LIFE CYCLE ASSESSMENT OF MUNICIPAL SOLID WASTE MANAGEMENT IN NEWCASTLE LOCAL MUNICIPALITY

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PREFACE

As the candidate's supervisor, I, Cristina Trois, agree/do not agree to the submission of this thesis.

__________________________Signed at___________________on__________________

Cristina Trois Place Date

DECLARATION - PLAGIARISM

I, …………………………………………….……………………., declare that

The research reported in this dissrtation, except where otherwise indicated, is my original research.

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Yasthil Maharaj

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ABSTRACT

The aim of this study is to improve decision support for municipal solid waste (MSW) management in South Africa through a consequential life cycle approach. To this end, an embedded case design framework is utilised to perform a single-case study on MSW in Newcastle Local Municipality (NLM), KwaZulu-Natal, South Africa. The case study focuses on the environmental impacts of MSW management in NLM, in turn; modelling five integrated waste management scenarios. The first scenario is the baseline in NLM, while the other four were constructed using the following technologies: landfilling, materials recovery facilities (MRF), composting, anaerobic digestion (AD), waste-to-energy (WtE) and waste reprocessing plants for plastic bottles, glass, aluminium, paper, other plastic and metal. The methodology adopted is life cycle assessment (LCA) standards in accordance with ISO 14040:2006 and ISO 14044:2006. The LCA was conducted using EASETECH as the modelling programme. The study found the baseline to have the highest environmental impact and the scenario containing thermal treatment to have the lowest environmental impact. An integrated waste management scenario utilising an AD plant to treat garden and food waste, an MRF to further sort recyclable waste for reprocessing and a landfill with a flare for residual waste, yielded a similar impact to the WtE scenario. Based on the results of the NLM case study, it is proposed that EASETECH is a reliable LCA modelling tool to evaluate the environmental impact of MSW management systems in South Africa. However, due the fact that this is a single-case study this assertion should be tested through further application of this waste LCA methodology for decision support in the context of other South African municipalities. In summary, this study illustrates the opportunity to explore the use of state-of-the-art knowledge, i.e., waste LCA (e.g., EASETECH) in order to compare alternative waste management systems and strengthen decision support mechanisms for MSW in the context of an emerging economy like South Africa.

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LIST OF ABBREVIATIONS

- AD – Anaerobic Digestion
- AoP – Area of Protection
- CDM – Clean Development Mechanism
- DAR – Depletion of Abiotic Resources
- DARF – Depletion of Abiotic Resources, Fossil
- DAT – Dome Aeration Technology
- DEA – Department of Environmental Affairs
- DME – Department of Minerals and Energy
- DST – Department of Science and Technology
- DTU – Technical University of Denmark
- EASETECH – Environmental Assessment System for Environmental TECHnologies
- EIA – Environmental Impact Assessment
- EP – Eutrophication Potential
- ET - Ecotoxicity
- FE – Freshwater Eutrophication
- GHG – Greenhouse Gas
- GWP – Global Warming Potential
- HTC – Human Toxicity, Carcinogenic
- HTNC – Human Toxicity, Non-carcinogenic
- ILCD – International Reference Life Cycle Data System
- IVC – In Vessel Composter
- IWMP – Integrated Waste Management Plan
- IWMS – Integrated Waste Management System
- LCA – Life Cycle Assessment
- LCI – Life Cycle Inventory
- LCIA – Life Cycle Impact Assessment
- LFG – Landfill gas
- LFGE – Landfill gas to energy
- MCDA – Multi-Criteria Decision Analysis
- MRF – Materials Recovery Facility
- MSW – Municipal solid waste
- NLM – Newcastle Local Municipality
- NMVOC – Non-methane Volatile Organic Compounds
- OFMSW – Organic fraction of municipal solid waste
- PAG – Plasma Arc Gasification
- PM – Particulate Matter
- POF – Photochemical Oxidant Formation
- RDF – Refuse Derived Fuel
- RE – Renewable Energy
- RSL – Regional Sanitary Landfill
- SATSA – System Approach to Technology Sustainability Assessment
- SETAC – Society for Environmental Toxicology and Chemistry
- STA – Sustainable Technology Assessment
- SOD – Stratospheric Ozone Depletion
- TA – Terrestrial Acidification
- WtE – Waste-to-Energy

1: INTRODUCTION

1.1 Rationale for the study

1.1.1 Problem Statement

The disposal of waste in landfills and subsequent decomposition of organic waste results in significant greenhouse gas (GHG) emissions (Bogner et al., 2008). In 2010, it was estimated that landfills accounted for the third largest anthropogenic source of methane or 11% of global methane emissions, which represents nearly 799 million metric tonnes of CO_2-equivalents (GMI, 2011). According to Bredenhann cited in Lemmer (2012), landfilling is the chosen method of waste management for 90% of the waste produced in South Africa. Bredenhann postulates that only 5% of waste should be landfilled, with the rest being recycled or treated by a waste treatment technology (Lemmer, 2012). The South African waste sector contributes approximately 4.3% to GHG emissions and the government has expressed the need to reduce organic waste disposal to landfills (Nahman et al., 2012). The country's waste management sector is characterised by a lack of recycling (waste separation at source), coupled with inefficient municipal solid waste (MSW) management practices and often a lack of political will (Couth and Trois, 2010). For an effective and sustainable integrated waste management system (IWMS) to be implemented, stakeholders need specific metrics to support decision-making and policy-making.

1.1.2 Background

Waste management is a key component of sustainable development[1]. In the context of a middle-income, developing country like South Africa MSW management is an escalating challenge. Zero waste[2] is a concept that major South African municipalities are starting to engage with at an urban policy and planning level. The Polokwane Declaration[3] aims to develop a zero waste plan by 2022, which will deliver an efficient and sustainable waste management system for South Africa (DEAT, 2001).

The National Waste Management Strategy outlines the waste hierarchy, which dictates that waste avoidance and reduction should be the first priority before recovery and re-use, treatment and disposal, respectively (DEA, 2010). A representation of this hierarchy is

[1] For the purposes of this dissertation, sustainable development is the ability to ensure that humanity meets the needs of the present without compromising the ability of future generations to meet their needs as defined by the Brundtland Report (UN, 1987).

[2] Zero Waste is a concept that refers to the maximisation of recycling, the minimisation of waste and reduced consumption. It endeavours to ensure all products are made for reuse, repair or recycling back into the market place or nature (Trois and Matete, 2007).

[3] The Polokwane Declaration was adopted at the first National Waste Management Summit in 2001. It outlines the visions and goals of waste management systems towards sustainable development.

presented in Chapter 2. The waste hierarchy promotes a “cradle to cradle” approach, which prioritises the recovery of all waste streams including all recyclables. Waste is viewed as a resource that can be utilised as inputs for other products (DEA, 2010). This is achievable through a household source separation programme, which will prevent wet, biogenic waste from contaminating dry, recyclable waste such as paper, plastic and metals.

Organic solid waste and the associated environmental hazards are often inefficiently managed in South African municipalities (Trois and Jagath, 2011); hence the need to assess the appropriateness and feasibility of deploying available appropriate waste management technologies in these municipalities. South Africa needs a solution that is cost-effective, socially acceptable and environmentally friendly. Moreover, this solution has to be implementable at local government level. Policy frameworks should be strengthened to support the move towards more sustainable waste treatment and zero waste.

Life Cycle Assessment (LCA) provides decision makers with a useful framework to compare different technologies and strategies for integrated waste management (Clift et al., 2000). LCA has been recognised as an instrument for researchers to quantify the full life cycle of MSW management systems (Zhao et al., 2009). An environmental LCA analyses the whole product system. It follows a specific product from creation to disposal, quantifying the impacts it has on the environment (Baumann and Tillman, 2004). For this study, LCA methodology as laid out in ISO 14040:2006 and ISO 14044:2006 will be followed. LCA studies consist of four phases. These are the goal and scope definition, the life cycle inventory (LCI), the life cycle impact assessment (LCIA) and interpretation. The EASETECH[4] modelling programme that was, developed as a tool for waste LCAs was used to assess the environmental impact of integrated waste management scenarios.

This dissertation focuses on Newcastle Local Municipality (NLM) as a case study. Newcastle has a population of 363 236 over an area of $1854km^2$. The Department of Environmental Affairs (DEA) has ranked it second as the greenest local municipality for the years 2012 and 2013 (DEA, 2012b, SAnews, 2013). NLM has rolled out a successful source separation programme, which makes it an ideal candidate for investigation. Furthermore, NLM has a privately owned plastic bottle recycling facility to which all waste plastic bottles in the municipality are routed. A waste life cycle assessment (LCA) was carried out on integrated waste management scenarios for NLM. The environmental impacts of each scenario were evaluated to allow for comparison and to identify the scenario with the lowest environmental impact.

[4] EASETECH was developed at the Technical University of Denmark and is discussed further in Chapter 3.

This waste LCA assesses five scenarios for integrated waste management. The first is the baseline scenario, which is the current MSW management system in NLM. The other four scenarios are built using a range of waste treatment technologies. These scenarios are developed in accordance with the waste hierarchy in an effort to promote sustainable development, i.e., each subsequent scenario improves the recovery and recycling of waste. The final scenario considers an IWMS for Newcastle in which the majority of the MSW stream is directed towards a waste-to-energy (WtE) plant.

The waste treatment technologies used to construct the scenarios include technologies for mechanical sorting, biological treatment and thermal treatment of MSW. The scenarios focus on increasing the level of source separation in the municipality. This requires a materials recovery facility (MRF), which sorts the recyclable waste for reprocessing. Biological treatments such as open windrow composting and anaerobic digestion (AD) are considered for treating garden and food waste. The thermal treatment considered in the final scenario is incineration or WtE. The scenarios all include landfilling for some substances and waste fractions.

LCA is among the most common tools used to assess environmental impacts. It expands the study's perspective to encompass more than waste management. This allows the impacts on surrounding systems to be accounted for, as they often have a larger effect than emissions from waste management (Ekvall et al., 2007). Environmental benefits from the following waste management processes can be accounted for: substituting virgin material production with recycled goods, energy recovery from a WtE plant reducing the dependence on energy sources like coal, and biological treatments substituting the production of artificial fertilisers (Ekvall et al., 2007).

MSW is, largely, not source-separated in South Africa (Trois et al., 2007). Trials are currently being run, in eThekwini Municipality, on implementing a two-bag system for source separation of MSW. This system separates paper from other waste. Unfortunately, this has not been formalised in any significant manner (DEAT, 2005). This makes it difficult for material and energy recovery. Waste is generated in households, collected by the municipality and taken to landfills. Some waste is first directed to recycling centres that separate it and remove some of the recyclables. This method leaves the organic and non-recyclable, non-organic fractions of MSW behind for treatment. Mixed waste reduces the energy that could be recovered from the organic fraction of municipal solid waste (OFMSW); it also reduces the potential for nutrient recovery.

MSW is composed of an organic and inorganic fraction. It consists mainly of household and commercial waste to be disposed of by the local authority (FFF, 2008-2010). The carbon content in MSW can be broadly separated into two groups: biogenic carbons and fossil carbons. Fossil carbons are found in products such as synthetic fabrics and plastic and are mainly non-degradable. Biogenic carbons are degradable carbons from food waste and paper (Couth and Trois, 2010). To increase the efficiency of the treatment of MSW, a highly effective separation and recycling system has to be in place. This will create a rich feedstock, of recyclables and organics, for alternative treatments to landfill.

As noted earlier, landfills are amongst the largest producers of GHGs and they will continue to produce large amounts of GHGs for decades (Harley, 2010). Research has shown that across Africa, the average organic content in MSW is 56% and the degradation of these organics, which produces methane, is a major contributor to GHG emissions (Couth and Trois, 2010). Landfills release methane gas into the atmosphere, which has a global warming potential of more than 20 times that of carbon dioxide (EPA, 2011).

Large municipalities, such as Johannesburg, with limited land space cannot sustain the current practice of landfilling MSW. The decomposition of organic waste leads to the release of GHGs, CO_2 and CH_4, as well as the production of soil and water polluting leachate in landfills (Lou and Nair, 2009). The urban population is growing and material flows are increasing. It is expected that about 68% of South Africa’s population will be living in urban environments by 2015 (Friedrich and Trois, 2010). This will have a significant impact on MSW management. Inefficiencies in the current MSW management system necessitate the development and understanding of alternative treatment systems.

The aforementioned waste treatment technologies were studied in greater depth to understand their impact and how they can be applied in South African municipalities to improve the MSW management system. Integrated waste management systems were assessed from a life cycle perspective to find the scenario with the lowest environmental impact for NLM. This study aimed to construct an approach that is premised on best practice, utilising state-of-the-art knowledge. It was motivated by the need to support local authorities in the effective planning and implementation of sustainable waste treatment projects, such as a WtE plant, in support of the Zero Waste plan for 2022 (Trois and Matete, 2007). Furthermore, the EASETECH modelling programme is assessed as a tool for conducting a waste LCA in South African municipalities to provide decision support to relevant stakeholders.

1.2 Research Questions

- What are the environmental impacts of five different waste management scenarios for NLM?
- Which MSW management scenario has the least environmental impact?
- Is EASETECH an appropriate LCA tool for modelling municipal waste management in South Africa?

1.3 Aim and Objectives

1.3.1 Aim

To provide decision support for MSW management in NLM

1.3.2 Objectives

- Evaluate the environmental impacts of the MSW management baseline in NLM
- Identify, explore and build potential scenarios for waste management in NLM in accordance with the waste hierarchy
- Critically evaluate the environmental impacts of each scenario through a waste life cycle assessment
- Analyse and estimate the accuracy and reliability of results through a sensitivity analysis
- Assess EASETECH as a LCA tool for modelling MSW management in South Africa.

1.4 Conceptual Approach to Research

This study is organised into six chapters: Introduction, Literature Review, Methodology, Case Study, LCA, and Discussion and Conclusion. Figure 1-2 details the conceptual approach used to structure the research. This introductory chapter presented the problem addressed in this study, the rationale for the research and the background used to develop the research design and case study. The literature review contextualises the study and provides detailed background on MSW management in South Africa, waste treatment technologies, decision support tools and the LCA methodology. Chapter three developed in conjunction with the literature, details the integrated method development, data collection and analysis, as well as how the LCA was streamlined and the EASETECH modelling programme.

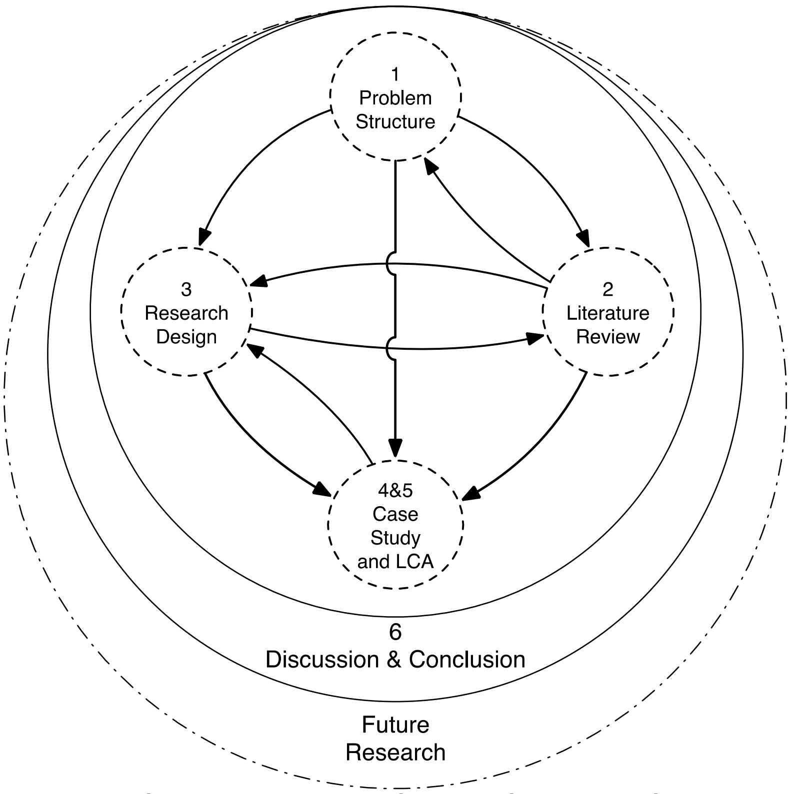

Figure 1 - 1: Conceptual Approach to Research

The fourth and fifth chapters are built from the knowledge gained in the first three chapters. They cover the case study and the LCA of MSW management in NLM. The case study provides important contextual information and the LCA details the assessment of the environmental impacts of the MSW management scenarios for NLM. Finally, the discussion and conclusion analyse the results and assess EASETECH as a tool for conducting waste LCA in South African municipalities. The final chapter summarises the study and offers recommendations for future research. The appendix details a portion of the LCI output from the EASETECH model for the baseline scenario.

2: LITERATURE REVIEW

This chapter provides a contextual understanding of MSW management in South Africa. It explores the concept of sustainable development and highlights energy issues in the country. The development of policies to control MSW and its management in South Africa are also considered. A range of waste treatment technologies are reviewed, some of which form part of the configurations for the scenario analysis of waste management in NLM. Finally, this chapter reviews a variety of decision support tools and approaches that could assist stakeholders in technology selection with a focus on LCA methodology.

2.1 Municipal Solid Waste Management in South Africa

MSW management in South Africa currently faces many challenges. Local government is responsible for MSW management. The most common obstacles that effective MSW management in South Africa encounters are equipment and financial management, labour management and poor planning at institutional level (CSIR, 2011).

The average South African produces 0,7kg of waste a day, with 42 million cubes of general waste produced per year (DEA, 2006). In 2012 the Department of Environmental Affairs (DEA) produced the National Waste Information Baseline. This aims to accurately and reliably track waste in South Africa including tonnages of waste recycled, landfilled, treated and exported (DEA, 2012a). South Africa landfills approximately 98 million tonnes from a total 108 million tonnes of waste per annum (DEA, 2012a). It is estimated that 10% of the total waste generated in South Africa is recycled (DEA, 2012a).

While landfilling may be the cheaper option in waste management it has many disadvantages. These include the cost and use of the land, and environmental hazards in the form of leachate and emissions to air, water and soil. Barton et al.'s (2008) study revealed GHG emissions in developing countries for a few general scenarios. The results were as follows: sanitary landfills with no LFG capture resulted in 1.2 tonnes of CO_2 equivalents per tonne of waste; open dumpsites released 0.74 tonnes of CO_2 equivalents per tonne of waste; sanitary landfills with gas collection and flaring released 0.19 tonnes of CO_2 equivalents per tonne of waste and sanitary landfills with landfill gas (LFG) capture and electricity generation produced 0.09 tonnes of CO_2 equivalents per tonne of waste (Barton et al., 2008).

Alternative waste treatment technologies can provide communities with an effective and sustainable IWMS that can reduce GHG emissions and possibly provide electricity that is not derived from fossil fuels. Certain technologies also allow for nutrient recovery from the organic fraction of municipal solid waste (OFMSW) for use as low-grade fertilisers and soil conditioners. Couth and Trois' (2012b) review of waste management practices in Africa identified the following three steps in sustainable waste management in urban communities in developing countries:

1. The removal of dry recyclable materials through a dirty materials recovery facility (MRF), door-to-door collection or waste picking on a landfill.
2. Extract the organic waste and compost it, recovering matured compost for sale.
3. Send inert and fossil carbon waste to a sanitary landfill. With the removal of the OFMSW, methane extraction should not be necessary as most waste will be non-degradable.

(Couth and Trois, 2012b)

The Council for Scientific and Industrial Research's (CSIR) study on good practices of waste management in South Africa notes that, good practice "arises from those people who have an intimate understanding of the problems, who work with the challenges daily, and through often simple approaches find successful, innovative and sustainable solutions" (CSIR, 2011). Seven aspects of MSW management are common in South African municipalities. These are waste collection and transport, waste storage, reducing, re-using and recycling waste and landfilling waste.

Figure 2-1 illustrates a typical waste flow diagram for South African municipalities. It details the MSW management practices followed by a large municipality, such as eThekwini. The dark grey arrow follows the route that mixed waste takes, while the black arrow shows the waste route that general (non-recyclable) waste takes if the system in place allows for it. Finally the green arrows show the ideal practices that should be in place in a developing country (CSIR, 2011).

Waste is generated in households, who store it between collection days. On a specific day of the week, the waste is collected and transported to a transfer station where it is moved to a different vehicle for transport to a materials recovery facility (MRF) and finally the landfill. In the green cycles, the collected waste is taken to buy-back and drop-off centres for recycling and re-use. Thereafter, a far reduced volume of waste is sent to landfill.

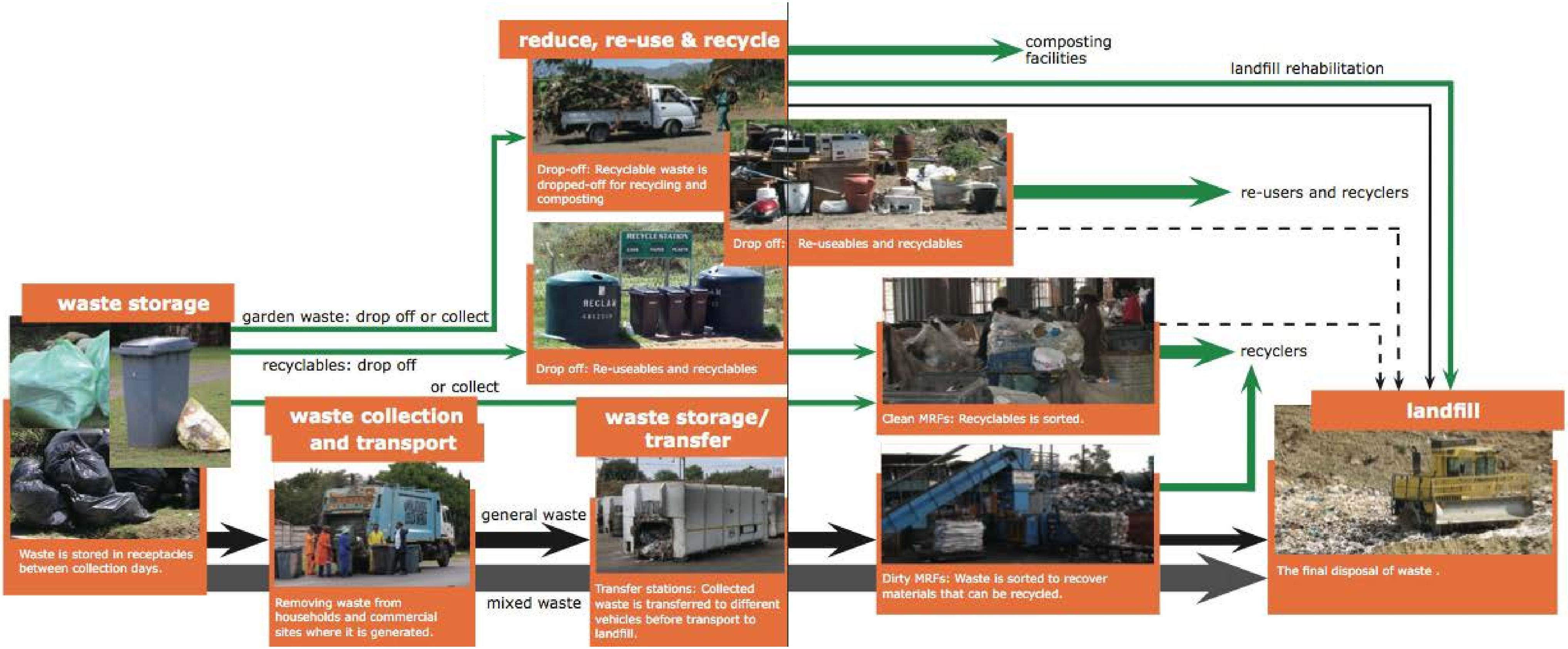

Figure 2 - 1: Waste Flow Diagram (CSIR, 2011)

Waste collection should preferably take place once a week. This serves to separate generated waste from the public for health purposes. The level of service can vary from kerbside collection to collection from central communal points and on-site regular, appropriate and supervised disposal, which is mainly reserved for remote rural areas (CSIR, 2011). Transport is an expensive part of the waste management service. It is therefore important to evaluate the cost efficiency of a range of transport methods. Transport types in a South African context can include a combination of many vehicles including wheelbarrows, bicycles, hand-drawn carts, bakkies, compactor vehicles and railway trucks (CSIR, 2011).

Waste storage occurs at different points in the waste management system. It is first stored in receptacles at the point of generation between collection days. The receptacles at generation points should allow for separation at source. Recyclables are stored at collection points for clean materials recovery facilities (MRFs), drop-off or buy-back centres. Waste is also stored at intermediate facilities in the waste management system before finally being disposed of, treated or recycled (CSIR, 2011). Different types of receptacles can be used to store waste, including bins with plastic bin liners, metal bins for hot ash, monkey proof bins and wheelie bins (CSIR, 2011).

South Africa has implemented the Waste Hierarchy[5], which requires reduction, re-use and recycling of waste before treatment or disposal. A source separation programme is essential for the success of a reduction, re-use and recycling campaign. Incentives and high levels of awareness are required to change consumer behaviour in South Africa, which calls for education. Separation at source will provide higher quality recyclables and a cleaner working environment in MRFs and for the recycling industry (CSIR, 2011). One challenge confronting such a programme is that recyclables and residual waste have to be collected separately, which could impose a strain on the collection and transportation system for MSW.

The final stage in most South African waste management systems is landfilling. There are a few basic requirements for safely disposing of waste on landfills. Access control and signage are required to keep people and animals out of the landfill site and allow for monitoring of the vehicles that enter the site. Waste vehicles should be weighed over a weighbridge and the types and volumes of waste being landfilled should be recorded. Landfills should also cover and compact the waste daily to use the space more efficiently and prevent the wind from spreading it. Furthermore, fires are a likely hazard due to the landfill gas present at the site. These should be avoided as much as possible (CSIR, 2011).

[5] The Waste Hierarchy is discussed further in Section 2.2.

2.2 Waste Management Policy in South Africa

Waste management policy and practice in South Africa has improved in recent years. Prior to the Waste Act of 2008 waste management was governed by different legislation that was administered by different governmental departments (DEA, 2009). This fragmentation led to poor waste management practices (DEA, 2009). Figure 2-2 shows the implementation and development of different waste policies between 1989 and 2009. The Waste Act (2008) focused and reorganised the country's waste management goals, which are explained in the waste hierarchy.

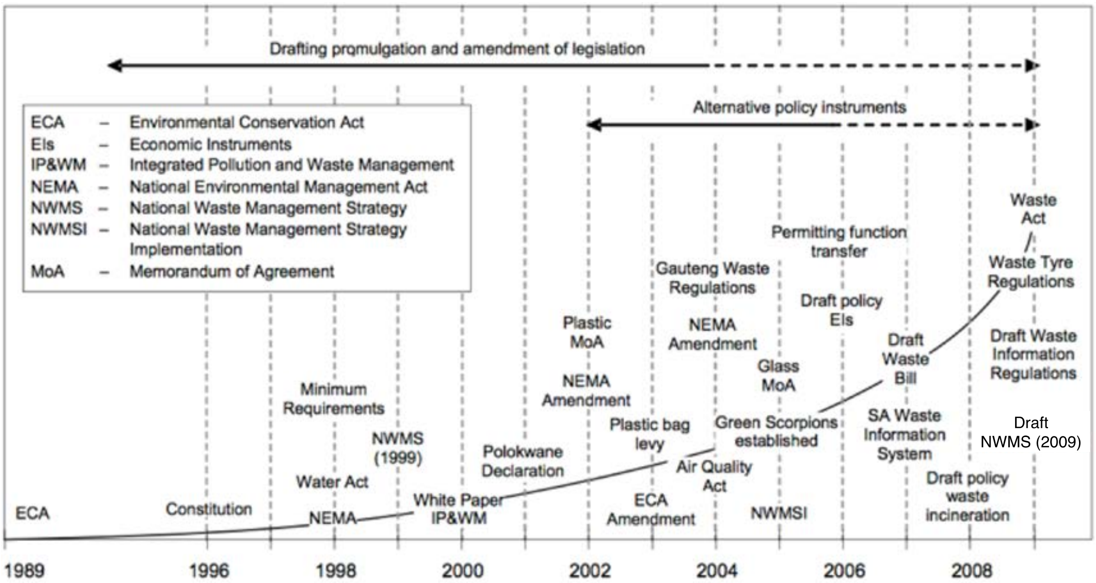

Figure 2 - 2: The History of Pollution and Waste Policy Interventions in South Africa (adapted from Godfrey and Nahman, 2008, cited in (Font Vivanco et al., 2012))

The Draft National Waste Management Strategy outlines the hierarchy of waste management in South Africa. This hierarchy is illustrated in Figure 2-3.

