle that are critical to the overall environmental impact (Chevalier *et al.*, 2003).

The LCA enables companies to incorporate into their environmental impact assessment the environmental implications of both their upstream and downstream activities, thereby empowering them to further mitigate harmful emissions attributable to these stages. The inter-connected industrial system in which raw materials are consumed and products are made is considered with attention given to both the products and by-products (including wastes generated).

2.2 *Life Cycle Assessment*

LCA is a key tool by which the objective assessment of environmental burdens is conducted. Although the methodology has its limitations, it continues to be uniformly applied and widely agreed to encompass the appropriate scale of an environmental analysis required. Pillay *et al.* (2003) described Life Cycle Assessment as a systematic way to evaluate the environmental impacts of products or processes by following a scientific methodology. It can be used to target opportunities for reducing environmental burdens created by a process or product (the focus of this study) or in selection of process technology, raw materials or energy sources.

In this Section, the life cycle methodology is presented. The impact categories used to analyse environmental burdens are discussed and the major contributors emphasized. In addition, the applicability of the LCA methodology to the energy analysis presented later in this thesis is assessed by review of academic studies that incorporated the LCA methodology in their quantification of burden avoidance resulting from changes in the configuration of energy generating systems.

2.2.1 Definition

An environmental LCA is a methodological framework that evaluates the environmental effects and burdens associated with any given activity from the initial gathering of raw materials from the earth to the point at which all materials are returned to the earth ("cradle-to-grave" approach). All activities related to the product life cycle incur environmental impacts due to the consumption of resources and emissions of substances into the environment.

These environmental impacts include climate change, stratospheric ozone depletion, tropospheric ozone (smog) creation, eutrophication, acidification, toxicological stress on human health and ecosystems, the depletion of resources, water use and land use. Environmental impact can be assessed in these, or similar, categories as midpoint indicators. Alternatively some researchers create an overall burden indication through the weighted average of impact categories.

The Society of Environmental Toxicology and Chemistry (1993) defined the LCA as "*an objective process to evaluate the environmental burdens associated with a product, process or activity, by identifying and quantifying energy and materials used and waste released to the environment, and to evaluate and implement opportunities to effect environmental improvement.*"

The definition of LCA given in the South African Bureau of Standards (SABS) and the International Organisation for Standardisation (ISO) 14040 standard (1997) is as follows:

> *LCA is a technique for assessing the environmental aspects and potential impacts associated with a product, by*
>
> - *Compiling an inventory of relevant inputs and outputs of a system*
> - *Evaluating the potential impacts associated with those inputs and outputs*
> - *Interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study*
>
> *LCA studies the environmental aspects and potential impacts throughout a product's life (i.e. cradle-to-grave) from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health and ecological consequences.*

Figure 2.1 presents a graphical representation of the LCA process replicated from Friedrich (2001), as adapted from SETAC (1997) and Wenzel et al, (1997).

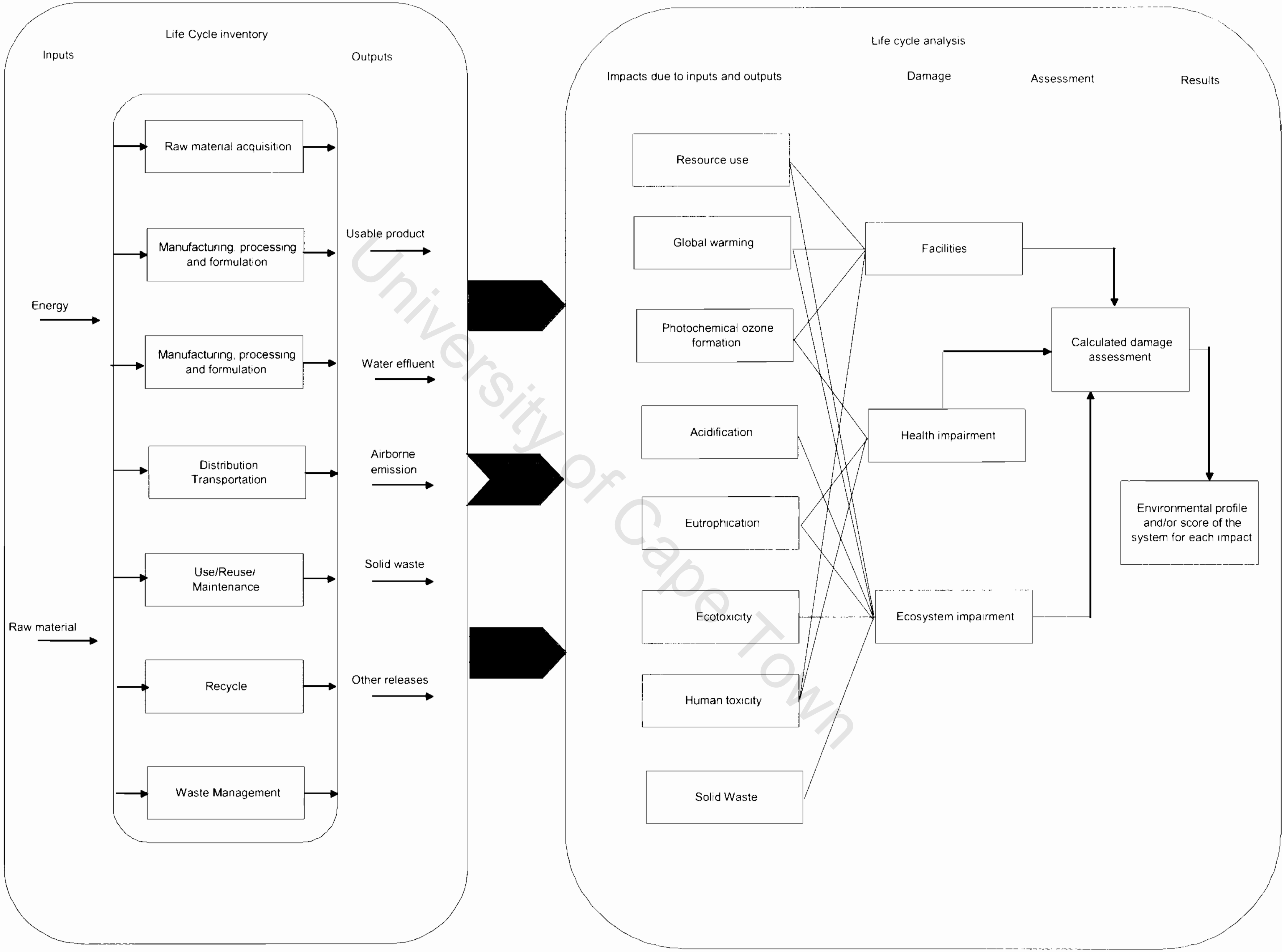


Figure 2.1: Graphical representation of the LCA (Friedrich, 2001)

2.2.2 The Boundaries of an LCA

The scope of an LCA needs be limited within defined system boundaries. Typical system configurations studied include a "cradle-to-grave" system including all contributions of raw materials and product disposal or a reduced "cradle-to-gate" approach, where the system is defined until product formation, but excluding use and disposal.

In either approach, the system is defined by that part of the process which contains the operations of interest. Including all material and energy flows, that which surrounds the system is denoted the environment. Any material entering or leaving the system crosses the system boundaries, and can be regarded as material taken in from or released to environment (Dewulf and Van Langenhove, 2005).

The placement of system boundaries are debated in the scientific community. System boundaries are commonly a function of spatial distance and geographic significance. System boundaries are also often defined in light of limited or inaccurate information pertaining to certain aspects of the process or product identified. The difficulties experienced by LCA practionioners in the placement of system boundaries are characterised through comparison of the work of Suh and Rousseaux (2001), Ozeler et al (2005) and Rafaschieri et al. (1999) below. This highlights the subjectivity and influence inherent in boundary definitions.

Suh and Rousseaux (2001), in an investigation of 5 alternative wastewater sludge treatment scenarios in the European context, did not take into account landfill gas treatment systems in the thermal recovery of energy generated by incineration or anaerobic digestion, so as to limit system boundary expansion. The same study excluded the treatment of waste liquids and gases rejected in the head of the waste water plant or stabilised in odour control systems.

In an analagous LCA by Ozeler et al (2005), a case study based in Ankara, Turkey, assessing five different municipal solid waste management methods, the system boundaries were complex, broad and defined as "*the moment when material ceases to have value, becoming waste and when waste becomes inert landfill material or is* *converted to air and/or water emissions or regains some value"*. However, in this study, the 5 different treatment methods originated from MSW management in different geographical areas of Turkey. Furthermore, it was assumed that solid waste from 5 of the 8 incorporated districts would not be routed to their geographically allotted landfill site, but rather routed via transfer stations to the landfill site servicing the waste originated from the other 3 districts.

In a study closely related to this one, Rafaschieri et al. (1999) carried out an LCA comparing electricity production from poplar energy crops with conventional fossil fuels by way of biomass gasification. In that LCA, CO_2 emissions were not considered for biomass combustion, although emissions caused by extraction, processing, transport and combustion of fuel for transport were completely taken into account.

2.2.3 Limitations of the LCA

There are 2 categories of problems facing LCA practioners in South Africa. The first set is related to the LCA methodology in general, the second set of problems is specific to South Africa.

Riva et al., (2006), commented on the most relevant challenges linked with the general LCA methodology:

- Lack of reliable data for various stages of the life cycle
- Homogeneity of data: data collected inside each single industry are used with data collected from sources or databases that often ignore the method used for the data collection or estimation.
- Temporal homogeneity: data that are used in conjunction often originate from or refer to different time periods, and this can cause inaccuracy in comparisons among different technologies
- Choice and definition of environmental indicators used for classification of impacts caused by the emission inventory.

A comment on work by Van Engelenburg and Nieuwlaar (1992) by Riva et al., (2006) highlighted uncertainties in data used in an LCA to provide an overview of the environmental impacts of conventional sources of energy. In this case, the limitation was addressed by distinguishing two cases per technology assessed, one of which estimated a low value of an indicator, the other estimated a high value of an indicator.

In the same paper, an LCA carried out by the Norwegian Institute of Technology (Bakkane, 1994), with the objective to present environmental life cycle data for Norwegian oil and gas production is commented on as follows: "*The report is very precise with regard to scope, limitations and definitions of various stages, however, it is weak with regard to estimating uncertainties and accuracy of the data used and the results produced*".

Critics argue that Life Cycle Assessments cannot cover all issues or every part of complex industrial systems and, therefore Life Cycle Assessments will always be incomplete in some way (Friedrich and Buckley, 2002).

A classic problem associated with LCA methodology is the problem of allocation. Allocation has been defined by Ekvall et al (2005) as, '*...the partitioning of environmental burdens and other material and energy flows to and from a technological activity between the products for which the activity is used...*". The problem is to define what percentage of the environmental burden emitted by an activity should be allocated to the product under investigation. It has been established that appropriate choices of allocation (and system boundaries) should be focused by the purpose of the LCA study (Ekvall et al., 2005) and geared towards facilitating the isolation of the specific products or processes being compared.

2.2.4 The LCA Model and Methodology

The LCA framework was developed by the Society of Environmental Toxicology and Chemistry (SETAC). The structured approach consists of four aspects: goal definition and scoping, detailing the life cycle inventory, impact assessment and improvement assessment.

2.2.4.1 Goal Definition and Scoping

This initial stage defines the aims and purpose of the LCA and the outcomes required. It defines the system boundaries and assesses all assumptions made throughout the Life Cycle Assessment (Dewulf and Van Langenhove, 2005). This section of the LCA should also specify the intended audience and application of the LCA

The scope of the LCA is a description of the product system in terms of the defined system boundaries and a functional unit. The functional unit is a normalised basis that enables the direct comparison of alternative products or processes (Rebitzer et al., 2004). Usually the functional unit is a unit of the service of the product (Curran, 1996). The purpose and scope should also be defined in relation to how the results are to be used (Garner and Keoleian., 1995).

Generally all operations that contribute towards the life cycle of the product or activity under investigation are enclosed within the system boundaries. These can be illustrated by the generalized cradle-to-grave flow diagram, reproduced from Curran (1996) in Figure 2.2. The inputs and outputs of processing the energy resources into usable fuels, illustrated as energy inputs in the Figure 5.1 are also included with the LCA investigation. Those processing steps can also have negative implications on the environment.

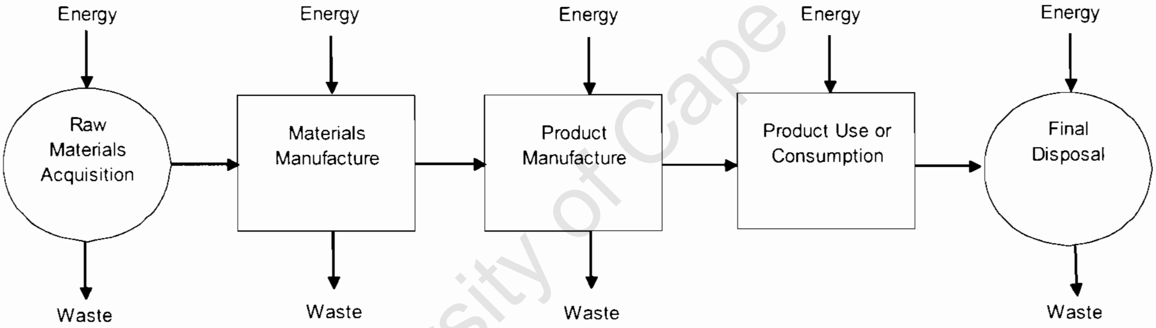


Figure 2.2: Generic life cycle assessment cradle-to-grave approach (Curran, 1996)

Although all unit operations that contribute to the life cycle of the system are included in the system boundary, the boundaries are not endless. The effects attributable to the unit processes contributing to the procurement of energy or raw material to be used in the process, relative to the effects resulting from the outputs directly attributable to the process, become negligible as one moves further away from the system assessed (Curran, 1996).

2.2.4.2 Life Cycle Inventory (LCI)

The LCI is a quantitative account of the resources used and released to the environment, based on the defined system boundaries and conditions. It includes raw material acquisition from the earth, processing of raw materials, intermediate product manufacture, product transportation, product distribution, product use and final disposition (Rebitzer et al., 2004). The data is collected with the ultimate aim of modelling the system. Hence boundary flows during the life-cycle of the product or process are described per defined functional unit (Rebitzer et al., 2004). Figure 2.3 adapted from ISO 14041 and duplicated from Friedrich and Buckley (2002) presents the main steps in a simplified diagram involved in producing an LCA inventory:

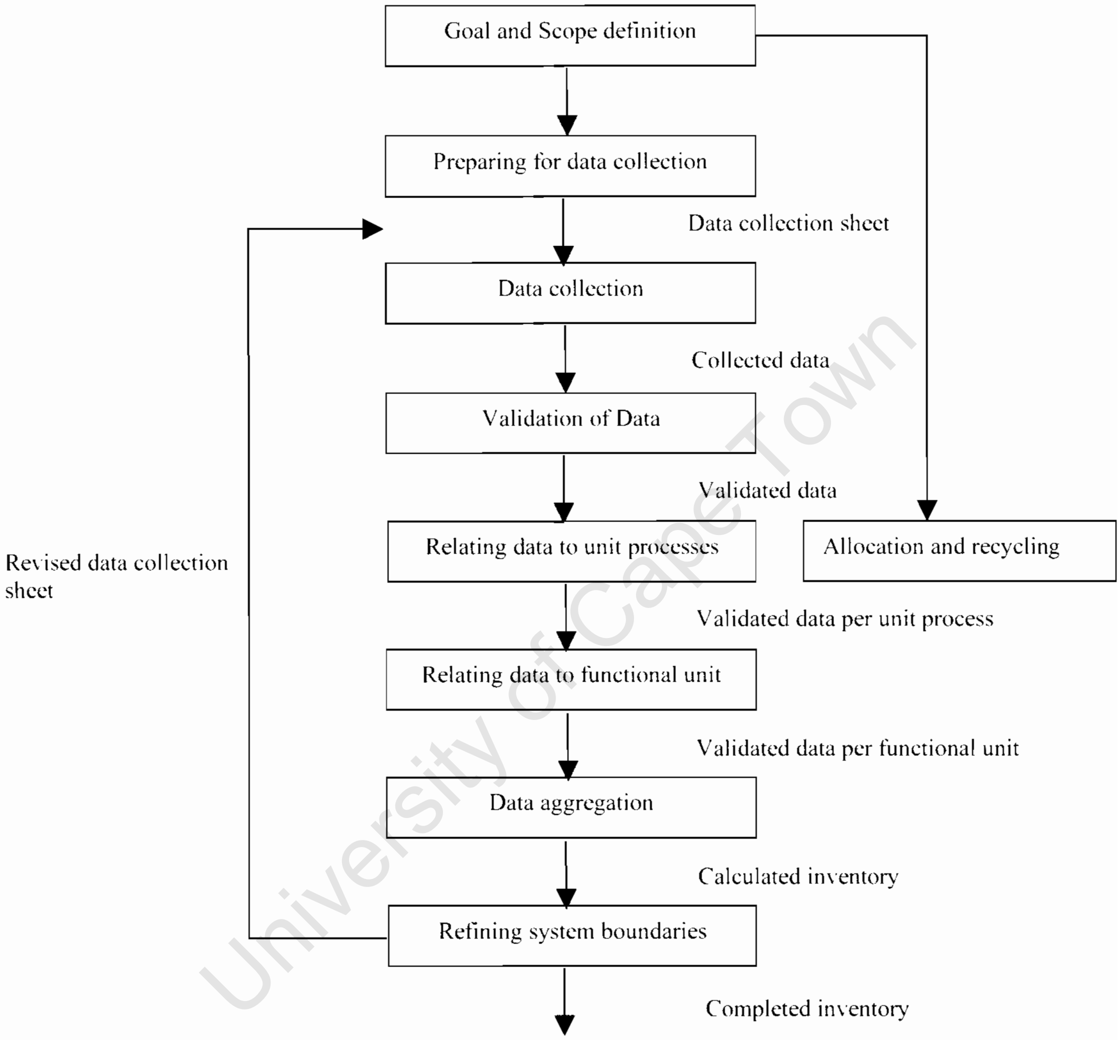


Figure 2.3: Inventory analysis procedure (duplicated from Firedrich and Buckley, 2002 as replicated from ISO 14041)

Conclusions drawn need be specific to the product, or process analysed. They are applicable for the particular study and address the original goals and objectives. One is unable to extrapolate results or generalize results for other processes, products or activities based on conclusions arrived at for any particular study (Rebetzer et al., 2004).

Usually, the calculation facilities of an adequate LCA software package are used here. A review of literature indicates the most common LCA software used is GABI 3 and Simapro. In this assessment the Simapro^{TM} life cycle analysis tool was used.

2.2.4.3 Impact Assessment (IA)

Impact assessment translates the results of the LCI into environmental impact measures by interpreting the emissions in terms of their actual detrimental effects (Gibbs et al., 2004). By doing so, the IA reduces the complexity and volume of the inventory data by converting the data into contributions to defined impact categories (Friedrich and Buckley, 2002). An Impact Assessment consists of three stages: classification, characterisation and either valuation or interpretation (Dewulf and Van Langenhove., 2005).

Classification involves defining and associating the various inputs and outputs to certain impact groupings, so that quantification in terms of the impact groups can be made. SETAC lists four general impact categories (Dewulf and Van Langenhove., 2005):

1. *Environmental or ecosystem quality*
2. *Quality of human life (including health)*
3. *Natural resource utilization*
4. *Social welfare*

These 4 general impact categories are elaborated upon in order to establish specific environmental focus points (impact categories) towards which the contributions from a system are investigated. The impact categories are defined within the scope of the investigation, and should be relevant to the goal of the LCA. The CML 2 baseline 2000 V2.1 assessment method allocates emissions according to their contribution towards the following impact categories:

- Acidification
- Abiotic depletion
- Photochemical oxidation
- Eutrophication
- Global warming
- Ozone layer depletion

- Human toxicity
- Fresh water aquatic ecotoxicity
- Marine aquatic ecotoxicity
- Terrestrial ecotoxicity

It is not uncommon for emissions from a process (or product life cycle) to contribute to 2 or more impact categories, although it is unlikely the contributions will carry the same weight to the relative impact categories.

Characterisation is the development of unit descriptors, as outcomes in conversion models used to translate the LCI data collected into a practical figure. For example, BOD data could be expressed as a fish mortality rate [Curran, 1996] or sulphur emissions could be expressed in terms of a contribution to acidification. Furthermore potency factors are used to express an emission to each environmental theme in terms of a uniform quantity. For example, a contribution to global warming is related to the effect of the reference CO_2. Methane has a potency factor of 21 fold CO_2. Once all the substances in a category are expressed in terms of the relevant equivalent or reference substance (in the case of global warming, the equivalent is CO_2), these can be summated resulting in a single score for each respective impact category. This procedure enables the development of the environmental profile of a system, which can be compared to the environmental profile of other systems across the relevant impact categories (Friedrich and Buckley, 2002).

Valuation involves the dimensionless weighting of the various impacts so that they can be assimilated between the impact groups. This makes it possible to tally a global environmental score by scaling the environmental profile with appropriate weighting factors which express the relative importance among the effects (Rafaschieri et al., 1999). Some members of the scientific community avoid or postpone this evaluation methodology to the end of the LCA, due to its relative subjectivity; however still recognising its use for comparative purposes (Rafaschieri et al, 1999).

Valuation is however used extensively and successfully in LCA studies such as Suh and Rousseaux (2001), Chevalier and Meunier (2005) and Rafaschieri et al (1999). In addition, Graedel and Allenby (1995) as cited by Ozeler et al. (2005) have completed extensive work around valuation methodology.

The EcoIndicator '99 impact methodology (for example) characterises distinct types of damage including damage to human health, damage to ecosystem quality and damage to resources. Scientific methods are used to relate the impact of a process and its damage. The weighting step expresses characterised impacts as points (pt), according to the EcoIndicator value system, which assess impacts according to their damage category (Chevalier and Meunier, 2005). Ekvall et al., in the editorial of the Journal of Cleaner Production (2005), reports on the further development of this assessment method. In comparing LCA studies, work is being done in expressing environmental impacts in terms of monetary units when environmental impacts need to be compared with other costs or benefits that by their nature are expressed in terms of money.

The alternative (and widely used) method at this stage regards decision making as explicit tradeoffs among different impacts. This method is known as ***interpretation.*** As reported by Friedrich and Buckley (2002), interpretation is performed in interaction with the three other phases of the LCA. The three principle steps of interpretation are: Identification of the significant issues based on the inventory and the impact assessment phases of the LCA, evaluation and conclusion and recommendations and reporting (ISO14043, cited by Firedrich and Buckley, 2002)

2.2.4.4 Improvement Assessment

This component encompasses an evaluation of the opportunities for burden reduction, associated with material and energy use and the subsequent environmental benefits to be incurred during the life cycle of the product or process. The opportunities for burden reduction incorporate all measures available for modification including product change, raw material changes and waste management, amongst others (Curran, 1996). Although there is no accepted methodology employed to complete this aspect of the LCA, it does facilitate environmentally conscious choices of production methods.

2.2.5 Description of the impact categories

2.2.5.1 Acidification

Acidification is caused by acid depositions of the three main pollutants: sulphur dioxide (SO_2), nitrogen oxides (NO_x), and ammonia (NH_3). These have a negative impact on water and soils. The resulting increase in soil acidity mobilises different fixed ions, which are subsequently absorbed by plants with harmful effects. Acidic soil run-offs harm aquatic ecosystems in rivers and lakes. The eco-changes attributable to acidification cause a resulting change in soil and water pH influencing soil and aquatic organisms. Damage is also visible on man-made limestone and marble structures (Hauschild and Wenzel, 1998). The reference substance used in characterisation is sulphur dioxide, SO_2.

2.2.5.2 Abiotic depletion

Abiotic depletion refers to the consumption of non-renewable and renewable abiotic resources. Abiotic resources are natural resources including energy resources such as iron ore and crude oil, which are regarded as non-living. There has been much work focussed on the characterisation of the impact category abiotic depletion, and as a result of being one of the most widely discussed impact categories, there are various unit descriptors used to describe this impact depending on the goal and scope of the LCA (http://www.leidenuniv.nl/). The reference substance used in characterisation is lead, Pb.

2.2.5.3 Toxicity indicators

Fresh water aquatic toxicity, marine aquatic ecotoxicity, human toxicity and terrestrial ecotoxicity are equivalent toxicity measures differentiated by the ecosphere into which they are released. Ecotoxicity is an indicative measurement of the concentration of chemicals in the environment and the resulting impact of those concentrations on bio-organisms. The reference substance used across eco-spheres is 1,4 dichlorobenzene, 1,4-DB.

2.2.5.4 Eutrophication

Eutrophication refers to the oversupply of nutrients such as N and P in soils and water. In aqueous systems, eutrophication results in excessive algal growth causing oxygen depletion and associated aquatic death. Eutrophication in soils results in a loss of biodiversity and results in frequently deleterious effects that can be of great concern to the user of the resource (Smith et al., 1999).

The reference substance used in the characterisation calculations take into account the amounts of phosphorus and nitrogen a substance can release into the environment when degraded. The reference substance used is phosphate, PO_4.

2.2.5.5 Global warming

Greenhouse gases absorb infrared radiation emitted by the earth, thereby upsetting the earth's natural radiation balance. This results in an increase in atmospheric temperature. The consequences of ensuing global warming include rising sea levels with ice-cap melting, regional climate changes, spreading of deserts, floods etc.

The characterisation factors used in the modelling of global warming were developed by the intergovernmental panel on Climatic Change (IPCC), an institution established by the UN Environmental Programme (UNEP) and the World Meteorological Organisation (WMO). The reference substance used is carbon dioxide (CO_2). The equivalency factors are sometimes termed global warming potentials (GWP) and are expressed as kg carbon dioxide equivalents per kg of gas.

2.2.5.6 Ozone layer depletion

Ozone layer depletion refers to the reduction in the amount of ozone in the stratosphere. The ozone layer prevents harmful wavelengths of ultraviolet light from passing through the Earth's atmosphere to its surface. The observed reduction in the amount of ozone in the stratosphere led to the adoption of the Montreal Protocol banning the use of chlorofluorocarbons (CFC's) and other ozone-depleting chemicals such as carbon tetrachloride, trichloroethane and bromine compounds known as halons. A complicated series of both solid and gaseous phase reactions are involved with a limited number of substances in ozone layer depletion (Hauschild and Wenzel, 1998). The resulting impact on humans includes diseases such as cancer or cataracts. The reference substance used for characterisation is trichlorofluoromethane, CFC11.

2.2.5.7 Photochemical oxidation

Smog is found in areas where vertical dispersion of air pollutants is restricted. Usually air temperatures decrease with increasing height above ground. Heated air layers near the earth's surface rise, causing the emitted air pollutants to be dispersed vertically and diluted.

With smog formation in winter, ground temperatures are sometimes lower than those of the upper atmospheric layers, causing the air to stay near the ground, restricting dispersion of pollutants (http://www.ec.gc.ca). Subsequently, the higher humidity levels in winter enable the conversion of sulphur dioxide to sulphuric acid, causing the smog to be acidic. Acid smog causes breathing problems and eye irritations.

Summer smog is created primarily by two pollutants, nitrogen oxides (NOx) and volatile organic compounds (VOCs). Often seen as a yellowish brown haze over the city during the summer months, smog is formed by the interaction of sunlight and these pollutants which originate from the burning of fossil fuels (oil, gas, diesel, and coal) in industry and motor vehicles, resulting in the formation of low level ozone (http://www.epa.vic.gov.au). Problems associated with summer smog include breathing problems and greater aggravation of existing heart and lung problems (http://www.epa.vic.gov.au).

The reference substance used in the characterisation calculations (or equivalency factors) is C_2H_4.

2.2.6 Applicability of the LCA methodology to evaluating renewable energy technologies

In recent times, environmental issues have been receiving increasing attention when evaluating the cost effectiveness of one energy source over another (Riva et al., 2006), and many LCA studies have been carried out on energy producing processes. Pehnt (2005) attributes this interest to the ever increasing requirement of climate gas mitigation and electricity system capacity deficits, market restructuring and deregulation.

Generally, results indicate reductions in environmental impact when comparing renewable energy sources to fossil fuels. While it is not feasible to present a comprehensive review of all renewable energy focussed LCA's, the following presents studies according to representative themes with their conclusions and implications for the use of LCA in the renewable energy industry.

1. *Dynamic systems and resulting implications of LCA's methodology as a policy making tool*

The difficulty of energy focused LCA's according to Pehnt (2005) lies in process and technological improvement. Pehnt argued that when incorporating the rate of technological development, in time, the environmental impact of what is considered today an environmentally friendly technology could potentially soon exceed a technology considered environmentally inefficient today. Factors such as improved efficiency, emissions characteristics, increased lifespan, improvements with regard to energy converters and advances with regards to services originating from transport systems will all contribute to further reductions of environmental impacts of renewable energy systems (Pehnt, 2005). Pehnt attempted to incorporate this time dimension in view of future technological developments into his analysis of renewable energy technologies. Pehnt went on to acknowledge the challenge of expanding the system boundaries, by highlighting rebound effects such as behaviour changes and the likelihood of increased consumer expenditure due to saved energy costs.

Pehnt extended the forecast of his study to a comparative assessment of energy generating technologies utilising fossil fuel and renewable fuel in 2010 and again in 2030. His findings highlighted clear advantages for renewable fuel under the headings of greenhouse effect and finite energy resources. However, his findings did not reveal a clear verdict for or against renewable energy technologies in all other impact categories and concluded the technological configuration, the energy source and the geographical and local conditions of the plant all play significant roles in its environmental impact.

2. *Comparison of energy generation from fossil fuels and renewable energy*

Goralczyl (2003) undertook an LCA in the renewable energy sector, and compared the environmental impact of 1GJ of energy production from photovoltaics, wind turbines and hydroelectric power. He concluded the research by comparing these technologies to energy generation from a variety of fossil fuels in fired power stations, including coal, natural gas and oil. Goralczyk reported coal to be the most environmentally harmful fossil fuel and natural gas to be the most environmentally friendly fossil fuel in power generation. His results indicated hydroelectric power to generate the most environmentally friendly renewable energy and photovoltaics to be the most environmentally harmful.

3. *Life Cycle Assessment of energy recovery from municipal solid waste and other bio-sources*

There has been much research cantered around energy generation from biomass and energy recovery from landfill gas. Berglund and Borjesson (2006), completed an LCA with the aim of describing the net energy output from biogas systems and found it to be affected by the raw materials digested, the system designed and allocation method chosen. The biogas life cycle extended from energy crop growth, harnessing and recovery, transportation of raw materials, anaerobic digestion, spreading of digestate and biogas upgrading and collection. The system boundaries included automobile manufacture and fuelling requirements (both transport vehicles and harvest vehicles), as well as fertilizer production and use.

The results showed that energy required solely for biogas plant operation accounted for up to 80% of the energy input, depending largely on the raw material used as the energy source. However, with biogas upgrading, the energy requirement of the plant was increased by 120-180%. Furthermore, primary energy input typically corresponded to not more than 20-40% of the energy content of the biogas produced.

Otoma et al., (1997), used LCA methodology to estimate the benefits of energy recovery and reduction of CO_2 emissions in MSW power generation. Their results indicated that in terms of life cycle energy balance, MSW generation is about the same as commercial power plants. However on a renewable energy basis, they claimed that the power generated in MSW management is 80 times larger than the energy required for generation equipment, hence MSW generation presents itself as a very effective means of recovering energy.

2.3 Waste water infrastructure

A review of the Western Cape waste water reticulation system is presented here to provide a context for the final stage of the life-cycle of waste water in the greater Western Cape region, specifically the final processing of the waste water from the brewery case study

It is the responsibility of the Wastewater Department to provide bulk wastewater reticulation and treatment services. Bulk waste water infrastructure of the Cape Metropolitan council consists of the following (Water Services Development Plan, 2001):

- 21 Wastewater treatment works
- 3 Marine outfalls
- 27 Major pump stations
- 15 Major interceptor sewers
- Approximately 120 km of bulk gravity sewers

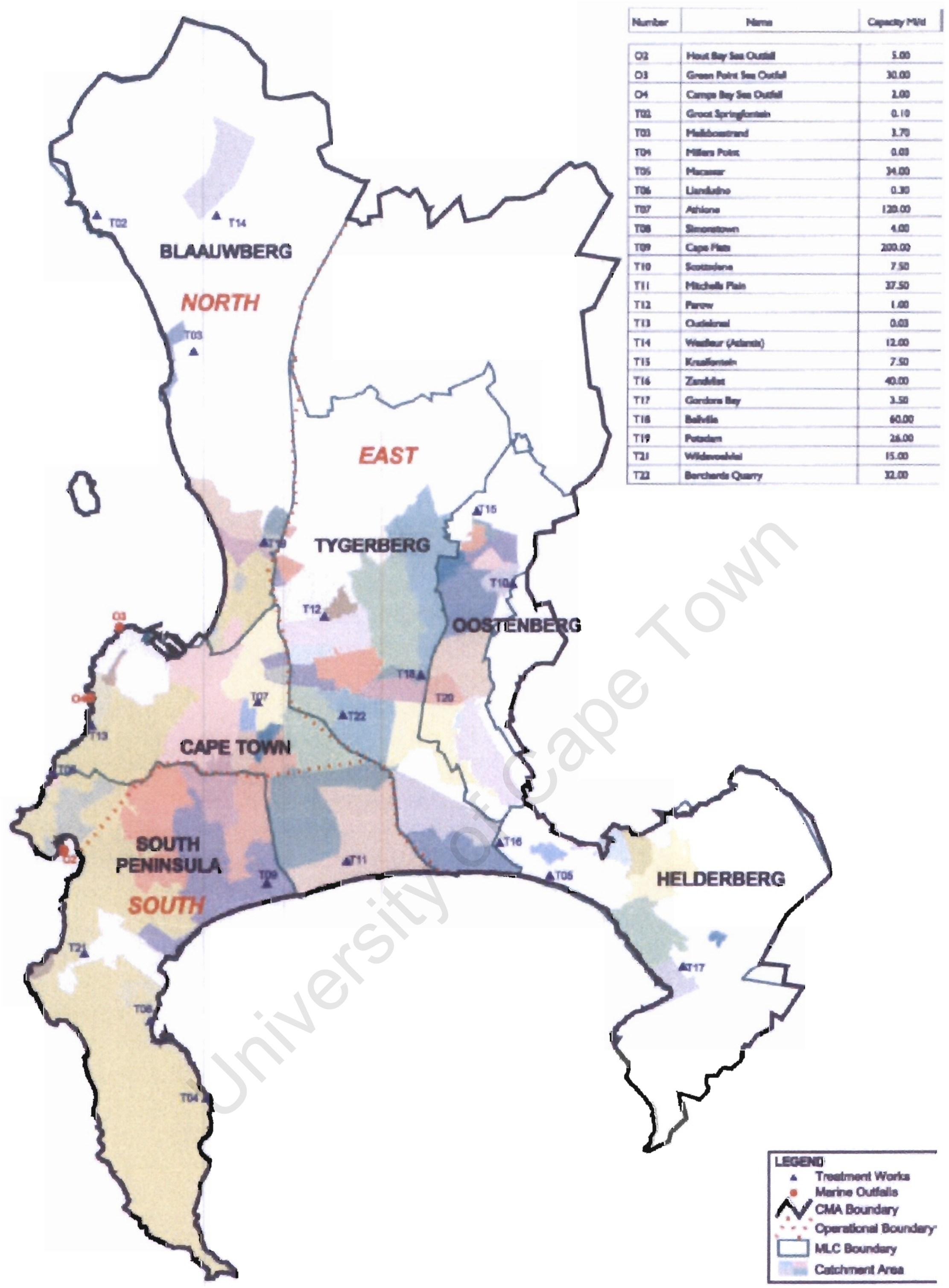
Moreover, the waste water treatment plants are categorised according to the regions they facilitate. Table 2.1 presents the 21 waste water treatment plants in and around the Cape Metropolitan Area (CMA) and their respective capacities, as replicated from the WSDP (2001). Figure 2.4 as replicated from the WSDP (2001) presents the location of the 21 waste water treatment facilities in the Western Cape. Figure 2.5 present the location of the 27 waste water pump stations in the Western Cape (WSDP, 2001). As reported in the WSDP (2001), the total wastewater flow (including storm water infiltration) generated in 2000 within the CCT amounted to 528 Ml/d. Approximately 6.5% of this amount (approximately 33.5 Ml/d) is discharged directly via marine outfall sewers and only approximately 9% of treated effluent is re-used. It was also reported there was a significant quantity that went unaccounted for although this amount is traditionally difficult to calculate.