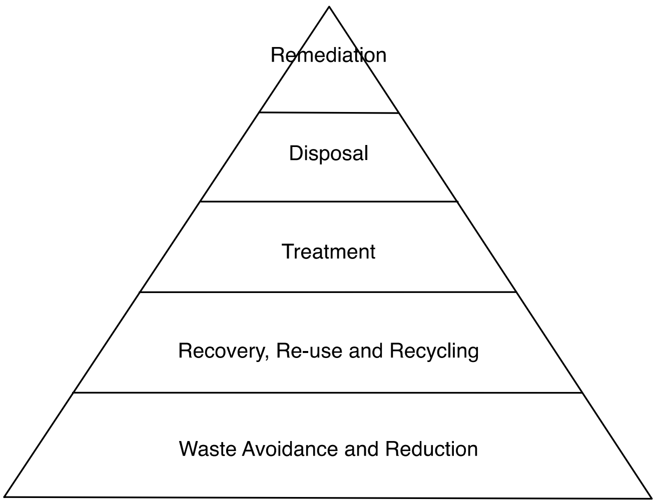

Figure 2 - 3: Waste Hierarchy (DEA, 2010)

This hierarchy details the order of priority of waste management. Every effort must be made to first avoid the generation of waste. If waste creation cannot be avoided, appropriate fractions must be recovered, recycled or reused. At the third tier is treatment of waste, which can include biological or thermal technologies like composting, anaerobic digestion or incineration. The final two stages are disposal of waste, such as to landfill, and the remediation of waste.

The Waste Act of 2008 as defines the "treatment" of waste:

> *'any method, technique or process that is designed to—*
>
> *(a) change the physical, biological or chemical character or composition of a waste; or*
>
> *(b) remove, separate, concentrate or recover a hazardous or toxic component of a waste; or*
>
> *(c) destroy or reduce the toxicity of a waste,*
>
> *in order to minimise the impact of the waste on the environment prior to further use or disposal'*
>
> *(DEA, 2008)*

In line with the zero waste development plan of 2022, IWMS should play a pivotal role in achieving this goal. Treating MSW with the appropriate combination of technologies would neutralise environmentally harmful waste and make it useful. Furthermore, improved management of MSW would fulfil the requirements of section 24 of the Bill of Rights of the Constitution of the Republic of South Africa, which states that:

"Everyone has the right -

a. to an environment that is not harmful to their health or well-being; and
b. to have the environment protected, for the benefit of present and future generations, through reasonable legislative and other measures that -
    i. prevent pollution and ecological degradation;
    ii. promote conservation; and
    iii. secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development." (Constitution, 1996)

Many of the current MSW management systems in South Africa utilise landfilling as the primary form of waste disposal. Landfilling is harmful to the environment, causes pollution and does not conserve the land. In order to bring the MSW management in line with the constitution, one step would be to institute IWMSs that follow the waste hierarchy and more sustainable practices. This would be achieved by incorporating a range of waste treatment technologies into municipalities' integrated waste management plan (IWMP). IWMPs aim to optimize waste management by improving efficiency and minimizing negative effects such as environmental impacts and costs (DEA, 2009).

Forty percent of South Africa's population currently receives inadequate or no household waste services (DEA, 2010). The lack of services can be partly addressed by implementing decentralized systems that utilise low technology options, each servicing smaller areas, thereby reducing the cost of transporting waste.

Waste treatment technologies such as anaerobic digestion and incineration or Waste-to-Energy (WtE) could use waste to produce renewable electric energy. The Department of Minerals and Energy's (DME) White Paper on Renewable Energy set the goal of achieving 10 000GWh of electricity from renewable energy (RE) by 2013, which is approximately 4% of electricity demand in SA (DME, 2003). Total electricity demand in 2013 is estimated to have been 41 539 MW of which the RE target is 1667 MW (Mashoko et al., 2013). This was to be achieved through the use of biomass, solar, small-scale hydro and wind power. The White Paper on RE notes that WtE is more flexible than landfill gas technologies (LFG) and has lower operating costs; however it has a higher capital cost (DME, 2003).

2.3 Sustainable Development and Energy in South Africa

The concept of sustainable development states, that one should be able to meet the needs of the current citizens of the world, without inhibiting future generations from meeting their needs (UN, 1987). Therefore, while people may use available resources, they should never deplete a natural resource (SAEP, 2003).

Energy is a critical consideration of sustainable development. For sustainable development to succeed, there is a need for clean, renewable energy resources that are affordable, have minimal impact on society and are environmentally compatible (Kothari et al., 2010). Four energy paths are generally, considered to achieve sustainability. These paths utilise current and alternative energy routes.

Kothari et al. (2010) identify the paths as: the continuation of current energy use tools with modifications; the global adoption of alternative energy technologies for electricity generation and transportation; supplementing current energy resources with alternative, renewable energy sources such as biomass and WtE technologies; and developing clean energy sources for distribution systems and production routes (Kothari et al., 2010). This study focuses on the third path of renewable energy from biomass sources and WtE technologies.

Different countries around the world have used different technologies to convert MSW and biogenic waste to energy. First world countries, such as Germany, provide us with best practice models for certain technologies. These include Incineration, Gasification and Anaerobic Digestion.

The Waste-to-Energy Research and Technology Council estimates that there are more than 700 WtE plants in more than 37 countries worldwide (WTERT, 2010). These countries' sustainable waste management strategies have adopted similar approaches to treat waste, including maximising recycling, composting, and minimising the amount of waste that is routed to landfill. An effective and sustainable recycling programme is the key to the successful implementation of waste treatment technologies. Such programmes require communities to be educated to separate at source and to be aware of the environmental and economic benefits of the recycling initiative.

2.3.1 Energy in South Africa

Renewable energy plays a pivotal role in sustainable development (Krupa and Burch, 2011). At the beginning of 2008, South Africa faced a major electricity crisis. Rolling blackouts spread throughout the country, leaving private homes, industries, businesses and commercial establishments without power for hours (Krupa and Burch, 2011). Insufficient planning for the maximum power demand, as well as strong economic growth and the mass electrification of many homes and businesses were key reasons for the electricity crisis (Krupa and Burch, 2011). Rolling blackouts occurred again in March 2014 due to wet coal reducing electricity production (Khuzwayo, 2014).

The National Energy Regulator Act of 2004 established the National Energy Regulator of South Africa (NERSA). NERSA is a regulatory authority that manages and regulates three industries in South Africa, which are each dominated by a single organisation, namely electricity generation (dominated by Eskom), the petroleum industry (Petronet), and the gas industry (Sasol) (DOE, 2012).

Three institutions are responsible for the generation of electricity in South Africa. Eskom produces 96% of total electricity, while private generators and municipal authorities produce 3.2% and 0.8%, respectively (Amusa et al., 2009). The energy sources used for electricity production are shown in Figure 2-4.

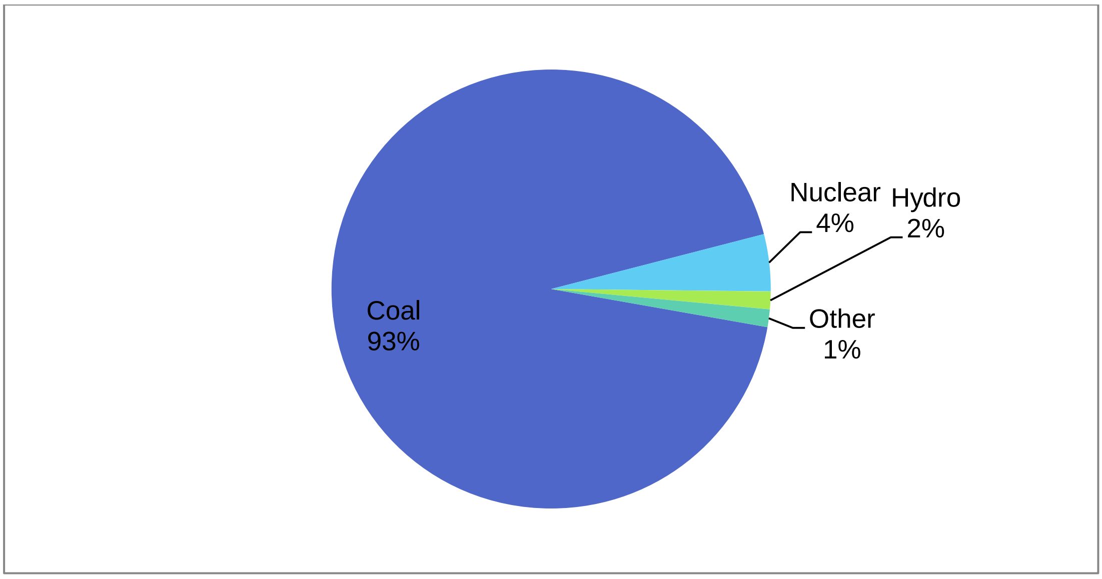

Figure 2 - 4: Energy Sources for Electricity Production (NERSA, 2006)

Figure 2-4, above, shows that coal is the primary source of energy for electricity production in South Africa. This is due to the fact that coal is relatively cheap and is available in more abundant quantities in South Africa than international markets (SSA, 2009). However, electricity production is a significant contributor to GHG emissions. More than 60% of the total GHG emissions in South Africa stem from the electricity generation sector (Inglesi-Lotz and Blignaut, 2011). Christoph Frei, secretary-general of the World Energy Council estimates that by 2050 renewable energy supply could grow to seven or eight per cent in sub-Saharan Africa (Frei, 2014).

Figure 2-5 illustrates energy use per sector in South Africa. The largest consumers of electricity are Industry (35%), Transport (25%) and Residential (25%) (Inglesi-Lotz and Pouris, 2012). Eskom has a total generating capacity of approximately 42 000 MW, with peak demand capacity of approximately 34 200MW (Krupa and Burch, 2011). Approximately 84.7% of the South African population receives electricity, with approximately 7.8 million having no access (StatsSA, 2011a).

1 MW of energy is sufficient to power 200 middle-income South African households. Eskom plans to spend R500 billion in the period leading up to 2017, which will add 11 000MW of capacity to the grid. The Medupi coal-fired plant, which is currently under construction, will provide 4 764MW of power. Consisting of six units, it is expected that the first unit will start delivering power by the second half of 2014 (Khuzwayo, 2014).

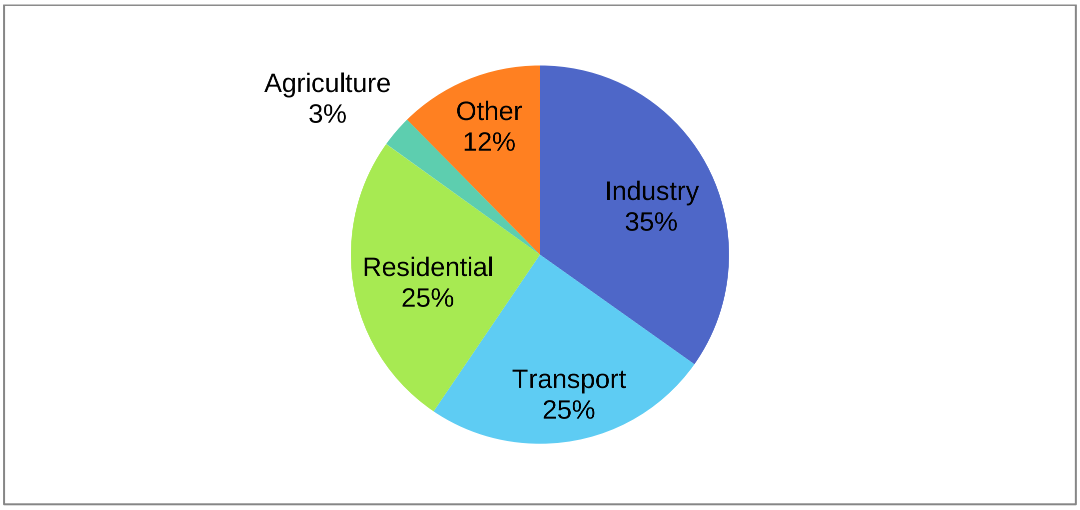

Figure 2 - 5: Energy Usage Per Sector (Inglesi-Lotz and Pouris, 2012)

In an effort to grow using the concepts of sustainable development and safe environmental practice, South Africa needs energy that is not as severely dependant on coal. Renewable resources such as methane generated from the decomposition of organic waste and compost production as a fertilizer could help reduce South Africa's reliance on coal and be an effective treatment for MSW. Incinerating waste in a WtE plant can provide energy to further reduce the reliance on coal.

2.4 Municipal Solid Waste Treatment Technologies

This section discusses the waste treatment technologies that form the scenarios for the NLM case study and LCA. It broadly examines a range of waste treatment technologies including landfills, mechanical sorting, biological technologies and thermal technologies. Technical aspects and relevant short case studies are presented in separate boxes.

2.4.1 Landfills

2.4.1.1 Best Practice for Landfills

The current best practice for landfills is a sanitary landfill (SL), which isolates the waste from the environment until it is safe (MIT, 2012). Four basic conditions must be met before a site can be considered a sanitary landfill. The first is full or partial hydrogeological isolation, which provides for lining in the form of soils or synthetic materials. This prevents leachate leakage and includes leachate collection and treatment. The second condition is formal engineering preparation. This includes a waste disposal plan and a final rehabilitation plan (MIT, 2012). The third condition is permanent control. This dictates that trained staff should be present at all times, from site preparation, to construction, through to waste deposition and operation and regular maintenance. Finally, the fourth condition is planned waste emplacement and covering, which requires the methodological placement of waste in spread layers and daily covering to prevent vermin and pests (MIT, 2012).

2.4.1.2 Landfill Gas to Energy

As noted earlier, landfills are large contributors to anthropogenic GHGs. This is a major disadvantage to the use of sanitary landfills as a waste management technology. An alternate or additional treatment method for biogenic waste is therefore required. This study focuses on Landfill Gas to Energy (LFGE). This can be considered an appropriate solution for the biogenic waste problem as it has already been successfully implemented in South Africa at the Bisasar Road landfill in Durban. Read (2013) states that an appropriate solution is a proven technology applied on a commercial scale that is appropriate to the local waste composition and climate. Furthermore, it is an affordable and sustainable technology that can be managed and maintained locally (Read, 2013).

In the LFGE treatment method, waste is placed in a sanitary landfill. The waste decomposes naturally to release methane, an important component of landfill gas (LFG). An underground network of pipes and wells transports the gas to a renewable energy facility where it is converted into electricity (WasteManagement, 2010). When LFG enters this system, it first passes through a filter, which removes any large fragments and some liquids, which could have been mixed with the gas. After this filtering the LFG is moved into a compressor that increases the pressure on the gas, allowing it to be used as a fuel (WasteManagement, 2010). The increase in pressure raises the temperature of the gas. The gas is then moved into an after-cooler, lowering the temperature of the gas and condensing any remaining moisture. The gas is passed through a second filter to remove this condensed moisture. It is then reheated to prevent any further condensation. Finally, the gas is combusted in an engine to create electricity (WasteManagement, 2010).

WtE and LFG capture practices are currently in progress on landfills. LFG is extracted from the landfill sites and converted to energy. A typical example of this technology is in use on the Bisasar Road landfill.

Box 2 - 1: Case Study on Bisasar Road Landfill

The Bisasar Road landfill is one of three landfills currently operating in Durban, South Africa. It receives about 3880 tonnes of general waste per day, making it the largest landfill in Durban. The city's other two landfills, Marianhill and Buffelsdraai, receive about 690 and 140 tonnes of general waste a day respectively (Friedrich and Trois, 2010).

The Bisasar Road landfill was established in 1980, it has a capacity of 21 million m^3, and an average depth of 40m (Couth et al., 2011). It is classified as G:L:B+, for the large landfill size and it accepts only general waste (CSWU, 2011). This landfill has had gas extraction technologies since 1996; however, in 2001 a large-scale biogas extraction system was implemented with the Clean Development Mechanism (CDM) (Couth et al., 2011).

The CDM aims to help developing countries achieve sustainable development and mitigate the effects of GHG emissions. It is a key component of the Kyoto Protocol (Marciano, 2008). Developed nations with large industrial sectors are permitted to invest in GHG emission reductions in developing nations. There are three characteristics of a CDM project:

1. Private companies fund GHG emission reducing projects in developing countries
2. The project must support sustainable development.
3. The "additionality" component must be met.

(Marciano, 2008)

The additionality component essentially means that the reduction in GHG emissions for the project must be additional to what would have been possible without the CDM funding. These reductions are then converted into certified emission reductions (CERs), which can be sold to developed nations to help them meet their carbon emission limits. One CER is equivalent to the reduction of one metric tonne of carbon dioxide equivalent (Marciano, 2008).

The Bisasar Road landfill is a small-scale CDM project, as are most LFG combustion and waste handling and disposal projects (Couth et al., 2011). It produced 218 000 CERs in 2009 in comparison with the Marianhill landfill, which produced 16 000 (Couth et al., 2011). At a rate of $14/CER for the Bisasar Road landfill, a payback period of four years is possible (Couth et al., 2011).

LFG to energy (LFGE) requires the extraction of LFG gas, through the use of horizontal and vertical wells, produced during the decomposition of the OFMSW on landfills. The decomposition occurs in five stages. In the first stage aerobic decomposition occurs as bacteria in air decompose wastes. Oxygen is used to produce carbon dioxide. This stage can take between a few months and a year (Bove and Lunghi, 2006).

Stage two is an acidogenic phase, in which anaerobic conditions are created, resulting in a slow energy release rate. This stage produces hydrogen, carbon dioxide, water and organic acids. The leachate created in this stage is acidic (Bove and Lunghi, 2006).

In stage three acetogenesis occurs, resulting in the oxidation of acids to acetic acids and the creation of oxygen and hydrogen. Stage four involves methanogenesis, which takes the products of acetogenesis and creates methane, at the same time using up the oxygen and hydrogen created in stage three. Finally stage five is maturation, which occurs after the waste has been through the earlier stages, resulting in low gas creation (Bove and Lunghi, 2006).

The Bisasar Road landfill has 77 vertical and 77 horizontal wells that extract the gas and transport it to six 1MW and one 0.5MW engine to create electricity (CSWU, 2011). Figure 2-6 shows one of the header stations from which each pipe can be controlled, opened or closed, should the biogas in that pipe become contaminated with oxygen.

Figure 2 - 6: Header Station for Pipe Control

The process of landfilling produces emissions in the form of biogas or LFG and leachate. The rate of production is approximately 150m^3 of biogas/Mg of MSW and 5m^3/hectare/day of leachate (Norbu et al., 2005). Leachate is extracted via pumps to be treated with wastewater sludge (Sobey, 2012). A typical composition of LFG is illustrated in Figure 2-7. Approximately 50-60% of the LFG is methane, while the rest is primarily carbon dioxide and a small percentage of impurities. Three key factors affect the amount of methane gas produced in a landfill. These are the amount of waste that has been landfilled, the fraction of that waste that is organic and the decay rate of the organic fraction (Friedrich and Trois, 2011).

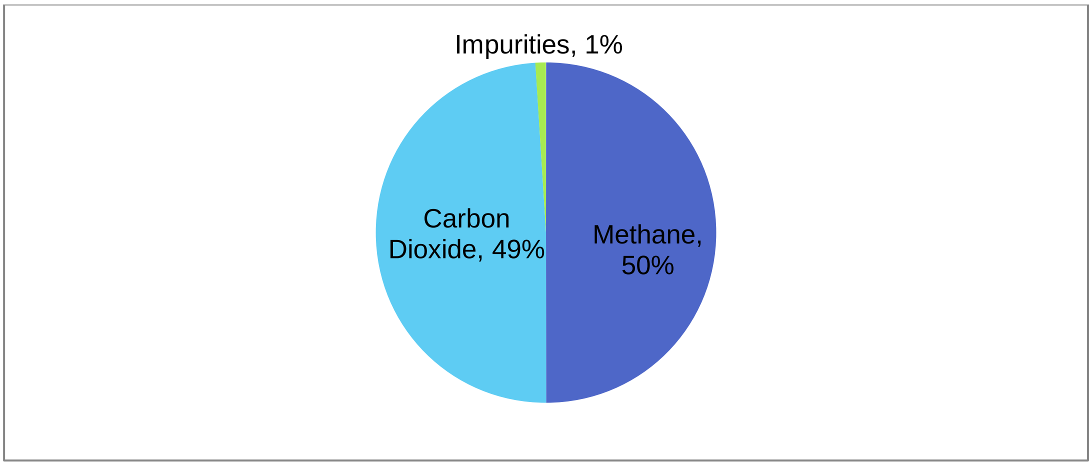

Figure 2 - 7: Landfill-Gas Composition (CSWU, 2011)

Leachate is a significant product of the decomposition of the OFMSW. Renou et al. (2008) state that it is an effluent that is created as a result of rainwater running through waste (Renou et al., 2008). In terms of composition, leachates contain large amounts of organic matter, heavy metals, ammonia-nitrogen, and chlorinated organic and inorganic salts (Renou et al., 2008). Before the leachate can be discharged, it must be treated to remove the organic matter and ammonium.

2.4.1.3 A Critique of Landfills

The externalities of landfills and LFGE include both positive and negative effects. One of the negative effects is the global warming impacts from methane and carbon dioxide due to the organic waste decomposition and the transporting of waste to the landfill. In addition, there are human health impacts from other emissions such as sulphur dioxide, nitrogen oxides, volatile organic compounds and particulates; these compounds also cause damage to buildings and crops. Leachate production also causes soil and water pollution, affecting both human and ecological health. Finally, there are also negative effects from noise and dust pollution, odours and the breeding of vermin and the unpleasant sight of the landfill for nearby residents (Nahman, 2011). In contrast, the positive externalities of LFGE are avoiding some global warming impacts and human health impacts by destroying methane gas to produce electricity (Nahman, 2011).

2.4.2 Material Sorting

2.4.2.1 Materials Recovery Facility

Materials Recovery Facilities (MRFs) form part of the waste treatment process by providing a method for the recovery of recyclables and separation of organic waste (Bovea and Powell, 2006). The recovery of resources from waste can provide much needed income for lower level economic sectors. Local governments can invest in MRFs in which recyclates are removed from the waste stream. The recyclates include paper, plastic, fabrics, metals and glass (Couth and Trois, 2010). There are three basic types of MRFs:

1. Clean MRFs – These treat source-separated materials and recover recyclables.
2. Dirty MRFs – These facilities treat unsorted collected MSW. Recyclable material is recovered from the unsorted waste.
3. High-technology MRFs – These facilities utilise the most mechanical equipment to recover recyclable materials. The capital costs of these facilities are high and some workers will be required to be more skilled; however less labour is required to sort the waste.

(UMDM, 2011)

In a typical facility that receives mixed waste, the equipment and processes that the waste goes through include pre-sorting, bag opening, manual sorting, screening with a cylinder for size separation, magnetic separation removing all ferrous metals and an eddy-current separator for removing non-ferrous metals (UMDM, 2011).

The screening allows for large waste materials to be removed and for most of the organic matter to be separated, further facilitating the separation process as it is easier to sort similar objects (Richard, 1996).

Figure 2-8 shows the layout of a typical MRF. It illustrates that recyclable materials such as glass, tin, plastic and cardboard are removed at each sorting phase. In the trommel phase, organic waste is separated from the waste stream. The figure also shows that recyclable materials are compacted and bailed for easy transport and storage.

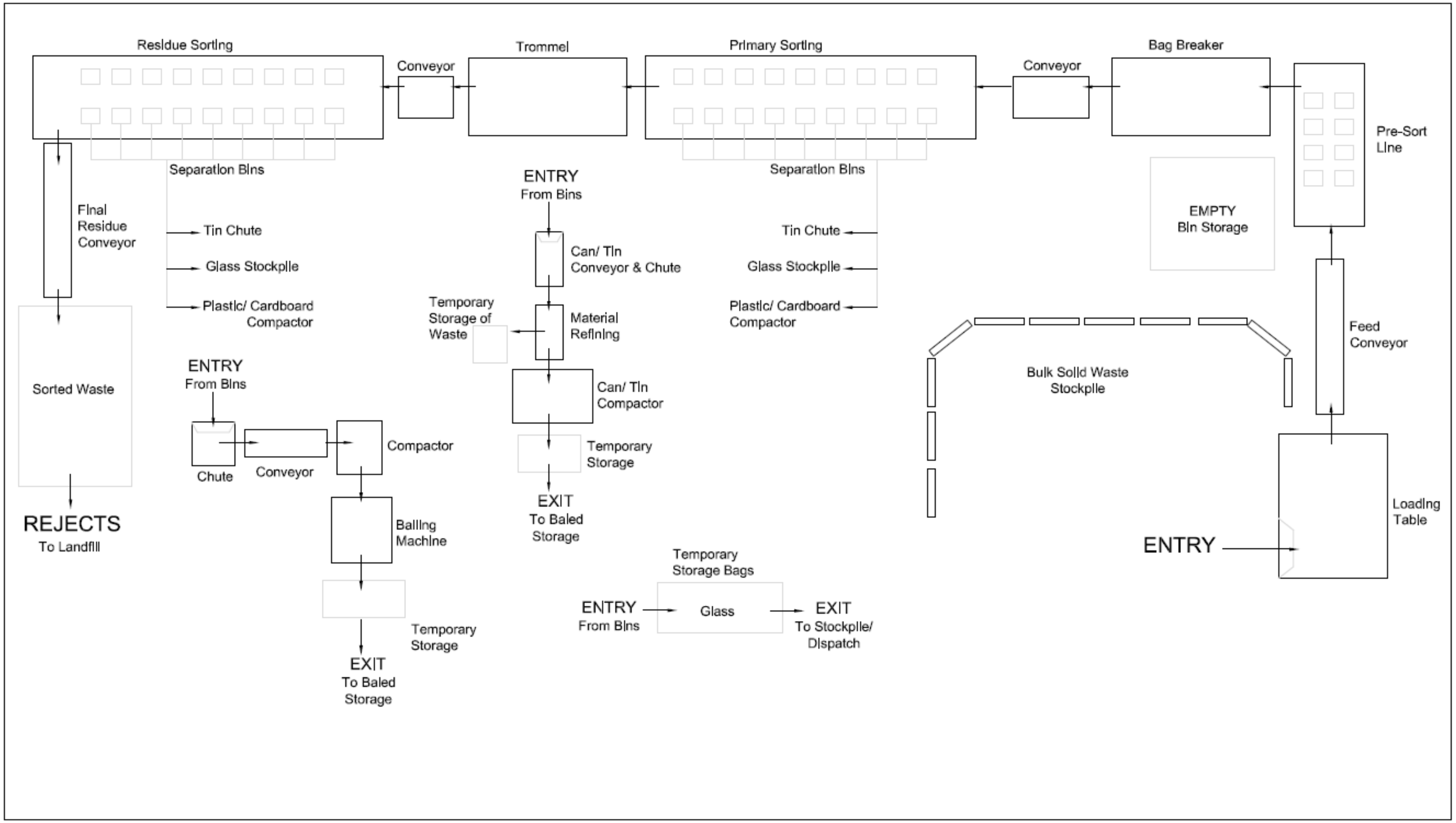

Figure 2 - 8: Typical Layout of a MRF (UMDM, 2011)

2.4.2.2 Informal Recycling and Waste Picking

In many developing countries, the urban poor earn an income from informal recycling (Medina, 2008). With regard to MSW management, informal recycling refers to waste recycling by scavengers or waste pickers (Wilson et al., 2006). Medina (2008) estimates that 15 million people in developing countries around the world are involved in and survive by waste picking. Waste pickers are generally members of vulnerable groups such as migrants, children, women and the unemployed. Economic factors are the primary motivation for waste picking. Many poor people choose it over starvation (Medina, 2008).

Tensions often arise between municipalities and waste pickers. Unorganised waste picking leads to a number of problems. It can result in neighbourhoods and cities with MSW scattered in the streets, and the waste pickers disrupt traffic when they use carts to transport the waste they have collected (Medina, 2008). Many municipalities have therefore banned waste picking activities, which drives these activities underground. Waste pickers adapt by picking at odd hours and by bribing the authorities (Medina, 2008). Most waste picking activities occur on the streets, in open dumps, and near landfills. Daily contact with waste is a health hazard and banning waste picking often leads to even lower incomes and worse working conditions (Medina, 2008).

Cities with a formal MSW collection, treatment and disposal system identify four main categories of informal waste recycling activities (Wilson et al., 2006). The first is itinerant waste buyers who collect dry, recyclable waste door-to-door, which they buy or barter from householders and then transport to a recycling shop, such as a buy-back centre. The second is street waste pickers who recover valuable material from mixed waste thrown on the streets and from communal bins prior to collection. The third category is the MSW collection crew that collects the waste from the vehicles transporting the MSW to the disposal site. Finally, the fourth category is the waste pickers on dumps who pick the waste prior to it being covered or pick the waste of the vehicles as they arrive at the disposal site (Wilson et al., 2006).

Organised informal recycling offers social, economic and environmental benefits (Wilson et al., 2006). It would be beneficial to the municipality and the waste pickers for informal recycling to be integrated into the formal MSW management system. A solution proposed by Wilson et al. (2006) is to provide a safe area for waste picking activities that is away from vehicles' movements and waste placement areas on landfill sites. An organised union of waste pickers could present a united front to government and industry, allowing them to become actors in the development process (Medina, 2008). Experiences in many developed countries have shown that it is more expensive to build a formal recovery system if an informal system has been destroyed. Developing nations can use the existing informal recycling system as an opportunity to improve both the efficiency of recovery in their municipalities and the working conditions of the waste pickers involved (Wilson et al., 2006).

2.4.3 Biological Technologies

2.4.3.1 Anaerobic Digestion

Anaerobic Digestion (AD) is a, "process by which a mixed culture of microorganisms break down matter in the absence of oxygen to form biogas and digestate" (Coulon and Villa, 2011). Municipalities throughout South Africa use AD to treat wastewater. It forms a critical portion of activated sludge treatment works and it can be extended to the treatment of OFMSW.

The AD of OFMSW occurs in three phases. The first is hydrolysis/liquefaction, followed by acetogenesis and finally methanogenesis (Caruso et al., 2006). The hydrolysis/liquefaction of organic matter involves the breakdown of complex matter into simple molecules by fermentative bacteria (Caruso et al., 2006). The next phase involves converting the monomers created in the first phase into oxygen, carbon dioxide and simple organic acids (Caruso et al., 2006). In the final phase, methanogens split acetic acid molecules to form carbon dioxide and methane (Caruso et al., 2006).

An AD system takes place in four stages: pre-treatment, digestion, gas upgrading or recovery and digestate treatment (Monnet, 2003). Figure 2-9 below shows a typical process flow diagram of AD.

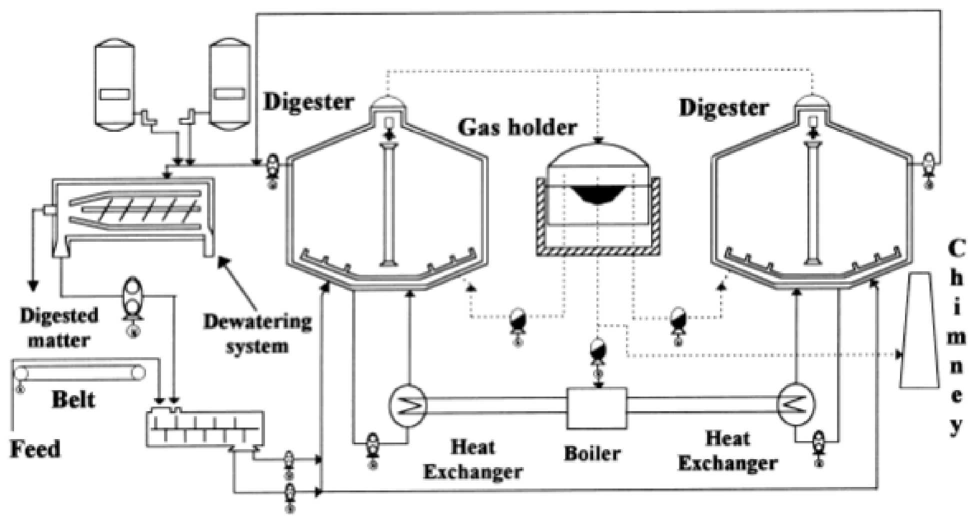

Figure 2 - 9: Anaerobic Digestion Flow Process Diagram

Stage One: Pre-Treatment

During this stage, the feedstock is prepared for the digestion process. This involves removing non-digestible and recyclable materials such as metals or glass (Caruso et al., 2006). This can be done using the separation at source method or the mechanical separation of municipal solid waste (MSW). Separation at source provides a higher quality of digestate, as most of the non-digestible material would be removed before arriving at the AD plant. However, source-separated waste still needs to be physically processed (Monnet, 2003).

Mechanical separation leads to a poorer quality digestate (Monnet, 2003). Methods such as manual separation to remove clearly inorganic materials or the use of screens to remove oversize items can be employed to separate the MSW. The aim of the separation is to achieve the highest quality of OFMSW to be transferred into the digestion stage of the AD system. The OFMSW is finally mixed and shredded to achieve uniform, similarly small sized particles for digestion (Monnet, 2003).

Stage Two: Digestion

The second stage of the AD system is the digestion process. Digestion can take place in two temperature ranges, each requiring a different retention time. Retention time is the time needed for the complete breakdown of the organic matter (Monnet, 2003). The two temperature conditions are mesophilic and thermophilic. Mesophilic conditions range between 20-45°C, mainly occurring at 35°C while thermophilic conditions are temperatures between 50-65°C, mainly 55°C. The retention time for these temperature conditions are 15-30 and 12-14 days respectively (Monnet, 2003).

Furthermore, the digestion stage can occur in three different types of digesters: one-stage, two-stage and batch systems (Vandevivere et al., 2002) Batch systems are the cheapest and most simple technology; accordingly they have good application value in developing countries (Vandevivere et al., 2002). Two-stage or multi-stage systems are the most complex and expensive options (Vandevivere et al., 2002).

One-stage systems involve all three phases of digestion occurring in one digester. An advantage of one-stage systems is that due to the more simple design, technical failure is less frequent and there are lower capital investment costs (Vandevivere et al., 2002).

The two-stage system usually involves two separate reactors. Phases one and two of the digestion process, namely hydrolysis/liquefaction and acetogenesis, occur in the first reactor. Phase three of the digestion process, i.e., the methanogenesis phase, takes place in the second reactor (Monnet, 2003). The two-stage system is advantageous to a feedstock primarily composed of rapidly degradable waste. This is because it allows for greater biological stability of the feedstock as the slower metabolising methanogens are separated from the acidogens (Monnet, 2003).

Batch systems are classified according to their locative treatment of the acetogenesis and methanogenesis phases of the digestion process. There is always a clear separation between these two phases. There are three different types of batch systems: the single stage batch reactor, the sequential batch system and the hybrid-UASB (upflow anaerobic sludge blanket) batch reactor (Vandevivere et al., 2002).

In the single stage batch reactor, the leachate is collected at the bottom of the container and is circulated back to the top of the matter (Vandevivere et al., 2002). This is comparable to partial mixing (Monnet, 2003). In the sequential batch system, the leachate is transferred to another reactor in which methanogenesis is occurring. The leachate from the second reactor is transferred back into the first reactor once it has been combined with pH-buffering agents and has a minimal acid content (Monnet, 2003). Finally, the upflow anaerobic sludge blanket reactor is comparable to the two-stage system discussed earlier. The reactor in which the methanogenesis occurs is replaced by a UASB reactor; this is best suited to dealing with liquid effluents (Vandevivere et al., 2002).

Stage Three: Gas Upgrading

The third stage of the AD system is to upgrade the gas created during the digestion stage. This enables the biogas to be used for fuels and electricity generation. The composition of the biogas generated from the digestion process is directly linked to the composition of the waste used as feedstock (Monnet, 2003). Biogas is primarily made up of methane and carbon dioxide (Petersson and Wellinger, 2009). By removing the carbon dioxide in the biogas, the energy content is increased (Petersson and Wellinger, 2009).

Before the upgrading process can occur, it is beneficial to clean the biogas in order to prevent corrosion and mechanical wear of the upgrading equipment (Petersson and Wellinger, 2009). The gas is cleaned by removing water, hydrogen sulphide, oxygen, nitrogen, ammonia, siloxanes and particulates (Petersson and Wellinger, 2009).

The upgrading of biogas involves the removal of carbon dioxide to form a more methane rich gas. This can be done using a number of technologies. Pressure Swing Adsorption (PSA) removes carbon dioxide from biogas by adsorption on a surface, often zeolites or activated carbon, that is under a raised pressure (Petersson and Wellinger, 2009). The second technology is Absorption. This involves the biogas travelling through a column with water running in the opposite direction. Following the principle that carbon dioxide is more soluble than methane, it follows that the water leaving the column will have a higher carbon dioxide content while the biogas will have a higher methane content (Petersson and Wellinger, 2009). Finally, the third technology is the use of membranes, which are permeable to carbon dioxide, ammonia and water, to separate the biogas into methane and carbon dioxide (Petersson and Wellinger, 2009).

Stage Four: Digestate Treatment

The digestate is the solid or slurry-like fraction of matter left after the digestion process (Petersson and Wellinger, 2009). The primary advantage of digestate is its nutrient-rich composition. This makes it an ideal candidate for soil treatment as a fertilizer (Monnet, 2003).

If the separation techniques employed are inefficient, the digestate can contain many impurities such as glass, metal, sand and plastic. These impurities cause negative public perceptions as they result in aesthetic damage to the environment (Monnet, 2003).

The primary ingredients of fertilizer, i.e., nitrogen, phosphorous and potassium (NPK), are the major components of the digestate remaining after digestion has occurred (Monnet, 2003). Treatment of digestate involves the process of dewatering and forming two products, the fibre and the liquor (Monnet, 2003). The fibre has a low content of plant nutrients and can be used as a low grade fertilizer and soil conditioner or composted into high grade compost (Monnet, 2003). The liquor, on the other hand, is rich in plant nutrients and due to its higher water content can be applied using standard irrigation methods (Monnet, 2003). The liquor can be used as a fertilizer.

These four stages form the basis for the AD of OFMSW, which is a popular method of treating organic waste in developing countries due to the opportunity for energy recovery and digestate production (Couth and Trois, 2010). However, the initial capital costs, operation complexity and equipment maintenance lead many developing countries to seek more economically feasible and simpler recycling and composting processes (Couth and Trois, 2010).

2.4.3.2 Aerobic Composting

Composting is a controlled method for the decomposition of biodegradable matter under measured conditions. It is an aerobic process that allows for the creation of thermophilic bacteria from the release of biologically produced heat. If temperatures continue to rise to between 60-70°C, pathogenic micro-organisms are destroyed and the final product material can be considered safe for land use (Couth and Trois, 2012a).

The advantages of Aerobic Composting are the fact that it is a faster method than AD, it produces less compounds with an unpleasant odour and, due to its high temperature process, pathogens, eggs and larvae of flies are destroyed (Mbuligwe et al., 2002). Compost from efficiently sorted organic waste can be used as a fertilizer, replacing mineral fertilizers; this leads to a reduction in nitrate leaching. However, composting of garden refuse from MSW in South Africa has yielded poor quality compost due to feedstock contamination from plastic bags and other portions of the waste stream (Couth and Trois, 2010). Furthermore, as a result of the aerobic nature of the composting process it produces less GHG emissions than landfilling (Friedrich and Trois, 2011).

Composting of organic waste is achieved using in-vessel composters (IVCs) and windrows. In developing countries, these technologies are utilised to control moisture content, temperature and oxygen (Couth and Trois, 2012a). Composting occurs in two stages, the fermentation or active composting stage and the maturation stage. In the fermentation stage, waste is first added to the windrow, where aerobic decomposition occurs, which is the consumption of oxygen by microorganisms. The temperature of the compost pile increases to between 40-60°C. As the decomposition rate slows, the maturation phase begins. This is indicated by a reduction in the temperature. Once the compost pile reaches the temperature of the surrounding air, the maturation phase is complete (Couth and Trois, 2012a).

As reported by Couth and Trois (2007), for biogenic composting to be successful, alongside a small particle size for maximum surface area for aeration, the characteristics presented in Table 2-1 should be achieved:

Table 2 - 1: Successful Composting Characteristics

Oxygen Concentration	> 15%
Temperature during composting	50 – 60°C
Moisture content	50 – 55%
Carbon to Nitrogen Ratio (C:N Ratio)	25:1 – 30:1
pH	6.5 – 8

The Carbon to Nitrogen ratio is particularly significant as these are the two most important elements in the composting process (Couth and Trois, 2012a). The carbon is the main source of energy, while the nitrogen produces protein for microbial population growth (Couth and Trois, 2012a; Norbu et al., 2005). If the carbon content is too high, the rate of decomposition slows. Alternatively, if there is excess nitrogen, the composting pile will release an unpleasant odour (SPE, 2006).

Waste Composting Technologies

In-Vessel composting is carried out in large metal tanks or concrete bunkers, in which the temperature and flow of air can be more easily controlled than windrows. IVCs are considered a high tech process for composting, with high costs and maintenance. This renders IVCs unsuitable for application in a developing country (Couth and Trois, 2012a). Furthermore, windrows are less energy intensive than in-vessel composting; hence their GHG emissions are lower (Friedrich and Trois, 2011). Composting GHG emission estimates are between 0.183-0.932 tonnes of CO_2 equivalents per tonne of waste (Boldrin et al., 2009).

Air can be provided to the composting pile using three methods; large pore spaces in the windrow providing passive aeration through Dome Aeration Technology (DAT), mechanical turning of the windrow, or sucking or blowing air through the windrow (Couth and Trois, 2012a). Mechanically turning the pile can temporarily increase the porosity of the windrow and release heat and moisture. This method takes 4-6 weeks for stage one of the composting process and 6-12 weeks for the maturation stage (Couth and Trois, 2012a). Oxygen can also be provided to the microorganisms requiring it, through blowing air or forced aeration of the compost. The rate is controlled by the moisture content and the porosity of the compost (Ekelund and Nyström, 2007).

Dome Aeration Technology (DAT) is a low cost, low energy solution to composting (Couth and Trois, 2012a). A steel mesh structure is used to create large air spaces in the windrow known as domes and channels. These domes and channels provide oxygen and temperature control by encouraging air flow through the windrow (Couth and Trois, 2012a). Domes are placed vertically in the centres of the piles, while the channels extend from the exterior towards the interior, without reaching the centre. This technology is also known as passively aerated windrows, as no turning is required. The hot gases developed during the composting are free to escape through the centrally located dome chimney (Couth and Trois, 2012a). Figure 2-10 provides a sample schematic of the DAT composting, showing the domes and channels.

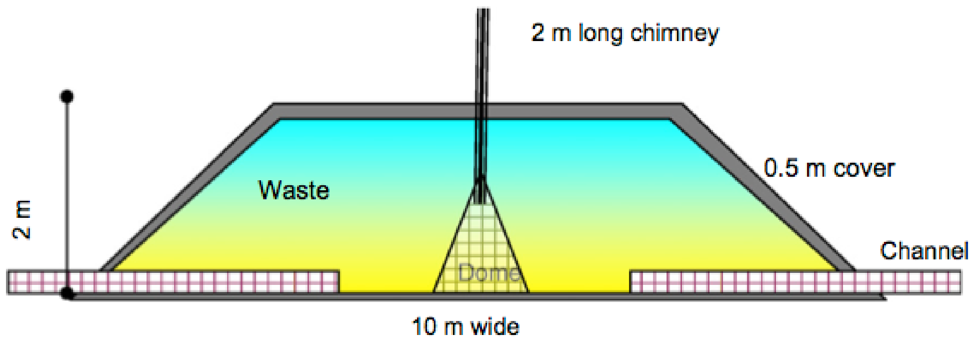

Figure 2 - 10: Schematic of DAT Composting (Couth and Trois, 2012a)

2.4.4 Thermal Technologies

2.4.4.1 Incineration

The incineration of MSW can be traced back to the first MSW incinerator in Manchester in 1876. This technology is well developed and has a long, controversial history as public attitudes changed from country to country (Christensen, 2011). Incinerators have developed into modern day WtE plants. MSW incineration is the thermal decomposition of matter in a surplus of air (Christensen, 2011). The driving motivation behind the deployment of this technology is that is reduces MSW volumes by up to 95% (Abd Kadir et al., 2013).

Three factors determine the suitability of waste as a fuel for incineration: heating value, ash content and moisture content. Tanner's diagram presented in Figure 2-11 can be used to determine if waste can be combusted without any supplementary fuel. In this diagram, the moisture content (W) of wet waste, the inorganic ash content (A) and the combustible solids (C) are compared to each other. Waste that falls within the shaded area does not need supplementary fuel for combustion (Christensen, 2011).

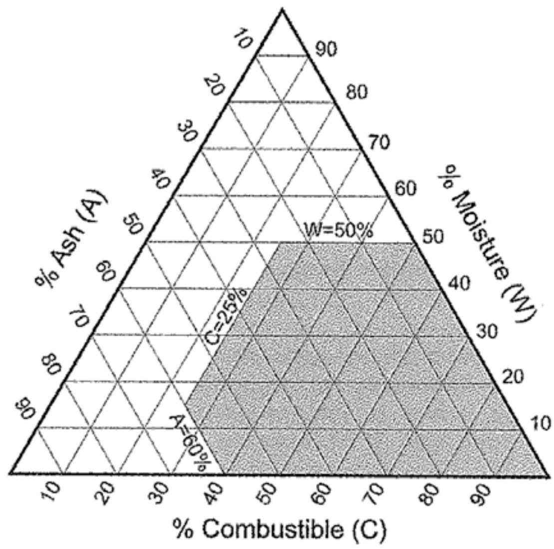

Figure 2 - 11: Tanner's Diagram (Christensen, 2011)

A typical incineration process is illustrated in Figure 2-12. This process uses a moving grate furnace and a horizontal steam boiler, which generates energy in the form of heat and electricity. The moisture content of the waste is evaporated during the early stages of the incineration process and the incombustible components of the waste form residues such as fly ash and bottom ash. In addition, the incineration process results in the combustible parts of the waste reacting with the oxygen in the air and the release of a substantial quantity of hot combustion gas (Christensen, 2011).

The combustion gas passes into the afterburning chamber from the furnace. The afterburning chamber has a temperature of approximately 850°C to ensure complete burnout. This temperature must be maintained for a minimum amount of time from the last inlet of combustion air. The European Union (EU) legislates this time as two seconds. The resultant flue gas is cooled through radiation and convection to the walls and surfaces of the boiler and furnace. Pressurised water in the boiler is heated and the energy is exploited in a steam turbine that is connected to a power generator. Approximately 25% of the steam's energy content is converted into electricity in a combined heat and power plant (Christensen, 2011).

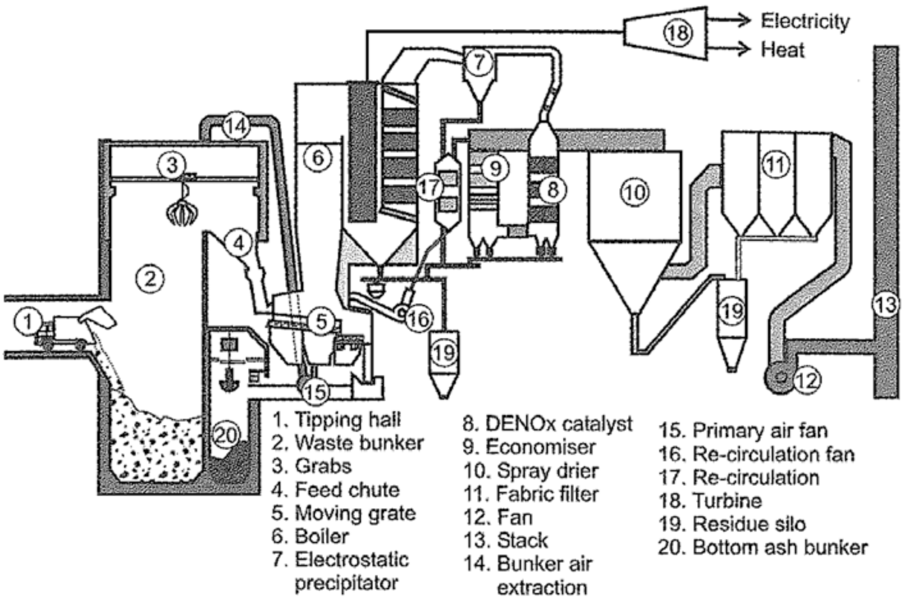

Figure 2 - 12: Typical Cross-Section of an Incineration Plant (Christensen, 2011)

2.4.4.2 Pyrolysis

Pyrolysis is the decomposition of organic matter by heat under a lack of oxygen (Wagner, 2007). The process is endothermic and it should be noted that no actual burning takes place (Young, 2010). Pyrolysis produces products in liquid, solid and gaseous form. The liquid is often referred to as bio-oil. It is volatile and can be used as a fuel. The solid fraction is a carbon product called char (Cheung et al., 2011). The gas produced is known as syngas.

Syngas is primarily composed of carbon monoxide and hydrogen, as well as smaller amounts of methane, nitrogen and carbon dioxide (FOE, 2009). The syngas is cleaned, i.e., particulates are removed, and this cleaned syngas is used to generate electricity.

Pyrolysis systems are easy to control, expand and reduce according to the needs of the incoming waste because the system is modular. It can be easily taken apart or have extra modules added, should more MSW enter the system (Caruso et al., 2006).

The pyrolysis system has four stages: preparation of the feedstock, heating, gas cleaning and electricity generation (FOE, 2009)

During the preparation of the feedstock, waste passes through three different processes. Firstly, MSW goes through sorting where inorganic materials are removed. Shredding follows sorting, where organic matter is shredded to similar sized particles (GES, 2012). Small particles are required to enable a fast reaction process (IEA, 2009). Finally the preparation ends with drying of the feedstock to reduce the moisture content. A lower moisture content allows for higher power generation (GES, 2012).

The heating of feedstock is the main process of the pyrolysis system. It is a mainly endothermic reaction that involves the cracking of matter (Cheung et al., 2011). Three reactors can be used for pyrolysis: the rotating kiln reactor, the heated tube reactor and the surface contact reactor (DEFRA, 2007).

The rotating kiln reactor operates at temperatures between 300-800°C (DEFRA, 2007). It can accommodate feedstock particles of a relatively large size, approximately 200mm. Feedstock is fed into the kiln from one side, which is heated externally. The rotating kiln ensures a continuous mixing of the materials, maintaining contact with the heated surfaces and gases (DEFRA, 2007).

The heated tube reactor is also externally heated and operates at approximate temperatures of 800°C (DEFRA, 2007). It also has the capacity for relatively large sized particles. With this reactor waste is transferred through the tube at a constant rate to ensure that the pyrolysis process is complete once it reaches the other end of the tube (DEFRA, 2007).

Unlike the other two reactors, the surface contact reactor can only accommodate small particle sizes (DEFRA, 2007). This reactor operates at high temperatures and the small particles are rapidly heated to maximise the process of pyrolysis (DEFRA, 2007).

The cleaning of the syngas involves the removal of unwanted impurities from the thermochemically-produced gas. Impurities include ammonia, hydrocarbons, nitrogen-containing gases, alkali metals and other particulates (Young, 2010). As noted earlier, in its basic form, syngas is composed of hydrogen and carbon monoxide. It can be converted to gaseous fuels, that is hydrogen using steam methane reforming (Young, 2010). It can also be converted to liquid fuels using the Fischer-Tropsch Synthesis method or the methanol synthesis process, amongst others (Young, 2010).

To generate electricity, the syngas can be burned in a boiler to power a steam turbine or used directly in a gas engine (DEFRA, 2007) DERFA (2007) suggests that the pyrolysis plant be located near an existing power plant, allowing the syngas to be transferred to it, thus maximising electricity efficiency. Figure 2-13 illustrates a schematic diagram of the MSW to energy process using pyrolysis.

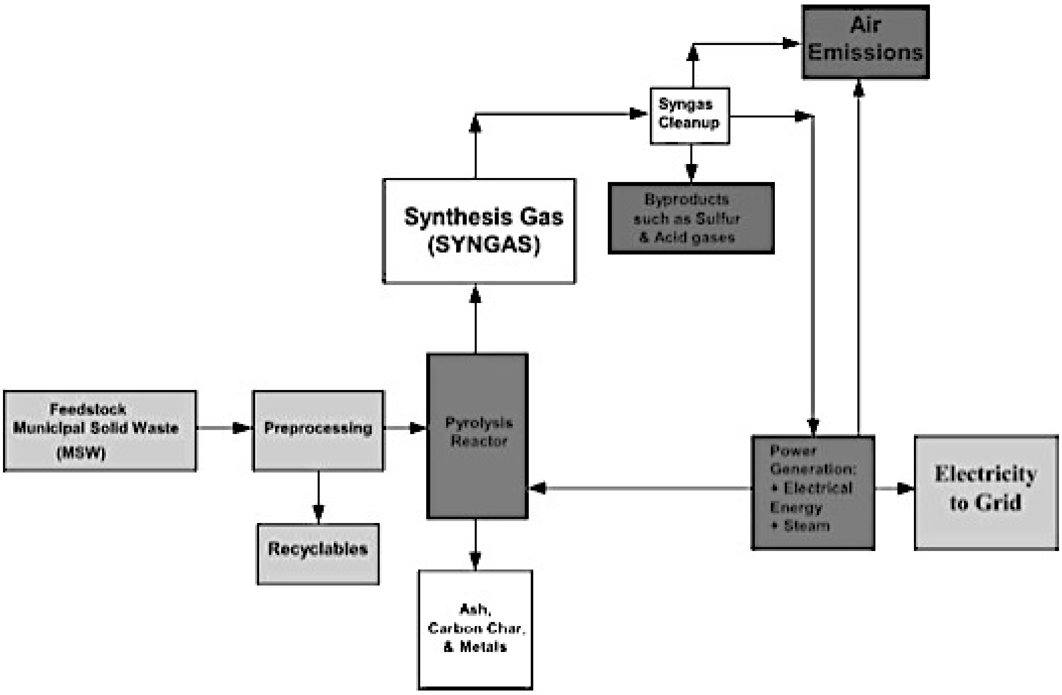

Figure 2 - 13: Schematic Process of Pyrolysis (Young, 2010)

Pyrolysis and Gasification are similar in their stages of the process.

2.4.4.3 Conventional Gasification

Gasification is the heating of organic matter in the presence of limited oxygen at temperatures above 650°C (DEFRA, 2007). A controlled amount of oxygen is allowed to enter the gasification reactor, enabling the organic matter to react (Young, 2010). The complex carbon molecules are broken down to simpler and more stable carbon monoxide and hydrogen molecules. The inorganic is converted to vitrified slag or ash.

Figure 2-14 illustrates the gasification process. One can see that the conventional gasification system is almost identical to the pyrolysis system, differing only in the treatment of the prepared feedstock.