Unaccounted for water is approximated to be as much as 198ML/day or 23% of total bulk water consumption by the Integrated Water Resource Planning Study (1999). This amount was not evenly distributed with the highest unaccounted for water analysis figures found to originate from low income areas. Further factors given by the report contributing to water losses include: mains leaks, service connection leaks, reservoir overflows, metering inaccuracies, illegal line connections and unbilled consumption. Indirect reasons given for the significant water losses include inadequate pressure in dated distribution systems and unqualified management of the system.

Water treatment is further regulated by national and international law including the National Environmental Management Act (NEMA). Regulations in terms of Sections 21, 22 and 26 of the Environmental Conservation Act (ECA) (No. 73 of 1980) were instituted in 1997 in an effort to uphold environmental integrity. These regulations stipulate the necessity of an Environmental Impact Assessment (EIA) prior to the construction of certain infrastructural facilities.

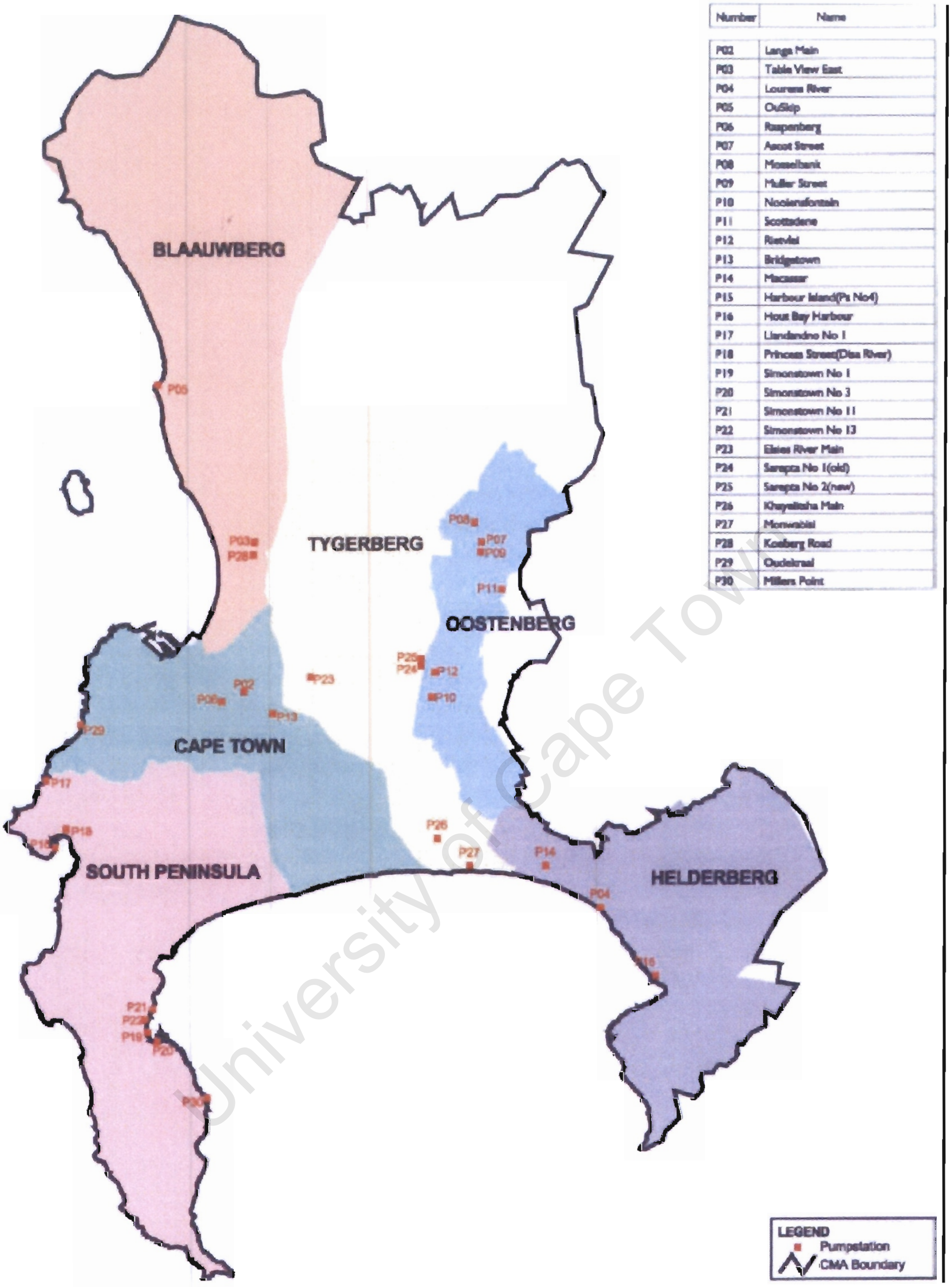
Table 2.1: Capacities of municipal waste water treatment facilities in and around the CMA (reproduced from the WSDP, 2001)

Name of waste water treatment plant	Capacity
NORTHERN AREA	
Athlone Wastewater Treatment Works	120 Ml/day
Potsdam Wastewater Treatment Works	32Ml/day
Dover Wastewater Treatment Works	0,1 Ml/day
Melkbosstrand Wastewater Treatment Works	2,5 Ml/day
Wesfleur Wastewater Treatment Works	14,0 Ml/day
Llandudno Wastewater Treatment Works	0,5 Ml/day
Oudekraal Wastewater Treatment Works	0,03 Ml/day
SOUTHERN AREA	
Cape Flats Wastewater Treatment Works	200 Ml/day
Mitchells Plain Wastewater Treatment Works	37,5 Ml/day
Wildevoëlvlei Wastewater Treatment Works	14 Ml/day
Simon's Town Wastewater Treatment Works	5,0 Ml/day
Miller's Point Wastewater Treatment Works	0,03 Ml/day
Macassar Wastewater Treatment Plant	34 Ml/day
Zandvliet Wastewater Treatment Plant	55 Ml/day
EASTERN AREA	
Borcherd's Quarry Wastewater Treatment Works	30 Ml/day
Bellville Wastewater Treatment Plant	46 Ml/day
Kraaifontein Wastewater Treatment Plant	7,0 Ml/day
Parow Wastewater Treatment Plant	1,2 Ml/day
Scottsdene Wastewater Treatment Plant	4,5 Ml/day
Gordon's Bay Wastewater Treatment Plant	3,5 Ml/day



Number	Name	Capacity Ml/d
O2	Hout Bay Sea Outfall	5.00
O3	Green Point Sea Outfall	30.00
O4	Camps Bay Sea Outfall	2.00
T02	Groot Springfontein	0.10
T03	Melkbosstrand	3.70
T04	Millers Point	0.03
T05	Macassar	34.00
T06	Llandudno	0.30
T07	Athlone	120.00
T08	Simonstown	4.00
T09	Cape Flats	200.00
T10	Scottsdene	7.50
T11	Mitchells Plain	37.50
T12	Parow	1.00
T13	Oudekraal	0.03
T14	Wesfleur (Atlantis)	12.00
T15	Kraaifontein	7.50
T16	Zandvliet	40.00
T17	Gordons Bay	3.50
T18	Bellville	60.00
T19	Potsdam	26.00
T21	Wildevoelvlei	15.00
T22	Borcherds Quarry	32.00

Figure 2.4: Location of the municipal waste water treatment facilities in the CMA



Number	Name
P02	Langa Main
P03	Table View East
P04	Lourens River
P05	OuSkip
P06	Raapenberg
P07	Ascot Street
P08	Mosselbank
P09	Muller Street
P10	Nooiensfontein
P11	Scottsdene
P12	Rietvlei
P13	Bridgetown
P14	Macassar
P15	Harbour Island(Ps No4)
P16	Hout Bay Harbour
P17	Llandudno No 1
P18	Princess Street(Disa River)
P19	Simonstown No 1
P20	Simonstown No 3
P21	Simonstown No 11
P22	Simonstown No 13
P23	Elsies River Main
P24	Sarepta No 1(old)
P25	Sarepta No 2(new)
P26	Khayelitsha Main
P27	Monwabisi
P28	Koeberg Road
P29	Oudekraal
P30	Millers Point

Figure 2.5: location of the waste water pump stations in and around the CMA

2.4 Anaerobic Digestion

2.4.1 AD Process

Anaerobic digestion (AD) is a naturally occurring process of decomposition by which organic matter is broken down microbially into its simpler chemical components under anaerobic conditions (Mckendry, 2001). The products of anaerobic digestion include a methane rich biogas and a digestate. Anaerobic digestion has been traditionally used for waste treatment but over the past few years, there has been an increased interest in the utilisation of the anaerobic digestion process in plant-fed digesters for energy generation (Lyberatos and Skiadas, 1999).

The anaerobic digestion process can be described in its simplest form, as a two stage process: In the first stage, complex organic compounds such as fats, proteins and carbohydrates are hydrolysed, fermented and biologically converted to volatile fatty acids. The second stage of the process involves the conversion of the short chain organic acids into primarily carbon dioxide and methane. The common VFA intermediates include acetic acid, propionic acid, butyric acid and to a lesser degree the longer chain VFA's (McCarty, 1964).

Due to the limited hydrogen availability for the methane forming reduction reaction, the methane produced is primarily due to the acetate reaction (Verma, 2002). McCarty, (1964), suggested that micro-organisms utilizing propionic acid and acetic acid are the most important in methane production. It was reported that up to 70% of methane generation is as a result of the conversion of acetic acid (Jeris and McCarty, 1965). Smith, (1966), proposed that approximately 73% of methane production was attributable to acetic acid.

Buswell and Mueller, (1952), correlated the amount of methane and carbon dioxide produced based on a knowledge of the organic composition of the waste stream using Equation 2.1:

$C_nH_aO_b + (n - a/4 - b/2)H_2O \rightarrow (n/2 - a/8 + b/4)CO_2 + (n/2 + a/8 - b/4)CH_4$ ...Eqn 2.1

McCarty (1964) showed that, theoretically, the amount of methane produced from stabilization of 1 kg organic waste by anaerobic digestion is 0.348 m^3 at S.T.P.

2.4.2 Effect of system conditions

The rate of methanogenesis is primarily affected by pH and temperature and to a lesser extent, ionic strength, nutrient availability and the presence of inhibitory substances (Pohland 1992, cited by Sacks 1997). The optimal pH for high rate digestion has been recorded between 6.8 and 7.8. However, the eventual pH is largely the result of the substrate fed to the digester (van Haandel and Lettinga, 1994 cited by Sacks, 1997). The pH is largely determined by the volatile fatty acid concentration in the digester and digesters typically employ buffering techniques so as to counteract the pH effects which high VFA concentrations would exert (Kotze et al, 1969 cited by Sacks, 1997). McCarty (1964) showed that below a pH of 6.6, significant inhibitions of the methanogenic micro-organisms occur, and as the pH continues to drop below 6.2, the mildly acidic conditions prove to be toxic to these micro-organisms. However, the fermentative bacteria continue to produce acids until the pH drops to 4.5. Clark and Speece (1970) claimed that steady state acetate fermentation was possible at pH levels as low as 4, but completely uninhibited between pH levels of 6 and 8. McCarty (1964) suggested a optimum range of between 7.0 and 7.2. Hanaki et al., (1981) reported on the inhibitory effects of long-chain fatty acids on the anaerobic digestion process. They found that with the addition of long-chain fatty acids, a lag period in methane production from acetate was observed.

Anaerobic digestion usually takes place in one of two temperature ranges: Mesophilic (30 to 40^{o} C) and thermophilic (50 to 60^{o} C) (Zinder et al., 1984). Most digesters are operated in the mesophilic range with optimum digestion occurring between 35 to 37^{o} C, thereby increasing the activity of the methanogenic bacteria reducing digester time and assisting in the liquefaction of fats and greases hastening their decomposition (Ross et al., 1992 cited by Sacks, 1997). Zinder et al. (1984) proposed that methanogenesis from acetate is optimal in-between 55-60^{o}C but completely inhibited at above 65^{o}C. Pfeffer (1974), reported on an optimum mesophilic temperature of 42^{o}C and an optimum thermophilic temperature of 60^{o}C.

The rate of digestion is dependant on the type of waste and microbe used. In AD process technologies, two types of reactors are used: the batch and continuous process. Ostrem et al, (2004) discussed the implications of each type of reactor, highlighting the long retention times of between 30-60 days commonly found in batch systems. The continuous process is characterised by the continuous processing to and removal of fresh substrate through the reactor, resulting in reactions occurring at a constant rate. As a result, effluent is a combination of completely digested and partially digested material and the residence time is calculated as an average across the substrate. Pfeffer, (1968), investigated the effect of increased loadings on digesters with the recycle of digested solids. He found that at shorter retention times, methane fermentation of volatile fatty acids dominates as the rate limiting step whereas at longer retention times, acid fermentation of the organic solids becomes rate limiting.

Research geared towards evaluating optimal conditions for efficiently running systems has been concentrated on the response of methanogens to various stimuli or inhibitory factors. Lyberatos and Skiadas, (1999), reported on the signs of a failing system. They identified a drop in the methane production rate, a drop in pH and a rise in CFA concentrations as characteristic of system instability. Reasons cited for system failure included feed overload, feed underload, entry to the system of an inhibiting substance and inadequate temperature control. However, at steady state anaerobic digestion has been recorded to stabilise as much as 80-90% of the degradable organic material, contrasted with a stabilisation rate of about 50%, even at normal loadings, of aerobic digestion (McCarty, 1964).

Anaerobic bacteria require primarily nitrogen and phosphorus for optimum growth. In sustained operations, it becomes necessary to supplement the treated waste if adequate quantities of the required nutrients aren't readily available. Speece and McCarty (1964), investigated the nutrient requirements of anaerobic organisms. Their work was based on an average composition of biological cells of $C_5H_9O_3N$. The nitrogen requirement was found to be approximately 11% of the cell volatile solids weight and the phosphorus requirement was found to be 20% of the nitrogen requirement. Trace concentrations of sodium, potassium, calcium, magnesium and iron are also required for adequate cell growth, however at higher concentrations, were found to exhibit biologically retarding effects.

Anaerobic digestion is treatment option that has been used extensively for the treatment of sludges and organic waste material. McCarty, (1964), summarised the various advantages of anaerobic treatment over aerobic treatment of organic waste; a higher degree of waste water stabilisation is possible, less biomass is produced per unit of organic material stabilized resulting in a lower nutrient requirement, there is no oxygen requirement for digestion and the methane gas generated results in the potential for economic benefit.

2.5 Bio-energy, Scrubbing and Utilization

2.5.1 Introduction

Bioenergy research is important because biofuels have the potential to replace petroleum fuels (Demirbas and Balat, 2006). Biofuels are liquid or gaseous fuels made from plant matter and residues such as agricultural crops, municipal waste and forestry products (Demirbas and Balat, 2006). Biofuels are generated from biomass by a variety of thermochemical processes including pyrolysis, gasification, liquefaction and supercritical fluid extraction as well as biochemical processes (Demirbas and Balat, 2006). Biomass provides approximately 14% of the world's energy needs, although in developing countries provides up to 35% of energy requirements (Demirbas, 2004). In comparison to fossil fuels however, biomass contains much less carbon, more oxygen, more silica and potassium, less aluminium and iron and has a lower heating value. Table 2.2 presents the differences in physical, chemical and fuel properties of biomass and coal. Cofiring of biomass offers an environmentally friendly alternative to conventional pulverised coal power stations, and refers to the combustion of biomass and coal simultaneously for power production. Cofiring with coal helps to reduce both NO_x and SO_x emissions, limits fuel costs and minimises waste and pollution, depending on the chemical composition of the biomass used (Demirbas, 2004).

Table 2.2: Fuel properties of biomass and coal (Demirbas, 2003)

Property	Biomass	Coal
Fuel Density (kg/m^3)	~500	~1300
Particle Size	~ 3mm	~100um
C Content (wt% of dry fuel)	42-54	65-85
O content (wt% of dry fuel)	35-45	2-15
S content (wt% of dry fuel)	Max 0.5	0.5-7.5
SiO_2 content (wt% of dry fuel)	23-49	40-60
K_2O content (wt% of dry fuel)	4-48	2-6
Al_2O_3 content (wt% of dry fuel)	2.4-9.5	15-25
Fe_2O_3 content (wt% of dry fuel)	1.5-8.5	8-18
Ignition temperature (K)	418-426	490-595
Dry heating value (MJ/kg)	14-21	23-28

Biomass is biochemically converted to biofuel through alcoholic fermentation or catalytic conversion to produce liquid fuels and anaerobic digestion to produce biogas. The organic portion of almost any feedstock can be broken down into biogas through anaerobic digestion, the details of which were discussed in Section 2.4. Biogas is composed primarily of methane (CH_4) and carbon dioxide (CO_2), with trace quantities of hydrogen (H_2), hydrogen sulphide (H_2S), nitrogen (N_2) and ammonia (NH_3) (Monnet, 2003). The feed stock composition has a large impact on the quality and quantity of biogas produced. Table 2.3, duplicated from Fair and Moore (1934) and cited by Pfeffer (1979), highlights the theoretical quantities and compositions of gas devised from different classes of organic material. Table 2.4 details generally accepted values for composition, physical properties, and combustion key numbers for natural gas and biogas (Jensen and Jensen, 2000). The gas is usually saturated with water vapour and may contain dust particles and siloxanes (Wheeler *et al.*, 1999).

Table 2.3: Physical properties for natural gas and biogas, resulting from the degradation of specific organic classes (Jenson and Jenson, 2000)

Material	Composition by weight		Volume from 1kg of dry material		$\%CH_4$ by Volume
	$\%CO_2$	$\%CH_4$	Biogas	CH_4	
Carbohydrate	74	27	$0.75m^3$	$0.37m^3$	50%
Fat	52	48	$1.44m^3$	$1.04m^3$	72%
Protein	73	27	$0.98m^3$	$0.49m^3$	50%

Table 2.4: Biogas and natural gas composition (Pfeffer, 1979)

Key Numbers		Natural Gas	Biogas
CH_4 (methane)	Vol %	91	55-70
C_2H_6 (ethane)	Vol %	5.1	0
C_3H_8 (propane)	Vol %	1.8	0
C_4H_{10} (butane)	Vol %	0.9	0
C_5+ (pentane)	Vol %	0.3	0
CO_2 (carbon dioxide)	Vol %	0.61	30-45
N_2 (nitrogen)	Vol %	0.32	0-2
H_2S (hydrogen sulphide)	ppm	~1	~500
NH_3 (ammonia)	ppm	0	~100
Water dew point	^oC	<-5	saturated
Net Calorific Value	MJ/kg	48.4	20.2
Density	kg/nm^3	0.809	1.16
Relative density		0.625	0.863
Wobbe Index (W)	MJ/nm^3	54.8	27.3
Methane Number		73	~135
Flame Temperature	^oC	2040	1911
Water dew point (flue gas)	^oC	59.7	59.2
Water Vapour (flue gas)	Vol %	18.8	19.3

The main difference between natural gas and biogas is the higher concentration of CO_2 observed in biogas. The Wobbe index (W) is defined as the ratio of the heat of combustion of a gas to its specific gravity. Only gases with a similar Wobbe index can substitute for each other in the same energy-generating applications.

The presence of incombustible materials reduces the calorific value of the fuel (Kapdi *et al.*, 2005), and need to be removed (or scrubbed) to increase the value of the Wobbe index.

- Desulphurisation is required to prevent corrosion and avoid toxic H_2S concentrations. The H_2S in biogas is burned to form SO_2 or SO_3, contributors to acid rain formation. In addition, the sulphur oxides lower the dew point of the stack gas facilitating the formation of the highly corrosive H_2SO_4.

- It is necessary to remove the water vapour to limit the formation of corrosive acidic solutions when reacting with H_2S.
- The removal of CO_2 enhances the calorific value of the fuel.

Furthermore, when utilizing the biogas, it is desirable to have a consistent gas quality with respect to its energy value.

2.5.2 Carbon Dioxide Removal

Commercially, five methods are employed for CO_2 removal. Only the first three are reviewed as operating cost limitations inhibit the applicability of the last two within the scope of this project.

a. Water scrubbing
b. Polyethylene glycol scrubbing
c. Chemical absorption
d. Carbon molecular sieves
e. Membrane separation

i. Water Scrubbing

The solubility of CO_2 and H_2S in water exceeds that of CH_4 by 25 fold and 62 fold respectively (Sander, 1999), hence they can be absorbed and removed using a H_2O scrub. The absorption process is operated counter-currently where the biogas is pressurised and fed to the bottom of a packed column and the water sprayed from the top (Kapdi *et al.*, 2005)

As claimed by Bhattacharya *et al* (1988), and reported by Kapdi *et al* (2005), a 100% pure methane gas is achievable depending on the dimensions of the scrubbing tower, gas pressure, composition of raw biogas, water flow-rates and the purity of water used.

ii. Polyethylene Glycol Scrubbing

CO_2 and H_2S are more soluble in polyethylene glycol than H_2O, reducing the pumping requirements and the consumption of scrubbing solution (Wheeler *et al.*, 1999). Furthermore, it also removes water and halogenated hydrocarbons. Selexol^{TM}

is an industrial solvent commonly used. Recirculation is always implemented, and Selexol^{TM} can be stripped with steam or inert gas (Wheeler *et al.*,1999).

iii. Chemical absorption

Chemical absorption as opposed to physical absorption involves the formation of chemical bonds between solute and solvent. A 10% aqueous solution of mono-ethanolamine (MEA) has been shown by Hagen (2001), cited by Kapdi *et al.* (2005), to reduce the concentration of CO_2 from 40% to 0.5-1% by volume. The solution can be regenerated after boiling for 5 minutes. NaOH, KOH and $Ca(OH)_2$ have been shown to sufficiently reduce CO_2 concentrations (Kapdi *et al.*, 2005). The contact time, concentration of scrubbing solution and turbulence within the liquid were reported to be primary factors influencing the degree of absorption.

2.5.3 Hydrogen Sulphide Removal

H_2S can be removed in the digester from the crude biogas or in an individual unit operation upgrading process as reported by Hagen (2001), and cited by Kapdi *et al* (2005). This is desirable as H_2S can contaminate an upgrading process centred on CO_2 reduction.

Commercially, H_2S removal can be classified into two distinct categories as reported by Wise (1981) and cited by Kapadi *et al.*, 2005.

1. Dry oxidation process
2. Liquid phase oxidation process.

i. *Introduction of air/oxygen into biogas system – Dry oxidation.*

H_2S can be removed from the biogas by introducing 2-6 % oxygen into the biogas system via an air pump. The sulphide in the biogas is oxidized to sulphur. The thiobacilli bacteria are able to oxidise the H_2S, whilst deriving their carbon from CO_2, according to the reaction: $2H_2S + O_2 \rightarrow 2S + 2H_2O$

Methane is explosive in the limits between 6-12% O_2. Consequently overdosing must be avoided (Wheeler *et al.*, 1999).

ii. Adsorption using iron oxide – dry oxidation.

Iron sulphide is easily formed on reaction of iron hydroxides with H_2S by passing the biogas over the iron oxide pellets (Wheeler *et al.*,1999). Following conversion to iron sulphide, the pellets can be removed for the exothermic regeneration of the iron oxide and elemental sulphur.

Wood chips coated with iron oxides have a larger surface area to volume ratio than plain steel (Wheeler *et al.*,1999). Approximately 20g of H_2S can be bound per 100g of iron oxide chips. Iron oxide pellets give the highest surface to volume ratio. They are made from red mud, a product of aluminium production. It was reported that at H_2S concentrations between 1000 and 4000 ppm, 50 grams of sulphur can be loaded per 100 grams of pellet (Wheeler *et al.*,1999).

Activated carbon dosed with potassium iodide (KI) in a pressure swing absorption system (PSA) is also used for this application. The carbon can be either replaced or regenerated. The H_2S is catalytically converted to elemental sulphur and water. Operating conditions include temperatures between 50-70 ^{0}C and pressures of 7-8 bar. (Wheeler *et al.*, 1999)

iii. Aqueous Scrubbing - Liquid phase oxidation process

H_2S removal on its own, using water, has not been shown to be cost effective. Water consumption is high, although effluent quality water can be used. With the addition of NaOH, the process becomes more chemical than physical in nature and the absorption of H_2S into water is improved. Formation of the insoluble salts sodium sulphide and sodium hydrosulphide pose disposal problems (Kapdi *et al.*, 2005).

Selexol^{TM} is an industrial solvent that provides effective scrubbing and requires lower volumes of scrubbing media than when water is used as the scrub solution.

Iron salt solutions like iron chloride have been shown to be very effective at reducing high H_2S levels (Kapdi *et al*, 2005). $FeCl_3$ is added directly to the digester slurry and H_2S is removed through the formation of insoluble precipitates.

Kapdi *et al* (2005) noted that, although all the above methods are suitable for H_2S removal, this process is most suitable and economically viable for smaller sized digesters. Final concentration of H_2S using this method is 10ppm.

2.6 Conclusion

This chapter has presented the subject material required to engage with the study undertaken. Industrial ecology was researched and the concepts behind sustainable development were discussed. The tools used for assessments of achieving the goals of industrial development were also presented. Anaerobic digestion was then briefly reviewed, the aim of which was to provide a basic overview of the digestive process and highlight the key variables affecting efficiency so as to better understand the WTF process. Biogas and the issues relating to its scrubbing and utilization were then presented in an effort to understand the challenges facing biogas utilization. In summary, the following conclusions can be drawn from the literature review:

Industrial ecology and sustainable development:

Without the reassessment of the current linear industrial model into a cyclical model, sustainability in light of limited resources is unachievable. Environmental problems cannot be localized to their point of origin but rather impact on a variety of ecosystem variables. Industrial ecology addresses this problem as it requires the tracing of material flows between industrial- and eco- systems highlighting opportunities for burden reductions and enabling accurate quantification of the extent of eco-disturbances. The Life Cycle Assessment analysis is a useful tool for tracing material flows and quantifying their impact on the environment.

Life Cycle Assessment:

The LCA is the most appropriate and therefore primary tool with which to compare alternate process or product systems. The Life Cycle Assessment methodology provides a formulated approach to assessing the environmental impacts of a product, enabling process optimisation and improvement. Difficulties may be encountered as appropriate LCA data may not be readily available, and assumptions are required in populating a LCI.

Anaerobic digestion:

Anaerobic digestion is a 2-step process whereby carbohydrates, lipids and proteins are biologically decomposed into methane and carbon dioxide via the metabolism of short chain volatile fatty acids. The VFA's are composed of primarily acetate, propionate and butyrate although the presence of alcohols has also been recorded. During methanogenesis, up to 70% of the methane produced is as a result of the conversion of acetic acid. Correlations developed by Buswell and Mueller (1952) describing the relationship between the organic substrate fed and digestate produced provide a useful means for stoichiometric calculations.

Biogas, scrubbing and utilization:

The volume and composition of biogas produced is dependent on the substrate fed to the digester. The methane concentration of biogas is commonly between 55 to 70% (by volume), and correlations relating the volume of biogas generated per kg organic material, have been presented in Section 2.5. Depending on the sulphur content of the biogas, desulphurisation may be required to limit corrosion and toxic H_2S concentrations. The CO_2 content can be reduced to increase the calorific value of the gas. Water can be used to effectively remove both H_2S and CO_2. The solubility of CO_2 and H_2S exceeds that of CH_4 by 25 fold and 62 fold respectively. With the addition of NaOH to the scrubbing solution, this process becomes commercially viable. Finally, effluent quality water can be used for scrubbing.

Chapter 3: Mass Balance

Chapter 3 presents the approach developed in modelling the SABMiller effluent treatment facility. This chapter aims to present a generic methodology with which one can quantify with fair accuracy biogas flow-rates and compositions from effluent treatment facilities based on limited process data (typical of smaller operations).

The mass balance aims to characterise the material flows in and around the WTF thereby enabling the calculation of its burden profile on the environment. The mass balance also aims to evaluate the potential for energy generation from biogas utilisation and consequently provides itself as a platform from which the burdens avoided by energy reclamation can be assessed. The chapter concludes with a statistical summary highlighting the validity of the calculations and assumptions and compares the results to data collected on-site.

3.1 Introduction

The data used for the material balance was sourced primarily from the anaerobic digester daily performance log. To eliminate fluctuations and obtain representative process values for effluent plant operation, data was aggregated on a monthly basis. By aggregating data on a monthly basis, the fluctuations attributable to peak production months would be accounted for and absorbed appropriately within the calculations. All data was reported as a daily average across each month (units of day^{-1}).

An illustrative process flow diagram is presented in Figure 3.1. The incoming streams to the effluent plant from packaging, the cellars and the brew house are combined into a single liquid stream prior to its treatment.

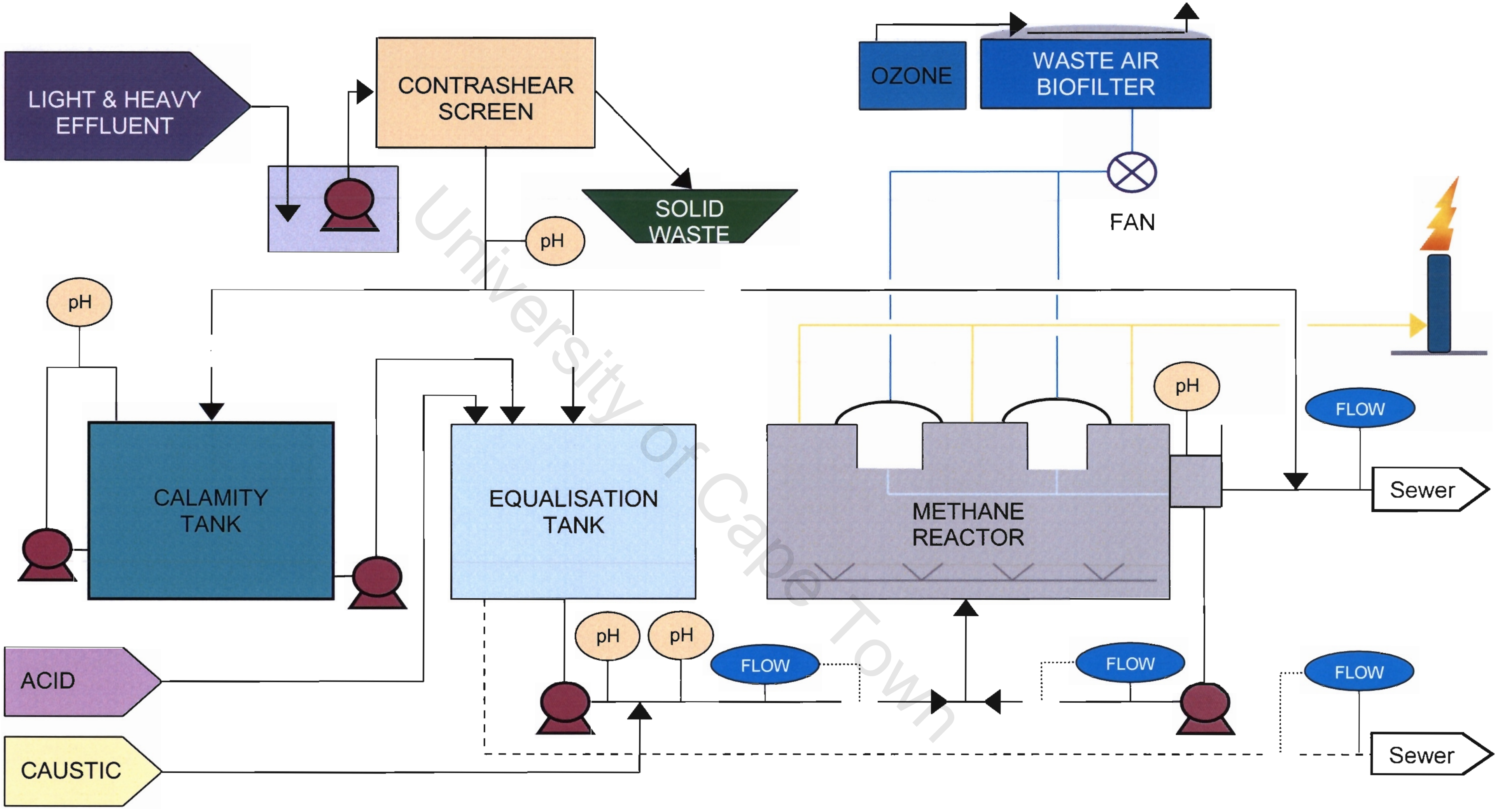


Figure 3.1: Illustrative process flow diagram of the SABMiller WTF

3.2 Material Balance Assumptions

There were primarily five assumptions used in the material balance calculations:

1. The detailed species-based composition of the effluent stream was unknown. Hence a likely composition was assumed, based on characteristic anaerobic digestion and brewery effluent waste constituents as reported in the literature. The composition of the organic stream was based on the predicted VFA composition post acidogenesis, i.e. the biological breakdown incurred in the anaerobic digestion of long-chain organic compounds into volatile fatty acids.
2. The calculated composition of biogas, although initially assumed, was adjusted to facilitate agreement when reconciling calculated and measured volumetric flowrates to flare in conjunction with separation efficiencies of the anaerobic digester and overall carbon balances. The initial estimation (or calculation starting point) was based on compositions of biogas included in the literature.
3. The separation efficiency of the digester in partitioning biogas selectively between flare and biofilter was inferred from the relative solubility of the gases present and therefore the likely separation efficiency.
4. Sludge generation or disposal was not included in the system boundaries in light of limited information concerning disposal rates. SABMiller Newlands Brewery reported no sludge disposal during the duration of the project, and the municipal treatment facility was unable to provide accurate sludge disposal volumes due to their infrequent anaerobic sludge dumping requirement. To avoid calculation bias, sludge generation and disposal was removed from the system boundaries. Hence the effect due to sludge disposal was eliminated from the analysis completely.