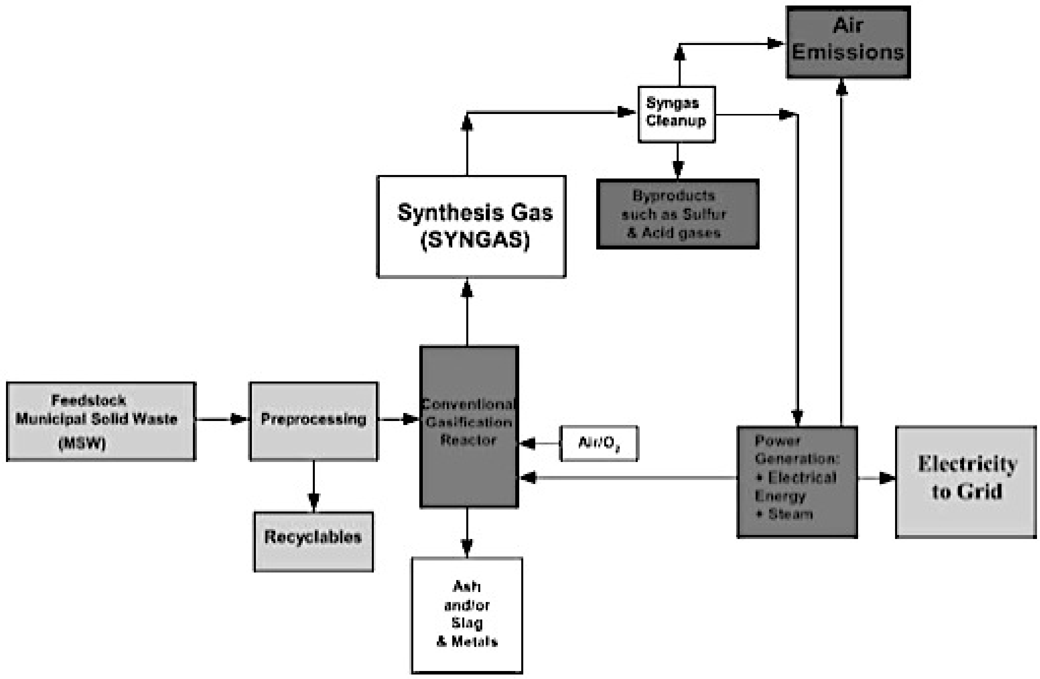

Figure 2 - 14: Schematic Process of Conventional Gasification (Young, 2010)

Gasification is a series of complex reactions. The first stage is combustion of the feedstock to produce gases, char and heat. The heat is then used to dry the organic matter and to kick-start the endothermic reactions to produce the syngas (Kishore, 2009).

The gasification system follows the pyrolysis system in terms of stages, i.e., preparation of feedstock, heating, cleaning of syngas and electricity generation. This similarity and the complementary nature of the reactions can lead to a combined pyrolysis/gasification reactor. This reactor heats the materials in a primarily oxygen-starved environment (Young, 2010).

At the bottom of the conventional gasification reactor is ash, slag or metals. This by-product is generally transferred to landfills for disposal (Young, 2010). This is one of the major drawbacks of using pyrolysis and gasification for MSW management (Young, 2010).

2.4.4.4 Plasma Arc Gasification

Plasma arc gasification (PAG) is a pyrolysis process that occurs at very high temperatures, between 4000-7000°C, often reaching up to 10 000°C (Bhasin, 2009b). Like pyrolysis and gasification, PAG produces syngas from organic waste matter, while the inorganic matter is converted to vitrified slag (Young, 2010).

The high temperature of this process is produced by an electric arc in a torch, which in turn converts a gas into a plasma (Young, 2010). The inorganic matter is converted to the glassy-rocklike substance, vitrified slag. PAG contains the toxic materials, making it much safer than the toxic ash produced by gasification (Bhasin, 2009a).

PAG essentially breaks down all matter, organic and inorganic, into elemental compounds, which can be reused and recycled (Bhasin, 2009a). As it is a pyrolysis process, it operates in an oxygen-starved environment; hence, no combustion takes place. Moreover, due to the high temperatures, toxic and non-toxic compounds break down within milliseconds and hence contaminating products such as flue gas are avoided (Bhasin, 2009a).

In the PAG process, waste is prepared by shredding it to the appropriate size. It enters the pyrolysis chamber and passes through the plasma torch. The torch operating at the high temperatures converts the waste into syngas and molten slag (Young, 2010). This slag is cooled to form the glassy-rocklike material mentioned above, which can be sold to the construction industry for many uses including tiles, insulation or landscaping blocks (Young, 2010). The syngas is extracted and cleaned up. No ash is produced in the PAG process (Bhasin, 2009a).

The syngas is then used to generate electricity by way of a steam turbine or gas turbine. Other by-products such as hydrochloric acid, hydrogen sulphide and hydrofluoric acid are neutralised appropriately (Bhasin, 2009a). Figure 2-15 illustrates a plasma arc gasification system. It details the process from waste pre-processing to the use of the clean gas to generate electricity and the by-products created along the way.

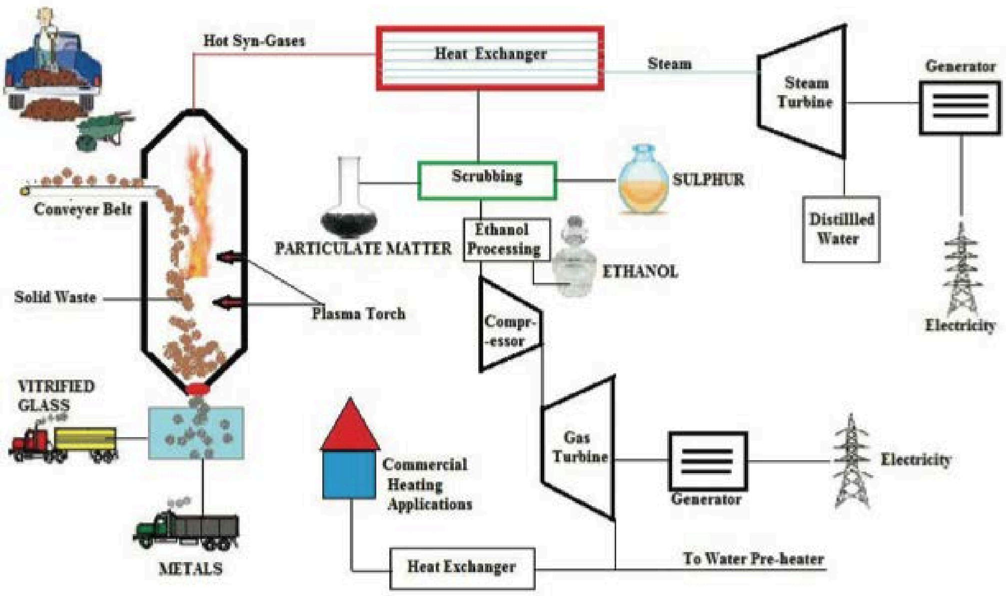

Figure 2 - 15: Plasma Arc Gasification Process (Ojha et al., 2012)

Figure 2-15 shows that the pyrolysis reactor does not allow any gases to escape into the atmosphere. It has an opening at the bottom to allow slag to be removed, and is lined with a strong, heat-resistant material. The hot gases moved to the heat exchanger are used to heat water to generate steam that powers the steam turbine (Bhasin, 2009a). The syngas is then transferred for scrubbing or clean-up, where the particulate matter, sulphur, acidic gases and other unwanted materials is removed (Ojha et al., 2012). The clean syngas is then transferred to the gas turbine for electricity generation.

Ojha et al. (2012) observe that, "Plasma gasification proves to be one of the most efficient methods for treating all type of solid waste without segregating them." While PAG is an expensive technology to implement (Bhasin, 2009a), it has been shown that it can be very viable for developing nations such as South Africa, as apart from income from electricity generation, all by-products can be sold at a profit (Ojha et al., 2012).

2.4.4.5 Thermal Technologies in South Africa

Thermal technologies provide a large volume reduction of the waste and can potentially produce energy; however, a few factors create barriers for deployment in a middle-income developing country such as South Africa. Thermal technologies for treating MSW require large capital investments and are complex processes that need highly technically skilled operators.

The Green Jobs Report states that pyrolysis technologies have significant capital costs and a high level of complexity, requiring highly skilled operators (Maia et al., 2011). These skilled engineers are available in South Africa, but the cost of hiring them to operate the technology would impact the viability of the operations (Maia et al., 2011). It has been estimated that PAG has an initial capital cost of approximately US$150 million (Ojha et al., 2012). This is approximately R1.2 billion. Such a capital investment is not feasible for a developing country. South Africa, like most countries in Africa, would not be able to fund thermal technologies (Couth and Trois, 2010).

Furthermore, controlled incineration is not considered a viable method for waste disposal in developing countries due to the high costs and unsuitable waste composition. Waste in developing countries has a high moisture content, a high fraction of organic content and lower calorific value (Friedrich and Trois, 2011). It is for these three reasons, funding, skills and waste composition, that thermal technologies are currently not considered viable alternatives to biological technologies or landfilling.

2.5 MSW Management – Decision Support Tools

This section outlines various theories of complex decision-making and highlights several tools to assist environmental decisions for MSW management. The principles underpinning decision-making are developed through the models of sustainable technology assessment, technology transfer, the systems approach to technology, sustainability assessment and multi-criteria decision analysis. This section also discusses tools for environmental decision-making that include environmental impact, technology and risk assessment, and introduces life cycle assessment.

2.5.1 Sustainable Technology Assessment

Sustainable technology assessment (STA) is a method of identifying and comprehending the probable impacts of the use of a new or modified technology (IETC, 2003). Worldwide, a wide range of sustainable technologies is available for the treatment of biomass waste. No single technology transfer system is applicable to all situations (IETC, 2003). These technologies are best suited to a specific context and situation. Technology selection depends on various factors including the socio-economic environment, culture, technical expertise, legislation and environmental considerations. The assessment of technology provides decision makers with a clear understanding of how a specific technology would perform in a particular context. STA often uses sustainability indicators or evaluation criteria to analyse appropriate options. The sustainability indicator categories are: economic, environmental, social, institutional and technical. In addition, STA enables decision makers to identify the appropriateness of a technology to satisfy their needs and fit their circumstances and capacities (IETC, 2003). Developers tend to use the following tools for waste treatment technologies: environmental impact assessments, environmental technology assessments, environmental risk assessments and life cycle assessments. Further information on these assessment methods is provided in Section 2.5.6.

It is preferable that the technologies that are employed are both environmentally sound and sustainable. This would entail technologies that protect the environment, pollute less, have sustainable usage of resources, recycle a larger portion of their waste and products, handle their residual waste in a more efficient and sustainable manner, and are more socially acceptable and economically viable than the technologies currently in use (IETC, 2003).

The International Environmental Technology Centre identifies the following eight functions of STA:

- the identification and development of socially desirable and useful technologies;
- support for relevant stakeholders in the creation of their approaches for the development of technologies;

- the assessment at an early stage of possible problems and disadvantageous consequences;
- supporting decision makers by identifying and assessing issues and problems;
- the enlargement of the knowledge base on these technologies, which strengthens policy making related to scientific and technological advancements;
- contributing to long term policies by providing information on possible developments and alternatives;
- promoting accountable and reliable science; and
- promoting public acceptance of technology-related progress

(IETC, 2003)

This section outlines the key considerations with regard to STA. It highlights a variety of methodologies and approaches that have been utilised and devised for STA.

2.5.2 Technology Transfer

In an emerging economy such as South Africa, STA is intricately linked to technology transfer. This is not just the transfer of high-tech equipment from a developed country to a developing country, or among the developing world. The transfer of technologies is concerned with the total system. This includes technical expertise, products and services, and equipment, as well as the operational and organisational procedures that accompany a specific technology (IETC, 2003).

Informed choice is crucial to the successful transfer of technologies. For a decision maker to select the most appropriate technology for their needs and context, the following requirements must be met:

- The needs should be clear, documented and comprehended;
- A variety of technology alternatives, information on which should be comprehensive and related to the required criteria;
- Decision support tools that will assist decision makers to select the optimal choice;
- Capacity to make the selected technology fully operational, satisfying all the required needs with minimal impact on the environment and culture. This is inclusive of the decommissioning process

(IETC, 2003).

2.5.3 Selection Criteria

The selection criteria are mainly used to assess the technology alternatives. These include social, environmental, economic and technical indicators. A technology's performance in terms of each criterion indicates its capacity to achieve the maximum possible outcome. Table 2-2 highlights some of the evaluation criteria that fall within the four sustainability indicator categories mentioned above.

Table 2 - 2: Sustainability Indicator Categories and Evaluation Criteria

Technical	Efficiency	This refers to the amount of useful energy that can be obtained from the technology. It can be assessed by the ratio of input energy to output energy.
	Safety	Waste treatment technologies are constantly undergoing development and improvement. The systems are dynamic. Continuous changes in the regulations on the environment, technology and public concerns make the analysis of safety demanding.
	Reliability	The capacity for a technology to perform as it was designed. That is, its resistance to failure. This criterion also includes the technology's ability to fail without catastrophic results.
	Maturity	This refers to the stage at which the technology exists. From testing to widespread distribution and usage of the technology.
Economic	CAPEX	The capital cost refers to all the costs involved in the initial set up of the equipment. This includes investment in the mechanical equipment, installation, construction of roads and buildings and labour.
	OPEX	The operating and maintenance costs include employees' wages and maintenance costs to prolong the lifespan of the technology.
	Fuel Cost	This is the cost involved in acquiring the input materials, i.e., the transportation costs of transferring waste from the production or collection point to the processing and treatment plant.
	Electric Cost	This is the cost of the electricity for the plant and any electricity used in the production of the final product.
	Payback Period	This is the period of time for the return on the investment.
	Service Life	This is the expected lifespan of the technology. This involves the probability of failure of the system.
Environmental	NO_x emission	This is the emission of all mono-nitrogen oxides. These are polluting molecules that contribute to global climate change and acid deposition.
	CO_2 emission	This is a measure of the quantity of carbon dioxide released as a result of the waste treatment process.
	CO emission	This a measure of the quantity of carbon monoxide released as a result of the waste treatment process.
	SO_2 emission	The sulphur dioxide that is released can be further oxidised to form sulphuric acid.
	Particles emission	These emissions are particularly hazardous to human health.
	NMVOC	Non-methane volatile organic compounds are compounds such as benzene, ethanol and acetone.
	Land use	This is an evaluation of the area of land required for the waste treatment plant. The land used for the plant directly affects the

		environment and landscape. It can also be considered a social criterion as it affects the positions of homes and parks.
	Noise	Noise affects the environment as well as human beings. It can disrupt the balance of animal life and human activity.
Social	Acceptability	This is an expression of the overall opinion of the local population. Social acceptability is a qualitative criterion.
	Job Creation	This is the number of jobs created by the creation of a waste treatment plant.
	Social Benefits	These could include job creation, changes in social life and income generation. This is also a qualitative criterion.

(Wang et al., 2009)

The evaluation criteria highlight the depth at which each sustainability indicator can be assessed. This is not an exhaustive list of indicators or criteria; it simply serves to show the most commonly used benchmarks.

2.5.4 Systems Approach to Technology Sustainability Assessment

A system dynamics approach to technology assessment is advantageous as it provides a more realistic assessment (Musango and Brent, 2011). This approach is incorporated into the broader scope of technology development for sustainability, which leads to a framework known as the system approach to technology sustainability assessment (SATSA). SATSA integrates three major components: sustainable development, the dynamic systems approach and technology development (Musango and Brent, 2011). A schematic of SATSA can be seen in Figure 2-16. The figure shows that while the combination of each component yields a valuable and different result, together, the three components provide for an improved technology sustainability assessment practice.

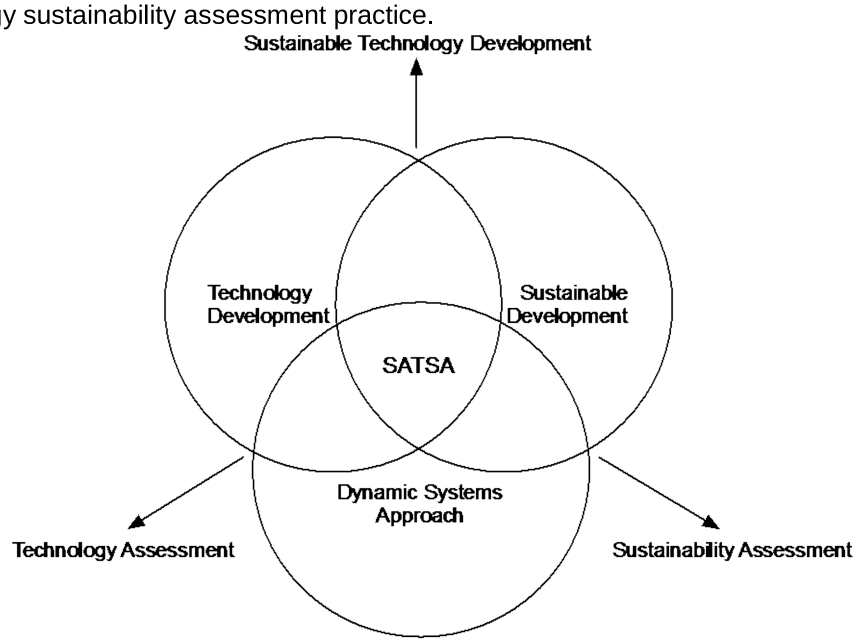

Figure 2 - 16: Schematic of SATSA (Musango and Brent, 2011)

The methodology followed in the SATSA is separated into two major steps: sustainable technology development and system dynamics modelling. Using the framework conceptualised by Musango and Brent (2011), a description of the methodology for waste treatment technologies is provided below.

Step 1: Sustainable technology development

This step entails two activities. The first is the development of waste treatment technology. This is followed by the identification of the available waste treatment technological options. Secondly, evaluation criteria must be identified within the sustainability indicator categories, as has been discussed above. Goals must be set to assess the performance of each waste treatment technology option in the environmental, social, technical, institutional and economic indicator categories.

Step 2: System dynamics modelling

System dynamics modelling consists of three primary activities: modelling the domain of waste treatment technology application, new waste treatment technology assessment and technology accommodation in the waste technology sector domain. The first phase, modelling the domain of waste treatment technology application, requires the development of a base system dynamics model. The modelling should include the inter-linkages between waste treatment technology systems and sustainable development sub-systems. One of the key aims of this phase is to expand the understanding of sustainable waste technology development in a particular context or region.

The second phase of step 2 is the assessment of new technologies. This includes mature technologies that are new to the region under consideration and have been identified as viable options in step 1. The final phase is the accommodation of waste treatment technologies in the waste sector domain. This key phase identifies the capacity for the waste technologies to be accommodated in the current waste management system and achieve the required sustainability goals.

2.5.5 Multi-Criteria Decision Analysis

Decision-making is more difficult in complex situations that incorporate a multitude of variables. Multi-criteria decision analysis (MCDA) addresses this dilemma (Wang et al., 2009). MCDA is best suited for complex problems that feature high levels of uncertainty, conflicting objectives, a variety of data and information forms, multiple interest groups and perspectives and a dynamic socio-economic and biophysical system (Wang et al., 2009). In comparison with a single criteria approach, which is to say, to identify the most efficient alternative for a low cost solution, MCDA employs a multi-criteria method that yields an integrated decision-making result (Wang et al., 2009).

The first steps of MCDA are to identify alternatives for assessment and to select the criteria to assess these alternatives. As noted in the previous subsection, criteria selection could yield similar results. These evaluation criteria should fall within the four sustainability indicators, i.e., economic, social, technical and environmental indicators (Wang et al., 2009).

The selected criteria are then weighted against each other. This is achieved by the use of one of two methods. The first is the equal weights method, which defines the criteria weight as

$$w_i = \frac{1}{n}, i = 1,2 \ldots n$$

This method requires both minimal knowledge of the decision makers' preferences and minimal input from the decision makers. It is weakened by the fact that it ignores the relative importance between criteria (Wang et al., 2009).

Secondly, a rank-order weighting method can be employed. In this method criteria weights can be described as follows

$$w_1 \geq w_2 \geq w_3 \geq \ldots \geq w_n \geq 0$$

$$where \sum_1^n w_i = 1.$$

Rank-order weighting methods can be separated into three categories: subjective, objective and combination weighting methods. Subjective weighting methods solely depend on the decision makers' preferences, while objective weighting methods use the initial data in mathematical methods to obtain criteria weights (Wang et al., 2009).

Once the alternatives have been identified and the weighted criteria to assess them have been selected, three different MCDA methods can be applied: elementary methods, unique synthesizing methods and outranking methods (Wang et al., 2009). Elementary methods include the weighted sum method and weighted product method. These methods calculate the weighting of the criteria against the performance of the criteria. The highest score identifies the best alternative (Wang et al., 2009).

Unique synthesizing criteria methods include AHP, TOPSIS, Grey relation method and MCDA combined fuzzy methodology (Wang et al., 2009). While the other methods assume that all criteria and their weights are expressed in precise numerical detail, the fuzzy methodology recognises the real-world practical constraints of such methods. The subjectivity of responses and information dictates that decision makers have to use linguistics to express these weights and criteria (Wang et al., 2009). The third type of MCDA methods that can be applied are the outranking methods. These are the elimination et choice translating reality (ELECTRE) method and the preference ranking organisation method for enrichment evaluation (PROMETHEE) (Wang et al., 2009). ELECTRE generally consists of two stages. The first is the construction of outranking relations and the second is to exploit these relations to yield the final ranking of the alternatives. ELECTRE methods are sometimes unable to identify a single best alternative, in which case it provides a list of the leading alternatives (Wang et al., 2009). This method is best suited to situations where there are few criteria, but many alternatives. PROMETHEE is similar to ELECTRE, however, while ELECTRE concentrates on the preferences, PROMETHEE takes the difference level between alternatives into consideration (Wang et al., 2009).

The final step of MCDA is to aggregate the results. This is achieved by applying a multitude of the aforementioned MCDA methods. This possibly yields a variety of results, which allows for aggregation. Aggregation is achieved either through voting methods or mathematical methods, which provides a more clearly best alternative (Wang et al., 2009).

MCDA is a powerful tool that can be very useful in providing methods for technology assessment. This is especially true for the assessment of waste technologies, where the context is complex and there are often varying and opposing goals and criteria.

2.5.6 Tools for Environmental Decision-Making

This section discusses four decision support tools that are commonly used for waste treatment technologies. These are Environmental Technology Assessment, Environmental Impact Assessment, Environmental Risk Assessment and Life Cycle Assessment. Table 2-3 present a summary of the important characteristics of these tools.

Table 2 - 3: Characteristics of Four Commonly Used Decision Support Tools

	Environmental Technology Assessment	Environmental Impact Assessment	Environmental Risk Assessment	Life Cycle Assessment
Purpose	Assesses implications of a technology and guides choices of technology	Identifies and predicts the environmental impacts of a project, policy or similar initiative; provides the basis for decisions on acceptability of the likely impacts	Risks to the environment and public health are estimated and compared in order to determine the environmental consequences of the initiative under consideration	Explicitly evaluates the environmental burdens associated with a product, process or activity over the entire life cycle
Scope	Implications for human health, safety and wellbeing, and for natural resources and ecosystems; costs of the technology intervention and the monetary benefits	Impacts on natural resources, ecosystems, human health, safety and wellbeing	Assessment of risks to the environment and human health	Implications for human health, safety and wellbeing, and for natural resources and ecosystems

Initiator	Proponent of technology; investor; stakeholders who may be impacted	Applicant for regulatory approval	Proponent of project or other initiative; investor; stakeholders who may be impacted	Proponent of project or other initiative; investor; stakeholders who may be impacted
Approach	A systematic, comprehensive and qualitative comparison of the pressures on the environment and the resulting impacts	Requirements often prescribed by regulatory authority, including identification of impacts, mitigation and monitoring measures and consultation	Hazard identification, dose-response and exposure assessments, risk characterisations	Life cycle inventory of energy and material requirements and wastes produced; impact analysis and improvement analysis
Timing	Scoping tool at the idea stage, before the development of a formal/full proposal	Prior to decision on whether or not the initiative should proceed	At any time, as determined by the initiator	At any time, as determined by the initiator
Regulatory Status	None – often used to screen options before more detailed assessment	Often required under environmental protection legislation, especially for larger projects or for proposed projects in environmentally sensitive areas	None - may be used to support the conclusions of assessments required by law	None – typically used by producers or consumers to assess the environmental merit of the product, process or activity

Adapted from (IETC, 2003)

All of the above tools are used for decision-making for waste management. However, in South Africa, only EIAs are mandatory and the other tools are applied on a voluntary basis. Nonetheless, since each tool addresses a different environmental aspect, better decisions are achieved by integrating and using them concurrently. In particular, LCA for waste management systems have proven useful in the international context (Cleary, 2009).

2.6 Life Cycle Assessment

Life Cycle Assessment (LCA) is a "cradle to grave" approach that quantifies the consequences of producing and using a product. This study is concerned with the environmental LCA of waste management. Waste management is often marginalised or overly-simplified in product LCAs (Christensen, 2011). A product LCA treats the waste produced as an output of the system, while a waste LCA is wholly focused on this "end-of-life" of a product (Christensen, 2011).

LCA policy is defined in ISO 14040 and 14044. These guidelines outline the stages of LCA, how each stage is to be carried out and the requirements for producing reliable LCA results. LCA modelling provides a quantitative account of resource and environmental issues in waste management that is useful in assessing alternative management systems and in locating where large environmental loads and savings take place within existing systems (Christensen, 2011).

LCA is often broken down into four stages: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and the interpretation of results including a sensitivity or uncertainty analysis. These stages are iterative. As the LCA progresses it is often necessary to return to an earlier stage and make adjustments before moving forward. Figure 2-17 presents these stages.

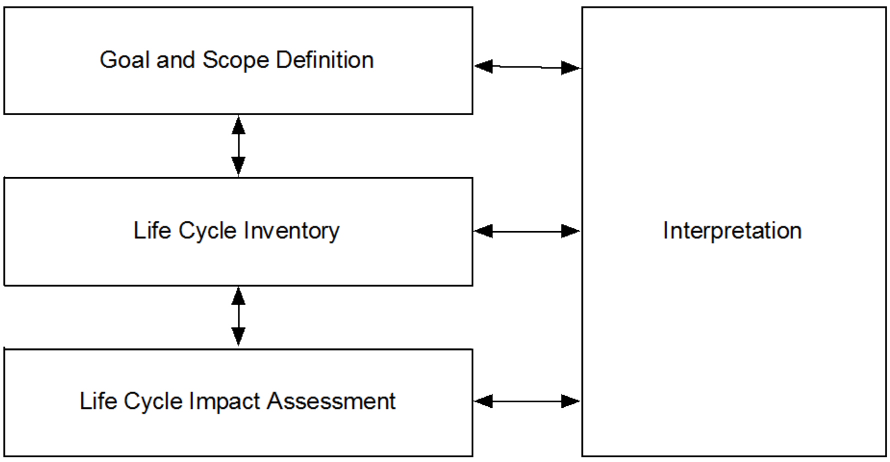

Figure 2 - 17: Stages of LCA

There are two approaches to LCAs, namely, consequential LCA and attributional LCA. Attributional LCA focuses on the physical flows that are environmentally relevant through a life cycle and its subsystems, while a consequential LCA aims to quantify changes in environmentally relevant flows due to possible decisions (Finnveden et al., 2009). One of the main differences between the consequential and attributional approaches is the use of marginal vs. average data. Marginal data is excluded from attributional LCA by a concentration on average data. Consequential LCAs make use of marginal data for, amongst other parameters, modelling electricity production. Marginal data better serves the purpose of assessing the consequences of decisions. It is postulated that consequential LCA should be the primary approach utilised for decision-making (Finnveden et al., 2009).

2.6.1 Goal and Scope Definition

Goal definition is the first step in an LCA. A goal is used as the basis for the scope and the modelling. If done correctly, this crucial stage leaves little to no value choice to be made in subsequent stages (Baumann and Tillman, 2004).

The ISO standard (ISO 14044:2006) requires the goal of the study to "unambiguously state the intended application, the reasons for carrying out the study, the intended audience and whether the results are intended to be used in comparative assertions intended to be disclosed to the public" (ISO, 2006b).

2.6.1.1 Functional Unit

To allow for comparability, all modelled flows for the system are related to a reference flow, which is linked to the functional unit (Baumann and Tillman, 2004). This must be clearly defined and quantifiable as one of its primary purposes is to provide a point of reference for mathematical normalisation of the input and output data (ISO, 2006b).