The assumptions made were modified as required by way of an iterative calculation procedure. In conjunction with the overall carbon balance, the results of the mass balance based on the assumed species concentrations were used to adjust the assumed concentrations as required. Through balancing the overall carbon balance by adjusting the initial assumptions made determining biogas composition and effluent feed composition, subject to the measured VFA concentrations, SS concentration in both the effluent feed stream and effluent stream from the WTF and flare flow-rate measurements, a higher degree of mass balance accuracy was obtained. This resulted in a more reliable material balance analysis.

3.3 Key Questions

Through completion of the material balance, the following key questions are addressed:

1. What is the composition of the biogas generated in the anaerobic digester?
2. What is the composition of the biogas processed to the flare?
3. What is the composition and flow-rate of the biogas processed to the biofilter?
4. How does the biogas flow-rate and quality fluctuate?
5. What reduction in COD is achieved by the anaerobic digester installed at Newlands Brewery?

3.4 Methodology and Key Considerations

The mass balance was calculated by sub-dividing the effluent stream into 4 components: organic, aqueous, solids and gaseous components of the stream. The constituents of each were then balanced on an overall elemental basis independently. The calculations were largely iterative in nature. Table 3.2 presents a sample summary of the data collected and used as inputs to the mass balance. A complete description of this data set is provided in Appendix A. Data were collected from June'04 till August '05. Steady state was only achieved from February-March'05, as shown in Figure 3.3. Figure 3.2 presents the salient details of the mass balance methodology and serves to enable a clearer understanding of the procedure outlined following the figure.

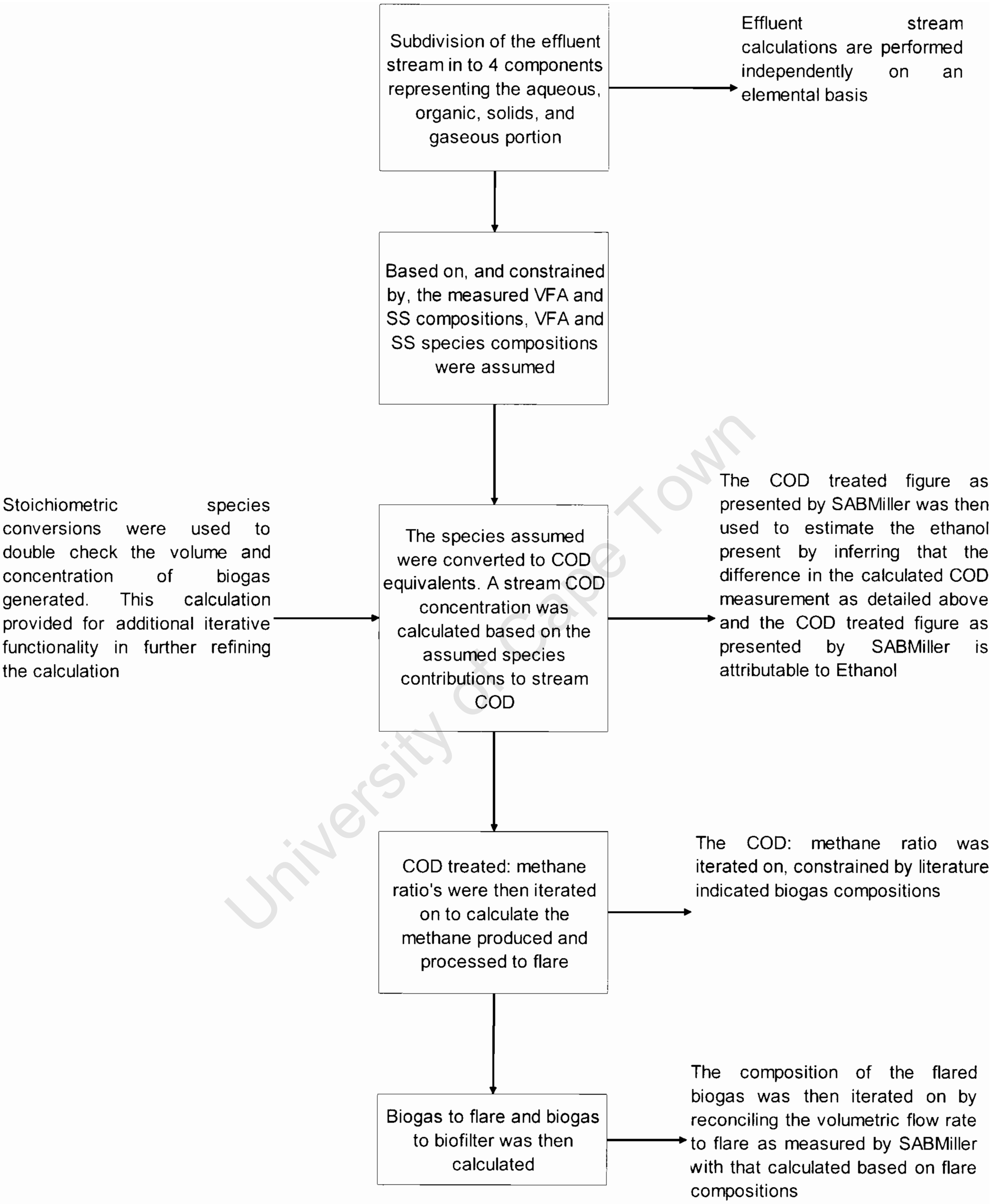


Figure 3.2: Flow diagram depicting mass balance methodology

Table 3.1: Select data collected from SABMiller Newlands Brewery anaerobic digester log book

	Mar	Apr	May	Jun	Jul	Aug
Volume to AD per day (kl/day)	2757	2785	2212	1825	2415	2847
Volume from AD to sewer (kl/day)	3844	3184	2561	2167	3038	3443
Volume to flare (Nm^3/day)	4100	4275	3846	3669	4369	5535
COD treated (kg/day)	11063	11536	10377	10171	11791	14935
Caustic Usage (kg/day)	1472	1725	1875	1352	1718	1984
VFA into methane reactor (mg/litre)	259	346	656	605	454	650
VFA out methane reactor (mg/litre)	0.00	0.00	0.00	0.00	0.00	0.00
pH in equalisation tank	5.14	5.55	5.26	5.17	5.47	5.39
pH in feed stream to methane reactor	6.67	6.88	6.44	5.77	6.12	6.06
pH in stream from methane reactor to sewer	6.71	6.70	6.73	6.77	6.73	6.71
COD in equalisation tank (mg/litre)	1702	2299	2668	2764	2561	2916
COD from methane reactor (mg/litre)	218	282	358	271	310	507
SS in equalisation tank (mg/litre)	610	803	870	865	860	983
SS from methane reactor (mg/litre)	152	185	237	132	238	474
SO_4 in equalisation tank (mg/litre)	610	803	870	865	860	983
SO_4 analysis to sewer (mg/litre)	152.00	185.00	237.00	132.00	238.00	474.00
NH_3 to sewer (mg/litre)	21.74	18.07	45.20	53.03	-	-
PO_4 to sewer (mg/litre)	8.46	9.81	11.63	12.53	-	-

Discrepancies were observed between the calculation of COD treated based on measurements taken from the equalisation tank and the methane reactor, and data on COD treated presented by SAB. This estimate of COD treated has been conservatively back calculated daily by SAB based on continuous automated flare flow-rate measurements. These discrepancies were reconciled by concluding that COD concentration measurements do not take into account the SS contribution to COD accurately and hence underestimate the amount of COD treated. The measured flare flow-rates are unachievable using the COD measurements as indicators of COD treated, without stoichiometrically accounting for a SS contribution to COD treated both entering the plant and exiting the plant. Based on COD concentration measurements (inferred COD treated figures) and literature indicated COD treated: methane ratios, measured flare flow-rates are unachievable. This discrepancy is potentially due to unrepresentative sampling. Furthermore, approximations by SABMiller plant engineers of the flare power correlated well with mass balance findings providing confidence in flare flow-rate measurements.

Further addressing the argument that the flow meter to flare was faulty, overall carbon balances indicate the likelihood of inaccurate COD readings. In addition, the plant was designed on a COD treatment capacity of 18,000kg/day. Based on this specification, the estimate of COD treated back calculated from flare flow-rate measurements (55-83% of treatment capacity) make more sense than the estimates of COD treated based on COD concentration measurements (25%-37% of treatment capacity) in terms of operation as a % of designed capacity. This conclusion is re-developed in Section 3.7, based on other findings. The mass balance used the estimate of COD treated reported by SABMiller as a starting point, but aimed to refine the estimate of COD treated and calculate flare compositions based on carbon balances and species compositions as determined by SS and VFA concentrations around the plant.

Based on an assumed effluent species composition consisting of an array of volatile fatty acids (VFA) and suspended solids (SS), constrained by measured VFA concentrations and SS concentration, the stoichiometric relationships between organic species consumption and biogas generated could be evaluated, using Equation 2.2. This facilitated the computation of the ratio of COD digested to methane generated used in calculations, by comparing COD treated figures (as per SAB data) with biogas generated according to Equation 2.2. This ratio was used in conjunction with an assumed biogas composition (later corrected in conjunction with an overall carbon balance) to determine the flow-rate of total biogas generated. The flow-rate of biogas to flare was known. Hence this ratio (COD:CH_4) and the above mentioned calculations facilitated an initial approximation of the biofilter flow-rate and the compositions of the gaseous streams processed to biofilter and flare. In order to satisfy mass balance requirements, this ratio was adjusted accordingly.

Constrained by VFA and SS measurements, the assumed organic compositions established a description of the carbon content around the effluent plant. Adjustments made to these species compositions, whilst more precisely satisfying overall mass and carbon balances, enabled a more accurate description of the likely composition of the effluent plant feed and outflow streams. Further adjustments were made by iterating organic compositions in conjunction with the ratios of COD treated to methane formed subject to satisfying flare flow-rate measurements within biogas composition limits as specified in literature. By calculating the stoichiometric biogas generated by way of the assumed species composition of the organic stream, in conjunction with comparing this result with overall carbon balances, accurate predictions, in this regard, could be made. The composition of the organic portion was adjusted by comparing a calculated stoichiometric COD (based on the inferred VFA species composition) with the measured COD, until these were reconciled via the simulated introducing of ethanol into the effluent stream – a contributor to COD. The organic proportion assumed is presented in Table 3.5.

Data pertaining to the amount of COD treated was used in conjunction with calculated COD: methane ratios to determine the likely methane content of the biogas. Mass balance calculations facilitated the calculation of a comparative COD-treated figure by including the theoretical stoichiometric contribution to COD from SS measurements. Calculated COD treated figures corresponded well with SAB presented COD treated figures (see Table 3.8). The calculated methane content of the biogas was constrained by specified ranges of biogas compositions given in the literature and the methane content of the flare gas was constrained by daily recorded flare flow-rate measurements. These calculation constraints were used in conjunction with total mass and carbon balances over the effluent plant to quantify the biogas generated whilst incurring no additional capital or analytical expenditure. The calculated biogas compositions are presented in Table 3.6, and variations in methane flow-rate with month are presented in Figure 3.3. Further results pertaining to the daily biogas fluctuations and equivalent power provision are presented in Figures 3.4 and 3.5 respectfully.

The biogas to flare calculation was constrained by flare flow-rate measurements. COD to methane ratios, in conjunction with data collected for COD treated, were used to calculate methane and subsequent flare flow-rates. This calculation was constrained, as mentioned above, by the upper and lower limits of the methane concentration in biogas (as specified by literature) and on-site flare flow meter measurements. The volume of methane calculated, in conjunction with flare flow-rate measurements and methane concentration limits (as specified in literature), enabled characterisation of the flare and biogas generated. In compliance with these limiting criteria and a satisfactory overall carbon balance, the biogas separation efficiency of the UASB and flare and biofilter species concentrations were intrinsically integrated into the solution methodology. By adjusting the separation efficiencies of the digester, constrained by the biogas volumetric flow-rates to flare (as measured), the overall carbon balance and biogas limiting concentrations, the likely separation efficiencies could be predicted. The separation efficiency is presented in Table 3.6. Again, by iterating the ratio of COD treated to methane generated, in conjunction with biogas separation efficiencies and biogas compositions, a more satisfactory overall mass balance could be achieved.

Finally, by comparing the biogas generated based on stoichiometric relationships between the carbonaceous species assumed to be present and their methanogenic conversions, with that calculated from the ratio of COD digested to methane generated, further confidence in the accuracy of the model could be inferred. These results are presented and discussed in Tables 3.7 and 3.8.

3.5 *Results*

3.5.1 Organic Component

The VFA components assumed to be present in the effluent stream exiting the brewery and entering the WTF are listed in Table 3.3. This composition was based on the likely brewery and municipal effluent compositions. As indicated by the literature, methanogenesis occurs predominantly via the bio-metabolic reduction of short chain VFA's such as acetate and formate or the metabolism of CO_2 and H_2. Higher chain VFA's undergo acetogenesis first.

The VFA composition assumed is given in Table 3.4. These VFA compositions were based on likely brewery effluent waste. The COD in excess of that accounted for by COD equivalents inferred by VFA measurements was attributed to ethyl alcohol. This resulted in ethyl alcohol concentrations of approximately 0.4-0.5 (mass fraction) of the organic portion of the stream, depending on the month in question. This assumption was deemed appropriate due to the likelihood of an alcohol being present in brewery effluent. It is also worthwhile to note at this point that the liquid portion of the effluent stream was calculated as if it were fictitiously separated from the aqueous portion of the stream. Hence, the presence of water is not represented in these results.

Table 3.2: Assumed makeup of the organic stream component of the incoming effluent stream

Component	Molecular formula	Molecular mass
Acetic Acid	$C_2H_4O_2$	Mr = 60
Propionic Acid	$C_3H_6O_2$	Mr = 74
Butyric Acid	$C_4H_8O_2$	Mr = 88
Caproic Acid	$C_6H_{12}O_2$	Mr = 116
Ethyl Alcohol	CH_3CH_2OH	Mr = 46

Table 3.3: Assumed mass fraction of the volatile fatty acids post acetogenesis

VFA	Mass fraction
Acetic Acid	0.44
Propionic Acid	0.32
Butyric Acid	0.14
Caproic Acid	0.10

3.5.2 Suspended Solids Component

Average starch, lipid and protein molecular formulae are given in Table 3.5 and were used in estimating the composition of the suspended solids portion. Furthermore the composition of this stream was conservatively estimated by recognizing that the majority of suspended solid brewery waste is starch. The larger particulates including hops and maize are separated out from the effluent stream so contribute marginally to the protein and lipid portion of the effluent. Biomass is not removed from the UASB. Anaerobic bacteria generate less biomass than aerobic bacteria and this has been well documented and observed in this case.

Table 3.4: Assumed makeup of the suspended solids component of the effluent stream

Component	Molecular formula	Molecular mass	Mass fraction
Starch	$(C_6H_{10}O_5)_n$	(Mr: 32400)	0.75
Lipid	$C_{51}H_{98}O_6$	(Mr: 806)	0.05
Protein	$(C_5H_7O_2N)_n$	(Mr: 22600)	0.20

3.5.3 Aqueous Component

The aqueous component of the model was populated using data collected from the SAB Newlands laboratory results log. These data included concentrations of phosphate, ammonia nitrogen and sulphate in the effluent stream. Nitrogen was modelled as aqueous ammonia and phosphorous was modelled as aqueous phosphate. The data are presented as monthly averages in Figure 3.2.

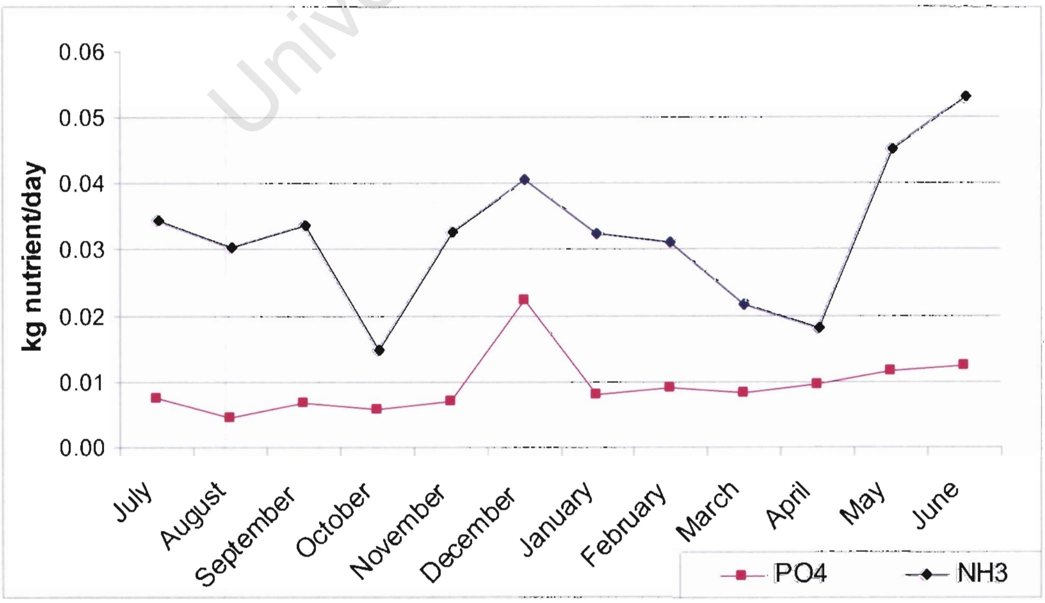


Figure 3.3: Monthly averages of aqueous species concentrations in the WTF effluent stream

3.5.4 Biogas Component

Flare characterisation remains the primary guide for the selection of energy capture technologies, as the flared biogas is the fuel that is to be recovered. The LCA also requires a quantification of the gaseous outputs for the inventory stage. Table 3.6 provides the calculated biogas composition and the ratio of biogas processed to the flare and biofilter as calculated. The separation efficiencies were estimated from both the relative solubilites of the gases present and adjustments to the mass balance model in reconciling the measured flare flow-rate with the calculated flare flow-rate. 99% separation represents an ideal system but by defining such a separation ratio, the base case scenario is generated against which all others are measured or investigated.

Table 3.5: Calculated biogas composition and mass balance based estimated separation efficiency of digester

Biogas	Vol %	% to flare	% to biofilter
Methane	69.1	100	<1
Hydrogen	0.5	100	<1
Hydrogen Sulphide	1.0	<1	100
Carbon Dioxide	29.4	20	80

The COD: methane ratio calculated was $0.342m^3$ methane generated per kg COD digested. These results are supported by the findings of McCarty (1964) who reported a typical ratio of $0.348m^3$ methane generated per kg COD digested. Although no sulphur has been assumed in the organic stream, in light of the conservative approach of this mass balance a marginal sulphur content of the order of ppm was assumed in the biogas. Energy capture technologies would need to be robust enough to handle moderate sulphuric acid formation, and the sulphur content of the biogas would need to be scrubbed if high concentrations of sulphuric gasses are found. Hence conservative sulphurous emissions have been estimated here localised to biogas calculations.

Figure 3.4 presents the average flow-rate of flared methane on a monthly basis as calculated by the methodology outlined here. Figure 3.4 illustrates the daily fluctuations in bioflare flowrate during the month of February 2005. Figure 3.6 translates Figure 3.4 into a power rating. The flow-rate fluctuated significantly from July 2004 till February 2005 following commissioning of the plant, until steady state operation was achieved during the first half of 2005. Flare flow-rates increased again during August. Calculations concerning the flow-rate and quality of biogas are based on steady state operation of the plant, that is, calculations were performed using data from February 2005. Volumetrically, the average flare flow-rate calculated between March and August is 4297 Nm^3/day, with an average *monthly* standard deviation of 661.5 Nm^3/month.

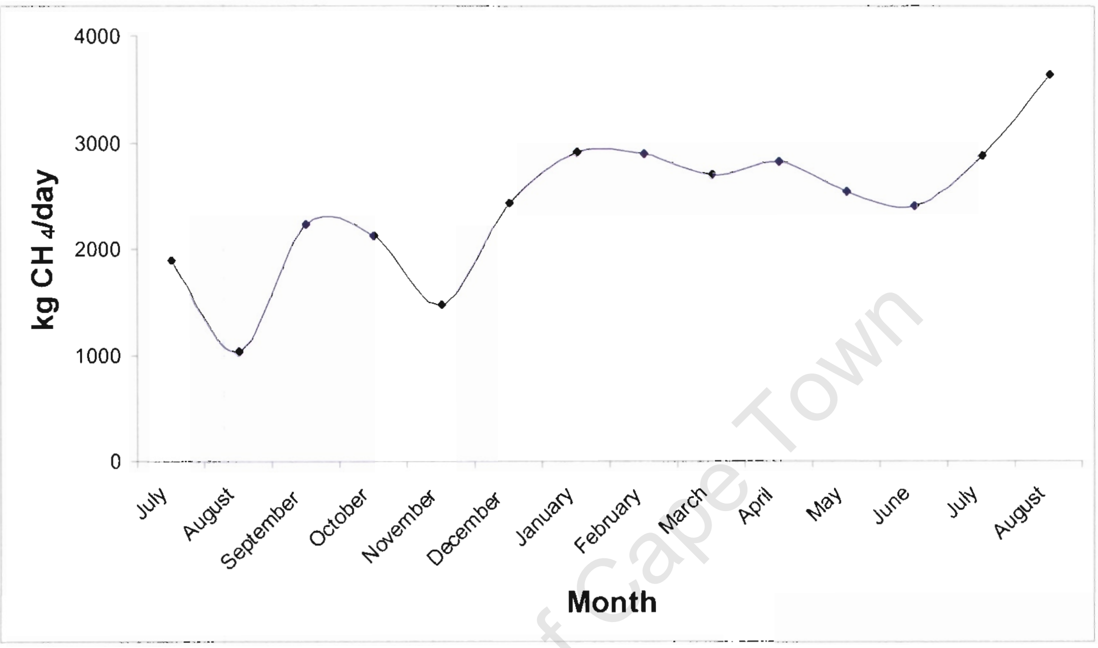


Figure 3.4: Monthly variation in methane flow rate from WTF

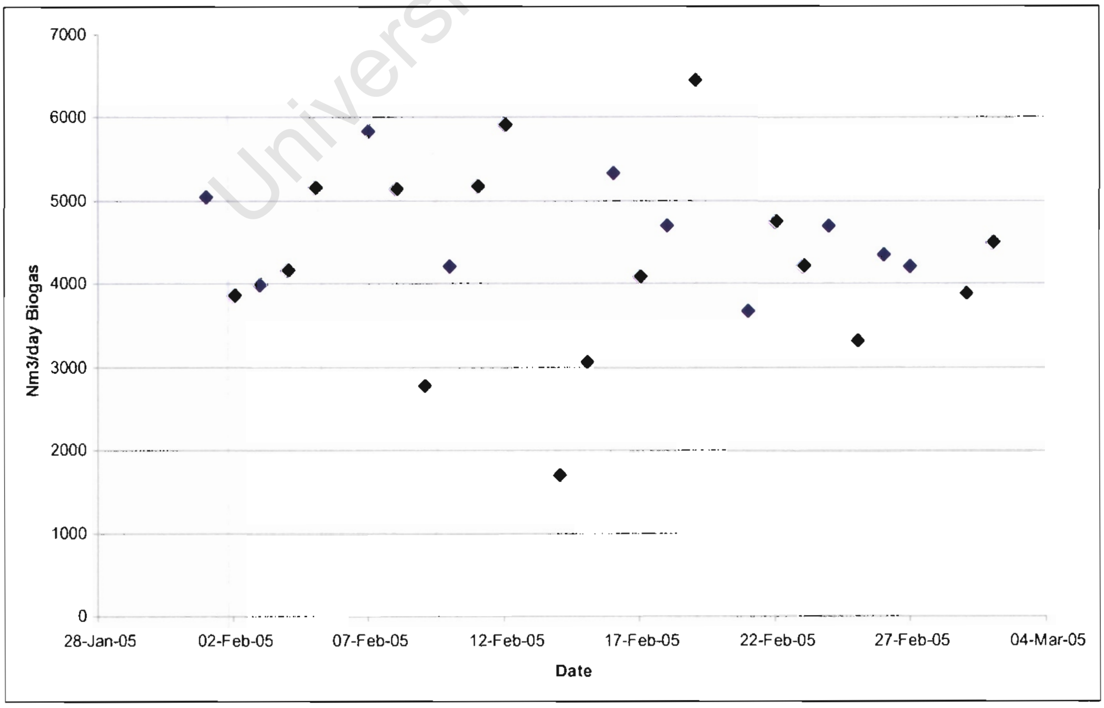


Figure 3.5: Daily fluctuations of biogas flow- rate during February 2005

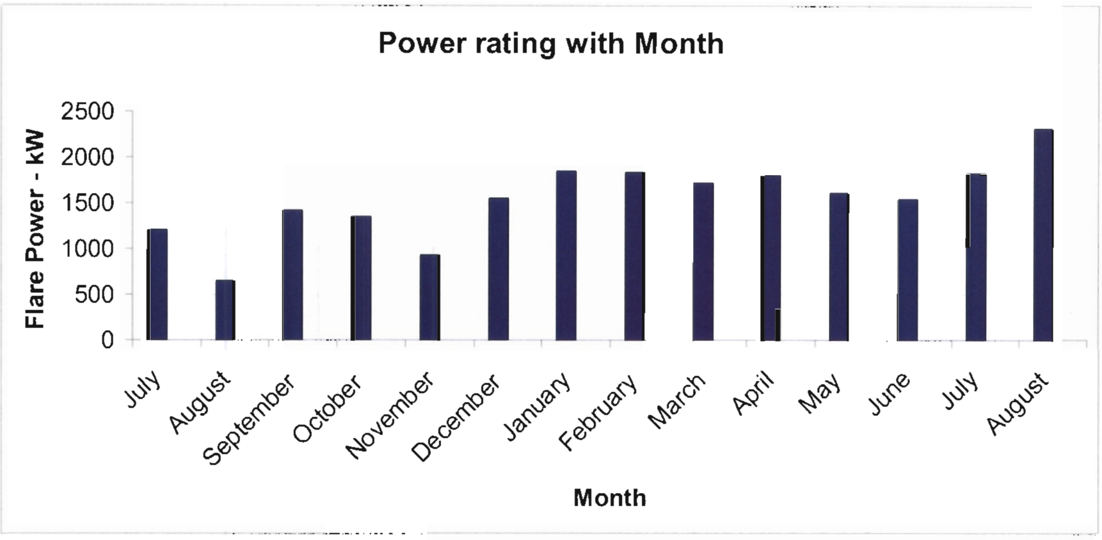


Figure 3.6: Monthly variation in power rating of flare

Based on the biogas flow rate determined and composition estimated, the flare power rating was calculated and is presented in Figure 3.6. A pure methane flare has a calorific value of 55 kJ/g, or 39 MJ/m^3. This value is partially diluted with the addition of carbon dioxide with a calorific value of 0 kJ/g.

As mentioned, it was cautiously estimated that the concentration of H_2S in the biogas varied between 10 and 20 ppm. Hydrogen concentrations were very small with a concentration of less than 1 ppm.

The average flare power from March to August was calculated as 1800 kW but varied between an average monthly maximum of 2315 kW (March) and monthly minimum of 1534 kW (June). This turn-down ratio, mirrored by fluctuations in biogas flow-rates could become problematic with reference to technological design. While it can be stabilized by better control of the effluent plant, design for flow variation is required to accommodate process upsets and power outages.

Based on the separation efficiency presented in Table 3.6, the methane content of the biogas flare is of the order of 92%. This results in a gas calorific value of 50.6 kJ/g or 36MJ/m^3. With an average steady state flare flow-rate of 2828 kg/day over the same period, the resulting energy available daily is 155.52 GJ (HHV).

3.6 Sensitivity Analysis

A sensitivity analyses was performed to prevent an over-estimation of the flare power available. The analysis assessed the change in power rating with a change in methane concentration of the biogas to flare. This analysis is then presented from a different angle by showing specifically how the calorific value of the flare changes with flare methane concentration. This analysis enables any fluctuations in flare composition to be taken into account.

The calculations were completed assuming a constant biogas flow-rate to flare regardless of flare CH_4 concentration, as apposed to linearly reducing the flow-rate with a change in methane concentration. This was done so as to simulate the effect of ineffective biogas separation.

This exercise aims to assess the impact of ineffective biogas separation on the calculated methane concentration to flare by quantifying the change in flare power rating observed with a change in methane concentration. It further accounts for the presence of process fluctuations.

i. *Power rating dependency on methane concentration*

The mass balance was used to evaluate the change in power rating of the flare with a change in methane concentration.

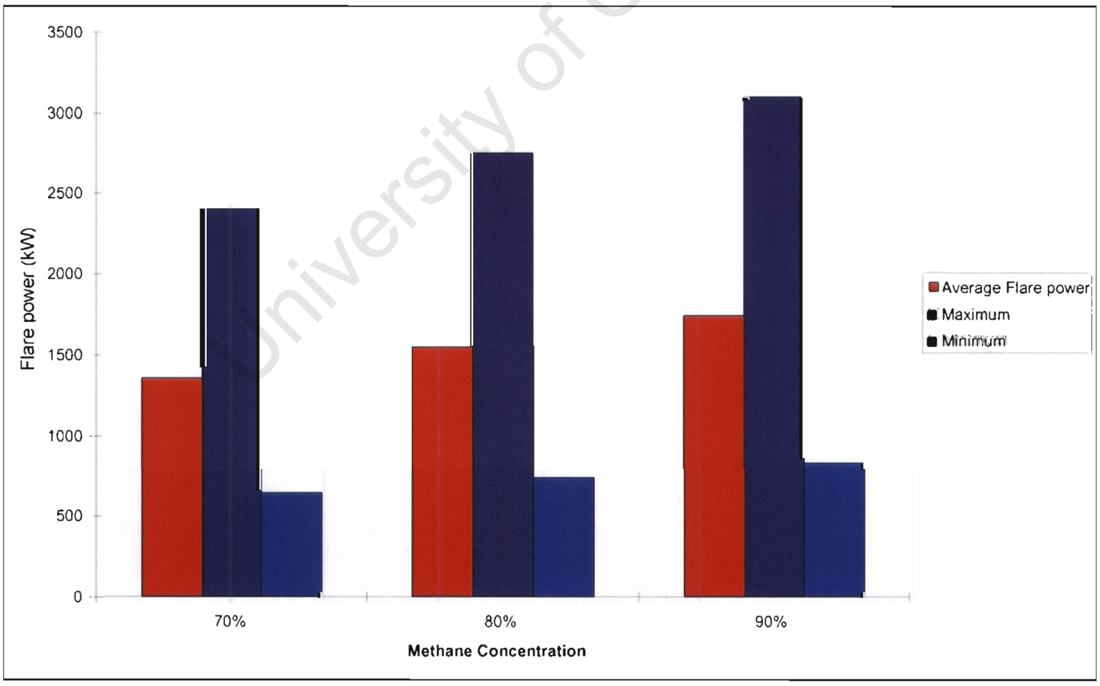


Figure 3.7: Flare power from the WTF with varying methane concentrations

Figure 3.7 shows the change in flare power with a change in methane concentration in the flare. In this particular assessment, data was aggregated monthly and over the period from March '05 to August '05. As depicted in Figure 3.6, during the months of

March to August 2005, assuming a 90% methane concentration in the flared biogas, the power rating of the flare was approximately 1800kW. With a 20% reduction in methane concentration in the flare, there is a 385 kW reduction in power outage from the flare. It is unlikely that the concentration of methane will fall below 70% in the flare stream as the biogas methane concentration is approximately 70% and the flare stream is concentrated in methane with respect to the overall biogas stream. At a methane concentration of 80%, the average flare power during the months between March and August is calculated at 1541 kW with a standard monthly deviation of 211kW. At a methane concentration of 70%, flare power during the months of March and August is calculated at 1349kW with a standard monthly deviation of 185 kW.

The maximum and minimum bars at each methane concentration illustrate the maximum and minimum monthly power ratings during the period of March to August 2005. This information provides the required insight for technology design purposes and an indication of the magnitude of fluctuations on a monthly basis at each respective methane concentration.

ii. *Calorific value dependency on methane concentration:*

Figure 3.8 defines the change in calorific value of the flare with a change in methane concentration. It is unlikely the flare will be less than 70% methane as this is the concentration of the biogas. At 92% methane (as calculated in mass balance), the calorific value of the flared gas is 37 MJ/m^3 resulting in an available thermal heat of approximately 154 GJ/day. At 80% methane concentration, the calorific value of the flared gas is 29.6 MJ/m^3, resulting in an available thermal heat of 134 GJ/day. At 70% methane, the calorific value of the flare decreases to 25.9 MJ/m^3 and results in a daily thermal availability of 117 MJ/day. These calculations were based on an average flare flow-rate of 4299 Nm^3/day (representative of the average flare flow-rate over the period of March to August).

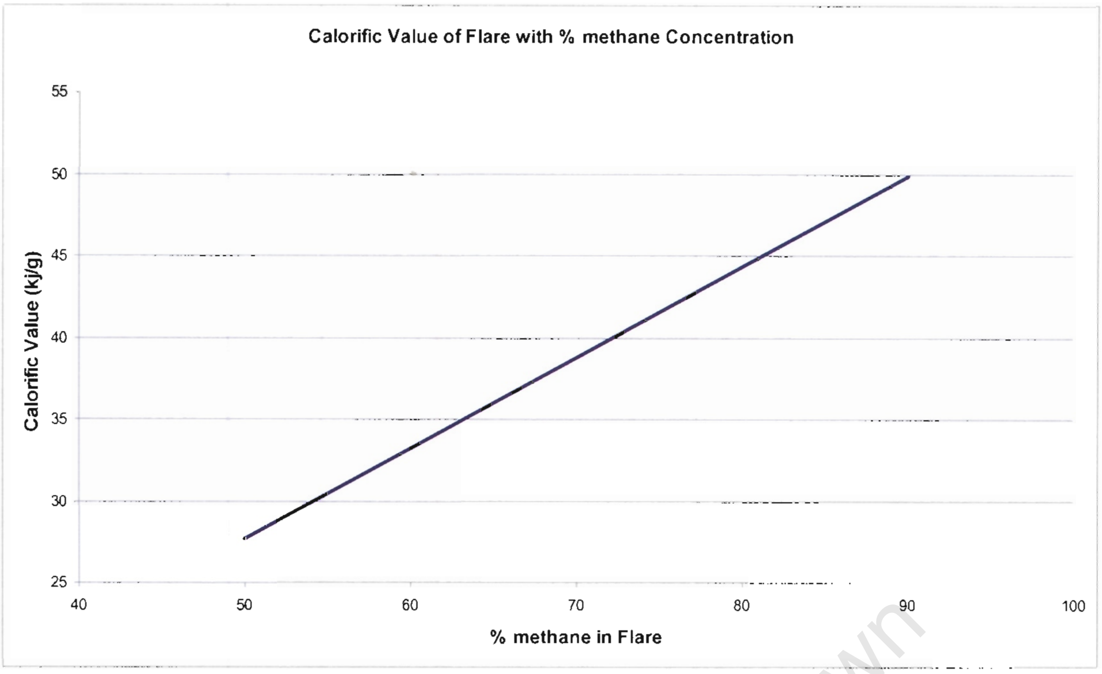


Figure 3.8: Change in calorific value of flare with methane concentration

3.7 Validity of Model

A statistical error analysis was carried out to assess the variability and reliability resulting from the assumptions defined in Section 3.2. The overall carbon balance error (based on an assumed SS and VFA composition defined by SS and VFA concentration measurements) ranged between 1% and 5% depending on the month concerned (see Table 3.7). As mentioned previously, the average COD: methane ratio is in agreement with literature (McCarty, 1964). Further iterations were made to balance the carbon content in the biogas with the incoming carbon to the effluent plant, within the constraints of a stabilized biogas concentration per month. The resulting biogas composition and flow-rate was calculated for each month and reflected a reliable result. The implication of this result is the effect of a constant biogas composition generated each month. Retention time and digester conditions are constant with month; hence reaction conditions are not expected to change substantially. Accordingly, the extent of the anaerobic reactions is likely to change only negligibly. Consequently it was necessary to define a biogas composition that satisfied the mass balance on a monthly basis with a negligible fluctuation in biogas composition.

Table 3.6: Error in Carbon Balance with month and resulting COD: CH_4 m^3

Month	Error in Carbon Balance	COD:m^3 CH_4 ratio
March	4	0.342
April	1	0.342
May	3	0.342
June	4	0.332
July	3	0.341
August	5	0.341
	Average Error (%)	**Average COD: methane ratio**
	3.3	0.342

Table 3.8 presents the difference between the estimation of COD treated based on SAB data collection and that calculated according to assumptions based on species compositions (as constrained by measured VFA and SS concentrations), the change in species constituents over the WTF, and their theoretical stoichiometric oxygen demand. Based on the assumed VFA and SS compositions inferred from VFA and SS concentration measurements, calculated COD treated figures correspond well with COD treated figures back calculated from flare flow-rate measurements as reported daily by SABMiller. This provides a higher degree of confidence in the conclusions drawn in Section 3.4, concerning inconsistencies in COD concentration measurements.

In order to assess whether calculated COD treated results differed statistically from reported COD treated figures, an analysis was carried out to evaluate the validity of the COD treated results (and hence species assumptions) obtained by the mass balance. The f-test can be used to indicate whether the variance of the two samples was equal, the outcome is presented in Table 3.9. The calculated p value indicated that a t-test with equal variances could be used in calculating whether the means of each sample set was significantly different. The results of the t-test (Table 3.10) indicated that there is no significant difference between COD values based on SAB data and COD values calculated according to the assumptions developed. This result gave additional validity to the effluent model proposed.

Table 3.7: Comparison between calculated COD treated figures, and figures estimated by SABMiller

Month	COD treated as per SABMiller Data (kg/day)	COD treated correlation (kg/day)
January	12234	10281
February	11906	18700
March	11063	8639
April	11536	10007
May	10377	8237
June	10171	7685
July	11791	9475
August	14935	10118

Table 3.8: f-test performed on data from Table 3.8

	12234.21769	*10281.065*
Mean	11682.7903	10408.5808
Variance	2505770.491	14187366.2
Observations	7	7
Df	6	6
F	0.1766	
P(F<=f) one-tail	0.02666	
F Critical one-tail	0.2334	

Table 3.9: t-test performed on data from Table 3.8

	12234.21769	*10281.065*
Mean	11682.7903	10408.5808
Variance	2505770.491	14187366.2
Observations	7	7
Pooled Variance	8346568.352	
Hypothesized Mean Difference	0	
Df	12	
t Stat	0.8251	
P(T<=t) one-tail	0.2127	
t Critical one-tail	1.7822	
P(T<=t) two-tail	0.4254	
t Critical two-tail	2.1788	

3.8 Results comparison with collected data

By comparing the results of the mass balance with data collected on-site, definitive conclusions surrounding mass balance accuracy could be made. The primary objective of the mass balance was the characterisation of the biogas and flare composition (as outlined in section 3.3). An analysis completed by PetroSA on the SABMiller P.E.

brewery (Ibhayi Brewery) is presented in Table 3.11. It is assumed that the biogas compositions of the two breweries are not significantly different. The mass balance calculated a methane flare concentration of 92% (vol) compared to a measured methane content of approximately 80%. Carbon dioxide in the stream feeding the flare was calculated at 8% compared with a measured concentration of 18%.

The Biogas composition was calculated as in Table 3.6. It was not possible to reference this data as overall biogas composition was not measured at either brewery. However, based on calculated biogas compositions (as per mass balance), and known flare compositions (as measured by PetroSA), a more accurate separation efficiency of 96.5% was calculated. Hence, although the assumption of perfect separation efficiency was not far from the truth, the 3.5% difference in efficiency results in the error observed in the gaseous compositions.

The PetroSA analysis gives further validity to the earlier conclusion drawn from discrepancies observed in Section 3.4. It is impossible to obtain flare compositions (as reported by PetroSA) in conjunction with measured flare flow-rate measurements, without stoichiometrically accounting for a SS contribution to a COD treated figure and remaining within the upper limits of what is considered at all a realistic COD: methane ratios. When incorporating a stoichiometric SS contribution to COD treated, the error becomes negligible as concluded in Section 3.6. The overall carbon balance based on an assumed VFA and SS composition as derived from measured VFA and SS concentrations (independent of measured COD figures), gives confidence in the accuracy of the flare measurements and sheds doubt on the accuracy of COD measurements.

Table 3.10 PetroSA analysis on SABMiller PE (Ibhayi) Brewery

Component	Mole %
Hydrogen	<.01
Oxygen	0.28
Argon	<.01
Nitrogen	1.71
Carbon Monoxide	<.01
Carbon Dioxide	18.8
Methane	79.2

3.9 Conclusion

The mass balance provided data characterising inputs and outputs from the WTF. This procedure has presented an alternate methodology for provision of LCA inventory data by estimating monthly organic, aqueous and gaseous material flows in and around the effluent plant. CH_4 and CO_2 compositions were calculated at 69.1% and 29.4 vol.% with an average methane flow-rate (from March '05 to August '05) of 4297 Nm^3/day and COD treated to methane ratio of 0.342. The appropriate validation of these results (t-test and F-test) has indicated confidence in the results obtained.

It is recommended that SABMiller Newlands Brewery address the discrepancies highlighted in the WTF log book. It has been found that the current COD measurements are potentially underestimating true COD concentrations, particularly in feed (and effluent) streams containing high SS concentrations (based on flare flow-rate measurements, Ibhayi Brewery biogas to flare sampling, and indicative biogas concentrations as determined by both calculations and literature).

Chapter 4 presents the Life Cycle Assessment of the waste water treatment management system. Where measured data were unavailable, mass balance results were used to populate the Life Cycle Inventory. However, data sources are discussed and where calculated results are used, appropriate reference is made.

Chapter 4: LCA of on site anaerobic digestion

An important key question that this thesis sets out to answer is whether on-site treatment of high COD wastewater truly serves to reduce environmental burdens, and if so, by how much. This chapter defines the goal and scope of the Life Cycle Assessment undertaken, presents the data used to populate the LCI and discusses the results and conclusions generated by the assessment. The framework is as discussed in Section 2.2 and follows goal and scope definition, inventory analysis, impact assessment and interpretation.

4.1 Goal definition

The goal of the LCA is to use determined material and energy flows within the framework of the Life Cycle Assessment to quantify the environmental benefits on-site anaerobic digestion. This assessment measures the impact of a fundamental process change on the environment and calculates an impact measurement of the process according to defined environmental impact categories.

The effect of altering process specification impacts on environmental burden, operational efficiency and cost. This framework allows for a sensitivity analysis of the process, quantifying relative impacts, and enables direct calculations for process optimization.

The methodology used in the Life Cycle Assessment for impact assessment or burden quantification follows the ISO standards framework, developed by SETAC and is discussed in the literature review.

The LCA was used to compare the environmental implications of various effluent treatment alternatives, including disposal to river without treatment, the current configuration (on-site waste water treatment and municipal treatment), disposal to river after on site treatment by the SAB WTF only and disposal to river after municipal treatment only. This analysis facilitates the quantification of environmental impacts of the water treatment facility (WTF) as a function of operational specifications.

This leads to quantification of the added benefit of routing treated effluent to the Athlone municipal treatment plant. It also enables the calculation of the environmental burdens avoided by installation of the on-site effluent plant. This comparison highlights potential improvement in treatment and outlines an optimum configuration and its resultant outcome as a goal for further development.

On evaluation of energy recovery options, and implementation of the most suitable technology with reference to SABMiller Newlands Brewery, further improvements in burden reduction are expected owing to energy recovery. Energy recovery offsets energy utilization by reducing energy usage from the grid, thereby contributing to the "avoided burden" category. The environmental benefits achievable by energy recovery are determined by repeating the LCA analysis under conditions of energy recovery in Chapter 7.

This thesis also aimed to develop insight into the difficulties of performing LCA studies in South Africa. Literature has been written on the difficulties associated with the limited availability of valid input and process data. Specifically, data pertaining to infrastructural support by auxiliary process are deficient in South Africa (Landu and Brent, 2006). It is a secondary goal of this thesis to develop an understanding of where these data gaps lie, and to assess the requirements for data generation in the hope of inspiring LCA practitioners to further develop South African data sets.

The intended ***target audience*** of the study includes both SABMiller process engineers responsible for process and efficiency improvement and the academic community responsible for generating awareness and methodologies to enhance sustainable process engineering. This study aims to present itself as a thesis that can be used by SABMiller to facilitate enhancement of their on-site effluent treatment facilities at their breweries around the country. Simultaneously, this study aims to serve as a generic research tool that can be used by the academic society to enhance waste water treatment plant performance by presenting the opportunities for improvement and the limitations of waste water treatment in terms of environmental burden reduction.

This LCA therefore presents itself as both a descriptive LCA with the intended purpose of describing or detailing the process, giving rise to previously unknown information, as well as a change-oriented LCA providing information that subscribes to process alteration possibilities.

4.2 Scope of Study

The ***system*** evaluated by the Life Cycle Assessment in this study is the waste water management system, treating waste originating from SABMiller Newlands Brewery prior to its disposal to river. Figure 4.1 is an illustrative depiction of the system and the unit processes contained therein.

The WTF treats liquid waste generated by the brewery. Prior to its treatment, the solids present are removed from the brewery effluent by a screening centrifuge and disposed of separately. The clarified brewery effluent is fed to a calamity feed tank where the effluent is dosed with a 44% (mol%) solution of caustic to neutralise its pH to between pH 6 and pH 8. This buffer tank enables the continuous operation of the anaerobic digester by controlling the acidity of the effluent feed stream. It also facilitates better effluent hold-up. Anaerobic digestion does not respond well to fluctuating process loads, so by adjusting the acidity of the effluent and smoothing its flow-rate, improved digester control is achieved (Verma, 2002). The pH-neutral effluent is then pumped to the up-flow anaerobic sludge blanket (UASB) reactor where it is treated anaerobically prior to disposal to sewer. In the event of process failure or under-capacity, effluent can be purged to sewer directly from the calamity tank.

The biogas generated is concentrated into two separate gaseous streams inside the UASB by utilizing the differences in solubility of the gases generated. The digester separates the biogas generated by making use of diagonally positioned baffles. The height at which the gas leaves solution determines the side of the baffle to which the gas is directed. A methane rich stream is processed to the flare and a carbon dioxide rich stream through the biofilter. Any H_2S present is oxidised by the sparging of ozone in the biofilter. H_2S emissions standards are stringent and this requirement is particularly stringent at SAB Newlands owing to its residential location requiring both odour and toxicity standards to be met.

The purpose of the SABMiller effluent plant (WTF), commissioned in 2004, is to handle the treatment of mixed brewery waste water, primarily for the reduction of COD, prior to disposal to the municipal treatment plant. The methane-rich biogas produced is currently flared. This flare is included in the system boundaries. Four system configurations for the waste management of brewery effluent are compared:

- Waste water → river
- Waste water → SAB WWT → municipal WWT → river
- Waste water → SAB WWT → river
- Waste water → municipal WWT → river

This enables the direct comparison of treatment options across impact categories, enabling the identification of key operational variables that impact on burden reduction. Although the municipal treatment facility is remote from the SABMiller effluent plant, it is included in the system boundaries by nature of its relative function, where required. The Athlone municipal treatment plant is the waste water facility that processes Newlands brewery effluent in combination with mixed effluents from the city and surrounding industrial areas prior to river disposal.

In comparing the various treatment options, the ***functional unit*** was defined as receipt of 1 kg of COD in brewery effluent entering any of the configurations of the effluent management system. The functional unit is a basis for data tabulation and all data is reported on this basis. The basis overcomes the allocation problem arising from the production of several brands of beer encountered where the basis selected is a specified volume of beer production. The functional unit chosen reflects the purpose of the effluent plant, and is directly related to water quality parameters that need to be taken into account when disposing effluent to river. It must be recognized that with a significant shift in production of one beer in relation to another, over an extended period of time, a change in emissions produced may be observed depending on the extent to which the effluent water composition varies with beer produced.

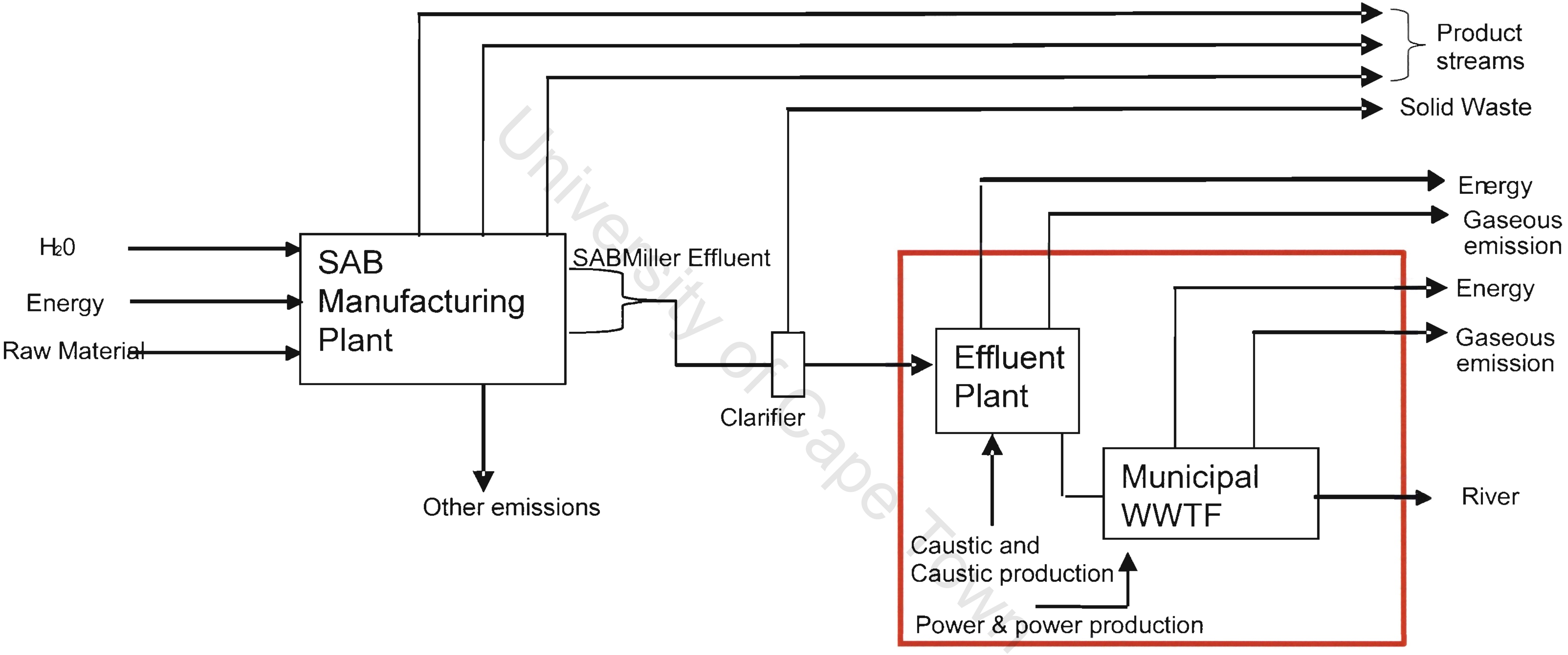


Figure 4.1: System boundaries enclosed by the Life Cycle Assessment

The ***boundaries*** of the system include all unit processes in the treatment of the effluent water, post contrashear solids removal. This includes chemical additions for pH adjustment as well as the energy used in process operation and regulation. The boundaries extend from the point where waste water exits the brewery process to the point of disposal of treated water to river. In the current configuration, this includes municipal treatment of the processed effluent, prior to disposal to river. The construction of the WTF (and municipal treatment plant) has been excluded from the system boundaries due to the fact that the plant is already constructed and this LCA aims to improve on operation rather than inform decision making concerning construction.

Although the municipal plant treats effluent both anaerobically and aerobically, the plant was modelled as a purely anaerobic facility due to a lack of available data. This assumption represents a worst case scenario in terms of gaseous emissions, but adequately quantifies aqueous emissions to river. The *products* produced by the municipal treatment plant include treated water to river and biogas.

The attribution of burdens to emitted quantities was easily related, due to the difference in physical nature of the emissions produced. For example, airborne burdens can be related to gaseous outputs and water toxicity can be related to liquid outputs. The relationship between burden production and waste water composition was inferred from the composition of the incoming water stream. Inventory data was tabulated on the basis of 1 kg COD entering the system. It was therefore possible to assign burdens accurately between the SABMiller effluent plant and municipal treatment based on the COD treated by each.

The ***data used*** in the inventory analysis were derived as follows:

- Data were collected from the daily performance log of the SABMiller effluent treatment plant from June '04 – August '05. These data were discussed at length in Chapter 3. The data set includes aqueous flow-rates and COD, VFA and SS compositions processed through the WTF. It also included pH measurements and volumetric measurements of the monthly gaseous flow-rate to flare. Caustic consumption was also recorded. Data pertaining to the kW rating of the WTF pumps, stirrers and waste gas fans were also collected. No data were available describing sludge removal, as since start-up till and during the duration of this thesis, sludge removal had not been necessary.

- An analysis of the biogas flare composition of the SABMiller PE brewery (Ibhayi Brewery) carried out by PetroSA, September '03, was collected. This dataset is presented in Chapter 3, Section 3.8.
- Limited data were available from the Athlone municipal treatment facility. No data were available describing sludge removal, although the assumption of a purely anaerobic process, where sludge growth is considerably slower, compensates for this. There were no data pertaining to measurement of gaseous emissions or gaseous flow-rates. Data collected were limited to input and output flow-rates, stream compositions (including all the required nutrient information) and energy consumption. The data collected were averaged over an annual period from July '04 to June '05. Electricity consumption was collected from February '05 to July '05. Finally, there was no reported chemical addition in the municipal treatment process. See appendix A for details.
- Mass balance calculations were used where little process information was available or known.
- The Simapro library was used to generate data for the burdens attributable to the secondary and tertiary levels of this study. This includes the environmental burdens attributable to caustic and energy production.

The accuracy of the results presented in this thesis is restricted by certain ***assumptions*** that were made in light of limited process data. There were primarily four assumptions used in the LCA:

1. The composition of municipal biogas was assumed based on literature sources. The composition was not measured, nor was the flow-rate measured. Correlations relating biogas produced to COD treated had to be used to estimate municipal treatment biogas flow-rates.
2. The municipal treatment plant was modelled as a purely anaerobic treatment facility. This allowed for a 'worst case scenario' calculation concerning

greenhouse gas emissions. This was in line with the conservative nature of the approach made within the thesis.

3. Sludge generation or disposal was not included in the system boundaries in light of limited information concerning disposal rates. SABMiller Newlands Brewery reported no sludge disposal prior to, or during, the duration of the study. Hence, no reliable data were available as to the likely requirement of sludge disposal or the forecasted necessity thereof. Sludge disposal fell outside the system boundaries, as a result of the impractically measurable rate of sludge build-up from the specific anaerobic digestive case-study analysed. The Athlone municipal treatment facility was also unable to produce accurate sludge disposal measurements due to their infrequent sludge disposal requirements. Hence, removing sludge disposal from system boundaries completely eliminated the impact of sludge disposal from the analysis, thereby standardising the comparison in light of limited information, and avoiding calculation bias. Regardless, sludge disposal is not expected to contribute significantly to results, owing to the apparent infrequency of sludge disposal.
4. Electricity generation was based on a country power generation mix of 90% coal, 4% nuclear, 6% hydropower. The burdens attributable to power generation were included in the study. Emissions resulting from the combustion of coal were specified as according to Eskom's 2001 annual report per kWh of power consumed: 0.89 kg CO_2, 3.61g NO_x, 7.91g SO_x, 0.031g ash emitted and 1.26l of water utilised. These figures do not change significantly year on year.
5. The power consumed by pumping processed effluent to Athlone is assumed to be equivalent to the power consumed for sewerage collection in the City of Durban as reported by Friedrich et al. (2006) as 0.14 kWh/kl of effluent moved from point of generation to the local municipal treatment facility.

Owens (1999) described the difficulty in the collection of data concerning complex systems. This is compounded with the recognized challenges of data availability in South Africa (Friedrich and Buckley, 2002).

Similar difficulties concerning pumping/processing data were described in a paper written by Landu and Brent (2006). They concluded a cradle-to-grave LCA study on the production of potable water in the Rosslyn industrial zone, north of Pretoria in the Tshwane metropolitan area. The life cycle extended from raw water extraction to water supply to the Tshwane metropolitan area. In that study, system boundaries ring-fenced the assessment around water and energy flows from one of two sources, the Zuikerbosch purification and pumping system, and excluded water and energy flows feeding the Tshwane metropolitan area from the Vereeniging purification and pumping station. In reality, these flows become a combined stream in the Palmiet booster station, feeding the Klipriviersberg storage facilities prior to municipal delivery. The same study further assumed that the impact attributable to raw water extraction from the Vaal River to be of minor impact. This thesis has attempted to quantify the impact of power consumption due to the pumping of effluent between its originating source (SABMiller Newlands Brewery) and the Athlone municipal treatment facility, by using the Friedrich et al., (2006) number mentioned above.

The CML 2 baseline 2000 V2.1 impact assessment method provided the evaluation methodology. The impact categories generated by the Simapro database were relevant to this study and included burden contribution to abiotic depletion, global warming potential, ozone layer depletion, human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, photochemical oxidation, acidification and eutrophication. These categories are consistent with the goal of this study in that they highlight impacts due to effluent pollution, indicating both direct and indirect environmental harm.

4.3 Inventory analysis

The data collected were related to the functional unit of 1 kg of COD entering the treatment management system. All data including energy consumption, aqueous and gaseous emissions and caustic consumption were related to this functional basis as reported by the SAB anaerobic digester log book. Appendix B presents a summary of data collected from the Athlone treatment. Table 4.1 presents the collated inventory table on the basis of the functional unit. Figure 4.2 presents an illustrative depiction of the unit process encapsulated by the system boundaries.

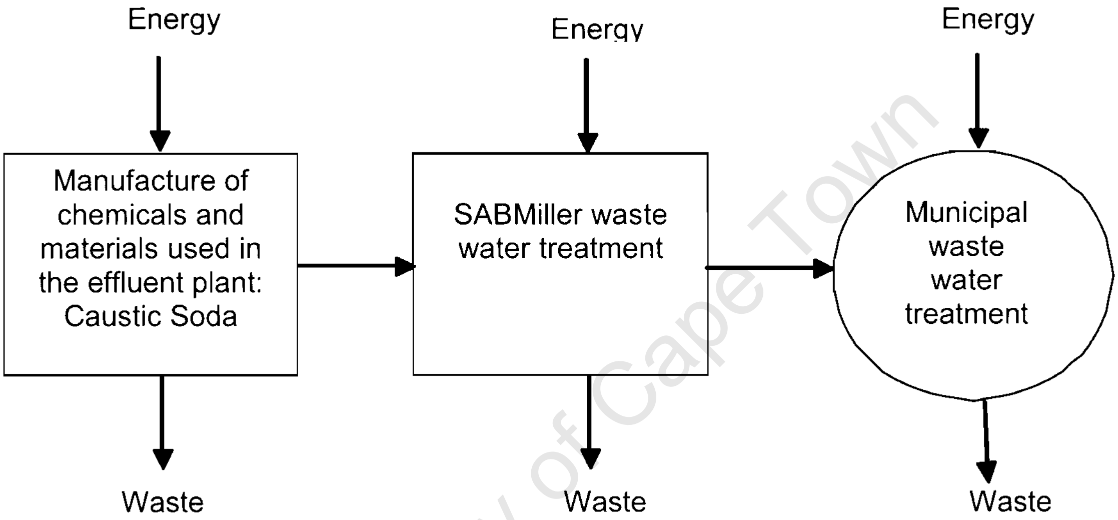


Figure 4.2: Unit process contained within system boundaries of LCA

Brewery effluent contains COD, phosphorus, sulphate, nitrogen, suspended solids and NaOH. In addition to these components, the output stream accounts for carbon dioxide, oxygen, nitrogen and water vapour. Power consumption also constitutes a significant input. The residual nutrients and COD leaving each system were calculated based on the nutrient and COD concentrations in the output stream. This enabled calculations pertaining to the digestive efficiencies of the anaerobic systems (SABMiller and municipal). Nutrient and COD reduction efficiencies were then used to calculate the respective mass flow-rates to river in sequential water management systems. Digester efficiencies are presented in Table 4.2.

Table 4.1: Life Cycle Inventory per functional unit - kg COD fed to the waste water management system

Inputs	SAB	Municipal	SAB and municipal	No treatment
COD (kg/kg COD)	1	1	1	1
P (kg//kg COD)	0.0244	0.0244	0.0244	0.0244
SO_4 (kg//kg COD)	0.1904	0.1904	0.1904	0.1904
N (kg//kg COD)	0.2149	0.2149	0.2149	0.2149
SS (kg//kg COD)	0.1904	0.1904	0.1904	0.1904
Power (kwh/kg COD)	0.1642	0.1095	0.2464	0.0663
NaOH (kg//kg COD)	0.1008	0.0000	0.1008	0.0000
Outputs				
COD (kg//kg COD)	0.0885	0.1018	0.0090	1.0000
P (kg//kg COD)	0.0028	0.0031	0.0004	0.0244
SO_4 (kg//kg COD)	0.0656	0.0674	0.0232	0.1904
N (kg//kg COD)	0.0094	0.0124	0.0005	0.2149
SS (kg//kg COD)	0.0656	0.0054	0.0018	0.1904
CH_4 (kg//kg COD)	0.0079	0.2181	0.0272	0.0000
CO_2 (kg//kg COD)	1.0160	0.5001	1.0603	1.9100
H_2 (kg//kg COD)	0.0002	0.0004	0.0002	0.0000
H_2S (kg//kg COD)	0.0069	0.0072	0.0075	0.0000
Water Vapour (kg//kg COD)	0.5839	0.1191	0.5944	1.1700
NaOH (kg//kg COD)	0.1008	0.0000	0.1008	0.0000

Table 4.2: Treatment efficiencies of the SAB WTF and the municipal WTF

	SAB	Municipal
COD	91.2%	89.8%
P	88.7%	87.4%
N	95.6%	94.2%
SO_4	65.5%	64.6%
SS	65.5%	97.2%

Phosphorus and nitrogen flow-rates from the SABMiller treatment facility were only measured in sewer discharge. Hence, based on relative COD reduction efficiencies, a scaled phosphorus and nitrogen efficiency was assumed for the SAB treatment plant. Hence, it was assumed the SABMiller treatment facility reduced phosphorus and nitrogen based nutrients 1.02 times better (91.2/89.8) than the municipal effluent treatment facility. Back calculations were then performed to calculate the entering Phosphorus concentrations and Nitrogen concentrations based on measured output nutrient compositions and reduction efficiencies. Input and output nutrient concentrations were (and are regularly) measured at the Athlone municipal treatment facility by municipal staff, thus enabling municipal efficiency calculations. SO_4 reduction efficiencies had to be calculated in the same way but for the municipal treatment facility combining input and output concentrations as recorded in the SABMiller WTF log book with the scaled reduction efficiency based on COD reduction as described above.

Table 4.3 presents the electrical requirements of both the SABMiller and municipal treatment facilities. Per month data (kWh) were calculated based on the assumption that the total installed equipment wattage of the SABMiller WTF operates for 24 hours per day 30 days per month. Although this provides an overestimation of the power draw on the facility in low production months, the data collected from the SABMiller treatment facility were limited to notification of the equipment ratings, and month on month variation in equipment specific power draw was unavailable. The installed wattage of the municipal treatment facility was calculated in reverse, starting with collected recorded monthly data (kWh consumed) and back calculating the total installed wattage assuming the same operating durations. It is interesting to note the rated wattage of the municipal plant is less than that of the SABMiller plant. This is a result of the economies of scale introduced by the larger volumes of waste treated by the municipal treatment works. Intuitively, the combined pumping and aeration requirements of the municipal plant are expected to weigh significantly upon the power requirements of the plant. However, as a result of pump station power consumption being attributed to pump stations feeding the effluent to Athlone, and not the municipal plant itself a large proportion of what would be power consumed by the municipal plant feeding effluent to its anaerobic (and aerobic) digesters is not attributed to the municipal plant. Further to the differences observed in the water treatment facility power draw, insufficient information surrounding the municipal treatment process was provided to make accurate inferences on the likely power draw attributable to aeration. Further, the magnitude of the aeration power requirement in relation to the total power draw of the facility is largely dependent a variety of factors including aerobic tank depth, oxygen effluent concentration, water chemistry, water temperature and mechanical system design. None the less, the intermediary power consumed by pumping effluent to Athlone has been accounted for in the calculations as discussed in Section 4.2. Hence the implications of pumping effluent to Athlone is fully incorporated and discussed in Section 4.4.

Table 4.4 (based on Table 3.10) presents a summarised description of the gaseous composition of the flare gasses prior to combustion. The nitrogen and oxygen present in the Ibhayi analysis (highlighted in Table 3.10) was assumed to due to the introduction of air in the gaseous sampling process and not as a result of nitrogen and oxygen generation from the digestive process. Hence the amount of CH_4 and CO_2 present in the flare feed stream was scaled up accordingly; with the removal of air from the flare feed stream composition. 100% combustion is assumed based on the combustion efficiency recorded at the SABMiller Ibhayi brewery. Furthermore, the life cycle extends all the way to the aerobic decomposition of residual COD emitted to river from the municipal treatment facility. Combustion products were calculated by making use of the following combustion reactions:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

$$2H_2 + O_2 \rightarrow 2H_2O$$

$$2H_2S + 3O_2 \rightarrow 2SO_2 + 2H_2O$$

Furthermore, COD was assumed to stoichiometrically aerobically decompose to CO_2 and H_2O_v. Anaerobically, COD was converted to 0.342 m^3 of methane per kg COD digested. Biogas produced anaerobically by the Athlone waste water treatment plant was assumed to have the composition as indicated in table 4.4.

COD effluent concentrations (as recorded in the AD log book) were used to model COD to river. Flare flow-rate data was based on reconciled COD treated figures as per the mass balance and calculated COD: methane ratios, calculated to be in agreement with both flare flow-rate measurements and literature. As a result, COD concentrations originating from the brewery process were calculated according to the COD concentrations processed to sewer as per AD log book plus the COD treated figure used to model biogas from the SAB effluent plant, i.e. the reconciled COD treated figure mentioned above. The average reconciled estimate of COD treated used in calculations (given in Table 3.8) is 10,392kg COD treated/day.

Table 4.3: Table showing power requirements of both the SAB and municipal treatment facility

Power requirements	SAB	Municipal
Effluent plant feeder	35	
Reactor feed pump	11	
Recirculation pump	7.5	
2 Stirrers (total power)	18	
Waste gas fan 1	3	
Waste gas fan 2	2.2	
Waste gas fan 3	7.5	
Miscellaneous pumps	11	
Biofilter	15	
Total installed power in kW (total volumetric capacity basis)	110.2	91.1
Per Month (kWh) (total capacity)	79,344	65,615
Maximum volumetric capacity (kl)	4500	150,000
Power delivered (kW) per kl	0.0245	0.000608

Table 4.4: Biogas compositions feeding the SABMiller flare and originating from the Athlone municipal treatment facility

Biogas Component	Flare feed stream (WTF) (%)	Generated by Athlone municipal treatment facility (%)
H_2	<.01	1
O_2	<.01	<.01
N_2	<.01	<.01
H2S	<.01	1
CO	<.01	<.01
CO_2	19.82	33
CH_4	80.19	65

Biogas composition (Table 3.6), in conjunction with overall carbon balances was verified by statistical analysis (Section 3.6), and further confirmed by the calculated COD: methane ratio of 0.342m^3 methane per kg COD digested, which correlates well with McCarty (1964) (0.348m^3 methane per kg COD).

In the mass balance, it was also assumed that only negligible amounts of CH_4 are processed to biofilter, hence for mass balance accounting purposes, it was assumed that all the CH_4 is processed to flare. This assumption was also partly based on the relative solubilities of the biogas generated and therefore the inferred likelihood of >99% separation.

However, for LCA purposes, based on the measured concentration of biogas processed to flare (PetroSA) and the calculated concentration of methane in the biogas generated, 96.5% of the methane generated was found to be processed to flare, and 3.5% processed to biofilter. This results in a 96.5% separation system with reference to CH_4. This calculation was done as follows: The total biogas to flare flow-rate was a measured variable. The concentration of methane in this stream was measured (PetroSA). From COD: methane ratios, the methane concentration in the biogas could be calculated, and hence, the separation efficiency of the digester could be calculated by way of simple mass balance. This results does not differ greatly from the >99% efficiency as used for calculations in the mass balance. 56% of the carbon dioxide generated in the AD was found to be processed to flare, resulting in a CO_2 concentration in the flare feed of approximately 19.8% (as per Table 4.4). Table 4.5 presents the biogas composition and average flow-rate (averaged over January '05 to August '05), originating from the SABMiller effluent plant, prior to biogas separation (methane concentration), based on a COD digested: methane ratio of 0.342.

Table 4.5: SABMiller biogas composition and average flow-rate

	Composition (vol %)	Flow-rate (Nm^3/day)	Flowrate to flare (Nm^3/day)	Flow-rate to biofilter (Nm^3/day)
CH_4	69.1	3554.0	3428.0	126
CO_2	29.4	1512	846.86	665
H_2	0.5	25.72	0	26
H_2S	1.0	51.44	0	51
Total	100	5144.0	4275.0	869.0

4.4 LCA Results and interpretation

4.4.1 Introduction

The resultant environmental impacts of the inventory results are presented following. As mentioned in Section 4.2, the systems studied include effluent discharged directly to river, effluent treated by the SABMiller treatment facility only, effluent treated by the municipal treatment facility only, and effluent treated by first the SABMiller treatment facility, prior to treatment by the municipal treatment facility before being discharged to river. The last waste water treatment scenario described above represents the current configuration at the SABMiller Newlands Brewery.

The treatment scenarios are presented across a range of impact categories thereby constructing the environmental profiles used to compare waste water management systems. Key results are emphasized, and major contributors to impact categories are highlighted and discussed.

4.4.2 Results

The environmental profiles of the waste water management systems are presented in Figure 4.3. Across impact categories, impacts per treatment system are scaled to a percentage of the treatment system generating the maximum burden. This provides for a relative comparison between impact categories, of which the relative importance is open to the interpretation of the LCA practioner (see Section 2.2.4.3). Table 4.6 presents the characterisation process across impact categories. This table was used to generate Figure 4.3.