2.6.1.2 System Boundaries

While the system boundaries are decided in the goal and scope stage of the LCA, as data is gathered during the LCI, it might become clear that the system boundaries need to be adjusted. Boundaries can be in relation to time, geography and the natural and technical system (Baumann and Tillman, 2004).

2.6.1.3 System Subdivision

System subdivision requires the system to be split into the background and foreground system. The foreground system relates to the processes that may be affected by the results of the LCA through decision support. It is the system that is under the direct authority of the decision maker. The background system consists of everything not included in the foreground system (Baumann and Tillman, 2004).

2.6.2 Inventory Analysis

The LCI analysis consists of the following three primary activities:

1. Use the system boundaries from the goal and scope definition to construct a flowchart.
2. Collect data for the activities involved in the waste management system, including documentation for the data collected.
3. Calculate the environmental loads of the system with relation to the functional unit.

(Baumann and Tillman, 2004)

2.6.3 Life Cycle Impact Assessment

The LCI calculates the environmental loads from the processes involved in the waste management system, while the LCIA translates those loads into environmental impacts. The environmental impacts considered in an LCA can be broadly grouped into three categories or Areas of Protection (AoPs): natural resource use, ecological consequences for the natural environment, and human health (Baumann and Tillman, 2004). The LCIA aims to make the results more comprehensible and readable by reducing the multitude of outputs from the LCI to about 15 impact categories. These could include climate change, stratospheric ozone depletion, photochemical oxidant formation, acidification, eutrophication, human toxicity, resource depletion and particulate matter.

The ISO standard for LCA (ISO 14040:2006) breaks the LCIA into a series of steps.

1. Selection of impact categories, category indicators and characterization models
2. Classification of LCI results
3. Calculate category indicator results through characterisation
    a. Develop LCIA profile for study (final mandatory stage)
4. Normalize results relative to reference information (optional)
5. Group results (optional)
6. Weight impact categories (optional)

(ISO, 2006a)

2.6.3.1 Impact Categories

Climate Change

Climate change impacts both the natural environment and human health. Man-made climate change is caused by the emission of GHGs, which absorb infrared radiation from the earth (JRC-IES, 2010). The Intergovernmental Panel on Climate Change (IPCC) developed a model to assess the radiative force of GHGs, which is now known as the Global Warming Potential (GWP). The GWPs of GHGs are used as characterisation factors for the impact assessment. These factors can be used to model an increase in temperature, which results in damage to the natural environment and human health. Human health concerns include increases in malnutrition and malaria, while environmental or ecosystem concerns include the loss of species or changes in biomass (JRC-IES, 2010).

Ozone Depletion

90% of the total atmospheric ozone can be found in the stratosphere. This ozone is vital for life as it stops harmful solar ultraviolet UV-B[6] radiation from reaching the lower levels of the atmosphere. This short wavelength radiation plays a key role in the development of skin cancer, increasing the risk to the human health AoP. It also affects aquatic ecosystems and terrestrial plant life (JRC-IES, 2010). The characterisation factor for this impact takes into account the destruction of the stratospheric ozone layer by ozone depleting substances from anthropogenic emissions (JRC-IES, 2010). Ozone depleting substances are chemicals that contain bromine and chlorine atoms. These elements have a long life in the atmosphere, which allows them to reach the stratosphere. Through heterogeneous catalysis, they are able to destroy large volumes of ozone molecules (JRC-IES, 2010).

Chlorine atoms can be found in chlorofluorocarbons[7] (CFCs) and bromine atoms in halons[8]. Chlorine and bromine atoms act as free radical catalysts in a series of degradation reactions, which result in ozone destruction. The sequence of reactions is shown below:

$Cl + O_3 \rightarrow ClO + O_2$

$Br + O_3 \rightarrow BrO + O_2$

$ClO + O \rightarrow Cl + O_2$

$ClO + BrO \rightarrow Cl + Br + O_2$

As can be seen, the final result of the reaction sequence is an oxygen molecule and single chlorine and bromine atoms, which can begin another series of reactions (JRC-IES, 2010).

Human Toxicity

A toxic impact category relies on models that take into account a chemical's fate in the environment and to human exposure. An LCIA accounts for the releases of all substances under consideration irrespective of the point in the system at which they are released. This impact category primarily concerns the AoP human health. The damage to human health can be carcinogenic or non-carcinogenic. Exposure through food or air allows the toxins to enter the body and the bloodstream. The main pathways under consideration are inhalation and ingestion of meat, dairy products, eggs or fish. This toxic impact category can be split into subcategories that consider cancer effects, the impact of ionising radiation, respiratory diseases and other non-cancer effects (JRC-IES, 2010).

Particulate Matter

Primary or secondary particulate emissions increase the ambient concentration of particulate matter (PM). PM can be measured in a range of ways, including total suspended particulates, PM with a diameter smaller than ten microns (PM_{10}), PM with a diameter smaller than 2.5 microns ($PM_{2.5}$) and PM with a diameter smaller than 0.1 microns ($PM_{0.1}$). Mechanisms that

[6] UV-B radiation has a short wavelength of approximately 300 nanometres.
[7] CFCs were commonly found in aerosols.
[8] Halon is an unreactive gas compound, often used in fire extinguishers.

emit substances such as SO2 and NOX form secondary emissions of PM. This impact has an endpoint effect on the AoP human health (JRC-IES, 2010).

Photochemical Ozone Formation (POF)

This impact category has an effect on both human health and the natural environment. Photochemically generated pollutants can have a negative impact because of their reactive nature. They are able to oxidise organic compounds on the surfaces they have exposed. Human health impacts occur when these compounds are inhaled and come into contact with the respiratory tract. They can harm the tissue and cause respiratory diseases. In similar fashion, the natural environment is impacted when the compounds come into contact with the surface of plants and cause oxidative damage on photosynthetic organelles[9] (JRC-IES, 2010).

Characterisation models for POF include volatile organic compounds (VOCs) and nitrogen oxides. Emissions of these two compounds lead to photochemical oxidation of VOCs, resulting in an increase in tropospheric ozone concentration. This can lead to critical exposure of humans and vegetation, causing damage to the AoPs human health and the natural environment (JRC-IES, 2010).

Acidification

Acidification impacts the natural environment. Generated by the acidification of airborne chemicals, acidification is the process of increasing the acidity of soil or water systems by hydrogen ion concentration. The three primary contributing substances to acidification are nitrogen oxides (NO_x), sulphur dioxide (SO_2) and ammonia (NH_3). A leaching of nutrient cations and H+ can lead to a loss of biodiversity and a decrease in bioproductivity (JRC-IES, 2010).

Eutrophication

Eutrophication deals with the effects of the nutrients, nitrogen and phosphorous, on terrestrial and aquatic ecosystems. Terrestrial eutrophication is caused by the accumulation of airborne emissions of nitrogen compounds like nitrogen oxides, NOx from combustion and ammonia, and NH3 from agriculture (JRC-IES, 2010). While terrestrial eutrophication is primarily concerned with nitrogen compounds, aquatic, freshwater, eutrophication is concerned with phosphorous. Eutrophication can lead to the depletion of oxygen near the bottom of the vulnerable system. Eutrophication impacts the natural environment through damage to crops, forestry, freshwater ecosystems, marine ecosystems and fishing (JRC-IES, 2010).

[9] A specialised or organised structure with a living cell

Ecotoxicity

Toxicity impact categories are based on relative risk and the associated consequences of the chemicals being released into the environment. Ecotoxicity impacts the AoP natural environment. Ecotoxicity considers the effect of emissions in the air, soil, and fresh and marine water on vegetation crops, and species living in the water and in the ground. Ecotoxicity damages marine, freshwater and terrestrial ecosystems (JRC-IES, 2010).

Abiotic Resource Depletion

The earth has a finite quantity of non-renewable resources. This impact category affects the AoP natural resources (JRC-IES, 2010). The depletion of abiotic resources is more than just one impact category. The first subcategory considers the loss of elements and fossil fuels based on the depletion of the element "antimony" and the second considers the loss of fossil energy from the earth's reserve in mega-joules (MJ) (Oers et al., 2002). Oers et al. (2002) state that, "Abiotic resource depletion is the decrease of availability of the total reserve of potential functions of resources."

2.6.4 Interpretation of Results

The interpretation phase of the LCA aims to provide results based on a combination of the LCI, LCIA and goal and scope. Conclusions consistent with the previous three phases should be presented with the limitations explained and recommendations provided (ISO, 2006a).

The ISO standard for LCA (ISO 14044:2006) divides the interpretation phase into three stages with several elements:

1. Identify significant issues based on the results of the LCI and LCIA phases
2. Evaluate for completeness, consistency and sensitivity checks
3. Provide conclusions, limitations and recommendations

Table 2-4 presents the six evaluation checks used in the interpretation of the results.

Table 2 - 4: Tests for Robustness of Results and Conclusions

Type of Test	Purpose of Test
Completeness Check	Check for data gaps in the LCI or completeness of the LCIA
Consistency Check	Check for appropriateness of life cycle modelling and methodological choices
Uncertainty Analysis	Check for the effect of uncertain data
Sensitivity Analysis	Identification and check of critical data
Variation Analysis	Check effect of alternate scenarios and models
Data quality assessment	Assess the degree of data gaps, approximate and appropriate data

Adapted from (Baumann and Tillman, 2004)

2.6.5 Life Cycle Assessment in South Africa

South African law does not require the use of LCA studies, and there is little reference to LCA in governmental policies and documents (DEAT, 2004). The Department of Environmental Affairs and Tourism has produced a series of information documents on integrated environmental management. One of these documents highlighted LCA. The following six challenges were identified in implementing LCA as a decision support tool:

1. The absence of a perceived need for LCA.
2. The scarcity of LCA expertise.
3. Difficulty in accessing high quality data.
4. Incorrect perceptions of the application of LCA in relation to other tools.
5. The high cost of LCA studies.
6. The lack of widely recognised and user-friendly impact assessment methods.

(DEAT, 2004)

As international industry and governments are moving towards "greener" methodologies, there has been a slow but increasing appreciation of the value of LCAs and life cycle engineering (LCE) as tools for environmental management (Brent et al., 2002). Data availability and data quality is a problem commonly experience by LCA practitioners at research institutions. Due to the lack of incentives, industries in South Africa are reluctant to provide LCI data (Brent et al., 2002).

Brent et al. (2002) highlight the barriers LCA practitioners could face in South Africa due to the lack of relevant LCIA methodologies for the local context. Most of the environmental impact categories developed by European institutions are Europe-specific. Impacts such as water resources, which are important to a water scarce country like South Africa, are excluded from many LCIA methodologies (Brent et al., 2002).

While there are many barriers to overcome, institutions like the CSIR are developing methodologies for LCIA in South Africa. There is growing external demand, and legislative requirements from the EU, for LCAs of products and goods exported from South Africa. While LCA in South Africa is still being developed, it is a growing field and the creation of a South African LCA network is the next step that is required (Brent et al., 2002).

2.6.6 Life Cycle Assessment in Waste Management

The previous section highlighted several barriers to the wide scale deployment of LCAs in South Africa. However, internationally, LCAs for waste management have become more widespread in the past decade. Clift et al. (2000) presented a methodology for utilising LCA as a tool to assess the environmental impact of waste management. Their study advocated that LCAs are the best way to structure information to guide the decision making process (Clift et al., 2000) and was, conceivably, the foundation of all subsequent waste management LCAs. This section summarises two international LCAs from developing countries that have been conducted on waste management in municipalities. These studies were selected as, like South Africa, the countries on which they are based (China and Indonesia) are considered Newly Industrialised Countries (Singal, 2014).

Zhao et al. (2009) investigated MSW management in Tianjin, China through a life cycle perspective with a particular focus on GHG emissions. The study evaluated the GHG emissions of the baseline scenario in Tianjin as well as those of a series of alternative scenarios. The functional unit was the total waste generated in the central districts of Tianjin in 2006. This study assessed seven scenarios. The baseline scenario treats 48.9% of the MSW in a WtE plant, 49.5% in a landfill and the remainder is open dumped. The six scenarios built for the study adjust the baseline as follows: the addition of LFG technology (S1); incineration of all MSW (S2); a recycling system including a MRF (S3); composting 50% of kitchen waste (S4); treating 50% of kitchen waste in an AD plant (S5); and an integrated system that recycles waste at 30% efficiency in a MRF, treats 50% of kitchen waste in an AD plant, incinerates 48.9% of the remaining waste in a WtE plant and treats the residual waste in a landfill with LFG technology (S6) (Zhao et al., 2009).

Some of the data were sourced from the ecoinvent database as specific data for the MRF and AD plant, amongst others processes, were unavailable for the Tianjin study. Other data sources were site specific (landfill and WtE plant) or taken from literature (electricity mix). This study focused on GWP as the only impact category and the scenarios were modelled in the Chain Management by Life Cycle Assessment (CML) software package (Zhao et al., 2009). The results of the LCIA showed the integrated system (S6) to have the lowest GWP, followed by the LFG scenario (S1) and WtE scenario (S2), which performed similarly. The AD plant and composting scenarios (S4 and S5) both reduced the baseline GWP by approximately 25%. The recycling scenario (S3) did not have a significant influence on the GWP due to the presence of a small recyclable fraction in the MSW (Zhao et al., 2009).

Another study by Gunamantha and Sarto (2012) investigated options for treating MSW, with a focus on WtE technologies, assessing the environmental impacts through a life cycle perspective. This study was conducted on the Yogyakarta, Sleman and Bantul regions of

Indonesia known by the acronym KARTAMANTUL. The goal of the LCA was to compare the energetic valorisation of each scenario (a total of five alternatives) with each other and to the baseline scenario. The functional unit of the study was one tonne of MSW from KARTAMANTUL (Gunamantha and Sarto, 2012).

In the baseline scenario for KARTAMANTUL, all waste is landfilled. The five alternate scenarios proposed for assessment were: landfilling with LFG recovery and treatment to produce electricity (S1); a combination of incineration and an AD plant for organic biowastes (S2); a combination of gasification and an AD plant for the organic biowaste (S3); complete incineration of all waste (S4); and direct gasification of all waste streams (S5). This study considered four impact categories: GWP, acidification, eutrophication and POF. Furthermore it accounted for the substitution for electricity production. Waste characteristic data was collected from the disposal site and data for the model parameters were taken from literature. The results of the LCIA showed that the direct gasification of all the waste (S5) had the lowest impacts for GWP, eutrophication and POF. The mix of gasification and AD (S3) resulted in the lowest impact for the acidification category; however, the direct gasification scenario (S5) performed very similarly (Gunamantha and Sarto, 2012).

These two studies illustrate how countries similar to South Africa, in terms of development, have used LCAs to assess the environmental impact of their waste management. They can therefore be compared with the LCA conducted on MSW management in NLM.

2.7 Chapter Summary

This literature review provided the context for MSW management in South Africa, focusing on policies that control municipal practices and highlighting the good MSW management practice techniques identified by the CSIR. The motivation for this study, which is to promote sustainable development, was further explored as well as South Africa's energy needs. Waste treatment technologies, some of which are used to build potential scenarios in the LCA, were explored. In addition, the literature review presented decision support tools and approaches that can be utilised by stakeholders to select technologies and assess scenarios. LCA as a decision support tool was highlighted. The literature review also discussed the phases of the LCA methodology and explored the impact categories, which are used in the LCA on Newcastle. The status of LCA in South Africa was investigated. Finally, two international LCA studies on waste management were presented for comparison with this study.

3: METHODOLOGY

This chapter presents the mixed methodological framework used in this study. It discusses the rationale for the research as well as the process involved in designing the study. The different methodological approaches used are highlighted and discussed. The purpose and method of streamlining the waste LCA are also examined. In this regard, the modelling programme used to conduct the consequential LCA, i.e. EASETECH, is reviewed. Finally the limitations and assumptions applicable to the study are highlighted.

3.1 Research Design

Waste management is a multifaceted field that varies depending on the socio-economic context, location and stakeholders involved. Hence, this study undertakes an embedded case study (i.e., integrating quantitative and qualitative data into a single case) approach, which performs an empirical inquiry that investigates contemporary municipal waste management in the South African context (Scholz and Tietje, 2002). The integrated methodological approach for this single case design was developed through an iterative process premised on key informant interviews, a systematic literature review, and purposively selected postgraduate coursework[10]. The researcher gained an appreciation of the complexity of IWMS as well as a theoretical and applied understanding of waste LCA modelling (i.e., formative scenario analysis) and decision support through the application of state-of-the-art knowledge.

Decision support for municipal waste management is a complex (i.e., heterogeneous material flows) and bureaucratic undertaking. Narrowing the assessment to the environmental impact of waste management systems allows for a more focused and internationally recognised technical approach, from which reliable outputs can be attained. Figure 3-1 presents a flowchart of how the study developed from the knowledge-building phase to decision support tool selection, case study selection and the decision to use EASETECH for the LCA model. The selection of this particular case study was the result of key informant interviews, available and accessible data, and desktop research. The rationale for the selection of Newcastle as the LCA case study is highlighted.

Data collected from the Newcastle Municipality and surrogate data from the EASETECH database and ecoinvent were used to model the environmental impacts of the current waste management system and alternative IWM scenarios. The results of this LCA were presented to the key informant from NLM.

[10] Coursework included short courses (Sustainable Cities and Ecological Design for Community Building) at the Sustainability Institute at Stellenbosch University and a course on the waste LCA model EASETECH at the Technical University of Denmark (DTU). This course covered waste management and LCA methodology.

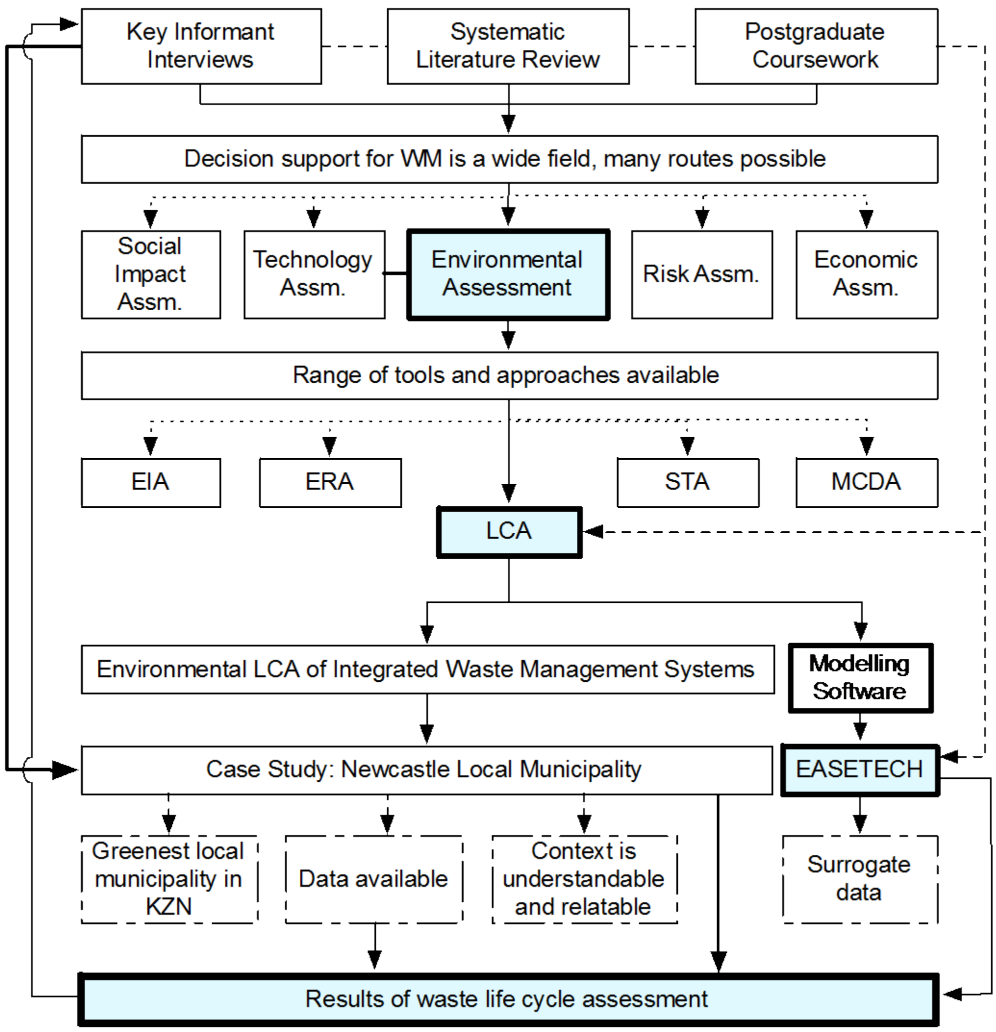

Figure 3 - 1: Research Design and Analytical Model

Being scientific in nature, this study focused on the environmental assessment of waste management, which has direct correlation with technology assessments, i.e., selecting the correct group of technologies for the context. As noted in the literature review, there is a wide array of tools and approaches to choose from in the environmental assessment field. This study chose to follow a life cycle approach to waste management assessment, as data was available as well as intellectual and technical support for EASETECH and the LCA methodology. Figure 3-1 illustrates the process followed in conducting this study, resulting in conclusions that can be drawn from the LCA which were presented to the key informant in NLM.

Due to the nature of LCA reports, aspects of the methodology and the rationale for this study are further explained in Chapter 5, in particular the Goal and Scope Definition, and LCI.

3.2 Integrated Methodology

This study integrates quantitative (life cycle assessment) and qualitative knowledge (key informant interviews) to gain empirical insight into the case and its potential development. Qualitative knowledge on the case was gathered from key informant interviews, which provided a nuanced contextualisation of local MSW dynamics and engendered the construction of scenarios for IWM in NLM. Quantitative data (for the life cycle inventory) was collected from the NLM, ecoinvent, and the EASETECH database in order to conduct a consequential life cycle assessment. This quantitative data was used to populate the models of IWMS for NLM. The models were built and assessed in the EASETECH waste management life cycle modelling software.

There are merits to an integrated approach. A quantitative method can be contextualised with the use of qualitative responses from key informants. In the case of this study, the key informant interviews were instrumental in identifying the case study, problem structuring, and data collection for LCA modelling.

3.2.1 Systematic Literature Review

A systematic literature review differs from a standard literature review in that the former aims to locate all the data on a specific subject regardless of the author's bias. This data can be from published or unpublished works (Nightingale, 2009). Nightingale (2009) adds that studies with significant findings, whether positive or negative, are preferred by high impact journals. A systematic literature review aims to locate all data to provide a balanced and unbiased summary of the literature on a particular subject (Nightingale, 2009).

A systematic literature review was carried out for this study; portraying the current status of waste management in South Africa, as well as the current status of energy supply and demand in the country. Waste management decision support tools and approaches, such as SATSA and MCDA were also reviewed. The systematic literature review aimed to encompass all factors, while remaining focused on topics relevant to the research question.

3.2.2 Qualitative Research Methodology

3.2.2.1 Key Informant Interviews

A series of qualitative, semi-structured interviews were held with a key stakeholder (the waste superintendent) in the field of waste management for NLM; these interviews included site visits to waste management facilities in Newcastle. The interviews for this study were conducted both telephonically and administered in person.

The interviews with the key informant were crucial in understanding the topic and in guiding the selection of a relevant case study. The interviews informed the selection of waste treatment technologies that are specific to the context and area. Indicators of importance vary between municipalities and stakeholders. The responses from the key informant interviews were used in conjunction with the knowledge gained from the systematic literature review to build an appropriate LCA model (i.e., scenario analysis) for the selected case study.

3.2.3 Quantitative Research Methodology

3.2.3.1 Life cycle modelling

The study aimed to model the current waste management system and four other possible scenarios for integrated waste management that may be applicable to NLM. The model was constructed through an environmental life cycle perspective. The environmental impacts of the waste management scenarios under consideration were evaluated and calculated from the point of generation, through to transport and collection, recovery, treatment and reprocessing. In other words, the entire life cycle of the municipal solid waste was assessed.

A wide variety of modelling tools are available from many different institutions around the world. Table 3-1 presents eight LCA modelling programmes that were researched for this study. The key features of each modelling programme are discussed and highlighted for comparison. Ultimately, EASETECH, the successor to EASEWASTE was selected and is discussed, as a modelling tool, in more detail in Section 3-5.

Table 3 - 1: Key Features of Waste Management LCA Models (Christensen, 2011)

Model	Functional Unit	Waste Fractions	Avoided Burdens	Landfill time frame	Capital burdens	Scope of analysis	Model outputs	Specific features
IWM-2	Management of total MSW in a defined geographical region over a defined time period	MSW subdivided into glass, paper, metal, plastic textiles, organic and other	Accounted for by subtracted system boundaries	Composition of gas and leachate based on current measurements – limited time frame	Not included	LCI, no impact assessment. Economic assessment of overall costs	Net energy use, 22 air emissions, occupied landfill volume, recovered materials and compost	CO_2 credit (negative burden) given to virgin paper production, which is assumed to result in re-planting of young trees with rapid CO_2 uptake. No differentiation done between fossil and biogenic CO_2
IWM Canada	WM from the point at which material is discarded into the waste	MSW subdivided into paper, glass, ferrous metals, aluminum, plastics, food waste, and other waste	Accounted for by subtracted system boundaries	100 years. Waste remaining after this period accounted for as residual waste	Not included	LCI, no impact assessment. Economic assessment of overall costs	Total energy used, 13 air emissions, 5 water emissions, residual solid waste	Inventory results converted into everyday equivalents. Wherever possible, impact equivalents have been selected that reference everyday activities that are significant sources of the pollutant
ORWARE	Treatment of waste generated within a certain area during a certain period of time	Household waste, industrial waste, construction and demolition waste (all with subcategories), sewage sludge	Accounted for by expanded system boundaries	Short time period extending until end of methane generating phase, complemented with infinite time frame with all landfilled material counted as potential emissions	Not included	LCI, no impact assessment. Economic analysis of financial costs and environmental costs of emissions	Energy recovery and use, approx. 30 different emissions to air, water and soil	Waste flows must be described in terms of elements; composition, which determines performance of treatment processes. New waste fractions easily added when elemental composition available

Table 3-1 (Continued)

Model	Functional Unit	Waste Fractions	Avoided Burdens	Landfill time frame	Capital burdens	Scope of analysis	Model outputs	Specific features
ISWM/MSW-DST	Management of 1 tonne of MSW as defined by the US EPA, set out for curbside collection	MSW subdivided (47 categories) into yard waste, paper, food waste, ferrous metals, aluminum, glass, plastic, miscellaneous, and commercial waste	Accounted for by subtracted system boundaries	Emissions are reported based on decomposition over 20,100 or 500 years	Not included	LCI, no impact assessment. Economic full-cost accounting reflecting total cost rather than dollars per tonne	Net energy use, 32 different air and water pollutants, solid waste, landfill disposal rate, recovered materials and compost	Structured as linear programming model. Allows optimisation by cost, energy use or certain emissions. Solutions can be constrained by, for instance, required minimum recycling, or avoiding a specific waste treatment process
WISARD	Collection and treatment of MSW generated by a local community over one year	MSW subdivided into ferrous metals, fines, glass, combustibles, nappies, non-combustible, nonferrous metals, paper, plastic, putrescible, textiles	Accounted for by subtracted system boundaries	Until end of biogas formation phase, corresponding to about 100 years	Included	LCI and impact assessment. Several characterisation methods included. Economic analysis of financial costs	Raw material extraction, water consumption, intermediate material input, emissions to air, water, and soil, residual waste, recovered matter, energy use	Different versions of Wisard developed for UK, France, Italy, and New Zealand. Waste flows must be described in terms of elemental composition. "Simplified results" relate model output to some quantity of environmental impact that is easier to interpret. Software enables Monte Carlo simulation to assess possible range of uncertainty

Table 3-1 (Continued)

Model	Functional Unit	Waste Fractions	Avoided Burdens	Landfill time frame	Capital burdens	Scope of analysis	Model outputs	Specific features
LCA-IWM: MSWMS	The amount of waste generated in a city and entering the waste management system within one year	Organic waste, mixed and residual waste, paper and cardboard, glass, metal, plastic and composites, mixed dry recyclables, electric and electronic equipment	Accounted for by subtracted system boundaries	Collection of gas until 10 years after closure, collection of leachate and treatment until 50 years after closure	Not included	Comparing scenarios of treatment activities. The prognostic tool provides input data to the assessment. Input data are also offered in two levels of default values. Assessment of environmental, economic and social performance	Emissions, resources consumption, material flows	Experienced users can change default values. Generates aggregated indicators for environmental, economic and social impacts, respectively
EASEWASTE	A given amount of solid waste generated for an area/city	48 material fractions. A few examples; newsprint, paper and cardboard containers, soft plastic, plastic bottles, wood, textiles, rubber, clear glass, aluminum, metal foil, soil, gravel, batteries	Accounted for by expanded system boundaries	The processes are divided into four separate independent time periods, which are: Waste placements, closure of landfill, active gas and leachate period, non-active period with no collection of gas and leachate. These periods can be set to as many years as desired	Not included	LCI and impact assessment	Consumption of all resources, emissions to air, water and soil and generation of solid waste for a solid waste management system	Provides detailed LCI and LCA tables on individual technologies as well as scenarios. Data can be exported to Excel. User can adjust all data. Calculated sensitivity ratios

Table 3-1 (Continued)

Model	Functional Unit	Waste Fractions	Avoided Burdens	Landfill time frame	Capital burdens	Scope of analysis	Model outputs	Specific features
WRATE	Quantity of municipal waste managed by a municipality over one year	10 waste streams, divided into 15 fractional components, which are further divided into sub-fractions with predefined elemental composition (67 fractions)	Allocation of all inputs to outputs. No system expansion	Infinite landfill time frame (20 000 years) to ensure that more than 99% of emissions are accounted for	Included	LCI. Several LCIAs and characterisation methods. Sankey diagram mass flow	Quantity of energy recovered, consumption of 180 resources, 350 air emissions, 280 water emissions, and 150 soil emissions	Object-based modeling. Use of Sankey diagrams. Automatic reporting functionality. Transparent user editable mathematical formula. Integrated result analysis. Unrestricted number of WM processes

(Christensen, 2011)

EASETECH was selected as the life cycle modelling tool because it provides highly detailed, robust results. It is the result of more than a decade of research and development, which has ensured that it is of the highest possible quality. The programme developers were willing to train the researcher and support the study by providing quality assurance on the scenarios built for comparison. Furthermore, EASETECH was available free of charge for academic purposes.