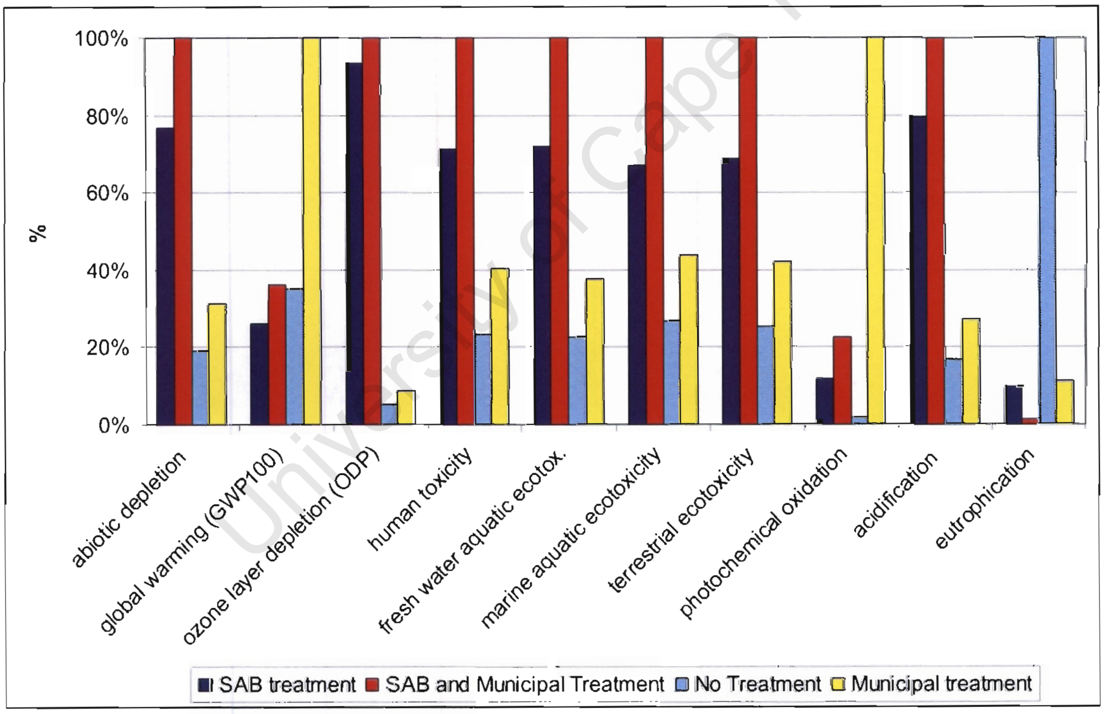


Figure 4.3: Characterised LCA results presented as a percentage of the maximum burden per impact category

Table 4.6: LCA equivalency factor scores

Impact category	Unit (eq)	SAB	SAB and municipal	No treatment	Municipal treatment
abiotic depletion	kg Sb	0.00207	0.0027	0.000511	0.000843
global warming (GWP100)	kg CO_2	1.46	2.02	1.97	5.61
ozone layer depletion (ODP)	kg CFC-11	2.54E-08	2.72E-08	1.45E-09	2.39E-09
human toxicity	kg 1,4-DB	0.0557	0.0784	0.0183	0.0317
fresh water aquatic ecotoxicity	kg 1,4-DB	0.00825	0.0115	0.00261	0.00432
marine aquatic ecotoxicity	kg 1,4-DB	209	312	83	137
terrestrial ecotoxicity	kg 1,4-DB	0.000813	0.00118	0.000299	0.000494
photochemical oxidation	kg C_2H_2	0.000159	0.000305	2.44E-05	0.00135
acidification	kg SO_2	0.00324	0.00408	0.000675	0.00111
eutrophication	kg $PO_{4\,3-}$	0.0116	0.00154	0.118	0.013

A general trend is observed when comparing SAB treatment and combined SAB and municipal treatment. Except in the eutrophication impact category, the results indicate a burden reduction when removing the municipal treatment element from the SAB treatment followed by municipal treatment waste water management system. Marine ecotoxicity shows the largest reduction in impact by 33.0%; ozone layer depletion shows the smallest reduction in impact between the two treatment options of 6.6%. Other key results include the reduction in global warming potential by 9.9%, acidification is reduced by 20.9% and human and fresh water toxicity is reduced by 28.9% and 28. 3% respectfully.

Eutrophication is reduced when including downstream municipal treatment. SAB treatment results in an 8.5% higher impact in this category, as a result of the higher COD and nutrient loadings released to river.

Municipal treatment fairs favourably in comparison with the other effluent management systems across all impact categories except global warming potential and photochemical oxidation. No treatment results in lower impact scores than any treatment except in the eutrophication impact category, as expected. No treatment involves no caustic addition and minimal energy consumption. However, this scenario's eutrophication scores at least 10-fold the other waste water management systems. No treatment is clearly very damaging to the local receiving environment. In addition no treatment is prohibited by law so is not an option for consideration. The addition of municipal treatment reduces the eutrophication score by 88.98%, SAB treatment only reduces the eutrophication score by 90.17%, and their combined effect is to reduce the eutrophication impact category by 98.69%. This result highlights the importance and potential of efficient waste water treatment systems.

When comparing SAB treatment followed by municipal treatment with purely municipal treatment, there is no clear trend across impact categories as to which waste water management system gives rise to a higher overall burden profile. This comparison has to be done on an impact category by impact category basis, with the relative importance of each category decided based on the objectives of the study. This comparison is worth making; prior to the installation of the WTF, effluent was being processed directly to Athlone for treatment. This comparison talks to the added benefits and avoided burdens resulting from the installation of the WTF. Across impact categories associated primarily with the aqueous phase, municipal treatment scores lower than the combined treatment scenario, translating into a relatively environmentally friendly emission profile. These categories include fresh water aquatic ecotoxicity (0.00432kg 1,4-DB, down from 0.0115kg 1,4-DB) and marine aquatic ecotoxicity (137 kg 1,4–DB, down from 312kg 1,4-DB). In addition, abiotic depletion scores favourably (0.000843kg Sb, down from 0.0027kg Sb). Eutrophication is the exception to this trend, where a combined SAB treatment and municipal treatment offer higher COD and nutrient removal capabilities (0.00154kg PO_4 $_{3-}$.., down from 0.013kg PO_4 $_{3-}$). Municipal treatment also results in lower impact scores concerning human toxicity (0.0317kg 1,4 DB, down from 0.0784kg 1,4 DB) and terrestrial toxicity (0.000494kg 1,4–DB, down from 0.00118kg 1,4 DB). When assessing impact categories characterised by equivalents associated with the gaseous phase, municipal treatment scores higher indicating an environmentally more harmful gaseous emission profile. This includes photochemical oxidation (0.00135kg C_2H_2,, up from 0.000305kg C_2H_2) and global warming (5.61kg CO_2, up from 2.02). Acidification and ozone layer depletion are exceptions to this trend where SAB treatment followed by municipal treatment dominates these impact categories. It is worthwhile noting that while ozone layer depletion is included in this analysis, the

CFC quantum emitted from these processes are negligible and do not carry significant or consequential weighting (see Table 4.6). Hence, this category will not be discussed further.

4.4.3 Discussion

The primary contributing factors to *Abiotic depletion* include electricity generation from coal and caustic consumption. Each factor contributes approximately equally to the SAB treatment abiotic depletion score, whereas energy generation from coal contributes approximately 61% to the consecutive waste water management system. This result is unsurprising due to the added energy expenditure arising from additional effluent pumping and municipal power consumption. Consequently, no treatment and effluent treatment score lowest in this category as no caustic is used in either treatment system and energy consumption is relatively low in both. Table 4.7 presents the relative contribution to abiotic depletion impact scores.

Table 4.7: Key contributors to Abiotic depletion

Abiotic depletion	SAB Treatment	SAB and Municipal	No Treatment	Municipal treatment
Coal comb.	0.00126	0.0019	0.000511	0.000843
Caustic	0.000801	0.000801	-	-
Process emissions	0	0	0	0
Total	0.002061	0.002701	0.000511	0.00843

Global warming potential (GWP) is characterised by CO_2 equivalents. Municipal CO_2 equivalents are significantly higher than SAB CO_2 equivalents due to methane emitted from the Athlone treatment facility, currently not flared. CH_4 carries a potency factor of 21 times that of CO_2 and therefore results in a higher contribution to the global warming impact category. No treatment still results in greenhouse emissions due to the aerobic decomposition attributable to the high COD loadings purged to river. Aerobic decomposition result in the emissions of CO_2, however, more biomass is produced by aerobic organisms per kg carbon consumed than anaerobic organisms, resulting in less gaseous carbon emitted than that amount associated with anaerobic decomposition. Consistent with literature, this result is reflected in the difference in global warming potential of 9.09% when comparing SAB treatment with no treatment. Residual COD processed by the municipal treatment post SAB treatment results in methane as well as carbon dioxide. This implication is observed by the higher impact score when including municipal treatment post SAB treatment. Global warming potential also results from additional energy expenditure although only marginally, so 82.19% of the GWP score can be allotted to carbonaceous emissions from the WTF in the assessment of SAB treatment only, 10.0% is as a result of coal combustion for power requirements and 8.15% is due to caustic consumption. Contributors assessed across treatment scenarios are presented in Table 4.8. The primary contributor to GWP across treatment systems are process emissions.

Table 4.8: Key contributors to Global warming

global warming	SAB Treatment	SAB and Municipal	No Treatment	Municipal treatment
Coal comb.	0.146	0.22	0.0591	0.0975
Caustic	0.119	0.119	-	-
Process emissions	1.2	1.69	1.91	5.52
Total	1.465	2.029	1.97	5.61

Human toxicity is dominated by SAB treatment followed by municipal treatment, SAB treatment, municipal treatment and then no treatment. This result is mirrored fairly consistently across all impact categories referenced to the equivalency factor 1,4 dichlorobenzene. These categories include in addition to human toxicity *fresh water ecotoxicity, marine aquatic ecotoxicity* and *terrestrial ecotoxicity*. Electricity from coal is the dominating contributor to these respective impact categories and as the coal contribution to electricity consumed is not dependant on the impact category assessed, a change in the relative scores across impact categories is not expected.

The impact category most comparable with global warming is the *photochemical oxidation* impact category, where for the analogous reasons, municipal treatment scores highest in this impact category, and no treatment scores lowest. In this case, the no treatment score is considerably less than its counterpart score in the GWP impact category. Photo-chemical oxidation is measured in terms of kg ethane equivalents – a hydrocarbon, characterising impact scores in terms of greenhouse emissions. CO_2 emissions contribute substantially less to this category than hydrocarbon emissions. The contributions to impact category is as illustrated in Table 4.9. NaOH is a key contributor as are process emissions and the environmental implications of coal combustion. The impact category is equally made up of all three inputs except in municipal treatment where process emissions dominate and no treatment where coal combustion dominates. Process emissions contributing to the municipal treatment score are an order of magnitude higher than the contribution of process emissions to other impact treatment options. This is clearly the impact attributable to the un-flared methane emitted from the municipal treatment facility.

Table 4.9: Key contributors to photochemical oxidation

photochemical oxidation	SAB treatment	SAB and municipal	No treatment	Municipal treatment
Coal comb.	0.0000604	0.0000906	0.0000244	0.0000403
Caustic	0.0000518	0.0000518	-	-
Process emissions	0.0000472	0.000163	0	0.00131
Total	0.000159	0.000305	0.0000244	0.00135

Acidification is characterised by sulphuric emissions and resulting acid rain. The organic composition of the effluent stream will determine to a large degree the process emissions contribution to acidification. The higher the sulphur content of the organic waste, the higher the sulphur content of the biogas produced. The biogas composition of the municipal biogas was assumed based on literature indicated biogas compositions. In addition, an H_2S content was assumed to be present in the SABMiller biogas (see Section 3.4.4). However, the higher scores cannot be attributed to additional hydrogen sulphide emissions in light of additional downstream anaerobic digestion as indicated in Table 4.10. However, when analysing Table 4.10, it becomes evident that acidification is due to both power consumption and caustic use. Moving effluent from site to Athlone incurs additional electricity expenditure which translates into additional sulphur per kg coal burnt. No treatment results in the lowest score in this impact category, due to sulphur emissions arising from only marginal electricity use. Caustic has a significant impact on this impact category contributing 48.0% of the SAB treatment acidification burden profile and approximately 38.4% of the SAB and municipal treatment acidification burden profile.

Table 4.10: Key contributors to Acidification

Acidification	SAB treatment	SAB and municipal	No treatment	Municipal treatment
Coal Comb.	0.00167	0.00251	0.000675	0.00111
Caustic	0.00157	0.00157	-	-
process emissions	0	0	0	0
Total	0.00324	0.00408	0.000675	0.00111

Eutrophication clearly shows the harm in effluent disposal directly to river. SAB and municipal treatment shows the most favourable score in this impact category due to the consecutive high efficiency COD and nutrient reducing facilities. The scores in this impact category are close and treatment methodologies can be ranked in order of COD and nutrient removal efficiencies. Hence, SAB treatment records the second most favourable score and municipal treatment the third. Table 4.2 presents the relative nutrient and COD reduction efficiencies of the SAB and municipal treatment facilities respectfully. Table 4.11 presents the relative contributors to eutrophication.

Table 4.11: Key contributors to eutrophication

Eutrophication	SAB treatment	SAB and municipal	No treatment	Municipal treatment
Coal Comb.	7.87E-05	0.000118	3.18E-05	5.25E-05
Caustic	0.0000969	0.0000969	-	-
Process emissions	0.0114	0.00133	0.118	0.0129
Total	0.0116	0.0015	0.118	0.013

A re-occurring theme is the significant contribution of *power consumption* and its influencing effects on the generated burden profiles. The power requirements of processing effluent to Athlone and environmental impacts thereof result in increased burdens when considering the introduction of off-site treatment, whether in addition to on-site treatment or independent of it. Table 4.12 presents the daily power requirements prior to and after taking into account the effect of pumping effluent to Athlone across effluent treatment systems. Environmental burdens are incurred from the additional consumption of power moving effluent to the municipal treatment facility. When comparing SAB treatment with the combined treatment system, the effect on including pumping power consumption in the inventory has significant implications. This effect can be considerable and can significantly affect conclusions drawn. In order to account for this factor when accurate data is unavailable, comparable data describing the effect of intermediate pumping power consumption needs to be collated and applied with caution on a case by case basis.

Table 4.12: Table showing the influence of pumping power consumption on results

Power requirements (kWh)	SAB treatment	Combined treatment	No treatment	Municipal treatment
Prior to pumping inclusion	1,872	1,918	756	802
with pumping to Athlone	1,872	2,364	756	1248

An LCA was carried out assessing the sensitivity of results to a change in pumping power requirement. The reported figure used (Friedrich et al., 2006) was multiplied by 2, so as to estimate the influence which a sizable error in this number, would have on the results. Figure 4.4 highlights the change in impacts comparing the current treatment configuration against itself encompassing an inflated figure for power consumed for pumping.

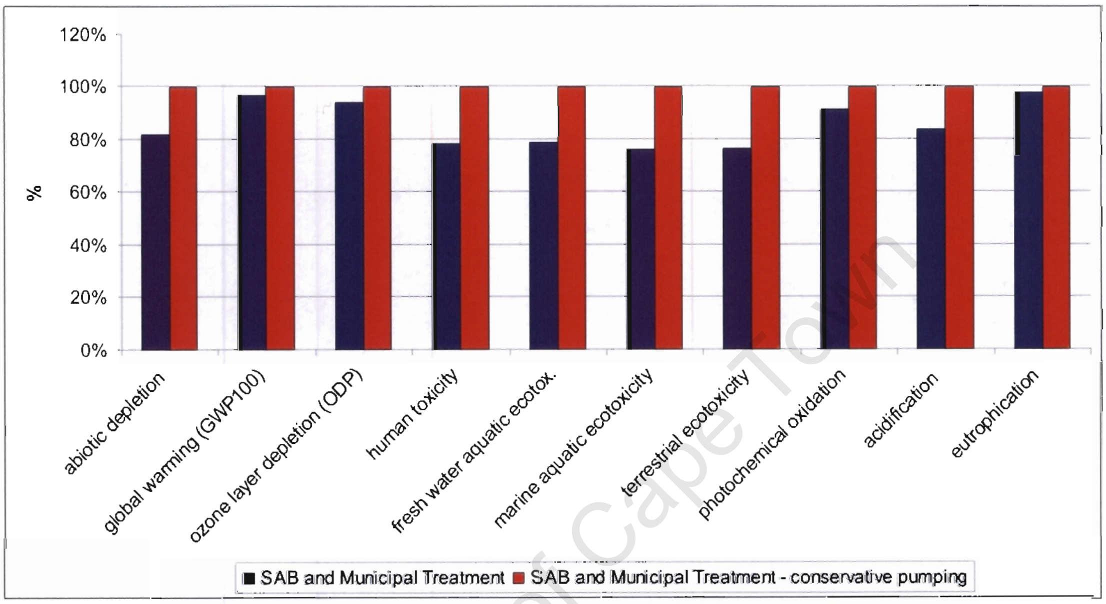


Figure 4.4: Sensitivity of results to estimated pumping power for effluent transfer to Athlone

As expected, an increase in power consumed results in an inflated burden profile. A 100% error in the power consumption from pumping between facilities results in an average increase of 15% across impact categories, with a standard deviation of 8.5%. In light of the original burden profile of the municipal treatment facility, qualitative conclusions originating from Section 4.4.2 would remain the same.

Being a key contributor, the influence of the power generating mix (fuel source) was also investigated. The LCA was carried out under the assumption of the national power mix generated from 90% coal, 4% nuclear and 6% hydro power. This is representative of the generating capacity of South Africa. The comparative study presented below was performed using an estimated regional (Western Cape) power generated mix of 50% coal and 50% nuclear power so as to assess the influence of a change in fuel type for power generation. A comparative LCA was undertaken, and the same waste water management system (SAB treatment followed by municipal treatment) was compared using the two generating mixes as described above. The results from this analysis are presented in Figure 4.5.

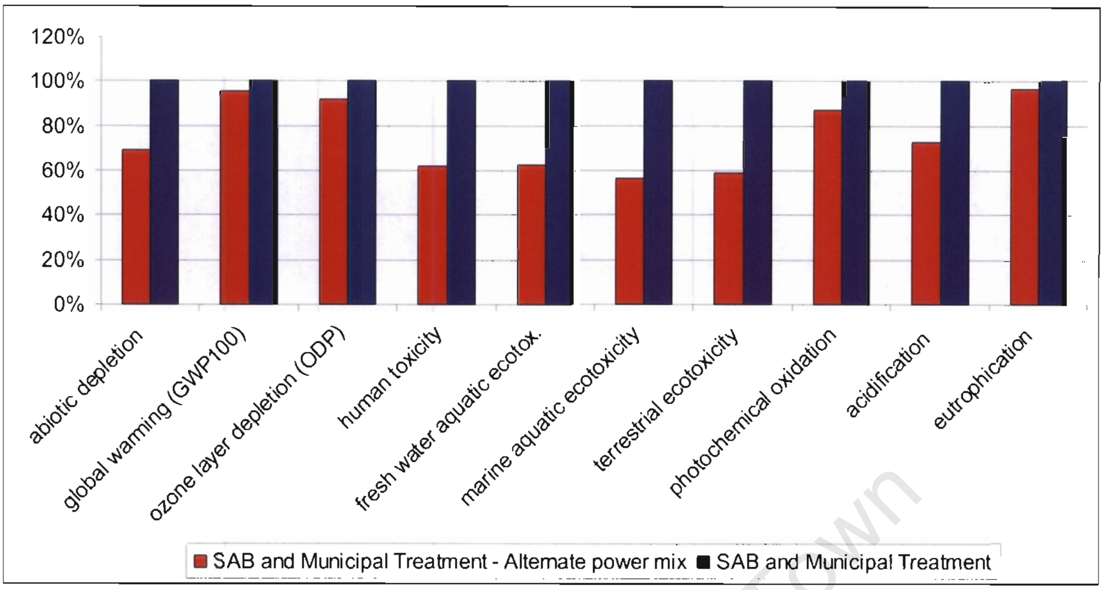


Figure 4.5: Effect of a change in power mix on LCA results

The results indicate an average burden reduction of 25.0% across impact categories with a standard deviation of 15.16%. The largest deviation is observed in the impact category marine aquatic ecotoxicity (43.5%). The smallest deviation is observed in the impact category eutrophication (3.3%) Significantly incorrect assumptions concerning power mix could give rise to incorrect conclusions concerning product or process alternatives, dependant on the impact category assessed. Hence, a study should consider, in light of the goal and scope, the likely impact of an incorrect power mix assumption across the heavily weighted impact categories investigated. This study assumed an accurate South Africa power mix, in an effort to generalise the study across South African provincial regions and in an attempt to remain generic in nature (in line with the goal of this thesis), whilst still applicable to the SABMiller Newlands Brewery.

4.5 Interim conclusion

The LCA results presented in Section 4.4 highlight the importance of adequate waste water management systems in light of the emission profiles of alternate waste water treatment options. A comparative assessment was made between four alternative treatment methodologies, and conclusions based on the relative impact of each treatment configuration could be drawn from results.

It was found that additional on-site effluent treatment helps to further reduce impacts on local river systems, however, it generally increases dispersed environmental burdens due to required raw materials and power. An unusual result for this case study is that global warming and photochemical smog impacts are significantly reduced with the installation of the additional on-site treatment; this is as a direct result of extremely inefficient handling of gaseous emissions at the municipal treatment plant.

Chapter 5: Technology Review

5.1 Introduction

Chapter 5 reviews the various technologies used in industry for combined heat and power (CHP) generation from biogas. CHP technologies were chosen to be the investigated technology due to their operational flexibility (both heat and power production), and because they offer power generating capacity in the event of grid failure. In line with the generic approach of this thesis, a revision of CHP technologies offers the widest range of choices in energy reclamation from organic waste by way of facilitating the interchangeable production of both electricity and heat.

It is noted that whilst some of these applications can generate energy from a variety of fuels, the focus is on biogas utilization due to the nature of the study in question. This review aims to achieve the following:

1. Understand the influencing parameters affecting CHP performance.
2. Assess several CHP technologies
3. Present a knowledge base for development of a decision-making template to select the appropriate CHP technology based on plant variables.

Chapter 5 starts by focusing on a description of the appropriate biogas utilization technologies. General operating mechanics are discussed including efficiency concerns. Machine maintenance is also reviewed as are factors affecting its continuous use, including start-up time and availability. Its suitability for specific thermal and electrical needs is discussed and the environmental concerns associated with operation are highlighted. Influencing ambient factors are also considered with reference to three particular external variables with a direct impact on CHP operation: Part-load performance, due to the fluctuating nature of the fuel feed from the digester resulting from both biogas flow-rate and quality, and the effects of altitude and ambient temperature should be quantified as these variables have significant effects on performance.

This will give rise to a matrix, indicating the key variables influencing operating performance. The review includes brief discussion on the various strategies of performance enhancement. The review aims to enable direct comparison across technologies based on the specific needs of SABMiller.

The required end-result of the technology review was to provide realistic technological choices to SABMiller that could be implemented and operated with immediate effect. The following presented literature review was based primarily on reputable technical sources by virtue of the nature of the outcome expected from this chapter. The recommendations made with reference to the technologies reviewed were therefore based on established and readily achievable results as established in an industrial environment.

Hence, the technology review and decision making template presented in Chapter 6 is based on information and data sourced primarily from the following 4 reports:

1. *"Catalogue of CHP Technologies"*, U.S. Environmental Protection Agency (U.S. EPA): Combined heat and power partnership, 2002.
2. *"Review of Combined Heat and Power Technologies"*, US Department of Energy, Office of Energy Efficiency and Renewable Energy, 1999.
3. *"Combined Heat and Power Resource Guide"*, Midwest CHP Application Centre, University of Illinois at Chicago Energy Resource Centre and Avalon Consulting, Inc in partnership with the US DOE, 2003.
4. *"proTERMO - Guidelines for Calculating Energy Generation in Combined Heat and Power Plants"*, Finish District Heating Association, financed by the Finish Ministry of Trade and Industry and the energy company Imatran Voima Oy, 1999

Where information was sourced from a reference other than one of the above four in Chapter 5, the reference is indicated adjacent to the text.

5.2 Introduction to CHP

Distributed generation (DG) is the strategic placements of energy generating equipment nearby the facility to which it provides energy. Development over recent years has seen a general shift in focus from electric only or heat only generation towards the operation of combined heat and power (CHP) units. CHP technology has enhanced the advantages of DG by increasing the overall efficiency of energy production. CHP technology is an energy conversion process whereby both electricity and useful heat are produced simultaneously in one process, by using a heat exchanger recovery process. The CHP application is environmentally more efficient as the energy source is typically biogas or excess steam recovered from a process.

CHP technologies recover what is otherwise waste heat from combustion gases, lubricating oils, cooling fluids and any other source of "waste" heat. In doing so the overall efficiency of fuel use in cogeneration (CHP) can be as high as between 85-89%. This is an improvement from the 40-45% efficiency observed from conventional or combined cycle condensing power plants, where excess heat is released to the environment. Thermal heat is then recovered in the form of hot water or steam, and can be used for process heating.

Although a key component of CHP is the production of electricity, CHP systems are designed according to the heating requirements of the facility as a result of the mechanics of the technologies employed. Thermal provision is generated from the downstream recovery of heat post power generation. Other advantages of CHP operation over single heat and power systems (SHP), which generate only heat or power, include the following

- An increase in the efficiency of fuel use due to the simultaneous generation of electricity and useful heat.
- The simultaneous heat and power production from non-fossil fuel resources resulting in a cleaner energy source with lower CO_2 and NO_x emissions. It has been estimated that up to 1000 tonnes of CO_2 per GWh of power production can be avoided (Pilavachi, 2002).
- Due to the strategic on-site placing of the technology, a reliable power supply is achieved that is not susceptible to power outages and grid failures. In addition transmission and distribution losses associated with grid-supplied electricity are avoided.
- CHP technologies can be easily tailored to provide for the thermal and electrical demands of a plant. The technology's operating versatility allows for good control and therefore a flexibility of power supply.

In the CHP unit, the prime mover either drives a generator for the production of electricity, or is used to power rotating equipment such as pumps and compressors. Typical prime movers used in industry today for include:

1. The reciprocating engine
2. The gas turbine
3. The micro turbine

5.2.1 Energy efficiency

There is a marked difference in the evaluation of efficiency between CHP and SHP systems. Cogeneration produces 2 products (both electricity and heat), and hence different concepts are employed to describe CHP operation from the conventional condensing power generation.

The heat rate is defined as the ratio of fuel used for power generation to the amount of power generated, i.e. the amount of fuel energy required to produce one kilowatt-hour of electrical output. It does not take into account the useful heat produced and is a measure of power generation only. The effective electrical efficiency (FUE) is the inverse of the Heat Rate. Studies performed by Bilgen, cited by Sue and Chuary, (2004), indicate that first law efficiency is strongly related to the power: heat ratio in a cogeneration facility. Efficiency is reduced by 40% when the power to heat ratio is increased from 1-20. However, 2nd law efficiencies are only reduced by approximately 2% for the same change in power: heat. Sue concluded that work is the valuable commodity of a power plant as it can be completely converted into heat, whereas heat cannot be completely converted into work.

Total CHP efficiency is defined as the ratio of the sum of the net electrical and net useful thermal output to the fuel consumed in its production. This definition does not incorporate the differences in qualities of energy. As a result the FREC efficiency standard was introduced in the US Public Utilities Regulatory Policies Act of 1978 (PURPA) to incorporate consideration of the quality of energy generated by CHP. The FERC efficiency is equal to the ratio of the sum of the electric power output and half the net thermal output of the CHP system to the fuel input to the system.

The percent fuel savings compares the benefits of CHP over the equivalent power produced by a single power producing system. It compares the fuel used in CHP to that used in a separate heat and power system for the equivalent energy generation.

A defining characteristic of CHP operation is the ratio of electricity to useful heat generated. This ratio may vary with operation. The power to heat ratio has an important bearing on CHP efficiency as the individual efficiencies of power generation and heat generation are appreciably different as illustrated in Figure 5.1, where 40% electric efficiency and 80% thermal generation efficiency is assumed. The CHP curve is based on using 5% less fuel. The overall efficiency here is based on the higher heating value of the fuel. Overall efficiency is a SHP measure of efficiency, but can be used to provide a comparative basis for the improvements in efficiency attributable to CHP. Overall efficiency is the ratio of the sum of the power and useful heat generated to the sum of the fuel consumed to produce each. The higher heating value (HHV) of combustion expresses the energy content or efficiency of energy generation assuming the water vapour in the combustion gases is condensed. In other words, HHV assumes the latent heat in the water vapour is used in energy generation. The LHV of a fuel is the analogous value assuming the water vapour generated on combustion of the fuel is not returned to its liquid state. In other words, LHV assumes the latent heat in the water vapour is not used in energy generation.

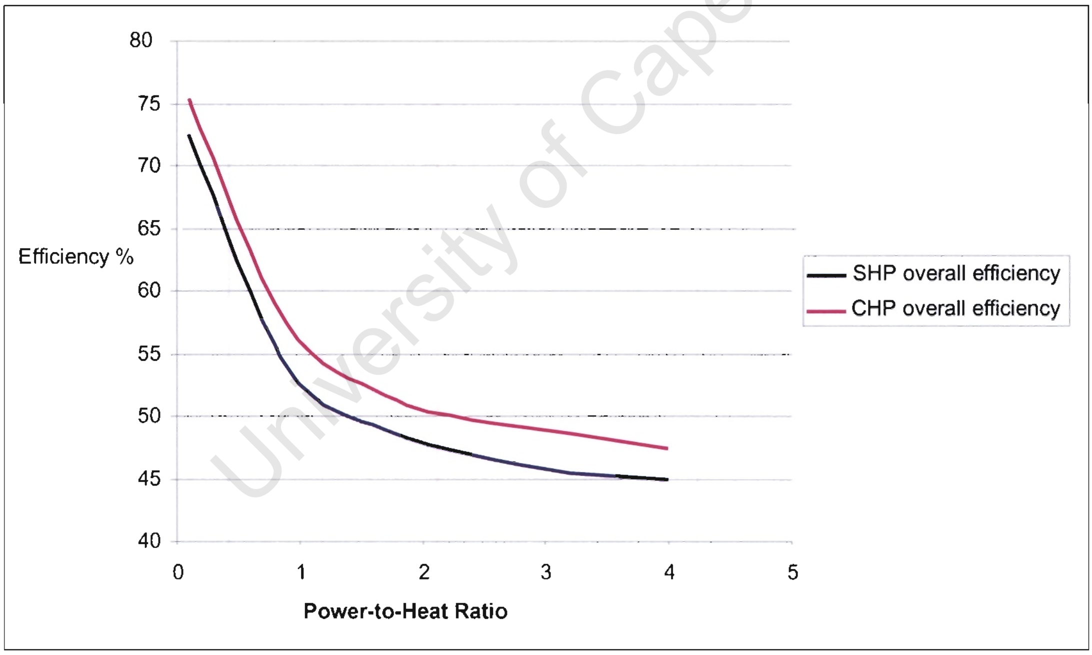


Figure 5.1: Efficiencies in equivalent power generation comparing CHP with SHP, based on a varying power: heat ratio (reproduced from US EPA, 2002)

The following is a summary of the above formula, as presented in the US EPA report of 2002 on CHP technologies, with notation used as follows:

Q: Net useful thermal output from CHP

P: Net electric power output from CHP

F: Total Fuel input to CHP system

Ef_Q: Ratio of net useful thermal output to the fuel consumed

Ef_P: Ratio of net electrical power output to the fuel consumed

Total CHP System Efficiency: $Eff_{Total} = \frac{(P+Q)}{F}$

FERC Efficiency: $Eff_{FERC} = \frac{(P+\frac{Q}{2})}{F}$

Fuel Utilization Efficiency: $FUE = \frac{P}{F - \frac{Q}{Ef_Q}}$

Percent Fuel Savings: $\%S = 1 - \frac{F}{\frac{P}{Ef_P} + \frac{Q}{Ef_Q}}$

In CHP calculations, Ef_Q is often assumed to carry an equivalent boiler efficiency of 80% (or 0.8) (US EPA, 2002).

The equations defined above are useful in quantifying the advantage of CHP systems over their SHP counterparts, and in correlating meaningful data for comparative purposes across CHP technologies and options.

CHP system benefit has also been maximized through the application of pinch technology. Depending on system constraints, CHP implementation via pinch assessment has shown itself to be a tool by which power and heat yield can be further maximized with the utilization of CHP technology (Berglin and Berntsson, 1998).

5.3 Applicability of CHP technology with renewable energy sources

Renewable energy sources over recent years have played an increasingly important role in energy generation. The integration of renewables with energy production facilities have become a major challenge for many industrial organisations (Pavlas et al., 2006). In addition to the environmental benefits incurred from utilisation of renewable fuel sources, additional benefits are to be gained in light of global trends in the price of crude oil and natural gas, electricity costs and from consideration of the political support bio-fuels are receiving worldwide (Pavlas et al., 2006). Furthermore, awareness of the limitations of conventional fossil fuel reserves has intensified the search for alternative fuels for use in conventional technologies including the internal combustion chamber and gas-turbine (Huang and Crookes, 1998).

Recently, much research has been performed around the applicable technologies for bio-fuel utilisation and their performance characteristics in a variety of industries for a variety of applications. This research on biofuel utilising technologies has stemmed from research focused on characterising energy generation from biomass sources although the two areas are closely interrelated.

Savola and Fogelholrn, (2006), investigated the feasibility of increased power to heat ratios of small scale CHP plants using biomass fuels and natural gas. CO_2 emissions were included in the analysis by evaluating how much fossil CO_2 would be saved in comparison to the case of where the additional electricity production resulting from CHP implementation was to be produced in a coal fired condensing power plant with an assumed 45% electrical efficiency. They concluded that a higher power to heat ratio would increase the economic feasibility of CHP facilities and reduce their fuel consumption and CO_2 emissions. Furthermore concerning energy recovery, they found that the integration of an engine to the CHP process offers economically feasible solutions in size ranges of 6 to 15MW, if these CO_2 savings are taken into account.

Franco and Giannini, (2005), completed research identifying perspectives for the use of biomass as fuel in combined cycle power plants. Arbon, (2002), reviewed a wide range of conversion options and biofuel sources, focusing predominantly on conventional combustion systems utilising steam turbines, but also covering gasification and pyrolysis with power generation from prime movers of the likes of gas turbines and reciprocating engines.

Murphy et al., (2003) investigated the technical/economic and environmental implications of biogas utilisation for transport fuel production (CH_4-enriched biogas) in an Irish context. The scenario investigated analysed the environmental implications of producing a CH_4-enriched transport fuel from the anaerobic digestion of MSW, with surplus biogas processed in a small CHP plant, providing electricity to power the digester and the scrubbing system. The system investigated was self-sustainable. They found that in the worst case scenario, greenhouse gas production was 15% that of a petrol or diesel powered vehicle.