The models were built in EASETECH, which provided a detailed appraisal of each scenario for the purpose of the waste-LCA. The life cycle modelling required input data, which included physical waste composition from NLM, diesel usage for waste transportation and collection and electricity mix supply data for South Africa. Furthermore, data was used from the EASETECH database to fill the gaps in the model.

3.2.3.2 EASETECH Database

The EASETECH modelling programme contains a detailed database for waste material fractions; elementary exchanges with the environment and a range of processes that can be used to build integrated waste management scenarios.

The material fractions catalogue contains a list of material fractions with their material properties defined. It consists of more than 70 fractions gathered from a variety of highly detailed waste characterisation studies carried out at the Technical University of Denmark (DTU). The elementary exchanges catalogue provides the user with approximately 3700 elementary exchanges that can be used to define the effects of process exchanges (Clavreul et al., 2013).

3.2.4 Case Study Methodology

This study highlights the case of the environmental impact of NLM's waste management. An effective case study requires an integration of data and knowledge from a variety of sources (Scholz and Tietje, 2002). Due to the complexity of waste management and the need for contextualised solutions, the case study method is a valuable approach. This case study utilised life cycle assessment as the method for knowledge integration. The key informant interviews revealed that waste management assessment and the selection of suitable treatment technologies is specific to an area, waste stream and socio-economic context. Solutions from one city or municipality cannot simply be transferred to another city. Each municipality has unique requirements.

This study is an embedded case study, which allows for a mix of methods utilising quantitative data, and the formulation of hypotheses or application of statistical analysis, as opposed to a holistic case study, which focuses on a purely qualitative approach (Scholz and Tietje, 2002). The purpose of this case study was research. The researcher was motivated to understand LCA as a decision support tool for integrated waste management and the appropriateness of EASETECH as a modelling tool in a South African context.

A case study is built on three levels; understanding the case, conceptualizing a model and finally, explaining the propositional logic of the case through data (Scholz and Tietje, 2002). Chapters Four and Five follow this structure. First, NLM's socio-economic status introduced and an understanding of the context is built. Second, the waste management scenarios are modelled for evaluation. Finally, these models and their results are analysed and reviewed through the LCIA and its interpretation phases.

LCA allows the case, i.e., waste management in Newcastle, to be evaluated with respect to its impact on related systems. LCA combines two types of knowledge integration, primarily, the method of systems, which uses a synthesis of subsystems by studying each subsystem separately (for example; soil, water and air). This is then integrated and related to other soft factors (for example; socio-economic context or history) (Scholz and Tietje, 2002). The secondary type of knowledge integration is the method of disciplines, which allows for knowledge to be combined from different fields, both the natural and social sciences. This method includes the assimilation of quantitative data and qualitative information, as required in a LCA (Scholz and Tietje, 2002).

3.3 Streamlining Life Cycle Assessment

This LCA was conducted in accordance with ISO 14040:2006 and ISO 14044:2006. As highlighted in Chapter 2, LCA is broken down into four stages. These are iterative; as the study develops, each stage leads from one to the next and back again:

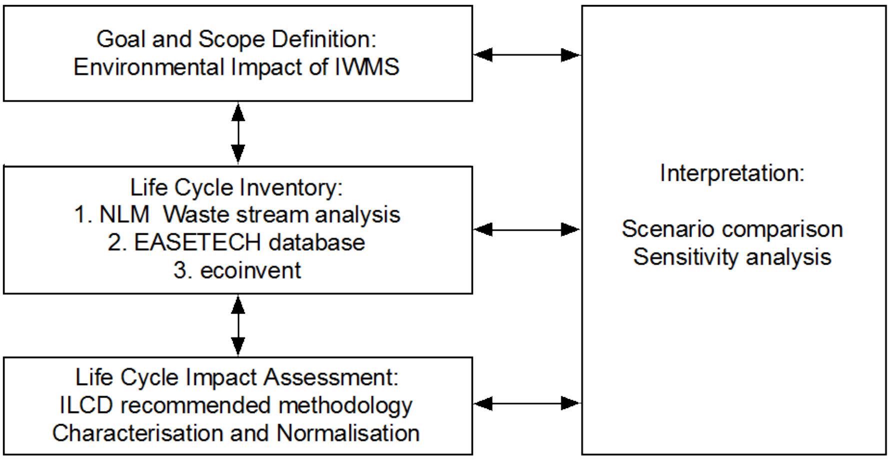

Figure 3 - 2: LCA Stages for NLM

Streamlining an LCA can involve a range of approaches. The Society of Environmental Toxicology and Chemistry (SETAC) identifies some of these approaches, including removing upstream or downstream components, using specific entries to represent data, using qualitative or less accurate data and using surrogate process data. This LCA was streamlined by utilising surrogate process data, which includes replacing selected processes with similar processes based on their chemical, physical or functional similarity to what was being replaced (Weitz et al., 1999). Streamlining was necessary due to a lack of resources such as a lack of available data on MSW in South Africa, the lack of data on waste treatment technologies in the country and time constraints. LCA is an uncommon tool, especially in SA, for the assessment of IWMS.

SETAC clarifies this approach by describing data as sometimes impossible or difficult to obtain. Hence, data that is based on a similar process, which is more easily obtainable, may be used instead. This approach is advantageous as estimates can be made for processes, where there would otherwise be no measure. However, caution should be exercised when selecting this surrogate data in order to ensure it is representative of the actual process under study (Weitz et al., 1999).

A streamlined LCA is more suitable if the results are to be used more for scoping and identifying problematic processes than for marketing and public policy and if it is for internal, rather than external use (Weitz et al., 1999). Following the approach set out by SETAC, this study can be considered a streamlined LCA, as surrogate data was used.

3.4 Data Collection and Analysis

Data collection is a vital step in conducting a LCA; it forms a part of the LCI stage of the LCA. For the LCA on Newcastle, data was collected from a variety of sources. A large range of data was required, including data on physical waste composition, electricity generation and the electricity mix, chemical waste composition, waste treatment technologies, reprocessing facilities, landfill, and diesel usage data. The data was sourced from; the NLM IWMP and the Superintendent of Waste Management at NLM, the ecoinvent database, and the EASETECH database developed at DTU.

The data collected was used to model the environmental impact of the scenarios that were built for analysis. Each dataset was assessed for quality according to five indicators: reliability, completeness, temporal correlation, geographic correlation and technological correlation as per Weidema and Wesnæs (1996). The best available data was used for the LCA and where surrogate data was used, experts at DTU confirmed its appropriateness and applicability. Data collection and analysis of the data quality is detailed further in the LCI in Section 5.2.

3.5 EASETECH and the Data Processing

3.5.1 History and Development of EASETECH

Drawing on their experience in waste management and life cycle assessment, DTU developed the Environmental Assessment System for Environmental TECHnologies (EASETECH). EASETECH aims to "perform the LCA of complex systems handling heterogeneous material flows" (Clavreul et al., 2013). This tool focuses on material flow modelling, using flow compositions as the foundation for the LCA calculations. Furthermore, it has an easy-to-use user interface for setting up scenarios of waste management systems. EASETECH comes preloaded with a detailed database covering elemental analysis of waste streams, waste treatment technology processes and exchanges with the environment, to name but a few. Furthermore, EASETECH calculates LCI and LCIA results as well as providing an opportunity for sensitivity analysis.

The foundation of EASETECH was built from the model EASEWASTE, which was released in 2004 and subsequently updated in 2008 and 2012. EASEWASTE handled a flow of material fractions, with different physical properties and chemical compositions, as a matrix of material properties and waste fractions. Fractions were grouped based on similarity or dealt with individually in different processes (Clavreul et al., 2013). Based on the experience gained from EASEWASTE, the development of more complex waste management systems, and the need for sensitivity and uncertainty assessment, the development of another LCA modelling programme was necessary (Clavreul et al., 2013).

3.5.2 Program Description and User Interface

This section briefly introduces the EASETECH programme and the user interface for building scenarios and calculating impacts. Figure 3-3 shows the home screen of the programme. The left sidebar (1) displays the material processes, projects, external processes and tests. The bottom section of the right-hand screen (2) displays information on the selected technology, the inputs and outputs from the processes and scenarios. The main part of the display (3) holds the scenario, which is being built.

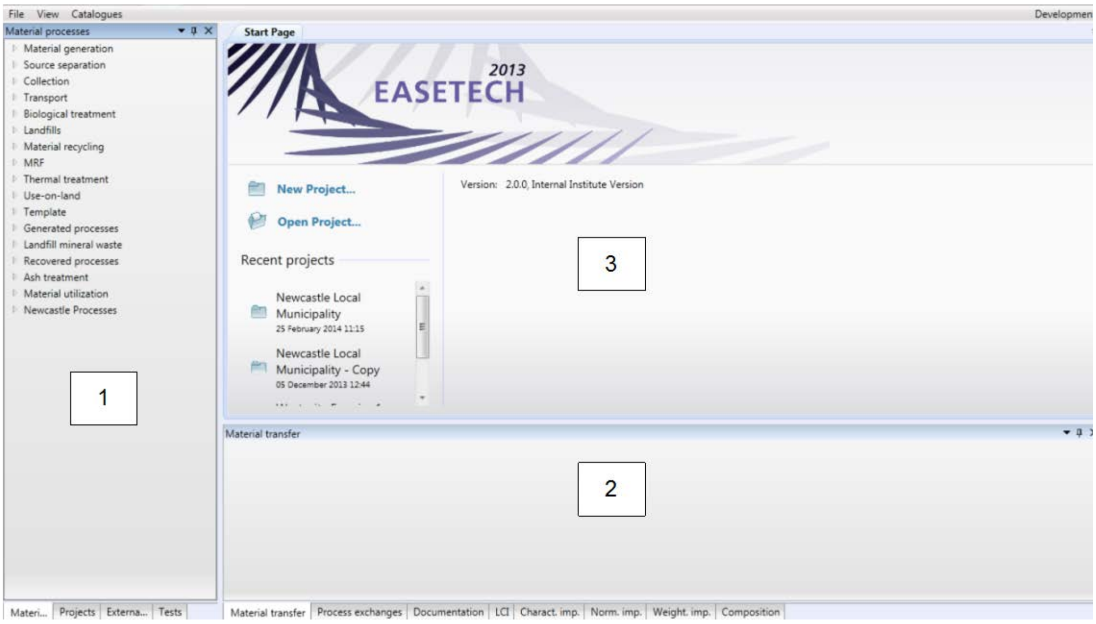

Figure 3 - 3: EASETECH Home Screen

Figure 3-4 shows an example of scenario that has been built using the material processes from the left sidebar. The template group of processes (1) has been expanded to show the various options from which a scenario can be built. These modules can be dragged and dropped into the main screen (2) to build the scenario.

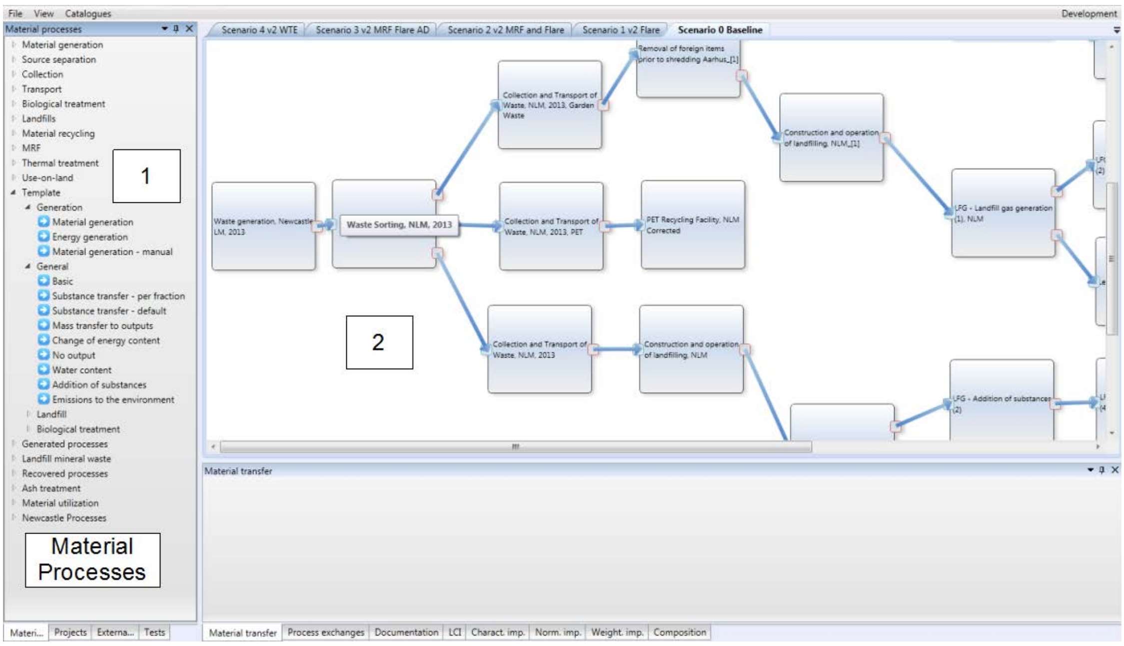

Figure 3 - 4: EASETECH Project Screen

In Figure 3-5 the "waste generation" module is highlighted (1). Selecting the "waste generation" module in the scenario and material transfer tab in the bottom bar shows the material fractions of the waste (2) that have been inserted and the "total amount," which is the functional unit chosen.

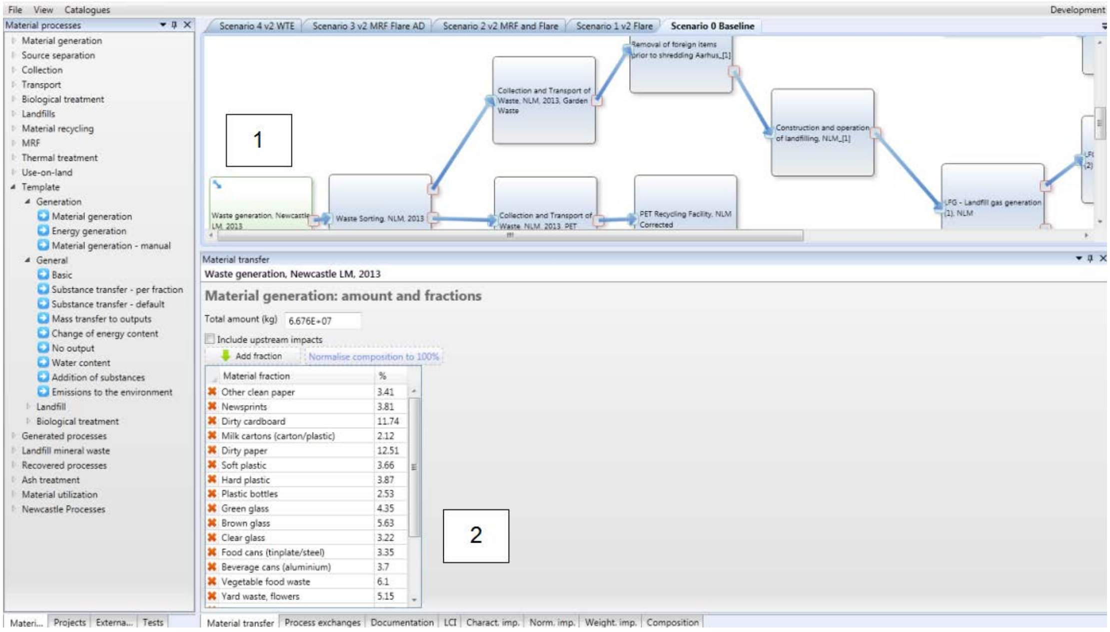

Figure 3 - 5: EASETECH Material Transfer

Figure 3-6 shows an example of the process exchanges that can be allocated to each technology or treatment module. In this example, the vehicle used for collection and transport is detailed and evaluated. Depending on the technology under consideration, one can insert processes such as electricity mix, virgin material substitution and water usage, amongst others.

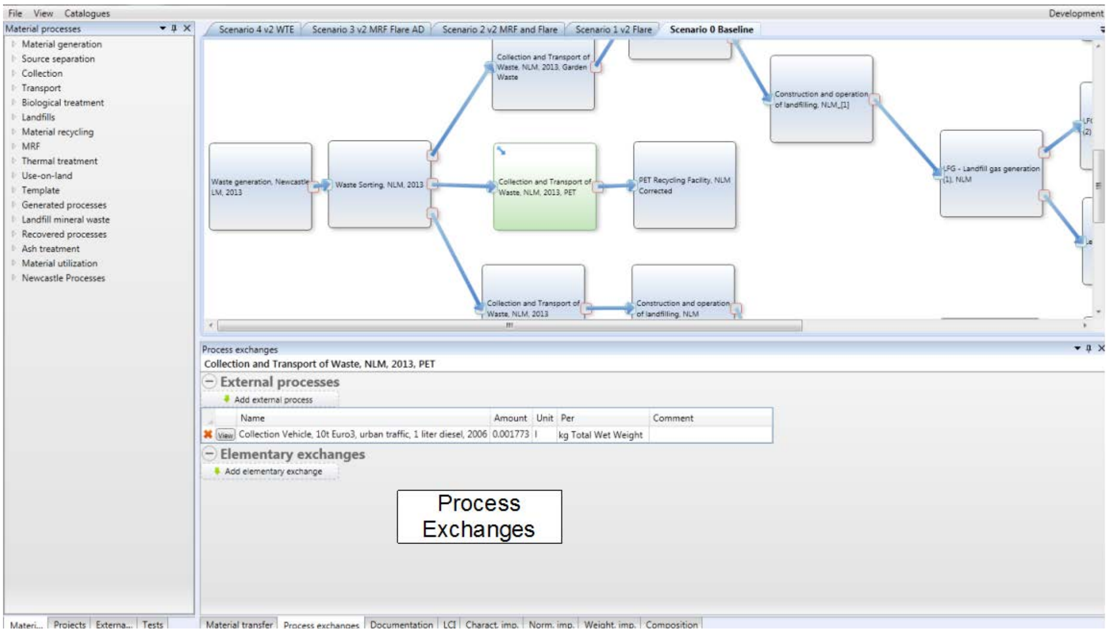

Figure 3 - 6: EASETECH Process Exchanges

Figure 3-7 displays the LCI for the chosen scenario. EASETECH provides a detailed breakdown of all the emissions from the scenario as well as assigning those emissions to a specific module in the scenario. Emissions include elements and substances that are emitted to the air, soil and water.

Figure 3 - 7: EASETECH LCI

Figure 3-8 shows the composition tab of EASETECH. This tab provides a detailed elemental and chemical analysis of the outputs from any technology or treatment module. In the example below one can see the output composition at the collection and transportation stage of the scenario after generation and sorting has occurred.

Figure 3 - 8: EASETECH Composition Output

Figures 3-9 and 3-10 show how EASETECH outputs the characterised and normalised impacts for the LCIA. Each impact category is totalled and evaluated according to each technology or treatment module, which allows one to see where the highest impact is coming from. The characterised impacts provide the results in the respective unit of each category, while the normalised impacts are provided in Person Equivalents. When a scenario analysis is run, the variations in the results can be seen in these two screens.

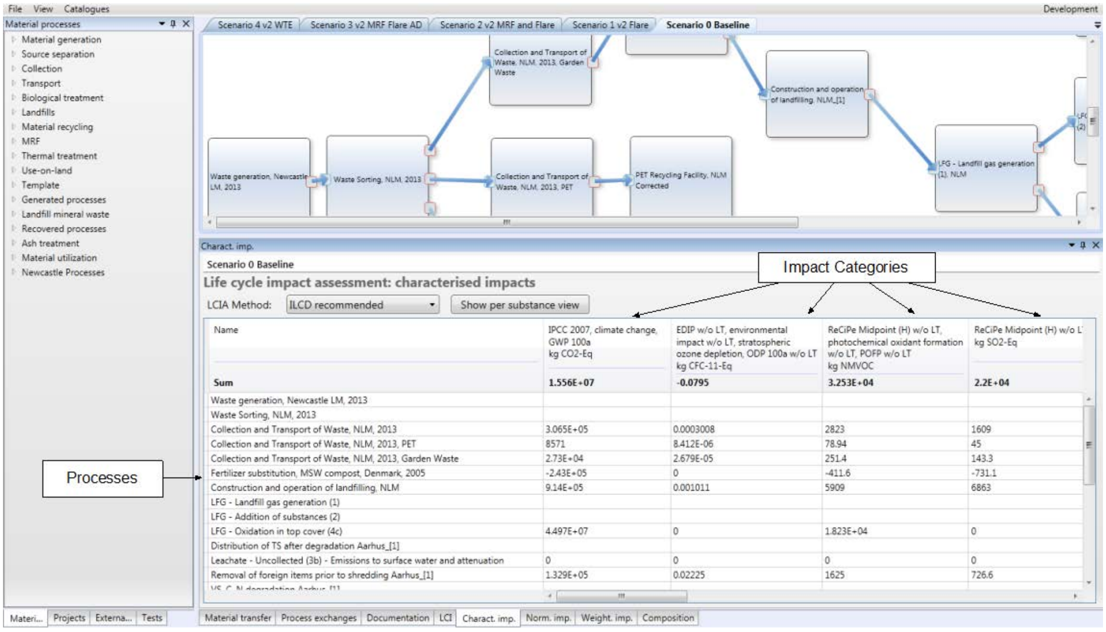

Figure 3 - 9: EASETECH Characterised Impacts

Figure 3 – 10: EASETECH Normalised Impacts

3.5.3 Data Processing in EASETECH

EASETECH was selected as the LCA programme to model the waste management scenarios for assessment. This section details how EASETECH is used to build a model and enter the data required to produce accurate results. The first step in building a scenario in EASETECH is to define the total amount of waste being analysed and the proportion of each fraction that constitutes the total amount. The data on the proportions and definition of each fraction was collected from NLM, while the correlating material fraction was selected from the EASETECH database. Each material fraction in the EASETECH database is defined by its chemical and elemental composition, which is used to calculate the environmental impacts of the scenario.

The next step is to sort the waste into the required streams for the scenario. For example, it could be sorted into three streams, as is the case for the baseline of NLM, i.e., plastic bottles, garden waste and residual waste. Each stream is assigned a percentage for efficiency of sorting and the remaining unsorted waste is assigned to the residual stream. Step 3 involves the collection and transportation of the waste from households to the waste treatment or disposal facilities. This step can separate the collection and transportation into separate processes depending on the type of vehicle used and the distance the waste is being transported. However, for NLM the vehicles are the same for collection and transport and the waste treatment or disposal facilities are not situated a significant distance from the collection points. For collection and transportation, the LCA conductor has to select the correct engine type for the vehicle used and define the amount of diesel used in litres per kilogram of the wet weight of the waste.

Step 4 is to build the treatment process for each stream of waste. In the baseline scenario of NLM, the residual waste is disposed of in a landfill. In EASETECH, the landfill process is separated into a range of activities. Firstly, the construction and operation of the landfill is accounted for by the diesel usage of the vehicles used to move earth, and electricity usage. Secondly, the LFG generation and the form of treatment or lack thereof are accounted for. Finally, the leachate generation and treatment is accounted for in the landfill process. The garden waste is composted. This process accounts for shredding the garden waste, including diesel and electricity usage. The composting process also accounts for the air emissions from the degradation of the waste in the NLM open windrow composting. Furthermore, it accounts for the compost's use on land and the substitution of fertilisers.

The third stream of the Newcastle baseline is plastic bottles, which are transferred to and treated at the PET recycling facility. This process accounts for water usage in reprocessing the plastic bottles as well as electricity usage, data for which was obtained from the ecoinvent database. This process also accounts for the substitution of virgin material. In similar fashion, each scenario was built using a combination of the data collected from NLM, the ecoinvent database and the EASETECH database. Technologies and processes were selected that best represent the Newcastle context, climate and geology.

Once the scenario has been built the next step is to check the LCI output and produce the characterisation impacts for the LCIA. EASETECH offers five LCIA methods, which can be edited, or a new method with specific characterisation factors can be created. This study used the International Reference Life Cycle Data System (ILCD) recommended method, which selects 12 impact categories for assessment and comparison. This is detailed further in Sections 5.1.2.3 and 5.3. The characterisation impacts for each scenario were exported from EASETECH into Microsoft Excel for presentation. The normalisation impacts follow the same methodology. Once extracted from EASETECH, the data was analysed and compared in Excel. This allowed for trends to be seen more clearly through the use of graphs, as can be seen in Section 5.3.

Moreover, EASETECH was used to conduct the sensitivity analysis, which is detailed in Section 5.4.2. To conduct this analysis, a parameter was first selected for assessment. For this LCA, one of the parameters selected was electricity production using hard coal, i.e., marginal electricity in South Africa. This parameter was altered by 10% in the model and the percentage change for the relevant impact category was assessed. In this way, the sensitivity of the model to change in each impact category and for relevant parameters was assessed.

3.6 Limitations and Uncertainty

Most LCA modelling programmes have been constructed in developed countries, for developed countries. This means that the models are data intensive and require a deep understanding of the scenario under analysis. This limitation applies to EASETECH. It is difficult to find high quality datasets that are appropriate for LCAs in South Africa. As discussed in Section 3.3, this LCA was streamlined by using surrogate or generic data. Datasets, data sources and data quality are discussed and reviewed in detail in Section 5.2.

Where possible, site-specific data, i.e., from NLM and from the process in question, were sourced; however the surrogate data was primarily obtained from the EASETECH database. While this data may not be site-specific, datasets based on technologies in similar climates, contexts and on similar ground conditions (if applicable) were chosen to minimise uncertainty and inaccuracy in the models. As a check on these assumptions, a sensitivity analysis was conducted and is presented in Section 5.4.2.

Furthermore, the LCA is valid only for NLM and the only waste stream under consideration is the MSW. The researcher is aware of other types of waste that are dealt with through other waste management systems, such as the waste from the coal mining industry in the municipality. This study therefore only models a component of the waste management system, i.e., the waste that is directly controlled by the municipality.