Arrieta and Lora, (2005), commented on the justified use of natural gas for power generation by high-efficiency installations typical of combined cycle thermal power plants. Their investigation identified temperature as the variable having the biggest influence on efficiency and power, and investigated its influence on a simulated 600MW natural gas powered combined cycle power plant holding pressure, inlet air's relative humidity, electric frequency, power factor and fuel characteristics constant. They also investigated the capacity of supplementary firing techniques to mitigate changes on power output and efficiency as a result of temperature changes. Over an ambient temperature range of 0^0C to 35^0C, they found a 75MW variation in net power of the gas cycle. Supplementary firing was found to largely mitigate power reduction, however this resulted in a reduction of thermal efficiency.

Huang and Crooks (1998) completed an assessment of simulated biogas as a fuel for the spark ignition engine. They altered the CH_4 and CO_2 concentrations of the biogas fuel in an effort to observe the performance and exhaust gas emissions of an engine under different operating conditions. They found the main influence of CO_2 in the biogas fuel was to lower the NO_x emissions and enable the compression ratio to be increased. However, when the CO_2 concentration was increased to 40%, power and brake thermal efficiency was reduced by 3%. In addition, CO emissions correlated with the air to fuel mixture and were almost unaffected by compression ratio or engine speed. Hence with rich fuel mixtures, they found a rapid increase in CO emissions when the CO_2 concentration in the biofuel increased above 30% although for leaner mixtures, power and thermal efficiency was reduced. The higher the compression ratio, the higher the mean effective pressure and brake thermal efficiency although increased emissions of NO, HC and CO were measured. They concluded that fast burning engine-design technologies using biogas fuels of high CO_2 content at elevated compression ratios would need to be adopted to enable better control between power, thermal efficiency and NO_x and HC emissions.

Berglin and Berntsson (1998) investigated the viability of CHP in the pulp industry using black liquor gasification. Typically, black liquor is recycled in the production of chemical kraft pulp to a recovery boiler which facilitates both chemical recovery and energy generation. Gasification presents itself as an alternative method to the conventional process as it also offers the advantage of dual functionality. Using pinch analysis, the research identified systems to maximise power and heat yields from an integrated gasification cogeneration system. They claimed that gas reheat improves the electric efficiency of the system by up to 6%, but leads to a small decrease in total CHP efficiency.

In a paper by Demirbas, 2004, gasification is presented as the latest generation of biomass energy conversion processes, reducing the investment costs of biomass electricity. He cites downstream CHP technology as the recovery process required to achieve high efficiencies by way of heat recovery and steam production.

As illustrated by the citations above, some of the most suitable industries for CHP technology include pulp and paper, chemicals manufacturing, food processing and recycled energy from landfill. Figure 5.2 presents the highest potential for CHP by building type (Midwest CHP application centre, 2003).

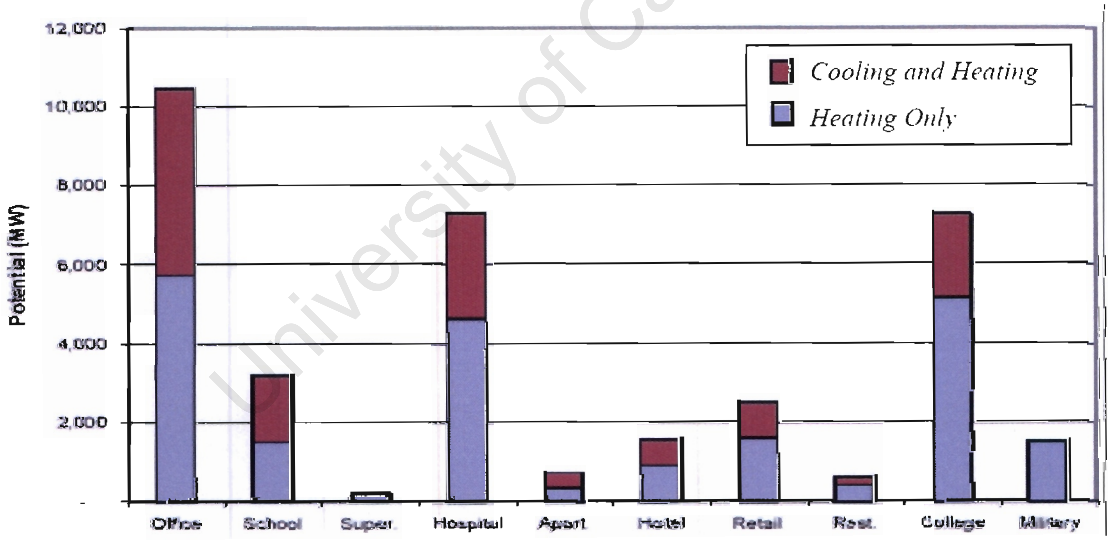


Figure 5.2: CHP applicability by location

Research indicates the viability of sustainable energy generation from bio-fuels and refers to the effectiveness of CHP technology in bio-fuelled energy generating plants in a wide variety of industries and applications. What follows in Sections 5.4 to 5.6 is a technically orientated review of mainstream CHP technologies and key considerations for their employment.

5.4 Gas Turbines

5.4.1 Operational description

The gas turbine is being used more and more frequently in CHP applications (Pilavachi. 2002). The Breyton thermodynamic cycle is largely associated with turbine energy generating systems. Typically gas turbines are utilized in larger systems (greater than 4MW) and have operating capacities of up to 250MW.

Power generation is based on expansion of combustion gas through a turbine, producing high-speed rotary motion that drives an electric generator. The thermodynamic steps include compression of atmospheric air, fuel ignition and the expansion of combustion gases through power turbines. The power produced by the expansion turbine and consumed by the compressor is directly proportional to the temperature difference of the gas over the device. The lower the atmospheric air temperature prior to compression, and higher the turbine inlet temperature post combustion, the greater the efficiency and specific power obtained from the unit.

5.4.2 Operating Modes

Gas turbines have three modes of operation: Power only operation (simple cycle operation), CHP operation (combined heat and power operation) and combined cycle operation. In the case of combined cycle operation, high pressure steam, generated from the cooling of the exhaust gases of the gas turbine in a steam boiler, is utilized to generate additional power by passing the steam through a separate downstream unit (steam turbine) in series with the gas turbine.

First law efficiencies for simple cycle operation for power only generation do not typically exceed 40% but with the advent of CHP technology, total CHP system efficiencies commonly reach 70% to 80% due to the utilization of the exhaust heat for steam or hot water generation.

5.4.3 Operating and efficiency Characteristics

Table 5.1 shows typical operational parameters for gas turbines at various capacities. It should be noted for comparative purposes that because the gas turbine makes use of a continuous combustion process it can handle a larger gas flow than the other prime movers reviewed, namely the microturbine and the reciprocating engine (Sue et al., 2005). The values in the table are characteristics for "typical" commercially available gas turbine generator systems, and serve to comparatively assess how operational parameters change with system capacity.

The installed costs are based on CHP systems generating 10bar steam in 2000. These figures give a relative indication of price. In addition, steam generation figures were based on a gas turbine exhaust temperature of 510^{0} C and a heat recovery steam generator (HRSG) exhaust temperature of 140^{0} C. Heat rates were collected from manufacturer's specifications. Steam output (thermal output) was correlated from industry publications.

Table 5.1: Operational characteristics of gas turbines at different weightings (US EPA, Sourced from the Energy Nexus Group, 2002)

System Characteristics	**System 1**	**System 2**	**System 3**
System electric capacity (kW)	1000	5000	10000
Total Installed Cost (YR:2000, $/kW)	1780	1010	970
Electric Heat Rate (kJ/kWh), HHV	16437	13283	12412
Electrical Efficiency (%). HHV	21.9	27.1	29
Fuel Input required (Gj/hr)	16.45	66.36	124.18
Fuel gas pressure required (barg)	6.54	11	17
CHP Characteristics:	System 1	System 2	System 3
Exhaust flow (1000 kg/hr)	19.958	73.481	143.335
Steam Output (1000kg/hr)	3	11.339	21.13
Steam Output (kW equivalent)	2080	7800	14540
Total CHP efficiency (%), HHV	68	69	74
Power: Heat Ratio	0.48	0.64	0.69
Net Heat Rate (kJ/kWh)	7040	6274	5868
Effective electrical efficiency (%), HHV	51	57	61

A CHP system is designed according to the thermal needs of the plant being powered hence the more power that is generated by the gas turbine, the less energy is available for steam generation. This power to heat ratio gives the operator some flexibility based on the requirements of the plant at any given time. It should be noted that higher steam pressures are obtained with lower overall efficiencies.

Berta et al., (2006) emphasised that although CHP plants need to be designed according to the thermal needs to the end-user, plant configurations must be flexible in that the two outputs of the plant (W and Q) can be changed swiftly as required. Gas turbines in various set-ups including combined cycle, with supplementary firing and with possibility of steam injection, meet this requirement and cover a wide operational field (Berta et al., 2006).

5.4.4 External Influencing Parameters

5.4.4.1 Part Load:

Figure 5.3 presents a typical part-load de-rating curve to illustrate the relationship between efficiency and load. There is also a strong correlation reported between an increase in emissions and a reduction in turbine load. There is an appreciable change in electrical efficiency at part load. This decrease results in a relative increase in heat available for steam generation. This can represent an operating advantage for installations with a high thermal requirement.

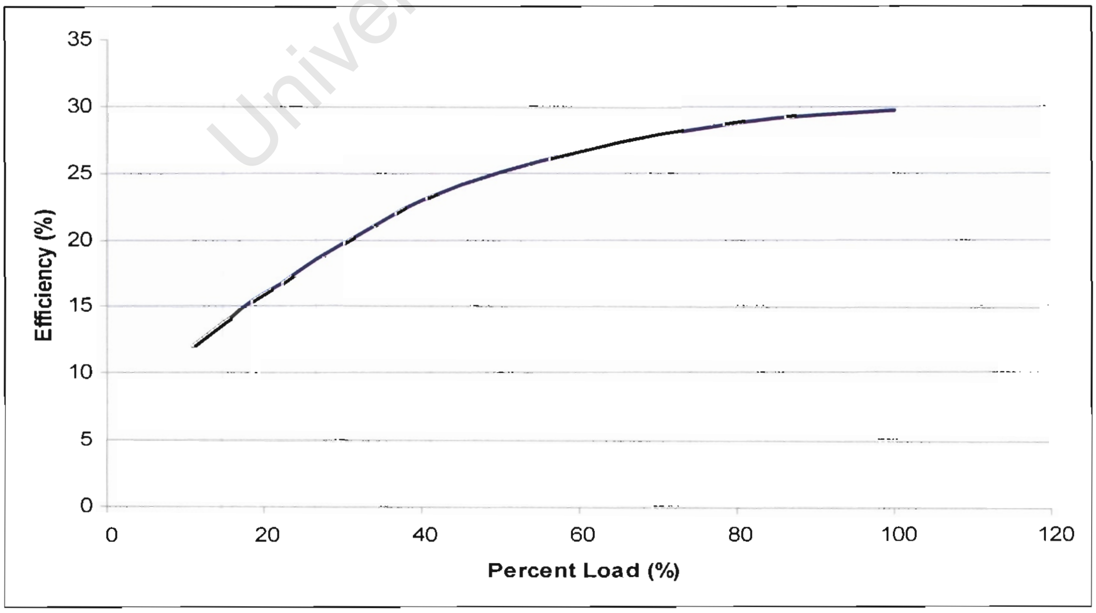


Figure 5.3: The effect of part-load on turbine de-rating (US EPA, 2002)

5.4.4.2 Effect of Ambient Temperature:

Ambient temperature has an indirect effect on efficiency and power output of a gas turbine through air density. A temperature increase, with resultant density decrease, results in a decrease in air mass flow-rate through the system, hence a net decrease in power output. Further, the decrease in density requires an increase in required power to compress the inlet air, hence a net decrease in power efficiency. Figure 5.4 illustrates the dependence of power and efficiency on ambient air temperature. The power is related to the rated power of the system at the International Organization for Standards (ISO) reference state of sea level and 15° C. It is clearly seen that inlet air cooling becomes advantageous for CHP operation owing to higher densities at lower temperatures.

Supplementary firing is a technique that can be used to counter this reduction in power resulting from a change in ambient temperature (Arrieta and Lora, 2005). This is revisited in Section 5.4.5 b.

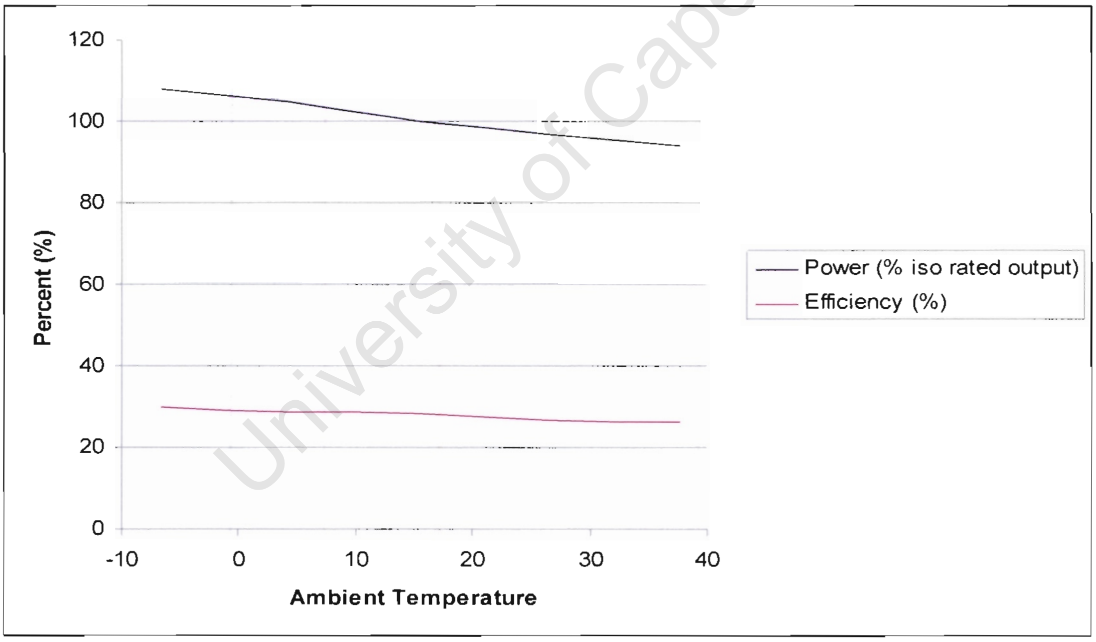


Figure 5.4: The effect of ambient temperature on power and efficiency of a gas turbine (US EPA, 2002)

5.4.5 Performance Enhancement

5.4.5.1 CHP Enhancement:

The exhaust gases contain 60-70% of the energy of the incoming fuel therefore gas turbine total efficiency approaches 70-80% with exhaust heat recovery. This energy can be used directly or to raise steam of between 10 and 80 bar. Figure 5.5 is a diagrammatic illustration of heat recovery with combined cycle operation in a CHP orientated gas turbine.

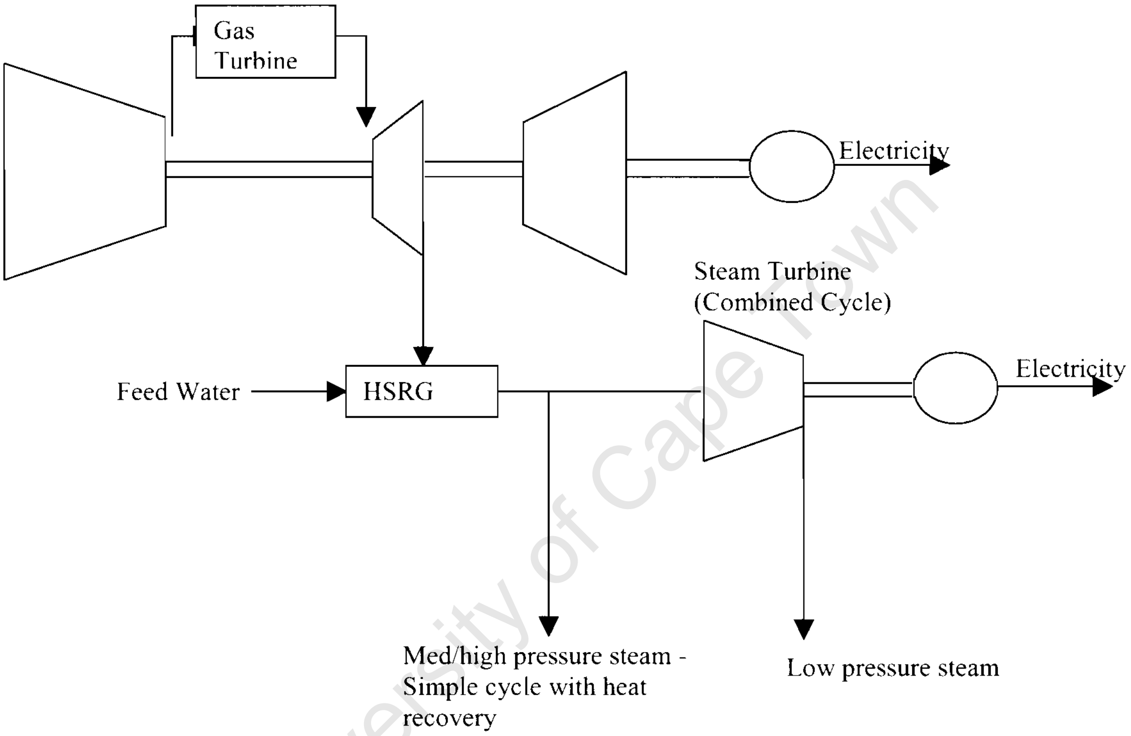


Figure 5.5: Schematic of a heat recovery system of a gas turbine (US EPA, 2002)

CHP total efficiency is limited largely by how much additional heat is recovered from the exhaust gases. Gas turbine exhaust temperature and heat recovery steam generator (HRSG) stack temperature directly influence the efficiency of heat recovery. A well run HSRG can recover up to 95% of the waste heat from the turbine exhaust.

Turbine exhaust temperature is a function of the operating pressure ratio and the turbine firing temperature. Typical turbine discharge temperatures lie in the range of 454 – 510 ^{O}C. Higher turbine exhaust temperature, for the same HRSG exit temperature, provide greater opportunity for producing steam. In the same light, a low HRSG exit temperature indicates a greater quantity of energy recovered and therefore a higher efficiency obtained. In consideration of the sulphur bearing fuel types, the minimum HSRG stack temperature is 150° C. This is well above the due point of sulphuric acid formation. Figure 5.6 shows the change in total efficiency with HSRG exhaust temperature.

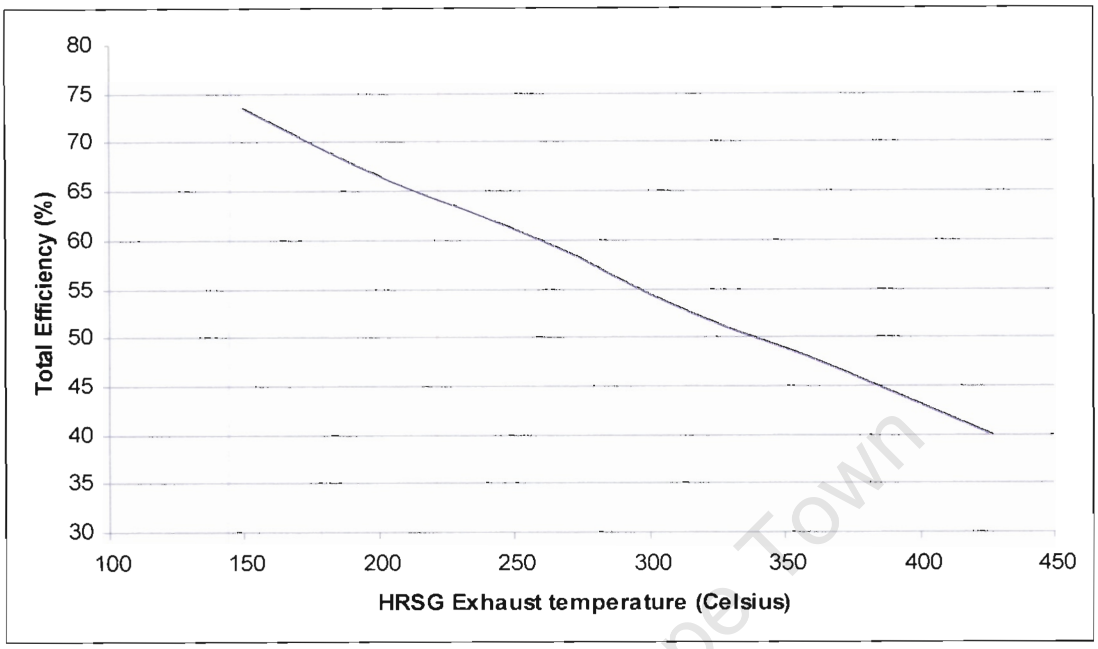


Figure 5.6: Effect of HSRG exhaust temperature on total efficiency (US EPA. 2002)

5.4.5.2 Overall Efficiency enhancement:

1. Supplementary Firing Techniques:

The un-combusted oxygen present in the combustion gases can be utilized by making use of supplementary firing techniques at combustion conditions. Less fuel is consumed in this step than in the combustion turbine for equivalent quantities of oxygen. The exhaust gas temperature entering the HRSG can be as high as 982^{O}C, potentially doubling steam production. The HHV efficiency of such an operation is usually 85% or more. Supplementary firing enables plant operators to trade steam production for power generation depending on plant demand.

2. Intercooling:

Intercooling increases the net power draw of the turbine by reducing the power requirement of the compression stage. By sub-dividing the compression stage into two stages and intercooling between the 2 stages the power requirement of the 2nd stage is reduced and net power delivered by the gas turbine is increased. This does result in an increased combustion fuel requirement as a result of the lower temperature feeding the combustor.

3. Pre-heating combustion air feed:

Preheating the air-feed in an HSRG using the turbine exhaust gases prior to combustion can significantly reduce fuel consumption and increase efficiency by up to 10 %. The installation cost of a recuperator is typically only justified when fuel costs are high. Recuperators can reduce the effectiveness of CHP operation by reducing the outlet temperature of the turbine, and therefore the available energy for producing steam – reducing power output by up to 15%. Industrial gas turbines generally exhibit turbine exhaust temperatures of between 426°C – 482°C.

5.4.6 Maintenance Requirements

Inspections are required every 4,000 hours, with overhauls required every 25,000-50,000 hours. Cycling operation can increase maintenance costs significantly. Gas turbines have the capacity to operate over the rated capacity for limited time periods. Maintenance costs per unit of power delivered are 33-50% of the analogous reciprocating engine costs.

5.4.7 Environmental implication

Primary pollutants from gas turbines include NO_x and carbon monoxide, CO. The sulphur content of the fuel determines the sulphur oxides emitted. The operating load of the gas turbine determines the levels of CO, and NO_x emitted. Emission compositions are dictated by the flame temperature in the combustion. The fixation of nitrogen and oxygen occur at higher flame temperatures (higher loads), resulting in NO and NO_2 being emitted. At lower flame temperatures (lower loads), lower thermal efficiencies are obtained, and incomplete combustion results in emission of CO.

There are several control mechanisms to limit the fixation of nitrogen or the incomplete combustion of biogas to carbon monoxide. The scope of this report only permits their mentioning. They include:

- Dilutent injection
- Lean Premixed Combustion
- Selective Catalytic Reduction
- Carbon monoxide oxidation catalysts

- Catalytic combustion
- Catalytic absorption techniques

Typical commercial gas turbines rate NO_x emissions between 25 and 40 PPM and carbon monoxide emissions up to 20 PPM.

5.5 Microturbine

5.5.1 Operational description

Microturbines are small electricity generators capable of burning gaseous fuels, creating high speed turbine rotation. Typical microturbine sizes range between 30kW and 350 kW, much smaller than their counterpart larger gas turbines. Microturbines can be connected in parallel, providing reliable power with the ability to service higher energy demands effectively. Recovered waste heat is commonly used to produce hot water or drive absorption cooling or desiccant dehumidification systems.

The inlet air is pre-heated by the exhaust gases in a heat exchanger or recuperator. The air is then compressed, only to be expanded through the turbine post-combustion. As with the larger turbines, microturbines operate on the Brayton thermodynamic cycle. Operation at higher temperature and pressure ratios results in higher efficiencies and specific power, as with the larger sized turbines. Material constraints however, limit pressure ratios to between 3.5 – 4 and turbine inlet temperature to maximum temperatures of 815^{o} C.

Figure 5.7 is a simple illustration of the components of a simple-cycle gas turbine with recuperator. The unit is very compact with few moving parts, low noise levels and low civil engineering costs (Pilavachi, 2002).

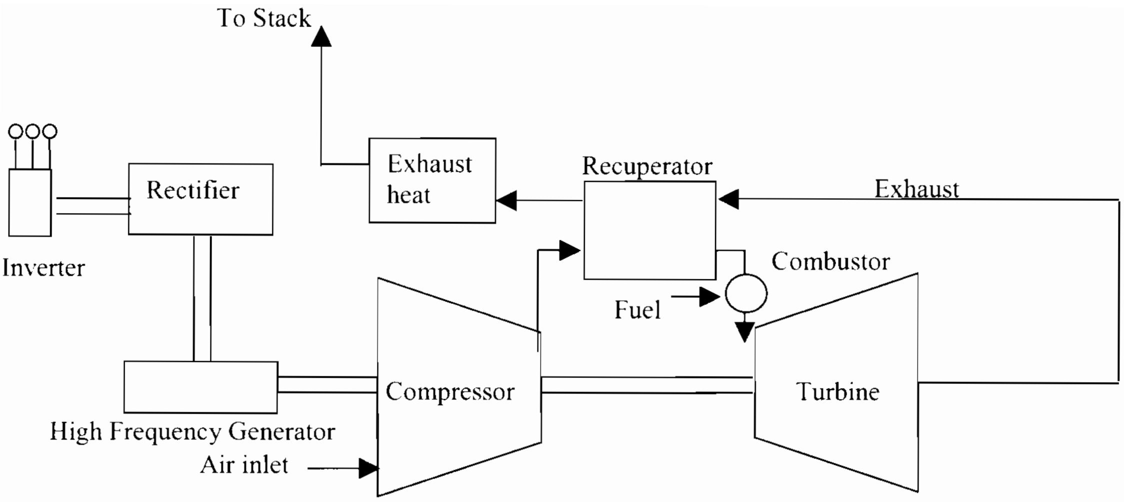


Figure 5.7: Schematic of the components of a simple-cycle gas turbine (US EPA, 2002)

5.5.2 Operating Modes

The micro turbine is typically a single-shaft, single-stage low pressure ratio gas turbine (Pilavachi, 2002). In addition where larger turbines use multi-stage axial flow turbines and compressors, micro turbines make use of single-stage radial flow turbines and compressors. This is because the latter offer better operating performance with smaller flows and minimize surface and end wall losses, despite the typically better efficiencies of the large-size axial flow devices. The rotational speed of the turbo compressor shaft is generally specified at 96,000 rpm for a 30 kW machine and approximately 80,000 rpm for a 75kW machine. There is no established correlation between rating and shaft rotational speed, although the trend indicates that as power rating decrease, shaft speed increases. Start-up lasts only minutes, and the conversion of high frequency AC output to either 50 or 60 HZ power for general use is 95% efficient.

5.5.3 Operating and efficiency Characteristics

Micro turbines are able to operate in both power only operation (simple cycle) or CHP operation (recuperatored) (Pilavachi, 2002). Thermal output is between 200 – 315°C. Table 5.2 below shows typical values for micro turbine operation. The values in the table are characteristic of "typical" commercially available gas turbine generator systems. Heat rates and efficiencies as reported by the US EPA were collated from manufacturers' specifications and industry publications. Available thermal energy was calculated based on manufacturer specifications on turbine exhaust flows and temperatures.

Table 5.2: Operational characteristics of microturbines at different weightings (US EPA, Sourced from Energy Nexus Group, 2002)

System Characteristics	System 1	System 2	System 3
System electric capacity (kW)	30	70	100
Total Installed Cost (2000$/kW)	2516	2031	1561
Electric Heat Rate (kJ/kWh), HHV	15383	14285	13332
Electrical Efficiency (%). HHV	23.4	25.2	27
Fuel Input required (Gj/hr)	0.461	1.0	1.333
Fuel gas pressure required (barg)	3.79	3.79	5.17
CHP Characteristics:			
Exhaust flow (1000 kg/hr)	1.175	2.286	2.841
Turbine Exhaust Temp (^{o}C)	260	223	260
Heat Exchanger Exhaust Temp (^{o}C)	65	54	55
Heat Output (kW equivalent)	64	108	163
Total CHP efficiency (%), HHV	73	64	71
Power: Heat Ratio	0.47	0.65	0.62
Net Heat Rate (kJ/kWh)	5812	7334	6016.9
Effective electrical efficiency (%), HHV	62	49	60

The microturbine pressure ratios of between 3 and 4 are very modest in comparison to the larger gas turbine pressure ratios of between 7 and 35. Often, micro-turbine systems are designed with pressure boosters. A booster however lowers net power efficiency and can add significantly to the cost per kW delivered as it requires up to 5% of microturbine power

5.5.4 External Influencing Parameters

5.4.5.1 Part Load:

Reductions in compressor speeds (resulting in a decreased mass flow rate) and reductions in turbine inlet temperature reduce the power output of the micro turbine. A step change from no load to full load takes the microturbine less than 15 seconds, making it very versatile in this respect.

Commonly when load changes, the turbine has still to run at design rotating speed. The micro turbine is susceptible to machine breakdown with repeated downloading, as the blades have a tendency to over speed due to an accumulation of stored energy in the unit. Kaikko et al, 2004, further investigated the influence of turbine inlet temperature and shaft rotational speed on part-load operation. Wang et al, 2004 proposed that part-load performance can be improved by variable speed operation as constant frequency of electricity can be assured through the control of the electronic equipment.

Figure 5.8, a typical part load de-rate curve, illustrates how power efficiencies change with micro turbine loading.

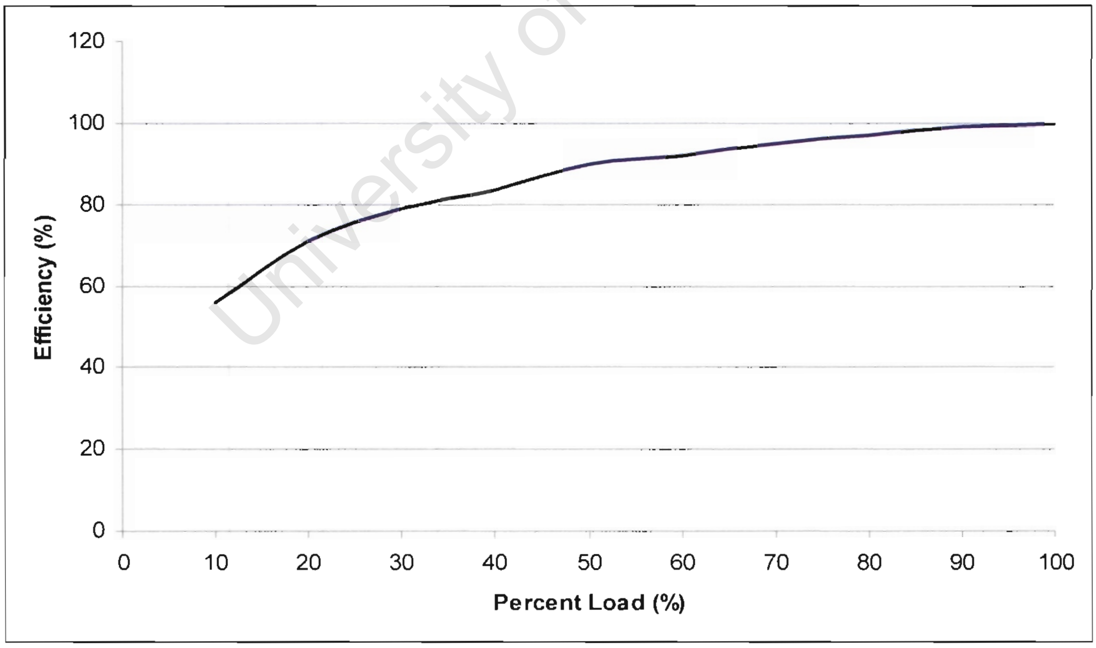


Figure 5.8: The effect of part-load on microturbine de-rating (US EPA, 2002)

5.4.5.2 Effect of Ambient Temperature:

Figure 5.9 illustrates the change in power and efficiency with an increase in ambient air temperature. Power is presented relative to the rated power of the system at the

International Organisation for Standards (ISO) reference state of sea level and 15° C. It is clear from Figure 5.9 that rate of decrease in power delivered with temperature increases with an increase in turbine rating. Efficiency decreases at a rate independent of turbine rating.

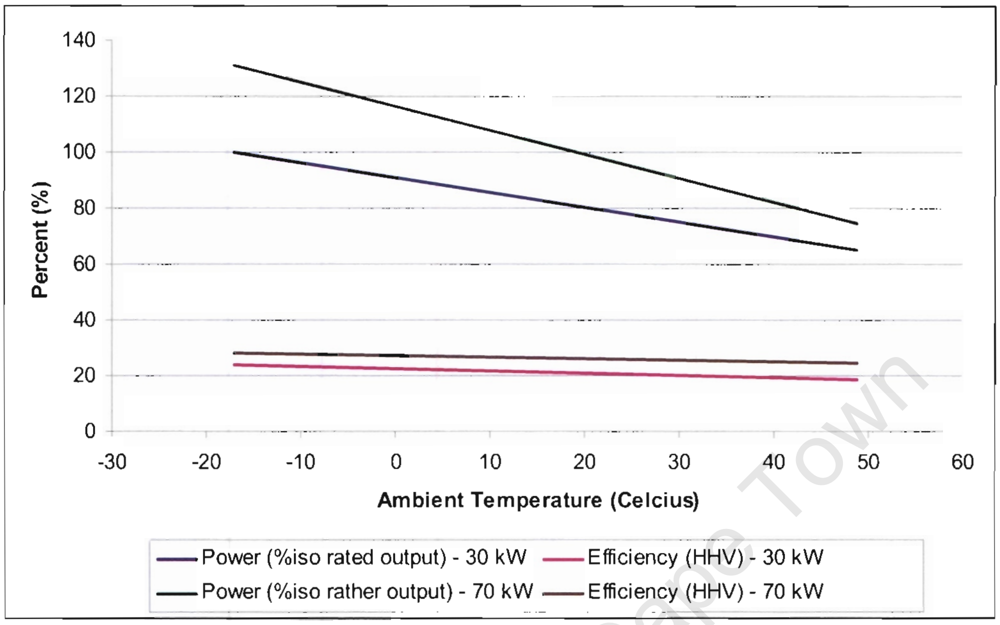


Figure 5.9: The effect of ambient temperature on power and efficiency of a microturbine (US EPA, 2002)

5.5.5 Performance Enhancement

5.5.5.1 CHP enhancement:

Recuperator addition lowers fuel requirements but can introduce additional pressure losses negatively effecting efficiency and performance. Microturbine performance is highly sensitive to even small fluctuations in internal pressure loses.

Recuperator performance is measured by the extent to which recuperator effectiveness increases cycle efficiency and the extent to which the pressure drop decreases cycle power. Effectiveness is defined as the ratio of actual heat transferred to the maximum achievable and is largely determined by recuperator surface area. Larger surface areas results in significant pressure losses, hence there is a design trade-off between cycle efficiency and cycle power. Traverso and Massardo (2005) reported that the two most well designed recuperators are the furnace-blazed plate fin type and the welded primary surface type. Furthermore, micro turbine CHP system efficiency is also a function of the exhaust heat temperature, and the exhaust heat temperature is a function of recuperator effectiveness.