3.7 Chapter Summary

This chapter highlighted and explained the methodology followed in this study. The first section explained the design of the research and the procedure that led to the creation of the topic and research questions. Figure 3-1 showed how qualitative knowledge was integrated with quantitative data to produce an LCA on the IWMS of NLM. The integrated methodology used for this research was further clarified in the following section. Life cycle modelling was integrated with knowledge gained from the key informant interviews to produce a case study on NLM. A range of LCA models was reviewed, with EASETECH selected as the modelling programme for this study. The method of knowledge integration was LCA, which was streamlined using surrogate data as explained in Section 3.3. Section 3.4 discussed the collection and analysis of the data and Section 3.5 described the modelling programme, EASETECH that was used to run the scenarios. This was followed by a step-by-step procedure description of how EASETECH was used to generate the results of the LCA. Finally Section 3.6 highlighted the limitations, assumptions and uncertainties inherent in the study.

4: CASE STUDY OF WASTE MANAGEMENT IN NLM

This chapter provides background on NLM, which is the focus of the LCA study. It contextualises MSW management in Newcastle by providing details on the location, socio-economic environment and industrial landscape. This chapter also describes relevant, unique aspects of waste management in NLM such as the PET recycling facility.

4.1 Geographic Profile

NLM is located in the Amajuba District of Northern KwaZulu-Natal, South Africa. It is one of three local municipalities that form the district. It is approximately 1854km^2 in area. Figure 4-1 presents a map of NLM.

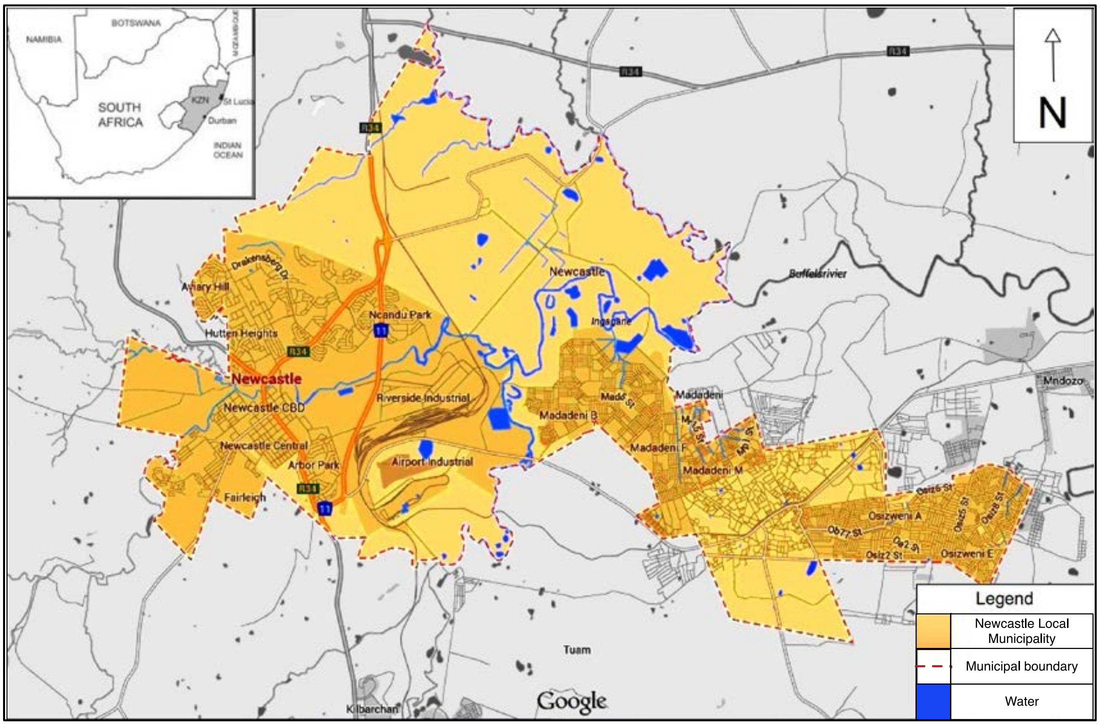

Figure 4 - 1: Map of Newcastle (Google, 2014)

NLM has a population of 363 236. The population is unevenly distributed, with 80% residing in Newcastle East. Forty six percent of residents are under the age of 19, while 27% are aged between 20 and 34.. Seventy three percent of the district's population lives in NLM. The population growth rate in the municipality between 1996 and 2001 was 2,93%; however between 2001 and 2011 the population grew by only 0,87% (NLM, 2013). This shows that, while the population is still increasing, the rate of growth has declined. This growth is concentrated in the eastern townships of Madadeni and Osizweni, which are underdeveloped areas whose residents mainly fall into a low-income[11] bracket (NLM, 2013). Of the 229 900

[11] The low income bracket in South Africa consists of people who earn R50 000 and below per annum (BMR, 2011).

people of employable age in Newcastle (15-64 years old), only 27.4% are employed, while 48.8% are not even economically active (StatsSA, 2011b).

4.2 Socio-economic Profile

There are approximately 84 272 households in NLM, which represents an increase from the 2001 total of 71 164. There is an average 4,3 people per household, a decrease from 4,6 in 2001. Average household income is illustrated in Figure 4-1. Many households (18%) have no income, while a similar number (19%) have an average income of between R9 601 and R19 600 per month. A further 18.6% of households earn on average between R19 601 and R38 200 per month. A 2005/2006 survey found that, on average, South African households spend about R56 152 per annum and have an average annual income of R74 589 (StatsSA, 2012). This means that more than 70% of NLM households are unable to meet national average expenditure and more than 80% are earning below the national average.

NLM has seen a steady improvement in the formal education of its citizens. The percentage of people without any formal education decreased between 2001 and 2011 from 13% to 7.8%, while the number of people who completed secondary education, i.e., matriculated, increased from 25.8% to 32.8% for the same period. While these categories have seen improvements, the number of people with tertiary education decreased from 8.2% to 4.4% between 2001 and 2011. NLM has difficulty in attracting and retaining highly qualified individuals, due to the lack of employment opportunities and tertiary institutions in the area (NLM, 2013).

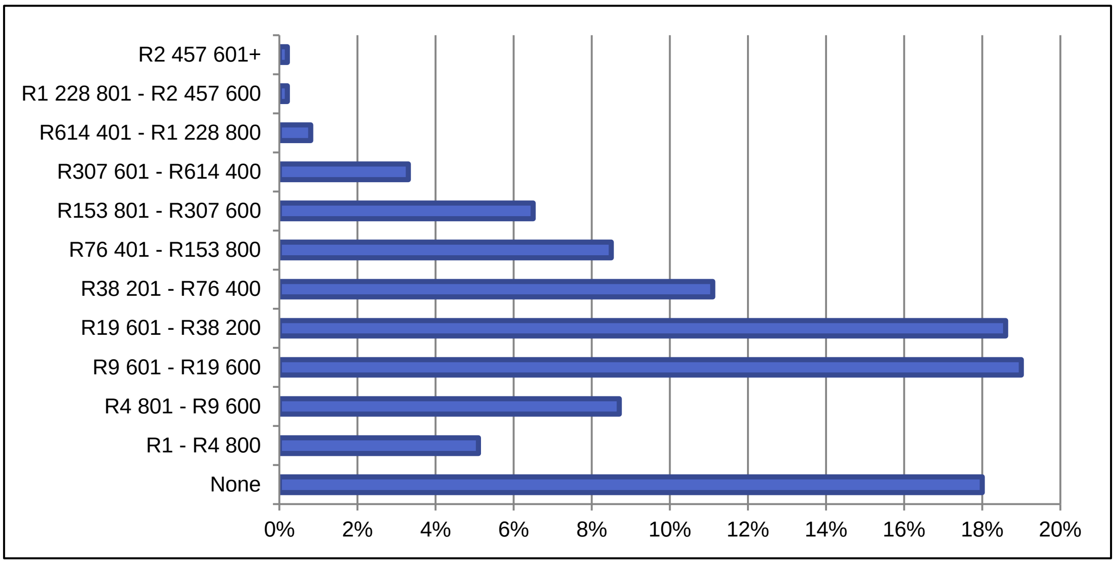

Figure 4 - 2: Average Household Income NLM (StatsSA, 2011b)

Newcastle receives electricity from Eskom in the order of 125 000 kilovolt-amps per month. Furthermore, there is an 18MW cogeneration plant, by International Power South Africa, that uses gas turbines to produce electricity. NLM has an electricity backlog of approximately

11.3%. National government requires the municipality to provide free basic electricity of 50kW to indigent households, which costs the municipality approximately R5 million per year.

4.3 Industrial and Economic Profile

NLM's economy is mainly driven by the manufacturing sector, which contributes approximately 27% to its total Gross Value Added (GVA). Coal is also mined in Newcastle, although it contributes only 2% to the total GVA. Manufacturing encompasses many sectors, including metal production, petroleum products, furniture and textiles (NLM, 2013). Manufacturing industries in Newcastle employ approximately 11 454 people, with 3 173 employed by the metal industry and 4 878 employed by the textiles industry. Figure 4-3 shows the contribution of each industry to NLM's total GVA.

The two dominant forces in Newcastle's industrial portfolio are ArcelorMittal steelworks and the Karbochem plant for synthetic rubber. The ArcelorMittal Newcastle Works produces approximately 1.6 million tonnes of finished steel products per annum, 45% of which is exported to international markets and employs 1 850 staff (ArcelorMittal, 2014). Karbochem produces polybutadiene and styrene – butadiene rubbers (Blechschmidt, 2013).

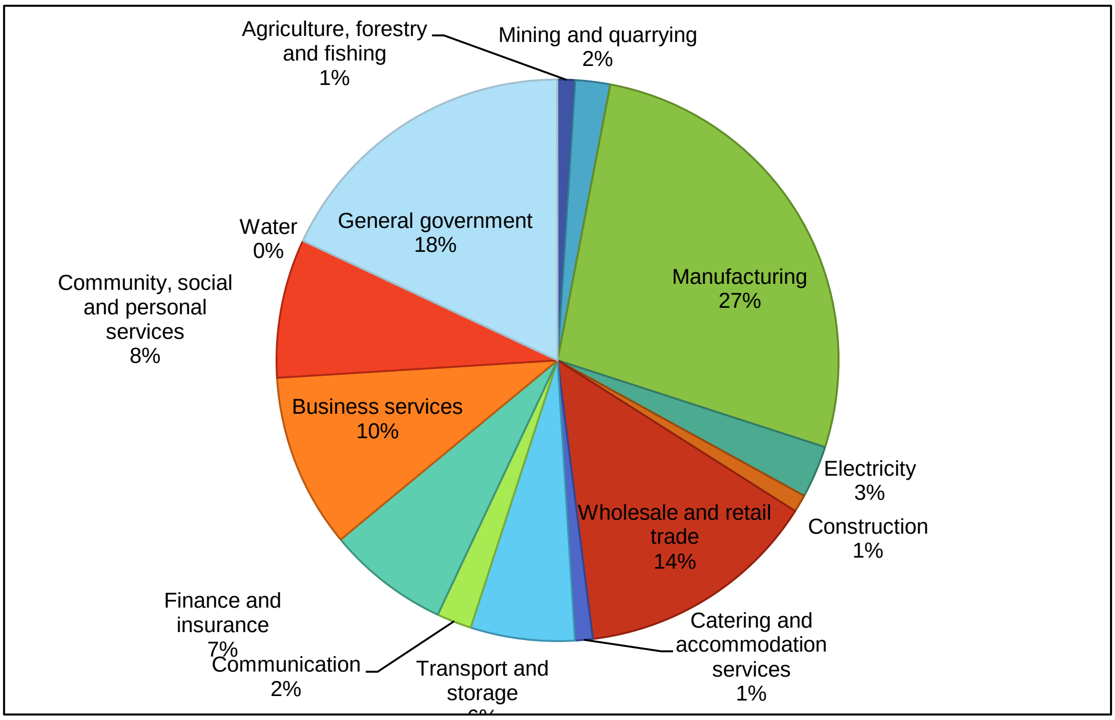

Figure 4 - 3: Contribution of Industrial Sectors to GVA (NLM, 2013)

4.4 Waste Management Profile

The Newcastle Department of Cleansing and Waste Management manages the MSW in the municipality. Newcastle has won the Greenest and Cleanest Town award for three consecutive years. This is the result of the “Newcastle Goes Green” project, which is a partnership of different municipal departments (Moodley, 2012). The current waste management system in NLM consists of a composting plant for garden waste, a plastic bottle recycling facility and a residual general waste landfill.

NLM generates approximately 66 758 tonnes of MSW per annum (Kelly, 2012). Table 4-1 below shows refuse disposal statistics for NLM. The majority of the municipality, 71%, has weekly refuse disposal either by a local authority or through a private company. The second most common method of disposal is for citizens to create their own informal refuse dumps. This can be hazardous to both the environment and human health.

Table 4 - 1: Refuse Disposal Statistics NLM

Refuse Disposal	Percentage
Removed by local authority/private company weekly	71
Removed by local authority/private company less than once a week	0.4
Communal refuse dump	0.9
Own refuse dump	23.2
No rubbish disposal	3.9
Other	0.5

(StatsSA, 2011b)

Figures 4-3, 4-4 and 4-5 show the detailed physical waste composition for three income groups: lower, middle and upper. The lower income group’s waste is characterised by high amounts of common mixed waste, 27%, and sand/ash, 11%. In contrast, the middle and upper income groups have considerably less common mixed waste, 10% and 12%, respectively. Common mixed waste is contaminated waste that cannot be separated into other fractions for recycling or accounting.

Middle and upper income waste streams are often characterised by a higher degree of recyclable materials. This could be due to better education that promotes increased environmental awareness, and the more efficient delivery of waste management services in these communities. However, in NLM the recyclable portion of the waste stream does not vary greatly between different income groups (Kelly, 2012).

With the exception of plastic bottles and garden waste, MSW in Newcastle is disposed of at the general waste landfill. It is classified as G:M:B+ (i.e., a general waste landfill of medium size, receiving less than 500 tonnes of waste per day, that produces a significant volume of leachate) and has been in operation since 1971. Figure 4-7 details the current operations of the landfill, i.e., cover being placed over newly landfilled residual waste. This medium-sized landfill is expected to close by 2017 and the process to identify a new landfill site is already underway. As seen in Figure 4-8, a new cell is being prepared to increase the capacity of the current landfill until a new site has been identified and developed. The garden waste is composted at a site run by the municipality next to the landfill. The resultant fertiliser is sold to citizens for their home gardens. NLM also has a designated area for waste picking near their landfill. This is a safe area, away from moving vehicles, where waste pickers can recover valuable materials for sale to recycling organisations. It is here that many remaining plastic bottles are removed from the landfill and taken to the PET recycling facility.

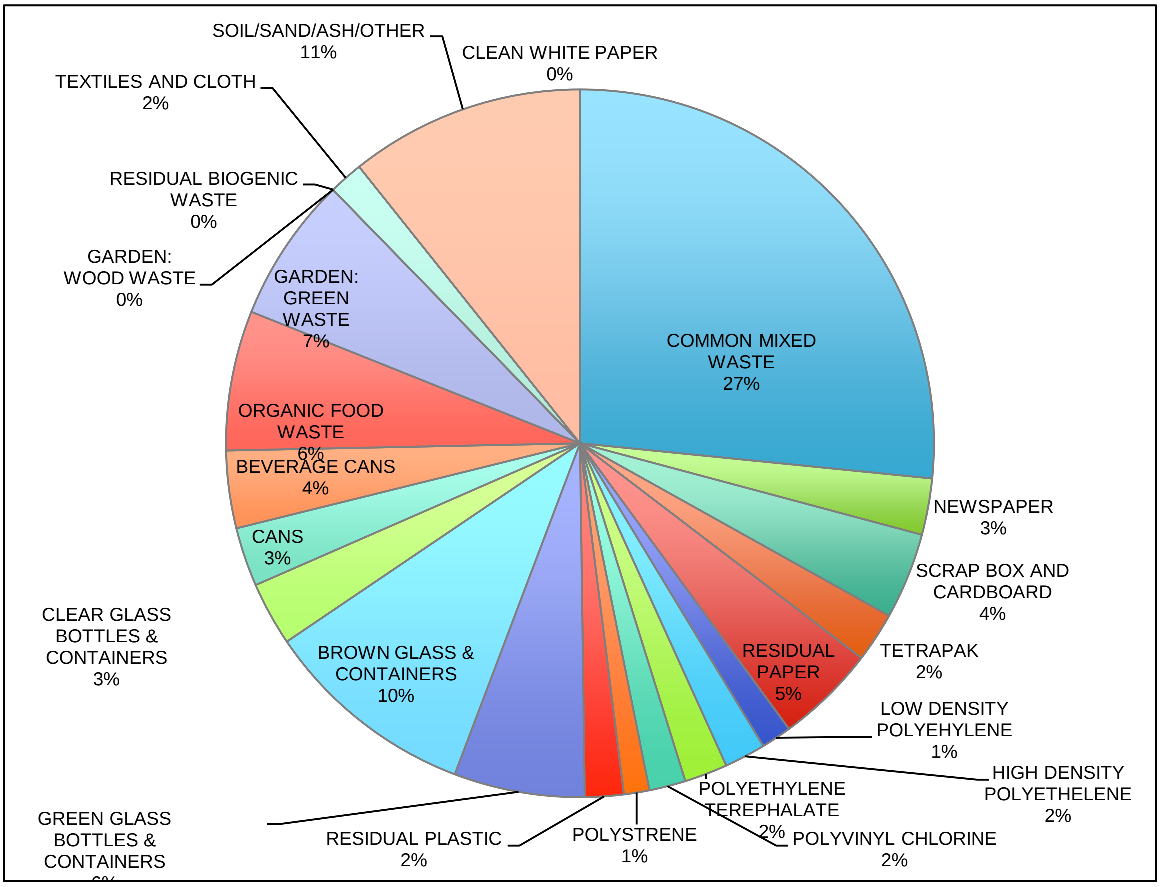

Figure 4 - 4: Lower Income Waste Composition

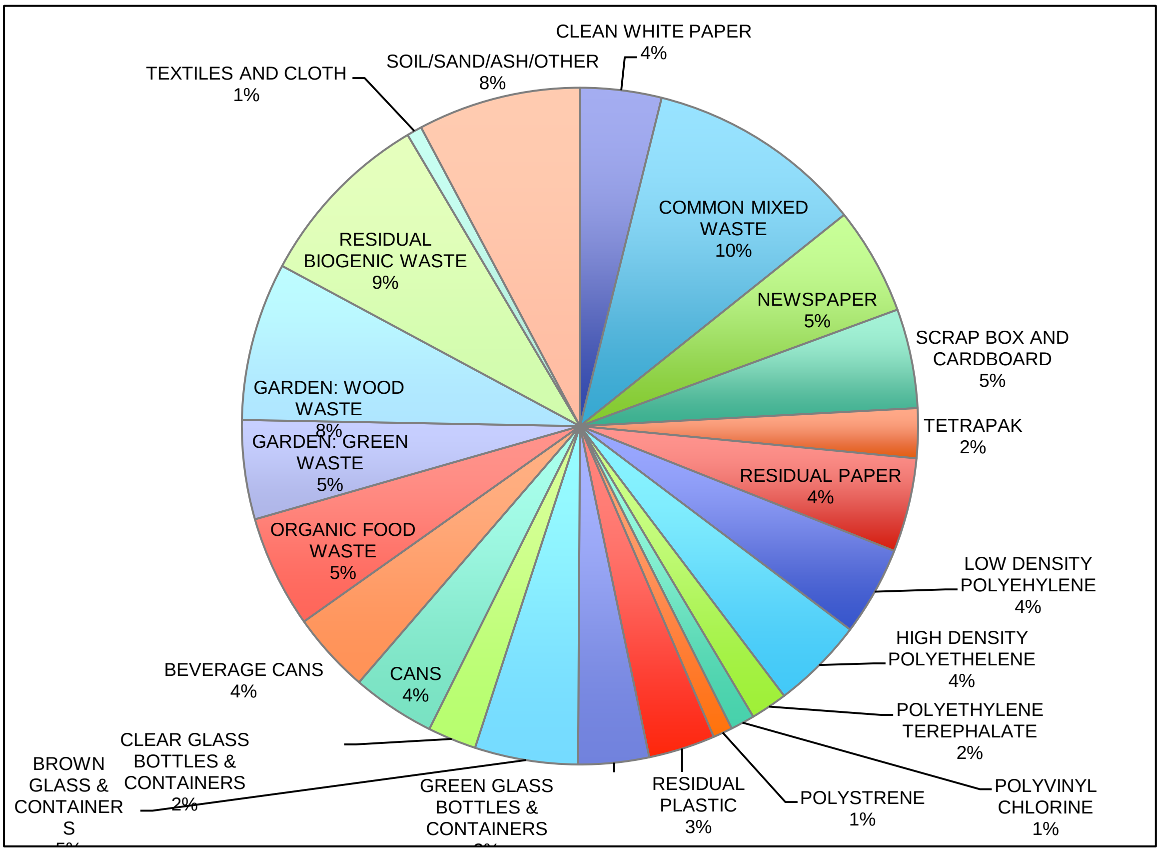

Figure 4 - 5: Middle Income Waste Composition

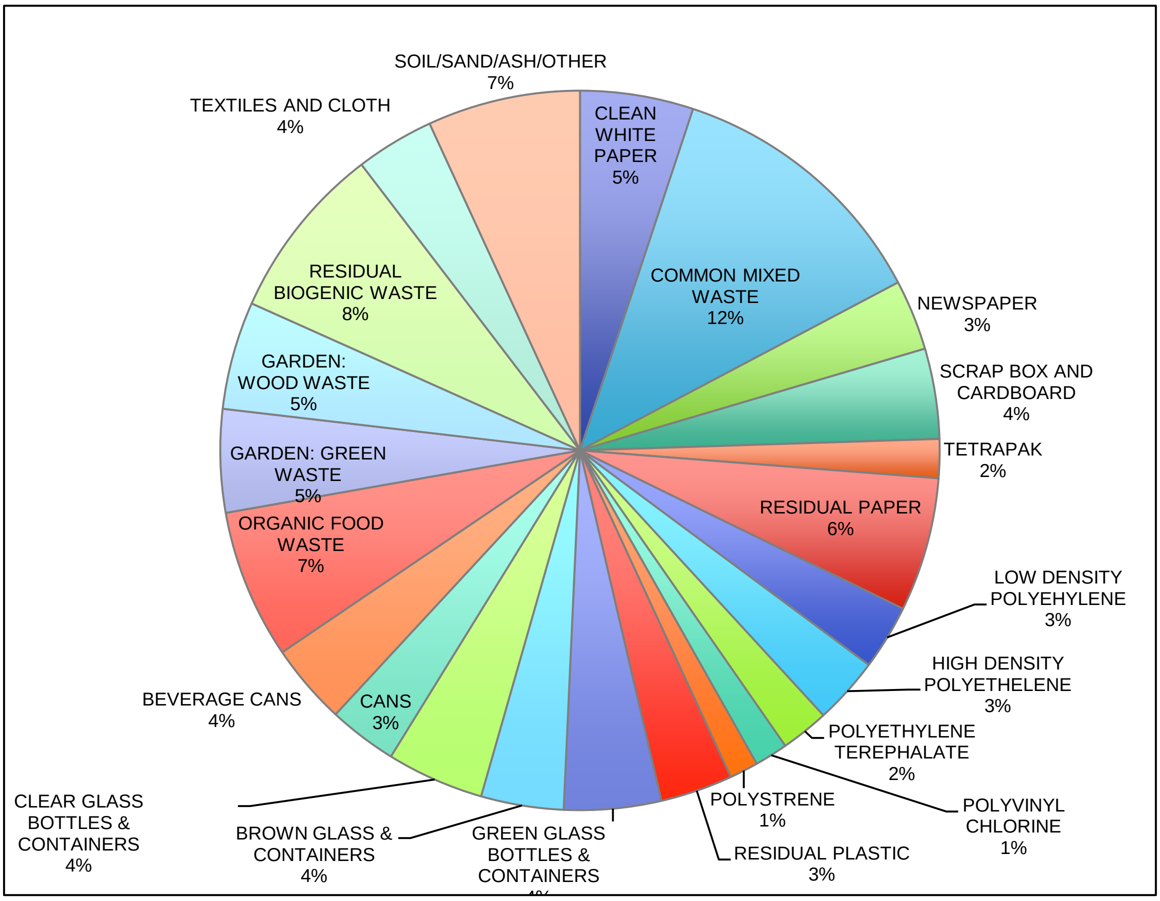

Figure 4 - 6: Upper Income Waste Composition

Figure 4 - 7: NLM Landfill Site

Figure 4 - 8: NLM Landfill New Cell

4.4.1 PET Recycling Facility

A privately owned, Chinese company runs a Polyethylene Terephthalate (PET) recycling facility that reprocesses all plastic bottles into hollow woven fibre. This section presents a brief overview of the facility through a series of images. Figure 4-9 shows a group of four images. Image 1 shows the plastic bottles that arrive at the facility and are stored outside, before being recycled. The first stage in the process removes the labels from the bottles and starts the washing process. Image 2 shows bottles that are manually shovelled through a funnel that leads the washing process. Image 3 shows the conveyor belt process that occurs after the washing, and label and cap removal. This process involves manual sorting and checking the bottles before they are chipped. Image 4 is the result of the chipping process.

Figure 4-10 details the melting and cooling stages of the recycling process. Image 5 shows four six hollow columns through which melted plastic is run. The melted plastic is run over several floors, in fine strings, and is cooled until it reaches the pulley system. This can be seen in Images 6 and 7. The string plastic is pulled along the pulleys to form a fine, non-woven rope that is placed in large plastic containers for further reprocessing, as shown in Image 8. Image 9, in Figure 4-11, shows the end result of this stage in the plastic reprocessing. The plastic in the filled containers is woven together (see Image 10) and run through a series of rollers to produce the woven plastic shown in Image 11. This is finally shredded and passed through a blower to produce the final product, hollow woven fibre, which can be seen in Image 12. The hollow woven fibre is used as stuffing for furniture.

Figure 4 - 9: NLM PET Recycling Process 1

Figure 4 - 10: NLM PET Recycling Process 2

Figure 4 - 11: NLM PET Recycling Process 3

4.5 Chapter Summary

This chapter presented background information on NLM and discussed certain pertinent aspects in detail in order to contextualise the study and the waste management assessment that follows. It should be noted that Newcastle is not a typical local municipality in South Africa. NLM is at the forefront of developing and improving MSW management in South Africa. This is illustrated by the awards the municipality has achieved over the past few years. A typical local municipality in South Africa may not have the detailed data on waste characteristics that NLM has collected, nor the high recycling rate for PETs as is the case in Newcastle. This presents Newcastle as an interesting case study as the local authorities are motivated to stay ahead of other municipalities and were hence willing to assist and support a study such as this.

5: LIFE CYCLE ASSESSMENT

The area under study is Newcastle Local Municipality (NLM), located in the Amajuba District Municipality of KwaZulu-Natal. The key informant interviews revealed that NLM is interested in exploring different treatment options for their MSW; hence as a starting point, this study aimed to assess the environmental impact of a range of integrated waste management systems through a life cycle perspective. This chapter integrates the qualitative and quantitative data collected into a life cycle assessment of integrated waste management scenarios in NLM.

5.1 Goal and Scope Definition

5.1.1 Goal of the Study

This study had two goals. The first was to quantify the environmental impact of the current (baseline) waste management system used by NLM. The second goal was to identify the optimal configuration of treatment technologies for integrated waste management in NLM that causes the least environmental impact. The combination of these two goals allowed for comparison of alternative integrated waste management scenarios to inform decision-making and strategic planning.

5.1.2 Scope of LCA Study

5.1.2.1 Functional Unit

Based on the literature and similar LCA studies, (Cleary, 2009), the functional unit of the study was selected as the total waste generated for a year in NLM. This enabled in a clearer understanding of the environmental impact of waste management in NLM over the year. The functional unit is 66 758 tonnes of MSW, which is based on a study incorporated into the 2012 IWMP for the municipality.