An effective recuperator (90%) is essential to the viability of a CHP system. Figure 5.10 highlights the relationship between recuperator effectiveness and microturbine electrical efficiency. A recuperator of high effectiveness can reduce fuel requirements by up to 40% in some cases (Pilavachi, 2002).

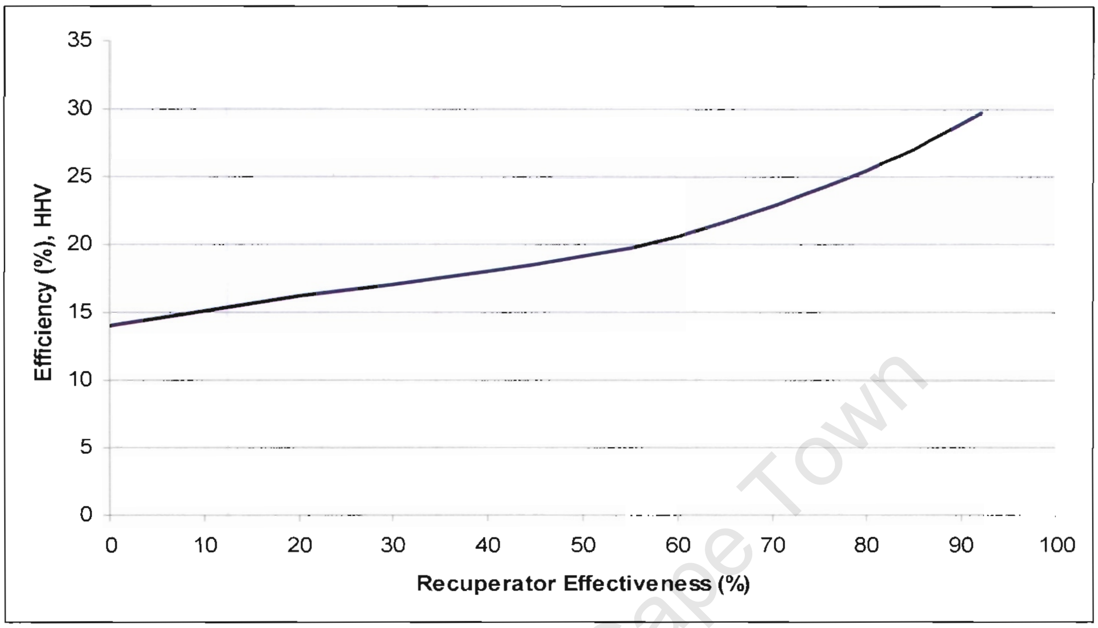


Figure 5.10: Relationship between recuperator effectiveness and microturbine efficiency (US EPA, 2002)

5.5.5.2 Overall Efficiency Enhancement:

1. Electrical efficiency:

The effect of pressure ratio on electrical efficiency as a function of temperature is illustrated in Figure 5.11. Each curve is at a constant turbine firing temperature. The most favourable pressure ratio is between ratios of 3 and 4.

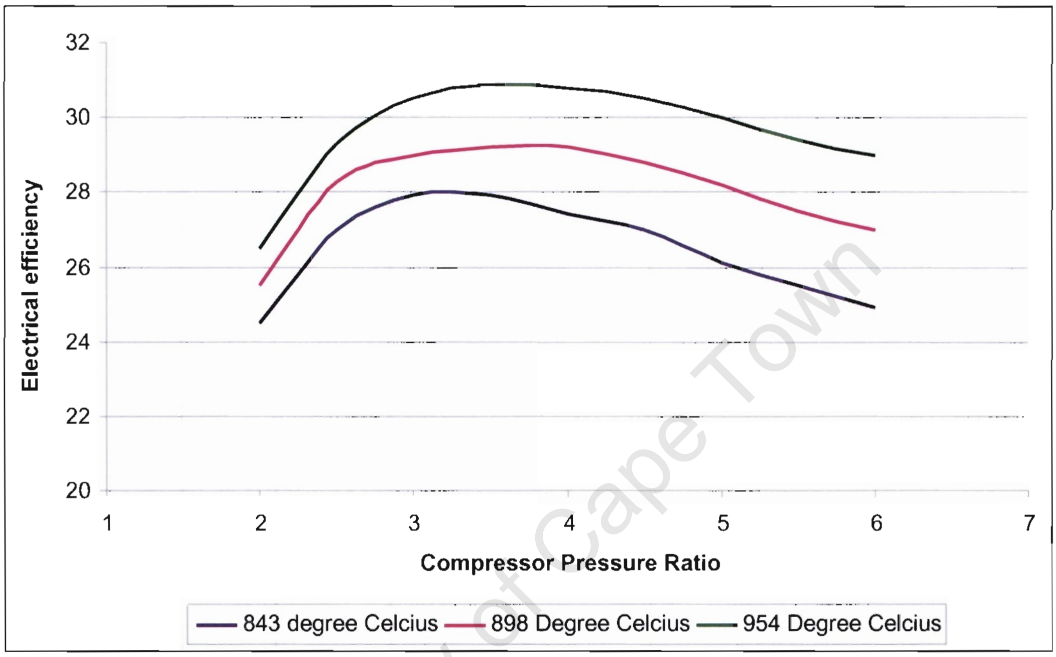


Figure 5.11: Effect of pressure ratio on electrical efficiency of a microturbine (US EPA, 2002)

Specific power is defined as the electric power produced by the machine per unit mass flow through the machine. Figure 5.12 presents the relationship between specific power and pressure ratio over the same range of firing temperatures as discussed before. Centrifugal forces on compressor blades limit compressor pressure ratios to between 3.5 and 5.

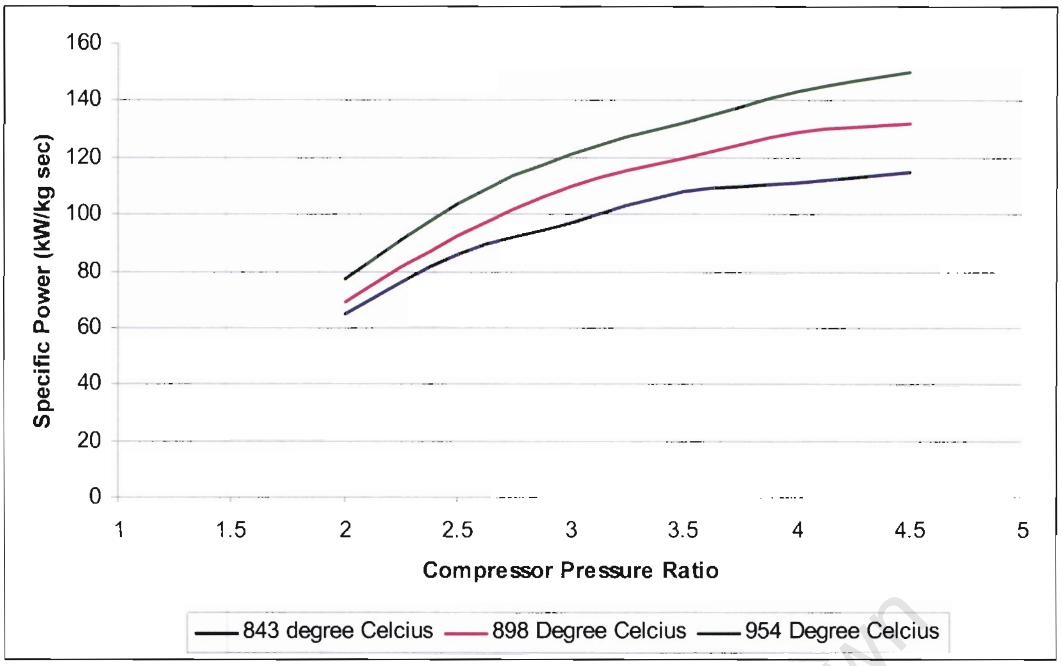


Figure 5.12: Effect of pressure ratio on specific power of microturbine (US EPA, 2002)

Electrical efficiency increases with turbine rating resulting in an increasing power to heat ratio. The result is less available thermal energy per unit of power produced.

2. Firing Temperature:

Higher firing temperatures result in higher efficiency. Larger turbines have become equipped with internal cooling systems so as to allow firing temperatures that exceed the limitations imposed by the materials of construction. These advancements however have yet to be incorporated into micro turbine systems.

3. Inlet air cooling:

By reducing the inlet air temperatures, compression power requirements can be reduced. The technology for achieving lower inlet temperatures is well established for larger turbines, and micro turbines are now incorporating inlet air cooling systems.

5.5.6 Maintenance

Micro turbines are characterised by few moving parts. Overhauls are required every 20,000-40,000 hours. Manufacturers target availabilities of between 98 and 99%. In addition, the general backup or parallel configuration of micro-turbines further ensures high availability of the system.

5.5.7 Environmental Implications

Lean premixed combustor technology is a standard feature on micro turbines operating with gaseous fuels. Lean premixed combustion reduces the quantity of NO_x generated during combustion. Thermal fixation of nitrogen occurs when the flame temperature exceeds the nitrogen fixation requirement in air temperature. Lean premixed combustion or dry low emissions (DLE) aims to lower local zones of high hot spot temperatures by pre-mixing a lean fuel air mixture prior to combustion. This avoids zones of high local temperature, thereby suppressing thermal NO_x formation. NO_x emissions below 9ppmv are not uncommon when using DLE technology.

Carbon monoxide emissions are a function of load as they were with the larger size turbines. At low load, there is insufficient residence time for the complete carbon combustion to CO_2. The level of CO emissions is attributable to how the system is run.

5.6 Reciprocating Engine

5.6.1 Technological description

Characteristically, reciprocating engines are reliable, low cost, offer fast start-up, follow load well and provide for good heat recovery. They have an operating range of between a few kW and 5 MW. Reciprocating engines exhibit higher electrical efficiencies (28-40% LHV) than gas turbines in CHP configuration and therefore require less fuel for the same power output. CHP efficiencies are in excess of between 70-80%. These high efficiencies are a direct result of the technological capacity to recover heat from a number of sources including the exhaust gas, engine jacket cooling water and lube oil cooling water. The exhaust gases contain 50% of the thermal energy, and can be used effectively to generate low pressure steam. Gas engines can be used as a direct mechanical drive for compressors, pumps etc., or can be coupled to alternators for generating electric power.

5.6.2 Operating Modes

There are two primary types of reciprocating engine:

- The spark ignition (SI) engine, which derives its fuel from natural gas

- The compression ignition (CI) engine, which is supplemented by diesel fuel.

The SI engine operates on an Otto-Cycle and the CI engine operates on a Diesel-cycle. Both engines consist of the same components – a cylindrical combustion chamber in which pistons connected to a crankshaft generate the rotary motion of the crankshaft.

The characterising difference between the two types of engines is the method in which the fuel is ignited. SI engines make use of spark plugs, igniting a well mixed fuel air mixture in the combustion chamber by a high intensity spark of timed duration. CI engines operate on an auto-ignition principle, whereby compressed air is fed into the combustion chamber at the auto-ignition temperature of the fuel, which itself is injected afterwards at high pressure.

Further distinguishing engine characteristics are the crankshaft speed (RPM), whether the operating cycle is a 2 or 4 stroke cycle and whether turbo charging is used. Stationary power generation in both the SI and CI engine utilizes a 4 stroke power cycle. This power cycle is outlined below:

1. *Intake stroke*: Introduction of air in a diesel engine or the air/fuel mixture in a SI engine into the combustion cylinder.
2. *Compression Stroke*: Compression of the cylinder. This step differentiates SI engines from CI engines.
    a. Diesel Engine: The fuel is injected at the end of the compression stroke and is self-ignited by the elevated temperature at high pressure.
    b. SI engine: The air-fuel mixture is ignited by a spark plug at the end of the compression stroke.
3. *Power stroke*: The piston is accelerated back to its starting position by expansion of the combustion gases.
4. *Exhaust stroke*: The combustion gases are released from the cylinder by an exhaust port.

There are three classes of engine in stationary power generation. The natural gas SI engine, the pure diesel engine and the diesel supplemented engine. The following discussion surrounds their functional differences.

1. Natural gas SI engine:

There are two ignition techniques concerning the SI engine.

1. *Open chamber technique:*

This method is utilized with stoichiometric air/fuel ratios. Its defining characteristic is the direct exposure of the spark plug to the combustion chamber air/fuel mixture.

2. *Pre-combustion Chamber technique*

This method is utilized with lean fuel/air mixtures. A lean mixture is an air/fuel mixture in which an excess of air is supplied for complete combustion. A rich mixture is a mixture where excess fuel is provided in relation to the amount needed for complete combustion with the available oxygen. In this technique, the spark plug is contained in a chamber on the cylinder head. The spark plug ignites a rich fuel mixture which shoots into the main combustion chamber igniting the remainder of the chamber.

A key benefit of lean fuel-air mixtures is the lower peak combustion temperatures reached, limiting the fixation of nitrogen and atmospheric oxygen. There is, however, a 1.5% reduction in efficiency in comparison with high NO_x emission tuning. Lean-burn gas engines have NO_x emissions in the range of 0.7-2.5gm/kWh

Knocking occurs when the air/fuel mixture ignites prior to complete compression. The pressure ratio is adjusted in order to avoid this. The operating pressure ratio is determined by the break mean effective pressure (BMEP), which can be interpreted as the "average" cylinder pressure on the piston during its power stroke. It is a measure of the effectiveness of engine power output. By turbo charging this intake stroke, more air can be forced into the combustion chamber ensuring complete combustion.

The efficiency of a SI engine is less than that of a diesel engine, due to the modest compression ratio. An SI engine produces only 60-80% of the power output of the diesel engine as the BMEP of a diesel engine exceeds that of a SI engine. The cost per kW of power delivered from a SI engine is therefore typically higher than that from a diesel engine. The operating electrical efficiency of the SI engine is typically between 22-40%.

2. Diesel Compression Ignition Engines:

The efficiency of a diesel engine is commonly rated between 30-52%. Compression ratios of 12:1 to 17:1 are required for auto-ignition, and fuel quality plays an important factor in the diesel engine's operation. Constant fuel qualities along with good internal fuel dispersion (attributable to engine design) are necessary operating characteristics for complete combustion and emission control. NO_x emissions can be 5-20 times (ppmv) that of a lean burn natural gas engine so enhanced emission controls become necessary. Efficient combustion does however result in a reduction of CO emissions. Hydrocarbon emissions are largely the result of the diesel grade chosen – be it heavy oil or distillate oil.

3. Dual Fuel Engines:

There are three types of dual fuel engines: The conventional low pressure gas injection engine, the high pressure gas injection engine, and the micro pilot pre chamber engine. Although designed as diesel compression ignition engines, they run on predominantly natural gas, fuelled by only a limited amount of diesel fuel as the pilot fuel (1-15%). Dual fuel engines exhibit lower NO_x emissions than diesel engines, but higher CO emissions on account of incomplete combustion. They can be tuned to run on either a dual fuel or pure diesel, and be converted with no downtime.

Conventional low pressure gas injection engine:

The engine operates by direct injection of natural gas into the chamber prior to air intake, in conjunction with 5-10% diesel pilot fuel. The engine's capacity is generally reduced by 5-20% of its rated capacity so as to avoid knocking and NO_x emissions are in the range of 5-8 gm/kWh. The turndown ratio is limited to not less than 95% of full-load injection rate, highlighting a questionable ability to handle load fluctuations.

1. High Pressure gas injection engine:

Natural gas is injected at high pressure into the combustion chamber along with pilot fuel. This is done in an attempt to limit the de-rating effect mentioned above. However, the benefit incurred is partially offset by the power requirement for gas compression. Between 3-8% of fuel consumption is pilot fuel and NO_x emissions are generally in the 5-8 g/kWh range.

2. *Micro pilot pre chamber engine:*

The pilot fuel is ignited in a pre-chamber thereby generating a high energy torch that ignites the lean, compressed fuel/air mixture facilitating the burning of highly lean fuel/air mixtures. Diesel pilot fuel generates a higher energy torch pilot fuel in SI engines. Furthermore, pilot fuel consumption can be configured to be as little as 1% of total fuel consumption. Compression ratios are only marginally reduced (as is the BMEP) and so the power rating of the engine is close to 100% of the analogous diesel designed engine.

5.6.3 Operating and efficiency Characteristics

Table 5.3 presents operational trends with SI engine operating size. These engines are specified as natural gas spark ignition engine CHP systems. Heat rates and efficiencies sourced were originally collected from manufacturer's specifications and industry publications. The available thermal energy recoverable was calculated from published engine data on engine exhaust, cooling jacket and lube oil temperatures. These thermal recovery estimates are based on producing hot water.

Table 5.3: Operational characteristics of a gas engine at various ratings (US EPA, Sourced from Energy Nexus Group, 2002)

System Characteristics	System 1	System 2	System 3
Base load electric capacity (kW)	300	800	3000
Total Installed Cost (2001$/kW)	1200	1000	920
Electric Heat Rate (kJ/kWh), HHV	11570	10810	10014
Electrical Efficiency (%). HHV	31.1	33.3	36.0
Fuel Input required (GJ/hr)	3.471	8.651	30.047
Fuel gas pressure required (barg)	>1	>1	>1
CHP Characteristics:			
Exhaust flow (1000 kg/hr)	1.49	4.94	21.93
Exhaust Temp (^{o}C)	575	465	364
Heat recovered from exhaust (GJ/hr)	0.865	2.236	5.845
Heat recovered from cooling jacket (GJ/ hr)	0.727	1.15	4.610
Total heat recovered (kW)	443	1025	3259
Total CHP efficiency (%), HHV	77	76	75
Power: Heat Ratio	0.68	0.78	0.92
Net Heat Rate (kJ/kWh)	4945	5036	5124
Effective electrical efficiency (%), HHV	0.73	0.71	0.70

5.6.4 External Influencing Parameters

5.6.4.1 Part-Load performance:

With load fluctuations, heat rate increases but efficiency is only modestly affected. Efficiency at half load is only 8-10% less than that at full load, although at less than half load, drastic reductions in efficiency are observed.

Diesel engines exhibit almost no reduction in efficiency for loads of between 50-100%. Figure 5.13 shows the part load performance of natural gas engines. In comparison to the part load curves of turbine prime movers, gas engines handle reductions in efficiency at part load much more effectively.

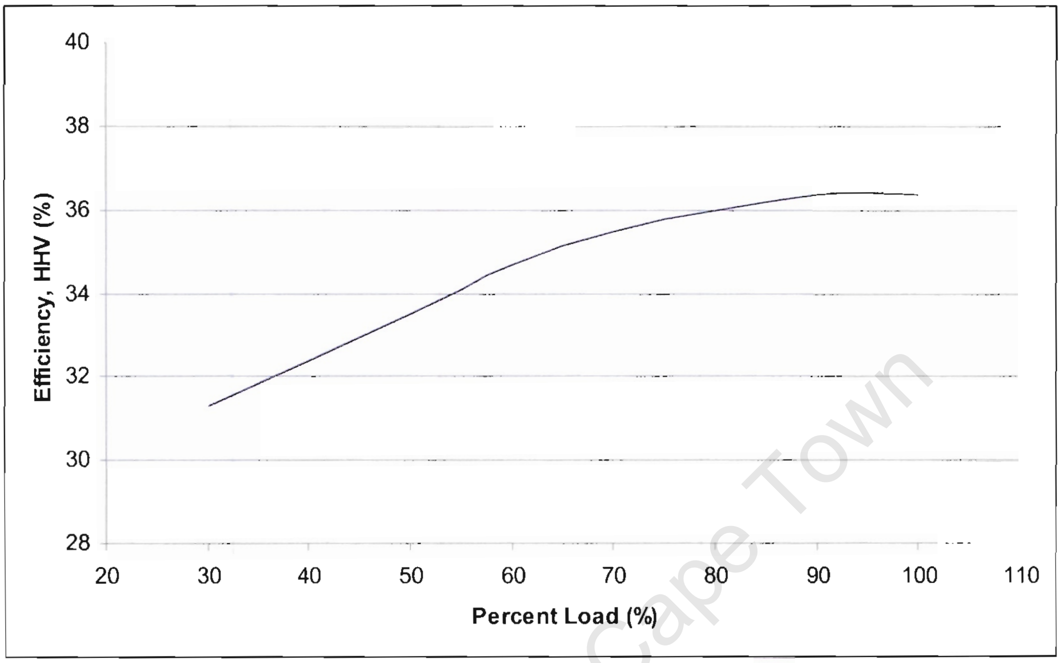


Figure 5.13: Effect of part-load on gas engine de-rating (US EPA, 2002)

5.6.4.2 Ambient Conditions:

SI engines are less affected by ambient conditions than turbines. It has been correlated that efficiency and power are reduced only 4% per every 300 meters starting 300 meters above sea level and 1% for every 5 degrees F above 77 degrees F.

5.6.5 Performance Enhancement

5.6.5.1 CHP enhancement:

60-70% of the total fuel energy input can be recovered from the exhaust heat and cooling systems. There are additional thermal recovery opportunities from the engine jacket coolant, lube oil and turbocharger cooler. Energy from an engine jacket cooling system can account for up to 30% of the input fuel, and is capable of producing hot water at temperatures of 100° C. Exhaust gases account for between 30-50% of the input fuel and reach temperatures of between 454-648°C. This can be used to generate low pressure steam of up to 10 bar effectively. By reclaiming energy from the exhaust gases and heating jacket, 70-80% of fuel energy is effectively utilized (in conjunction with power generation).

The exhaust temperature is largely dependent on exhaust on composition. So as to avoid the condensation of corrosive products, most heat recovery systems limit the exhaust outlet temperature to not less than 121-176°C.

Figure 5.14 illustrates a general set up of an engine system and a potential thermal energy reclamation system.

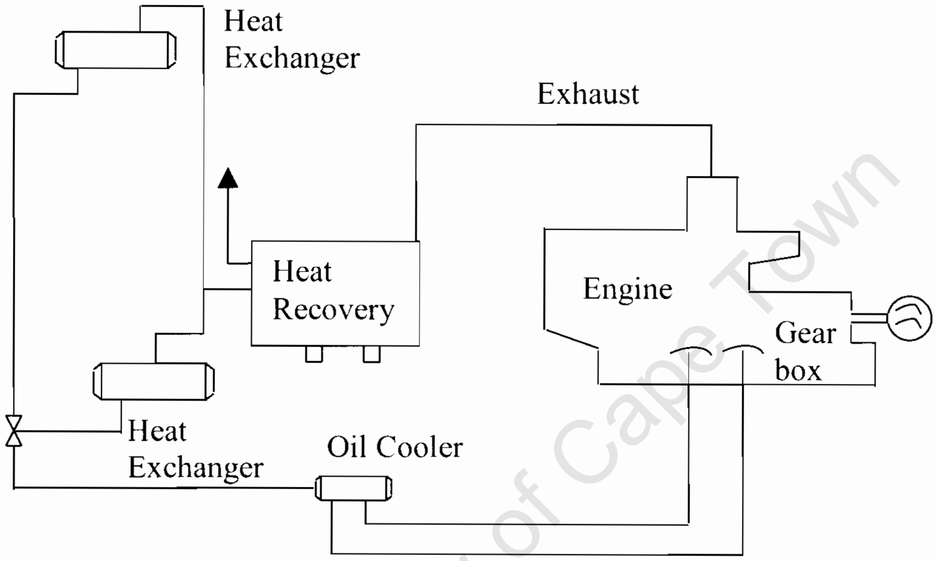


Figure 5.14: Schematic of a energy recovery system applied to a gas engine (US EPA, 2002)

The closed loop cooling system is the most common method of heat recovery. Coolant is circulated through the engine followed by a heat exchanger. The ebullient cooling system offers an alternative by making use of natural circulation of a boiling coolant through the engine. This method can extend engine life and improve combustion efficiencies. In addition, ebullient cooling systems enable the recovery of thermal energy from water jacket temperatures of up to 130°C, whereas closed loop cooling systems operate with coolant temperatures of between 87-121°C.

5.6.5.2 Overall Efficiency Enhancements:

1. Turbo charging:

Improved turbo charging and efficient inter cooling enhances peak combustion pressure and air charge density within the combustion chamber increasing the BMEP level. This leads to higher power output and greater efficiency. Increased cylinder pressure results in elevated temperatures; the compression ratio and turbo charger boost level therefore both require good control to avoid equipment explosion. Turbo charging can boost inlet air pressure by a 3:1 or 4:1 ratio.

5.6.6 Maintenance

Reciprocating engines are maintenance intensive. Engine oil, filters, coolant and spark plugs replacement occurs every 500-2,000 hours. Top end overhauls are required every 8,000-30,000 hours and major overhauls are required every 30,000-72,000 hours.

Compensating for this cost is the fact that reciprocating engines often do not exhibit economies of scale. Smaller engines give better $/kW rates than larger engines. The availability of gas engines has been reported between 90-95%.

5.6.7 Environmental Implications

Gas engines emission profiles have improved considerably over the past number of years due to improved combustion control and catalytic converters. Advanced lean burn natural gas engines produce NO_x emissions of 50 ppmv at 15% O_2. Varying levels of NO_x, CO and SO_x are emitted depending on the composition of the fuel burnt. Generally, engines operating on natural gas emit only insignificant levels of SO_x. NO_x generation is dictated by nitrogen fixation.

5.7 Summary and Conclusion

A summary table, highlighting the advantages and disadvantages of each of the technologies reviewed, has been presented to enable a quick direct comparison across technologies and facilitate a preliminary selection concerning the applicable technology based on design characteristics and its purpose. This summary matrix is presented in table 5.4.

Table 5.4: Summary matrix of technologies reviewed (US EPA, 2002)

Technology	Gas turbine	Microturbine	Gas Spark Ignition Engine	Diesel Compression Ignition Engine
Capacity (MW_e)	1-500	0.03-0.35	0.05-5	0.03-5
Power Efficiency (HHV)	22-36	18-27	31-36	27-45
Overall Efficiency (HHV)	70-75	65-75	70-80	70-80
Effective Electrical Efficiency	50-70	50-70	70-80	70-80
Power to Heat Ratio	0.5-2	0.4-0.7	0.5-1	0.5-1
Part Load Performance	Poor	Average	Average	Good
CHP Installed Costs (2000 $/kW)	800-1800	1300-2500	900-1500	900-1500
Availability	90-98	90-98	92-97	90-95
Hours to Overhaul	30000-50000	5000-40000	24000-60000	25000-30000
Start-up Time	10min-1hr	60 Seconds	10 seconds	10 seconds
Fuel Pressure Required (bar)	8.27-34.4	2.75-6.89	0.06-3.1	0.3
Noise	moderate	moderate	high	high
Thermal Output Potential	heat, hot water, LP-HP steam	heat, hot water, LP-HP steam	hot water, LP steam	hot water, LP steam
Effect of Ambient Conditions	High impact	High Impact	minimal impact	minimal impact
Emissions	25-40 PPM NO_x, 20 PPM CO	9 PPMV NO_x	50 PPMV NO_x	50 PPMV NO_x

Chapter 6: Energy Recovery

6.1 Introduction

Chapter 6 applies the knowledge presented in Chapter 5 to evaluate the most suitable technology applicable for energy recapture from the biogas generated at SABMiller Newlands Brewery. The technology selection matrix, Table 5.4 is used to evaluate the most suitable technology for energy recovery in the context of the Newlands brewery and trade-offs between technologies are identified and discussed. It should be noted that boiler configurations have not been excluded in this comparison, in light of the electric power producing capacity a CHP unit offers that a boiler does not. Attempting to weigh up the benefits of different forms of energy yet referencing these benefits within a framework of external criteria (including methane flow-rate, load fluctuations, ambient conditions, etc) that impact on the very selection of technologies, is unconstructive. The boiler configuration is however revisited in Chapter 7 when comparing environmental impacts across effluent management systems – in this case, environmental impact comparison across different forms of energy is a worthwhile exercise as an environmental impact profile is a common denominator of all power producing equipment.

In supplementing the utility requirements of the brewery through energy capture from biogas generation, scope of this project has been limited to evaluating the benefits of steam and power generation owing to the expected benefit these two utilities provide (Maritz, 2005). This was motivated by the expected increase in electricity costs and the energy consumption reduction initiatives discussed below.

6.2 Utility Specifications

Steam to SABMiller Newlands Brewery is provided at 10 bar (179.97 °C). Its average rate of usage is 230 tonnes per day, with variation between 200 and 250 tonnes per day. The enthalpy of saturated vapour at 10 bar is 2777.9 Joules per gram. Electricity demands are recorded at 720 MWh weekly, but vary between 680 and 760 MWh. It is estimated by SAB plant engineers that between 40% and 50% of this power usage is consumed for utilities. Currently 125 MJ of energy is expended per Hl of beer. An energy expenditure initiative is in place to reduce brewery energy consumption by 15% by 2015.

The plant runs continuously for 361 days per year with plant wide upkeep scheduled over the other 4 days. The brewery also shuts down intermittently throughout the year during power outages from the national grid. Power generation from biogas is expected to reduce disruption of production and unscheduled periods of downtime owing to discontinuities in electricity supply. It can take 45 minutes before the brewery is operating at full capacity after a power outage. It has been suggested that should power to the boiler feed pumps be sustained during a power outage, start-up could be achieved more quickly with substantial savings in running costs.

6.3 Decision making procedure

Berta et al, (2006), identified two different guidelines for CHP facility design, captive oriented and export oriented:

1. The first revolves around setting up the system in an effort to meet end-user thermal and electrical loads with peak performance indices coinciding with the characteristic demand from the user.
2. The second method would entail scaling up of the CHP facility with the aim of providing the total heat load of the end-user and co-currently producing the maximum excess electricity permitted by legislative bodies. Excess power is sold back to the national grid resulting in additional economic profit.

This analysis is a captive oriented one, and aims to calculate the maximum benefit to the SABMiller Newlands Brewery without scale-up or retrofitting. Outlined below is a descriptive approach of how the technology selection matrix presented in Table 5.4 is used to assess the technology most applicable for energy capture from biogas generation, depending on the plant specific conditions of the Newlands Brewery. This approach can be extended to other facilities around the country, where environmental conditions and plant particulars differ from the Newlands case.

Figure 6.1 presents the flare rating between the months of January to August. The flare is rated at an average of 1.564 MW during this time with monthly fluctuations of between 1.3MW and 2.0MW (in March, '05). This result is in agreement with previous estimations by SABMiller on-site engineers. Based on this rating capacity, use of gas turbines for power generation is not proposed as the flare calorific value is not sufficient to sustain turbine operation (see Section 5.4.1). Hence the technology options considered for power generation from biogas in the context of Newlands brewery are gas engines, diesel engines or microturbines.

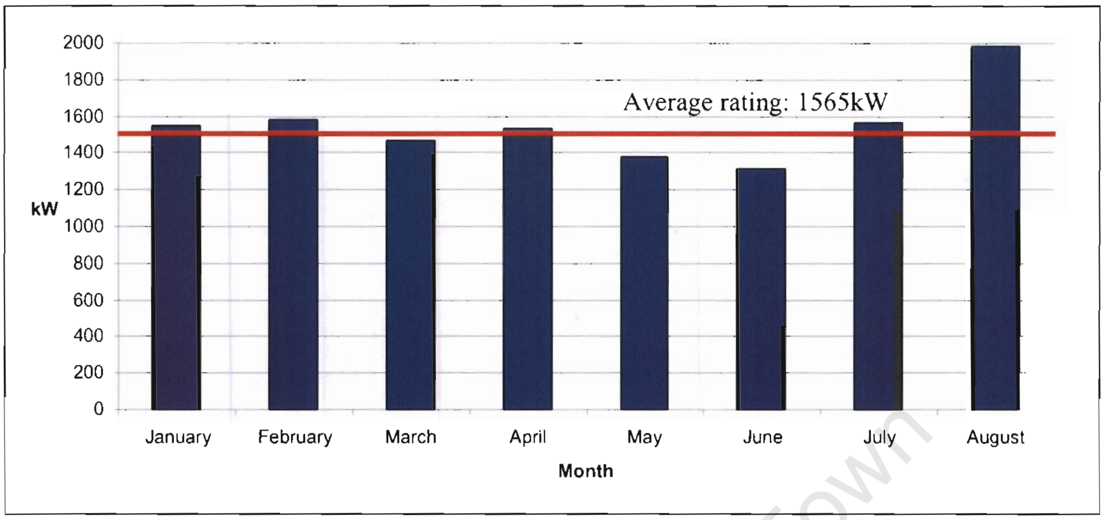


Figure 6.1: Change in flare rating with Month

Based on a steam usage of 230 tonnes per day at 2777.9 J/g, the equivalent power of steam usage is 7.39 MW, equating to a weekly requirement of 1242 MWh. The on-site power to heat ratio is readily calculated as 0.580. Comparison of this power to heat ratio with the selection matrix presented in Table 5.4 clearly indicates that microturbines and gas and diesel engines are suitable for this facility based on a range of operations with respect to power: heat ratio.

A direct comparison between microturbine and gas/diesel engine operation is presented in Table 6.1. Gas/diesel engine power efficiencies exceed microturbine efficiencies. Overall CHP efficiencies exceed that of microturbines by between 5-10%. Furthermore, microturbine costs exceed gas/diesel engine costs, and the specified operating range of the microturbine limits the power recoverable to a maximum of 350kW, unless more than one turbine is installed (see Section 5.5.1). Although more expensive, the multi unit facility does allow for better control when taking into account fluctuating biogas flow-rates from the effluent plant. Microturbines can be installed in parallel to enable the system to follow the power requirements of the facility as they increase or decrease.

Table 6.1: A direct comparison of the advantages and disadvantages of micro-turbine and gas/diesel engines (US EPA, 2002)

	Advantages	Disadvantages
Microturbine Power Efficiency: 18%-27% Overall Efficiency: 65%-75%	small number of moving parts compact size low emission no cooling required	high costs low mechanical efficiency limited power capacity
Gas/Diesel Engine Power Efficiency $_{\text{gas engine}}$: 31%-36% Overall Efficiency $_{\text{gas turbine}}$: 70%-80% Power Efficiency $_{\text{diesel engine}}$: 27%-45% Overall Efficiency $_{\text{diesel turbine}}$: 70%-80%	high efficiency even at part load fast start-up low costing overhaul can be carried out on site Requires a low pressure gas feed	high maintenance costs lower temperature CHP applications high air emissions requires cooling high noise level

Part-load performance is a critical decision-making criterion when concerned with fluctuating biogas flow-rates and following power demands by the facility. The part load performance characteristics of engines are good up to a loading drop of more than 50% (see Figure 5.13). Engine efficiencies are reduced only 2% from 50-100% loading, whereas the part load performance of microturbines exhibit an efficiency drop of 10-15% on a reduction of 50% loading (see figure 5.8).

Engines operate with higher noise levels, although noise can be contained depending on whether the engine is contained inside or positioned outside the utility house. From an environmental perspective, microturbines emit 9ppm NO_x on a volumetric basis in comparison to gas/diesel engines emitting up to 50ppm NO_x. Feed pressures required for gas/diesel engines (0.06-3.1 bar) are substantially less than that required for microturbines (2.75-6.67 bar), reducing compression requirements.

Microturbines are considerably more affected by ambient temperatures. Gas engines are only negligibly affected by ambient conditions. This is an important consideration taking into account the significant changes in temperature from mid-year winter to the February summer months in Cape Town. Section 5.5.4 b and 5.6.4 b details the relative impact of temperature changes on the microturbine and gas engine respectively.

6.4 Conclusion

Using the comparative matrix and power: heat ratio detailed above, gas engines are the most suitable option for energy capture from the biogas produced in on-site waste water treatment at SABMiller Newlands Brewery due to their low operating cost, higher efficiencies and suitability based on flare flow-rate, methane concentration and gas flow-rate fluctuations.

They are robust enough to sustain continued operation at fluctuating effluent feeds, and are capable of absorbing the variations in ambient conditions commonly observed in Newlands. Furthermore the installation costs of the gas engine are less than that of the microturbine.

Gas engine overhauls can be carried out on site by in-house staff, and are more infrequent than those required by microturbines. This allows for a more self-sustaining operation.

Finally, gas engines exhibit fast start up times. In light of the requirements of back-up power, fast start-up times enable a higher degree of control of power provision, exceeding the control provided by power generating equipment that requires longer start-up times.

Chapter 7: Energy Recovery and Re-Integration

7.1 Introduction

In Chapter 7, the additional environmental benefits incurred as a result of energy capture and re-integration are assessed. The benefits are a direct result of the grid-energy expenditure avoided.

The use of the LCA methodology introduced in Section 2.2 and applied in Section 4.4, is extended in this chapter to quantify the benefits incurred by energy capture and re-integration. This enabled a direct comparison between the current operational configuration of the SABMiller Newlands Brewery and the scenario involving the recovery of energy discussed in chapter 6. The comparisons are based on the impact categories presented in Chapter 4. By quantifying the change observed within each impact category, direct correlations between burdens emitted and resulting impact sustained could be established.

7.2 Approach

The analysis completed in Chapter 4 juxtaposed the environmental impact profiles of various waste water management systems servicing the SABMiller Newlands Brewery. The study established a treatment benchmark, by comparing the environmental impacts of all possible effluent treatment scenarios across a range of impact categories. The analysis presented in Chapter 7 aims to compare a new treatment configuration with those presented in Chapter 4; the current treatment configuration (SAB treatment followed by municipal treatment) with onsite energy re-integration from the methane flare. The intention of this analysis is to evaluate the additional environmental benefits of biogas reclamation and energy generation. The current treatment configuration forms the point of departure in this comparison so as to highlight the environmental benefits incurred as a result of energy generation and re-integration relative to the environmental impacts attributable to the benchmark scenarios presented in Chapter 4.

This chapter presents an extension of the LCA presented in Chapter 4. Table 7.1 presents the relevant details from the energy balance, highlighting flare power based on biogas flow-rates and the calorific value of methane. Table 7.2 presents CHP calculations pertaining to both electrical and thermal power produced based on achievable efficiencies of a gas engine as specified in literature (see Section 5.6) and commonly observed CHP unit availabilities (specifically 95%). Table 7.3 presents the calculations pertaining to the avoided energy consumption as a result of energy capture and re-integration. Calculations in Table 7.3 have been based on an enthalpy of 10 bar steam of 2777.9 kJ/kg. Calculations have been performed on a flare flow-rate of 4275Nm^3/day; which is approximately the average flow-rate over the period from January to August (4317Nm^3/day). No gas scrubbing has been assumed, as the sulphur content of the gas (in the form of H_2S) was found to be negligible, indicating the efficient separation of H_2S from the biogas processed to flare (see Table 3.10).

Table 7.1: Summary energy balance

Flare flow rate (Nm^3/day)	4275
% methane	80.19%
Methane flow (Nm^3/day)	3427
Methane flow (kg/day)	2433
Calorific value of Methane (MJ/kg)	55
Power of fuel (MJ/day)	133856
Power of fuel (KJ/day)	133856410
Power of flare (kW)	1549

Table 7.2 Summary CHP calculations

Flare power available (kW)	1549
Electrical efficiency	33%
Thermal efficiency	50%
Electrical output (kW$_e$)	511.3
Heat output (kW$_{th}$)	774.6
Availability of CHP Unit	95%
Electrical output (kW$_e$) taking into account availability	485.7
thermal output (kW$_{th}$) taking into account availability	735.9

Table 7.3: Summary avoided power calculations

Power avoided straight off grid (kW)	485.7
Power avoided straight off grid (kWh/day)	11657
Amount of 10 bar steam generated by CHP's kW$_{th}$ (kg/s)	0.2789
10 bar steam (tonnes/day)	24
Breweries steam consumption (kg/s)	2.66
Total energy requirement to produce required steam amounts (kW)	7784
Energy requirement to produce substituted steam amount (kW)	815.4
Hence, energy requirement on a per day basis(kWh) to produce substituted steam	19,570

The assumption of 100% combustion is not inconceivable, as premature combustion is more likely to occur than incomplete combustion resulting in knocking (see Section 5.6.2). Furthermore, gaseous emissions comprised of CH_4 from the municipal treatment facility and SABMiller WTF (CH_4 which was processed through biofilter), CO_2, H_2O, H_2 and H_2S (from both the municipal treatment facility and the WTF). Aqueous and organic emissions remain the same as those modelled in Chapter 4. The Simapro^{TM} data base was used to generate the burdens attributable to plant operation and the functional unit remained 1 kg COD processed as defined in Section 5.

Table 7.4 presents the life cycle inventory collated for the LCA on the basis of a functional unit of 1kg COD processed to effluent management system. The calculations presented in Table 7.2 (and 7.3) were also performed assuming the re-routing of methane to a boiler operating at 95% thermal efficiency, and the data pertaining to the LCI of that alternative is also presented as indicated in Table 7.4.

Table 7.4 Life Cycle Inventory

	SAB and Municipal	SAB and Municipal with re-integration (CHP)	SAB and Municipal with re-integration (boiler)
Inputs			
COD (kg/kg COD)	1	1	1
P (kg/ kg COD)	0.0244	0.0244	0.0244
SO_4 (kg/ kg COD)	0.1904	0.1904	0.1904
N (kg/ kg COD)	0.2149	0.2149	0.2149
SS (kg/ kg COD)	0.1904	0.1904	0.1904
Energy (kWh/ kg COD)	0.2464	-2.4923	-3.0147
NaOH (kg/ kg COD)	0.1008	0.1008	0.1008
Outputs			
COD (kg/ kg COD)	0.0090	0.0090	0.0090
P (kg/ kg COD)	0.0004	0.0004	0.0004
SO_4 (kg/ kg COD)	0.0232	0.0232	0.0232
N (kg/ kg COD)	0.0005	0.0005	0.0005
SS (kg/ kg COD)	0.0018	0.0018	0.0018
CH_4 (kg/ kg COD)	0.0272	0.0272	0.0272
CO_2 (kg/ kg COD)	1.0603	1.0603	1.0603
H_2 (kg/ kg COD)	0.0002	0.0002	0.0002
H_2S (kg/ kg COD)	0.0075	0.0075	0.0075
Water Vapour (kg/ kg COD)	0.5944	0.5944	0.5944
NaOH (kg/ kg COD)	0.1008	0.1008	0.1008

7.3 LCA Interpretation

Figure 7.1 presents a graphical representation of the benefits incurred as a result of energy reclamation in comparing the effluent treatment scenario of SAB treatment followed by municipal treatment. Across impact categories, impacts per treatment system are scaled to a percentage of the treatment system generating the maximum burden (as per Section 4.4). Table 7.5 presents the data used to construct Figure 7.1.

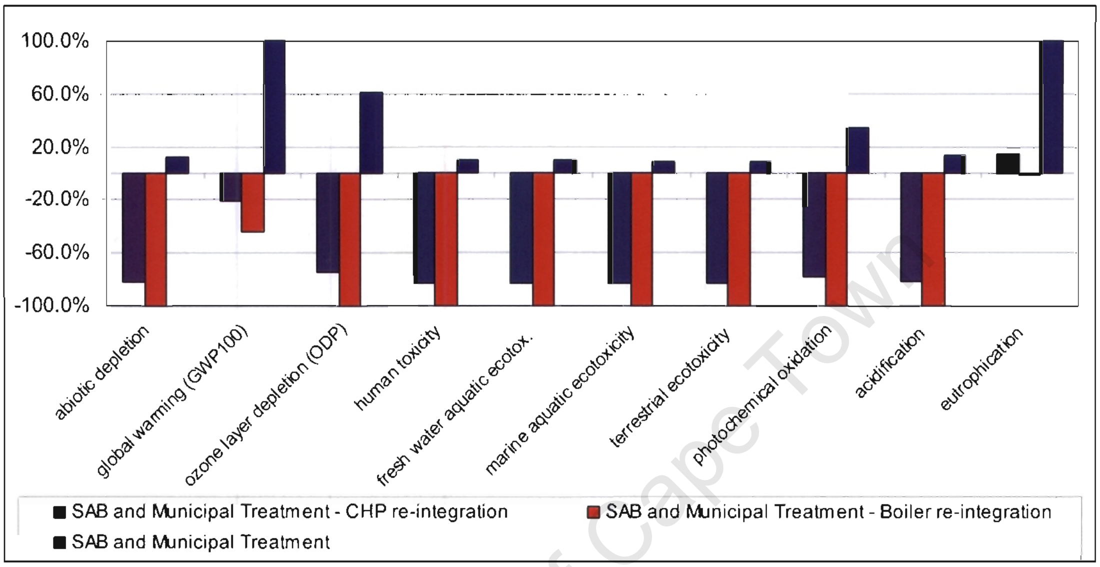


Figure 7.1: Characterized Life Cycle Assessment results presented as a percentage of maximum impact

Table 7.5: Life Cycle Assessment impact scores across impact categories

Impact category	Unit	No reclamation	Boiler re-integration	CHP re--integration
abiotic depletion	kg Sb	0.0027	-0.0224	-0.0184
global warming (GWP100)	kg CO_2	2.020	-0.8830	-0.4170
ozone layer depletion (ODP)	kg CFC-11	2.72E-08	-4.42E-08	-3.27E-08
human toxicity	kg 1,4-DB	0.0784	-0.820	-0.6760
fresh water aquatic ecotox.	kg 1,4-DB	0.0115	-0.1170	-0.0965
marine aquatic ecotoxicity	kg 1,4-DB	312.0	-3,770	-3,120
terrestrial ecotoxicity	kg 1,4-DB	0.0012	-0.0135	-0.0112
photochemical oxidation	kg C_2H_2	0.0003	-0.0009	-0.0007
acidification	kg SO_2	0.0041	-0.0291	-0.0238
eutrophication	kg $PO_{4\,3-}$	0.0015	-2.40E-05	0.0002

Significant environmental savings are observed across impact categories, due to the elimination of the effluent treatment power requirement. With reference to CHP re-integration, abiotic depletion impact scores have been reduced by 781% from 0.0027 kg Sb/kg COD fed to -0.0184 kg Sb/kg COD fed. Global warming potential has been reduced by 121% from 2.02 kg CO_2/kg COD fed to -0.417kg CO_2/kg COD fed. Human toxicity has been reduced by 962% from 0.0784 kg 1,4-DB/kg COD fed to -0.676 kg 1,4-DB/kg COD fed. A similar reduction in fresh water aquatic ecotoxicty was observed (939%) from 0.0115 kg 1,4-DB/kg COD fed to -0.0965kg 1,4DB/kg COD fed. The largest reduction in impact score is the marine aquatic ecotoxicity of 1100% from 312 kg 1,4-DB/kg COD fed to -3120kg 1,4_DB/kg COD fed. Terrestrial ecotoxicity was reduced by 1049% from 0.00188 kg 1,4-DB to -0.0112 kg 1,4 DB. Photochemcial oxidation was reduced by 330% from 0.000305kg C_2H_2/kg COD fed to –0.000702kg C_2H_2/kg COD fed. The acidification impact score was reduced 683% from 0.00408 kg SO_2/kg COD fed to -0.0238kg SO_2/kg COD fed and eutrophication was reduced 85% from 0.00154 kg PO_4/kg COD fed to -0.000227 kg PO_4/kg COD fed.

7.4 Conclusion

The energy generated by the flare is in excess of the energy consumed by the waste water management process. This provides opportunity for manufacturing plant-reintegration over and above facilitating the power requirement of the effluent process. This is represented here by the negative burdens attributed to effluent treatment with the reclamation of energy in either a CHP engine or boiler. Specifically, there is an energy surplus of between 2.49kWh/kg COD fed (CHP integration) and 3.01kWh/kg COD fed (boiler integration) depending on choice of reclamation system.

Across impact categories, burden reductions resulting from fuelling a boiler are, surprisingly, in excess of the burden reductions resulting from CHP operation. Although typically, CHP operation is the thermodynamically sensible option, in this case system-wide 1st law efficiencies are higher when the recovered methane is utilised to fuel a boiler rather than generating both heat and power in a gas engine. This results from the configuration where steam is generated on-site by use of an electrode boiler as established in Chapter 6. Power generated for this boiler, is produced by a 90% coal, 4% nuclear, 6% hydro country mix, with the standard 34% 1st-law efficiencies for the coal fired generation plants. Hence the process by which steam is generated on-site includes the efficiencies attached to the combustion of coal in conjunction with the efficiencies of the electrode boiler. Hence, fuelling the boiler directly results in the elimination of coal fired power station efficiencies, however losing the flexibility of both a combined heat and power generating facility.

In developing and extending the methodology of this thesis as a generic research tool, the result of this Chapter highlights the importance for considering the context of the study in addition to the thermodynamics of the system under assessment. The requirements of the company need to be assessed co-currently with the environmental aims and strategy of the company, thereby influencing the recommendations made surrounding the re-integration of energy from biogas.

The results of the analysis presented in Chapter 7 present SABMiller Newlands Brewery with an explicit trade-off between the option providing for enhanced flexibility in terms of power production, and the option providing for additional environmental savings but at a reduced level of operational flexibility.

This result leads to the conclusion that in future applications of the methodology developed in this thesis, consideration should be given to the context of the research so as to streamline and tailor the investigative study accordingly.

An earlier discussion with SABMiller management might have established a more appropriate order to the research presented by this thesis. The environmental impact of the various re-integration options might have been more appropriately positioned earlier in the thesis depending on SABMillers' motivation for the research. The research was carried out in the order presented as it was understood that the potential for on-site supplementary power was a key motivation for energy capture and re-integration. It was understood that re-integration to the boiler was not a viable option during the course of this thesis. As a result, direction was taken from a technical perspective and less so from an environmental perspective. However, in extending the methodology developed by this thesis past this research, it would be prudent to assess the perceived importance of environmental considerations versus operational considerations early on, so as to tailor the process accordingly.

Chapter 8: Conclusion and Recommendations

8.1 Conclusion

Waste water and effluent systems impact on both the social and environment spheres of society. In particular organic loadings on natural ecosystems need to be kept within the assimilative capacity of the environment. The consequences of effluent streams with high COD concentration, low pH and high nutrient concentration are eutrophication and the general degradation of the ability of soil and water systems to sustain plant or aquatic life.

Anaerobic digestion presents the unique potential of a concurrent waste treatment and energy generating process. Furthermore, on-site anaerobic waste water treatment with energy re-integration facilitates an industrial ecosystem in itself, minimizing the negative effects of anthropogenic activity. This project aimed at evaluating the environmental burdens and benefits of on-site waste water treatment. As methane generation represents a major burden of anaerobic WWT, the potential for burden avoidance, energy capture and reintegration was studied. The thesis reviewed energy capture technologies, and presented a generic selection tool through which the most suitable technology can be chosen for energy capture based on inherent plant characteristics. Thereafter, the evaluation of the environmental benefits and burdens of on site WWT with energy capture and re-integration was completed.

The LCA study highlighted the value of on-site waste water treatment with and without energy re-integration by using the SABMiller Newlands Brewery as a case study. It was found that there was a marked decrease in burdens generated when comparing the current treatment configuration to a SAB only effluent system. Although the effects of eutrophication were reduced as a result of additional water treatment, the consecutive treatment configuration resulted in increased burdens across the other impact categories.

Increased burden generation was found to be attributable to the increased electricity requirements associated with pumping effluent to the Athlone municipal treatment facility. Pumping requirements were found to be significant, having a large impact on results and indicating the value of targeting a portion of the treated for local re-use if of sufficient quality. Sodium hydroxide as a neutralising agent was also a key parameter, influencing impact categories within the same order of magnitude as burdens attributed to power consumption.

Although no treatment resulted in the lowest impact scores across most impact categories, its contribution to eutrophication was significantly higher than the other treatment systems as expected, and global warming potential was approximately half that of the combined SAB and combined treatment configuration. Table 8.1 presents the scores across impact categories as a function of treatment management system relative to the current configuration. It is clear that with further on site effluent treatment, there is a marked improvement in the eutrophication score over all other waste management systems.

Municipal treatment fairs favourably against the other viable treatment options, although less so in the global warming and photochemical oxidation impact categories. The higher impact scores in these categories are a direct result of the un-flared methane generated during treatment. The eutrophication impact category is also higher on use of municipal treatment only relative to the combined treatment system or treatment with the SAB system only , due to the higher COD and nutrient reducing efficiencies of the other treatment systems.

Table 8.1: Impact scores referenced relative to combined SAB - municipal treatment

Impact category	Unit (eq)	SAB and Municipal Treatment	SAB treatment	Municipal treatment	No Treatment
abiotic depletion	kg Sb	1	0.7975	0.2668	0.1617
global warming	kg CO_2	1	0.7321	2.6842	0.9426
ozone layer depletion	kg CFC-11	1	0.9545	0.0604	0.0366
human toxicity	kg 1,4-DB	1	0.7273	0.3792	0.2189
fresh water aquatic ecotox.	kg 1,4-DB	1	0.7408	0.3456	0.2088
marine aquatic ecotoxicity	kg 1,4-DB	1	0.6720	0.4363	0.2643
terrestrial ecotoxicity	kg 1,4-DB	1	0.6943	0.4016	0.2431
photochemical oxidation	kg C_2H_2	1	0.5642	4.0299	0.0728
acidification	kg SO_2	1	0.8313	0.2229	0.1355
eutrophication	kg PO_{43-}	1	7.2500	8.1250	73.75

With energy capture and re-integration, the treatment burden profile is clearly reduced. Negative environmental impact is recorded, meaning in this case, the process is not only self-sustainable but environmentally beneficial as well. The net result of energy capture and re-integration is an effluent treatment system which is both cost effective and environmentally friendly. Table 8.2 presents the relative impact scores across waste water management systems with energy re-integration.

The environmental impact of energy re-integration into both a gas engine and boiler was investigated. CHP technology was deemed most suitable in light of SABMiller's requirement of flexibility, and because the CHP unit can be used to create back-up electrical power so as to hedge against grid outages. On a 1st principles approach, fuelling the boiler would be environmentally and thermodynamically more beneficial and potentially offer larger cost savings. CHP configuration offered fuel utilization efficiencies of 83%, and the technology has potential to absorb the day-by-day load fluctuations observed by the study. The steam generating potential of CHP configuration at the observed heat: power ratio of the Newlands brewery, gave further comfort to the technology decision.

Table 8.2: Environmental impact scores foe energy re-integration, referenced relative to SAB followed by municipal treatment

Impact category	Unit	SAB and Municipal	Boiler re-integration	CHP re-integration
abiotic depletion	kg Sb	1	-6.962	-5.665
global warming (GWP100)	kg CO_2	1	-0.390	-0.167
ozone layer depletion (ODP)	kg CFC-11	1	-0.801	-0.513
human eco-toxicity	kg 1,4-DB	1	-9.737	-8.026
fresh water aquatic eco-toxicity	kg 1,4-DB	1	-9.280	-7.640
marine aquatic eco-toxicity	kg 1,4-DB	1	-12.006	-9.936
terrestrial eco-toxicity	kg 1,4-DB	1	-10.976	-9.024
photochemical oxidation	kg C_2H_2	1	-2.579	-2.006
acidification	kg SO_2	1	-5.663	-4.598
eutrophication	kg PO_{43-}	1	0.020	0.176

The value of this study lies in its wide-spread applicability across industry sectors. The SABMiller Newlands case study was approached generically to illustrate the methodology used in its assessment. This thesis can be used as a template whereby the methodology employed can be superimposed on any anaerobic treatment facility to assess and identify areas for burden reduction, and opportunity for energy reclamation.

The study showed the viability of energy generation from organic waste water treatment and the potential benefits thereof. On-site waste water treatment resulted in a favourable emissions profile in light of avoided power consumption attributed to effluent pumping. The investigated case study showed that with energy re-integration, a burden reducing process is developed, as power generation well exceeds power consumption of the effluent management system. Process engineers in all industries need to be conscious of this when designing water treatment facilities, and consciously access these opportunities; be it the potential for enhanced COD reduction or energy reclamation when implementing waste treatment alternatives.

The LCA proved to be an effective tool for quantifying and comparing process modifications across environmental impact categories, and a range of technologies is available for energy generation from biogas. Applications of this study extend to energy generation from landfill gas, rural farming settlements and the majority of organic waste generating industries.

Data limitations included accurate Athlone municipal treatment data. Pumping power consumption had to be estimated based on the Durban municipal reticulation system. Biogas flare compositions were assumed equivalent to SABMiller's Ibhayi Brewery. A secondary aim of this thesis was to assess the data gaps and their implications in LCA studies. Sensitivities analyses were performed highlighting the influence of pumping power consumption, and national electricity mixes. It was found that electricity mixes can contribute significantly to results, depending on the difference in fuel composition. Intermediate pumping requirements were also found to have significant impact, potentially changing conclusions across impact categories.

While every effort needs be made to ensure reliable input data, LCA studies will always invariably have data gaps and omissions. It is necessary to estimate the influence of assumptions made in light of limited data, and if possible quantify their potential implications as performed in Section 4.4.3. Sensitivity analysis enables the measurement of error which in turn, can be incorporated by LCA practitioners in decision-making.

8.2 Recommendations

As a direct result of the potential benefits incurred by energy re-integration (determined in Chapter 7), on-site waste water treatment should be supplemented by energy recovery and re-integration. It is recommended that a gas-engine of rated capacity be installed on site. The electricity generated can be used to supplement the power requirements of the SABMiller Newlands Brewery, and totally mitigate power requirements of the effluent facility. This would make the effluent plant self-sustainable.

The benefits of energy capture and re-integration can be extended to all SABMiller breweries across the country. Taking into account plant location, capacity and operating characteristics, the technology selection matrix can be applied prior to the tendering process taking place.

It is worthwhile investigating the energy generating potential of the municipal waste water treatment plant. Considering the volumes of waste treated in conjunction with the plant's electricity requirements and in light of power shortages in the Western Cape, the Athlone Municipal Treatment Facility has the opportunity to sustain its treatment operation from the biogas liberated from its anaerobic treatment works. Further, it could supplement the power requirements of the surrounding communities. At minimum, the biogas currently being released from the Athlone municipal treatment plant should be flared to mitigate the currently harmful environmental effects attributable to methane release.

The reclamation of flared biogas also lends itself to the opportunity for generating additional revenue in the trading of certified emission reduction certificates (CERs). In light of global carbon reduction initiatives, this opportunity would be worthwhile exploring as it presents the potential for the trading of carbon credits with a carbon credit affiliate present in an annex 1 country, thereby indirectly supplementing engine installation costs.

With additional on-site effluent treatment, there is the opportunity for direct disposal of treated waste water directly to river, by-passing municipal treatment completely. It is recommended to initiate further research into anaerobic digester retention times, temperature and microbial culture with the aim of further reductions in COD levels on site. The cost of municipal treatment could subsequently be avoided completely as could the significant environmental burden of pumping. This would enable the complete mitigation of effluent treatment costs and result in an entirely self-sustaining effluent treatment process in line with the concepts introduced in Chapter 2 concerning industrial ecology. An alternative to the discharge of treated water to the Liesbeeck river might also be its use as grey water on adjoining sports files – thereby replacing fresh water use.

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Appendix A:
Data pertaining to the SAB municipal treatment facility

	Units	July	August	September	October	November	December	January	February	March	April	May	June	July	August
Volume to AD per day	kl/day	3188.50	2306.00	3221.13	3038.18	3787.93	3781.86	3524.33	3715.95	2757.00	2785	2212	1825	2415	2847
Volume to flare	Nm3/day	3161.67	1560.81	3385.28	3228.61	2232.29	3688.71	4335.46	4412.27	4100.00	4275	3846	3669	4369	5535
COD treated	kg/day	8531.48	4211.71	8829.21	8712.12	6023.63	9953.67	12234	11906	11063	11536	10377	10171	11791	14935
Casutic Usage	kg/day	1532.14	920.00	2187.10	2763.33	2953.33	3289.66	2493	1844	1472	1725	1875	1352	1718	1984
VFA into methane reactor	mg/litre	535.40	441.13	467.59	426.71	483.84	414.59	409.32	448.65	351.00	346	656	605	454	650
VFA out methane reactor	mg/litre	0	0	0	0	0	0.00	0	0	0	0	0	0	0	0
Ph in equalisation tank		6.12	5.97	6.48	5.42	5.35	5.32	5.71	5.37	5.14	5.55	5.26	5.17	5.47	5.39
pH in feed stream to methane reactor		7.90	8.12	7.22	8.05	7.46	8.14	7.45	6.72	6.67	6.88	6.44	5.77	6.12	6.06
pH in stream from methane reactor to sewer		6.89	6.78	6.81	6.86	6.88	6.82	6.76	6.72	6.69	6.7	6.73	6.77	6.73	6.71
COD in equalisation tank	mg/litre	2369.32	2134.40	2368.91	3004.39	3214.61	3018.62	2450.55	2402.24	1702.75	2299	2668	2764	2561	2916
COD from methane reactor	mg/litre	218.54	277.97	449.22	853.61	843.74	669.00	349.38	240.76	213.00	282	358	271	310	507
SS in equilization tank	mg/litre	771.04	668.25	844.50	901.84	911.84	976.33	841.83	822.34	469.25	803	870	865	860	983
SS from methane reactor	mg/litre	135.29	152.53	330.89	761.89	822.25	688.50	391.86	181.50	190.00	185	237	132	238	474
SO4 analysis in equilization tank	mg/litre	no data	no data	no data	no data	no data	no data	841	822	610	803	870	865	860	983
SO4 to sewer	mg/litre	no data	no data	no data	no data	no data	no data	334.25	127.13	152	185	237	132	238	474
NH3 to swerer	mg/litre	34.488	30.267	33.575	14.800	32.800	40.640	32.525	31.225	21.740	18.065	45.200	53.033	-	-
PO4 to sewer	mg/litre	7.738	4.678	6.775	5.800	7.067	22.538	8.083	9.075	8.462	9.810	11.633	12.533	-	-

Appendix B:
Data pertaining to the municipal treatment facility

A. Treatment Data	Units	Readings	Average	Minimum	Maximum					
Raw Wastewater Flow	Ml/day	50	90.4	48	148.1					
		Raw Wastewater				Final Effluent				
B. Analytical Data		Readings	Average	Minimum	Maximum	Readings	Average	Minimum	Maximum	DWAF Effluent Guideline
Suspended Solids	mg/l	51	320	132	492	52	9	2	28	25
Volatile Suspended Solids	mg/l	18	250	102	375	0	0	0	0	
Dissolved Solids	mg/l	0	0	0	0	15	677	435	761	
Settable Solids	ml/l	51	13	4	35	0	0	0	0	
COD	mg/l	51	786	251	1084	52	80	51	125	130
COD (filtered)	mg/l	0	0	0	0	36	74	39	102	
TKN as N	mg/l	45	57.2	19.3	76.9	45	5.3	2.7	17.3	
Ammonia as N	mg/l	51	34.7	14.2	57.6	52	2	0.2	13	10
Nitrate plus Nitrite as N	mg/l	0	0	0	0	51	7	0.1	12.3	
Total Phosphorus as P	mg/l	46	8.7	3	13	44	1.1	0.2	8.7	
Orthophosphate as P	mg/l	51	4.8	0.9	8.2	52	0.9	0.1	8.5	
pH		51	7.3	6.3	8	52	7.2	6.7	7.6	5.5-9.5

Month	Municipal treatment works Electricity Consumption (kWh)
Feb-05	59872
Mar-05	66356
Apr-05	66083
May-05	67544
Jun-05	65997
Jul-05	67839

Appendix C:
Tabulation of inventory data pertaining to LCA presented in Chapter 4

No	Substance	Compartment	Unit	SAB treatment	SAB and Municipal Treatment	No Treatment	Municipal treatment
1	Coal, 18 MJ per kg, in ground	Raw	kg	0.114	0.159	0.0366	0.0604
2	Coal, brown, 8 MJ per kg, in ground	Raw	g	17	17.5	0.357	0.59
3	Energy, potential, stock, in barrage water	Raw	kJ	122	147	20.3	33.5
4	Gas, natural, 35 MJ per m3, in ground	Raw	l	1.06	1.6	0.43	0.709
5	Gas, natural, 36.6 MJ per m3, in ground	Raw	l	12.1	12.1	x	x
6	Iron ore, in ground	Raw	mg	46.4	46.4	x	x
7	Limestone, in ground	Raw	g	1.06	1.06	x	x
8	Oil, crude, 42.6 MJ per kg, in ground	Raw	g	9.02	9.65	0.507	0.837
9	Sand and clay, unspecified, in ground	Raw	mg	20.2	20.2	x	x
10	Sodium chloride, in ground	Raw	g	59.5	59.5	x	x
11	Uranium, 451 GJ per kg, in ground	Raw	mg	1.56	1.69	0.102	0.168
12	Water, process and cooling, unspecified natural origin	Raw	cm3	534	534	x	x
13	Wood, unspecified, standing/kg	Raw	g	0.878	1.32	0.354	0.585
14	Ammonia	Air	mg	0.864	1.3	0.349	0.576
15	Benzene	Air	µg	140	150	7.88	13
16	Cadmium	Air	µg	1.9	2.24	0.278	0.46
17	Carbon dioxide	Air	kg	1.26	1.37	1.96	0.588
18	Carbon monoxide	Air	mg	89.1	98.3	7.47	12.3
19	Dinitrogen monoxide	Air	mg	1.45	1.9	0.362	0.598
20	Hydrocarbons, aromatic	Air	mg	2.5	3.46	0.77	1.27
21	Hydrocarbons, chlorinated	Air	ng	6.56	9.85	2.65	4.38
22	Hydrocarbons, halogenated	Air	ng	40.3	40.3	x	x
23	Hydrogen	Air	mg	203	241	x	425
24	Hydrogen chloride	Air	mg	59.4	81.7	17.9	29.6
25	Hydrogen fluoride	Air	mg	4.71	7.08	1.9	3.14
26	Hydrogen sulfide	Air	g	6.86	7.49	x	7.18
27	Lead	Air	µg	38.1	51.7	10.9	18

28	Manganese	Air	µg	21.3	29.6	6.62	10.9
29	Mercury	Air	µg	7.71	10.6	2.3	3.79
30	Metals, unspecified	Air	mg	11.8	17.6	4.71	7.78
31	Methane	Air	g	8.73	28.4	0.254	219
32	Methane, bromotrifluoro-, Halon 1301	Air	µg	2.11	2.26	0.121	0.2
33	Nickel	Air	mg	0.144	0.179	0.0277	0.0457
34	Nitrogen oxides	Air	g	1.26	1.53	0.215	0.356
35	NMVOC, non-methane volatile organic compounds, unspecified origin	Air	mg	428	436	5.99	9.9
36	PAH, polycyclic aromatic hydrocarbons	Air	µg	3.74	4.76	0.819	1.35
37	Particulates	Air	g	0.568	0.696	0.103	0.171
38	Radioactive species, unspecified	Air	kBq	133	144	8.84	14.6
39	Sulfur oxides	Air	g	2.18	2.76	0.472	0.779
40	water	Air	kg	0.584	0.594	1.17	0.119
41	Zinc	Air	µg	71.9	97.9	20.9	34.5
42	Aluminum	Water	g	0.176	0.249	0.0582	0.0961
43	Ammonium, ion	Water	mg	1.08	1.2	0.096	0.159
44	AOX, Adsorbable Organic Halogen as Cl	Water	µg	1.64	1.75	0.0909	0.15
45	Arsenic, ion	Water	mg	0.356	0.502	0.118	0.194
46	Barium	Water	mg	15.2	21.1	4.72	7.79
47	BOD5, Biological Oxygen Demand	Water	µg	323	333	8.36	13.8
48	Cadmium, ion	Water	µg	9.62	13.4	3.03	5.01
49	Chloride	Water	g	3.85	4.32	0.376	0.621
50	Chromium	Water	mg	1.77	2.49	0.583	0.963
51	COD, Chemical Oxygen Demand	Water	kg	0.0885	0.00901	1	0.102
52	Copper, ion	Water	mg	0.884	1.25	0.292	0.482
53	Cyanide	Water	µg	3.15	3.61	0.375	0.619
54	DOC, Dissolved Organic Carbon	Water	µg	185	186	1.35	2.23
55	Hydrocarbons, aromatic	Water	µg	397	423	21.7	35.9
56	Hydrocarbons, chlorinated	Water	ng	597	634	29.5	48.7
57	Hydroxide	Water	g	42.8	42.8	x	x
58	Iron	Water	mg	78.1	101	18.1	29.9

59	Kjeldahl-N	Water	µg	100	105		4.22		6.97
60	Lead	Water	mg	0.909	1.27		0.294		0.485
61	Mercury	Water	µg	0.28	0.383		0.083		0.137
62	Metallic ions, unspecified	Water	mg	22.1	29.7		6.09		10.1
63	Nickel, ion	Water	mg	0.89	1.25		0.294		0.486
64	Nitrate	Water	g	9.4	0.547		215		12.4
65	Nitrogen, total	Water	µg	675	716		32.5		53.7
66	Oils, unspecified	Water	mg	11.8	12.6		0.676		1.12
67	PAH, polycyclic aromatic hydrocarbons	Water	µg	5.76	6.17		0.331		0.546
68	Phenols, unspecified	Water	µg	64.2	69.2		3.96		6.54
69	Phosphate	Water	mg	10.6	14.9		3.49		5.76
70	Phosphorus	Water	g	2.77	0.351		24.4		3.09
71	Radioactive species, unspecified	Water	Bq	1.21E+03	1.31E+03		81.2		134
72	Sodium, ion	Water	g	58.4	58.4	x		x	
73	Solved substances, inorganic	Water	g	0.535	0.787		0.203		0.335
74	Sulfate	Water	g	66.7	24.6		191		67.9
75	Sulfide	Water	µg	14.2	15.2		0.842		1.39
76	Suspended solids, unspecified	Water	g	65.6	1.85		190		5.35
77	Suspended substances, unspecified	Water	mg	127	130		2.38		3.93
78	TOC, Total Organic Carbon	Water	mg	16.9	17.3		0.303		0.5
79	Toluene	Water	µg	54.8	58.6		3.02		4.98
80	Zinc, ion	Water	mg	1.77	2.5		0.586		0.968
81	Mineral waste, from mining	Waste	g	5.54	5.54	x		x	
82	Waste in bioactive landfill	Waste	g	1.92	1.92	x		x	
83	Waste in incineration	Waste	mg	30.2	30.2	x		x	