5.1.2.2 System Subdivision and Boundaries

The system boundaries of this LCA include all the activities involved in collecting and handling the waste, treating it, reprocessing recyclables and disposing of the waste in NLM in the Amajuba District of KwaZulu-Natal. The study takes a consequential approach. Material recovery as a result of waste picking activities is included in the efficiency of the home sorting process.

The boundaries of the baseline system are illustrated in Figure 5-1. The foreground system includes waste sorting, collection and transport, the treatment technologies and the use or production of the end product. The background system includes energy, water and the fuel required to run the integrated waste management system and the emissions caused by the foreground system to the air, water and ground. The background also includes the virgin material substitution that takes place due to reprocessing and recycling.

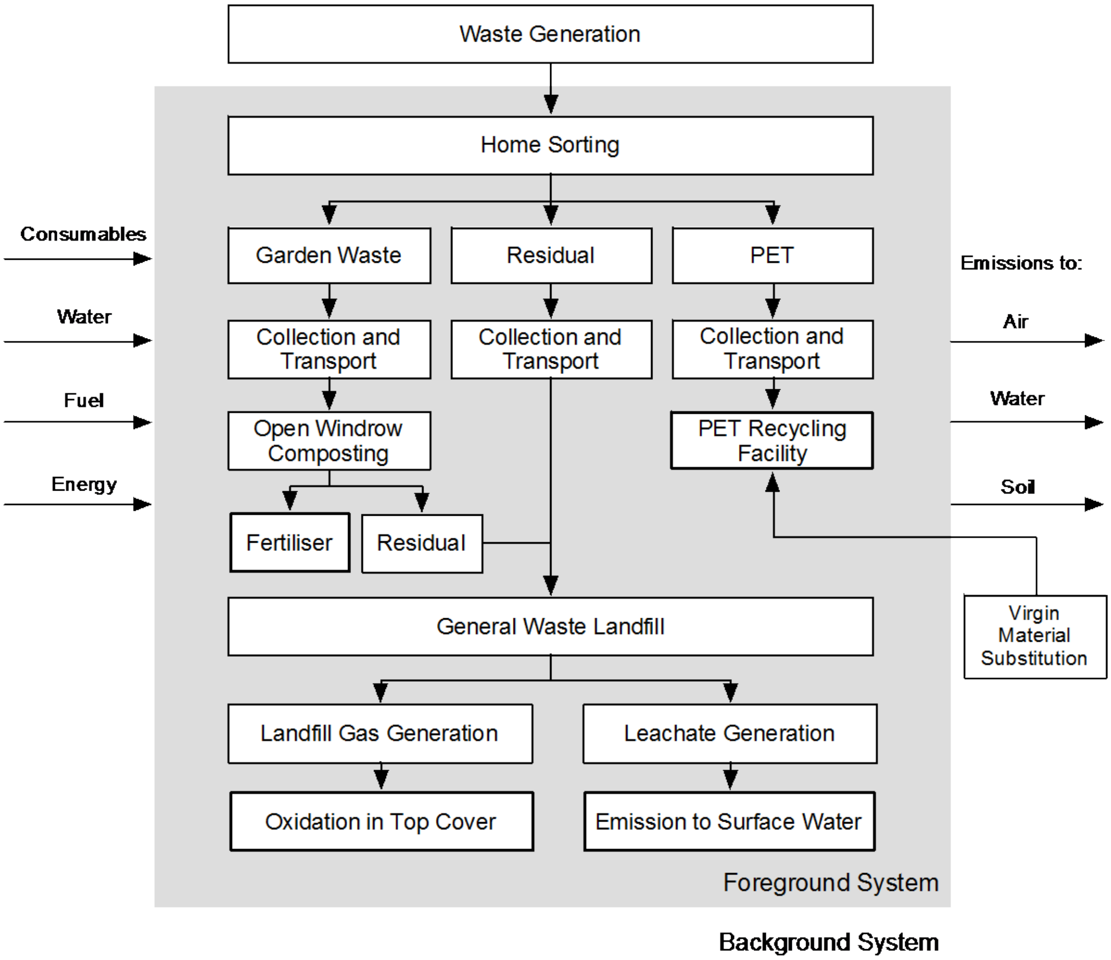

Figure 5 - 1: System Boundaries of Newcastle LCA

5.1.2.3 Impact Categories

The ILCD recommends a range of LCIA categories for an LCA. The categories selected for this study were based on these recommendations, which have an effect on the three AoPs: human health, the natural environment and natural resources. The following assessment criteria are considered in the impact assessment phase of the LCA.

- Climate Change through Global Warming Potential
- Stratospheric Ozone Depletion
- Photochemical ozone formation
- Terrestrial acidification
- Eutrophication potential
- Freshwater eutrophication
- Depletion of abiotic resources, fossil and non-fossil
- Human toxicity, carcinogenic and non-carcinogenic
- Particulate Matter
- Ecotoxicity

5.1.3 Description of the Scenarios

The five scenarios under consideration in this study were built with the waste hierarchy in mind. Starting at the baseline, each subsequent scenario, up to scenario 3, added a level of complexity. Scenario 1 adds a flare to the baseline. Scenarios 2 and 3 added a MRF, which in turn would increase the recycling in NLM and scenario 3 added an AD plant for better organic waste treatment and energy recovery. Scenario 4 aimed to test the environmental impact of a WtE plant for comparison with the other scenarios. While not exhaustive, these scenario choices allowed the researcher to test the validity of the waste hierarchy, which suggests a preference for recycling over thermal treatment and over landfilling from an environmental standpoint (Finnveden et al., 2005).

5.1.3.1 Baseline Scenario

The baseline scenario is the current practice of waste management in NLM. NLM manages 66 758 tonnes of waste per annum. As illustrated in Figure 5-2, waste generated at household level is split into three streams. The fraction of garden waste being composted is estimated at 90%, 99% of PET (plastic bottles) is reprocessed, and the remaining fractions form part of residual waste. The garden waste and residual waste is routed to the same site, on which there is a general waste landfill and a composting plant. The plastic bottles are taken to the PET recycling facility where they are reprocessed into hollow woven fibre. The landfill produces leachate, which is uncollected and untreated and the landfill gas is oxidised in the top cover.

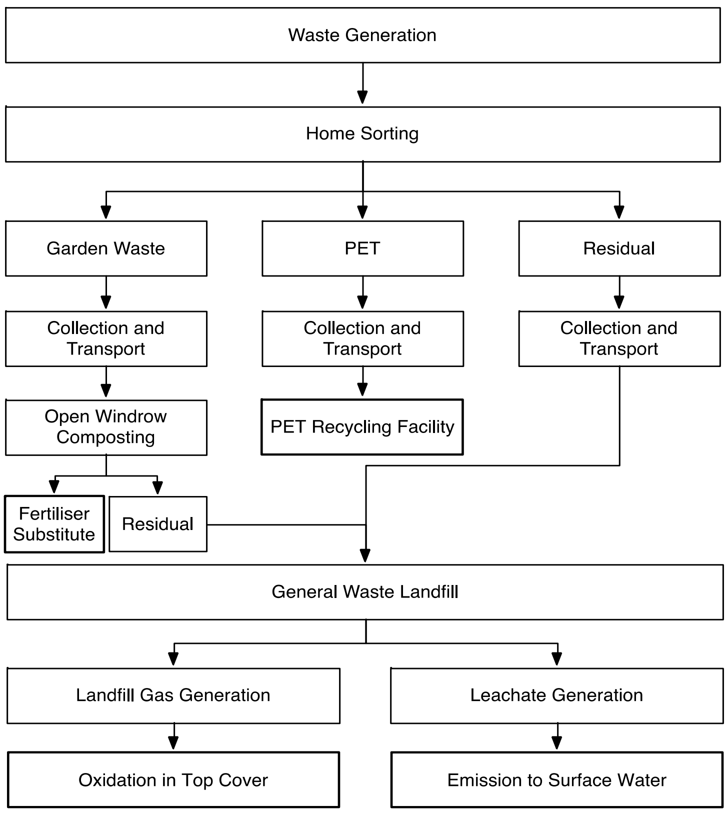

Figure 5 - 2: Baseline Scenario NLM

5.1.3.2 Scenario 1

Scenario 1 follows directly from the baseline scenario. This scenario adds a gas collection system and a flare, which transforms CH_4 to CO_2 at 97%, to the landfill technology. As with the baseline, the garden waste is chipped, shredded and composted in open windrows. The resultant compost is sold as a fertiliser substitute to local citizens. The residual waste from the composting heaps is routed to the landfill along with residual waste from the households. Figure 5-3 illustrates the processes involved in this scenario.

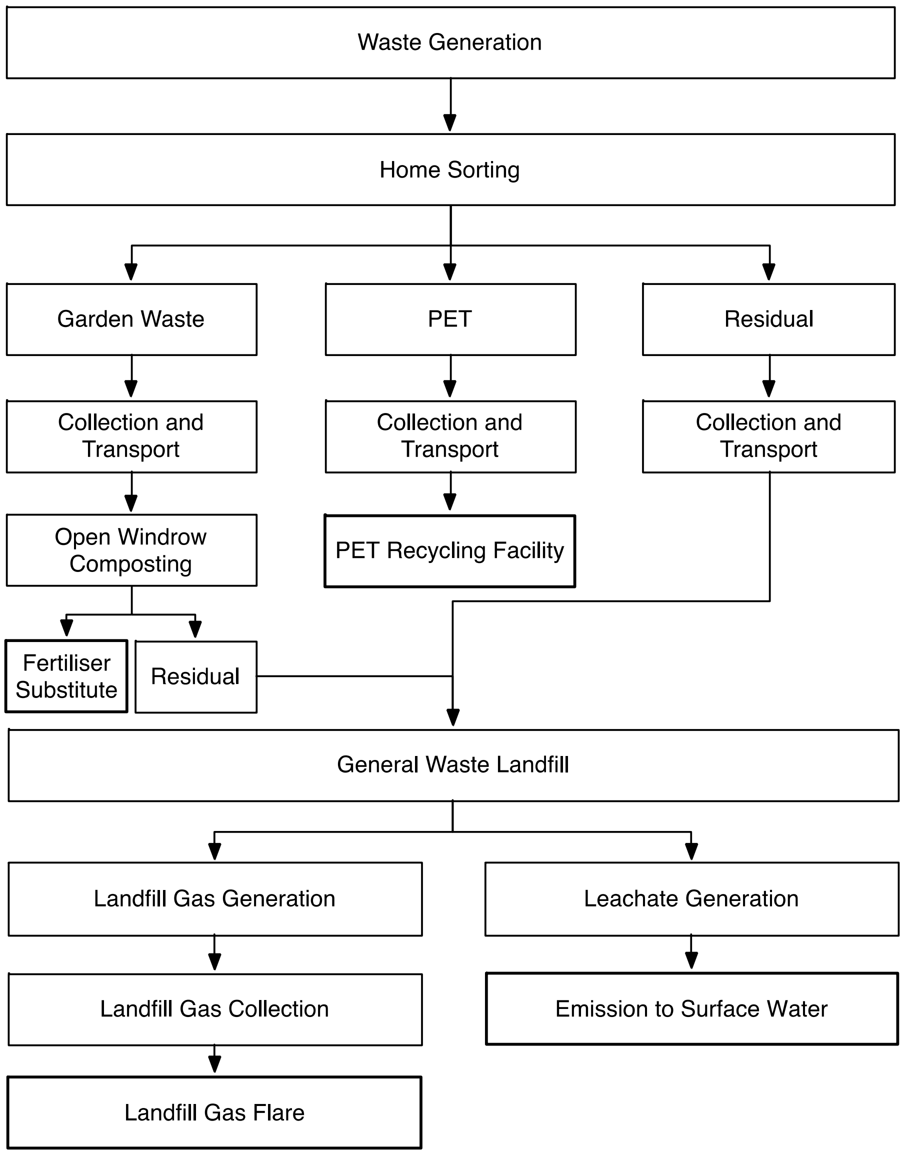

Figure 5 - 3: Scenario 1 NLM

5.1.3.3 Scenario 2

Scenario 2 adds another stream to the source separation (see Figure 5-4). In this scenario, waste is separated into four streams at household level. These are garden waste, dry waste, PET (plastic bottles) and residual waste. Garden waste is composted as described in the baseline and Scenario 1. Residual waste from households and composting is sent to landfill. The plastic bottles are still reprocessed at the private PET recycling facility. The model estimates that dry waste is separated at 50% efficiency for each recyclable fraction. Furthermore, it includes 25% food contamination in the dry waste stream. The major addition to this scenario is the MRF. Source-separated dry waste is sent to this facility where it is further separated into six streams. The waste streams leaving the MRF are plastic, paper, metal, glass, aluminium and residual waste. The recovered plastic, paper, metal, glass and aluminium materials are transported to their respective reprocessing plants. The paper is reprocessed into cardboard, the plastic into PE high density granulate, glass into new bottles, and metal into steel sheets, while the aluminium is recycled.

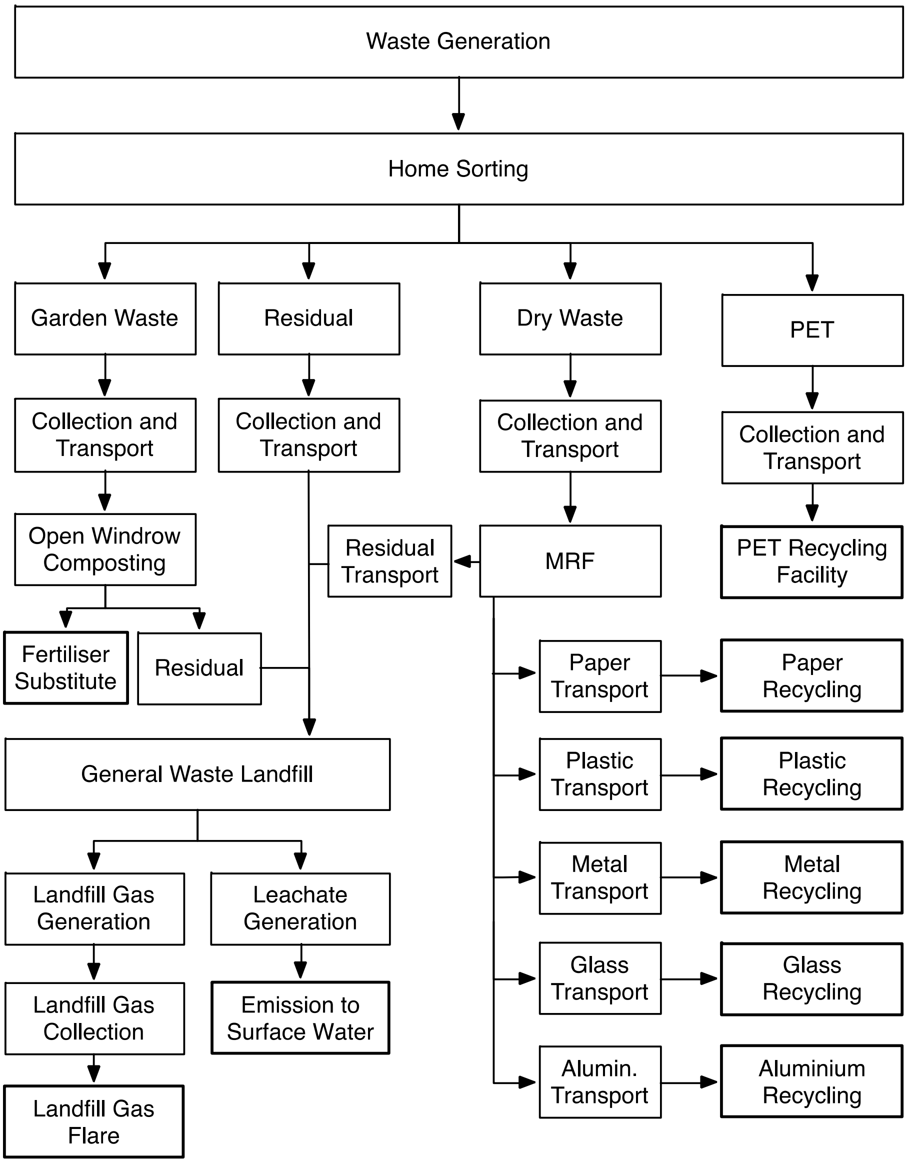

Figure 5 - 4: Scenario 2 NLM

5.1.3.4 Scenario 3

Scenario 3 is similar to Scenario 2; however waste, is source separated into five streams, as shown in Figure 5-5. The additional separate food waste stream is separated at 50% efficiency. It is added to the garden waste stream as this biogenic waste is now anaerobically digested instead of composted. The anaerobic digestion process will result in two products, namely, the digestate and biogas. The AD plant has a gas yield of 70% of the anaerobically digestible carbon. The digestate will be sold as a fertiliser substitute, as is currently happening with the compost and the biogas will be used to generate electricity that will be fed into the grid. Electricity recovery efficiency is 39%.

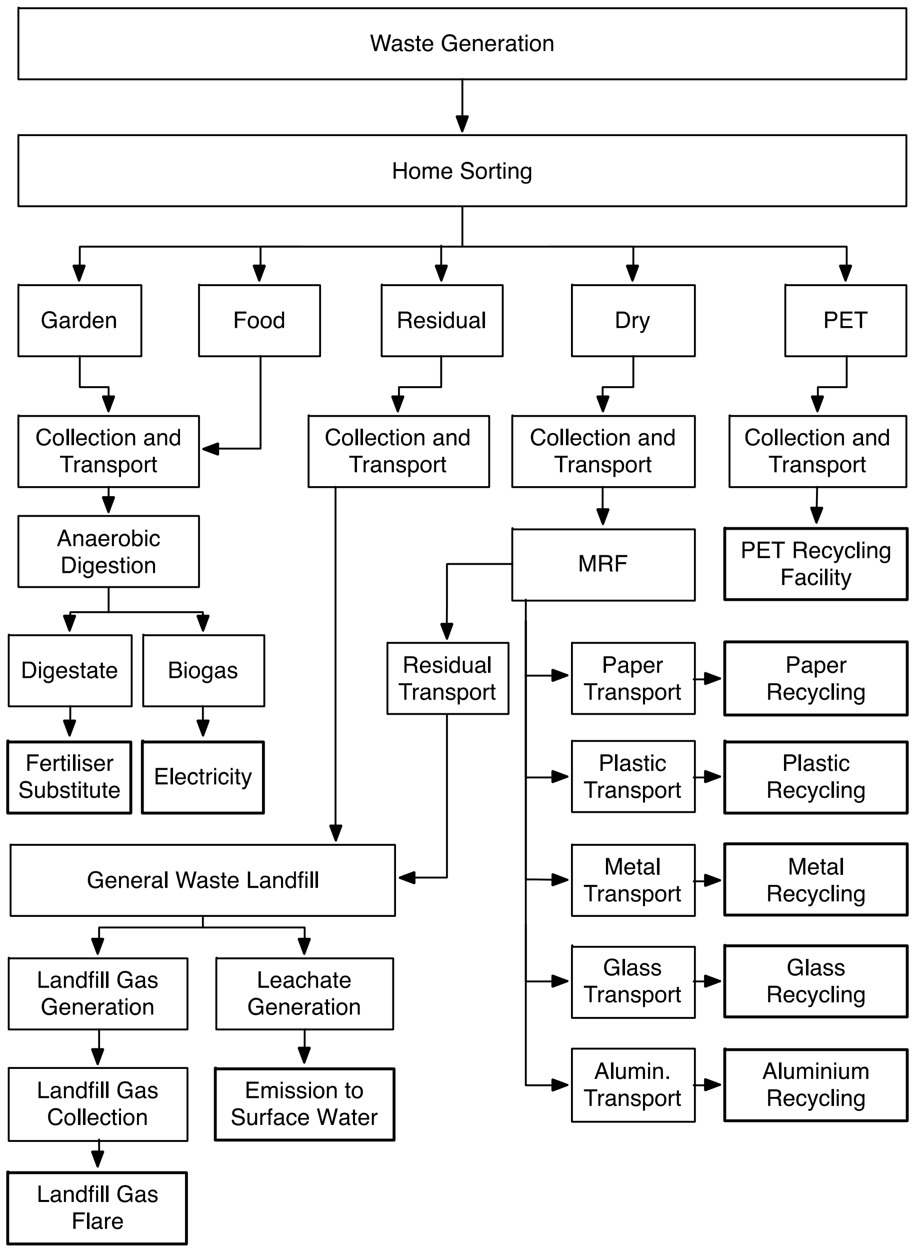

Figure 5 - 5: Scenario 3 NLM

5.1.3.5 Scenario 4

Scenario 4 takes a different approach to integrated waste management by using a WtE plant to treat the waste and generate electricity. In this scenario, 99% of plastic bottles are still removed from the system and sent to the PET recycling facility, as this is a private organisation. 100% of the residual waste is collected and routed to a WtE plant where it is incinerated to generate electricity at an efficiency of 22%. There are four major outputs from this process: iron and aluminium scraps, fly ash and bottom ash. The ash is sent to a bottom ash landfill where the leachate generated is collected and treated. The aluminium and iron scraps are transported to their respective reprocessing facilities where they are recycled. The electricity generated is plugged back into the grid to substitute the marginal electricity produced from hard coal. Figure 5-6 illustrates this scenario.

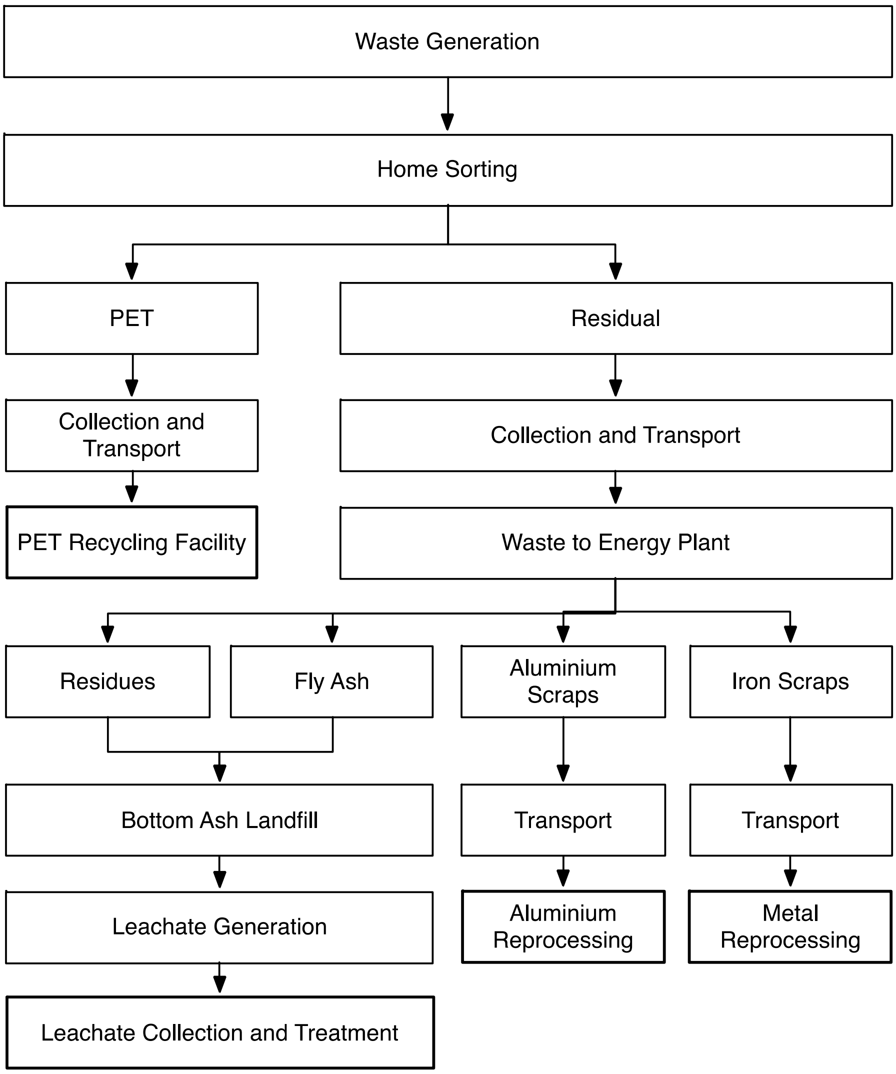

Figure 5 - 6: Scenario 4 NLM

5.2: Life Cycle Inventory

5.2.1 Inventory Data Sources

Data was collected from three main sources: the Newcastle municipal Department of Cleansing and Waste Management, which provided waste composition and diesel usage data; the ecoinvent v3 database, which provided the electricity mix and marginal electricity datasets specific to South Africa, and the EASETECH database, from which chemical waste analysis and waste treatment technologies datasets were utilised. The EASETECH database provided the surrogate data that was used to streamline the LCA. Data of this nature were unavailable for Newcastle, i.e., NLM does not have detailed chemical waste composition datasets. Surrogate data for treatment technologies were used, as many of the technologies under consideration are new to the South African landscape and hence datasets are either difficult to obtain or do not exist. This subsection further clarifies each of these data sources and the datasets used in this study. Please refer to Appendix A for an example of the LCI output from EASETECH.

5.2.1.1 Waste Composition

The physical waste composition was collected from the NLM solid waste department. The municipality studied their MSW over a two-week period for the IWMP, and separated it into 23 streams. This is illustrated in Figure 5-7.

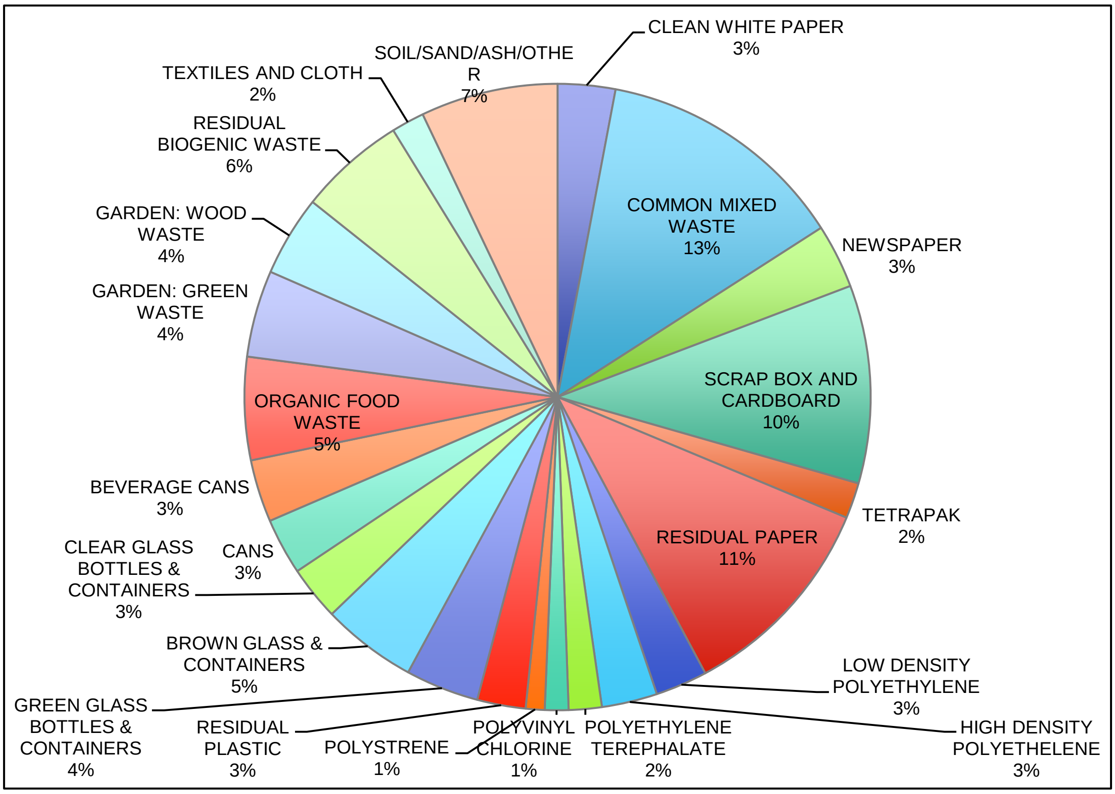

Figure 5 - 7: Newcastle MSW Composition

5.2.1.2 Electricity Mix and Marginal Electricity

Electricity mix and marginal electricity production data were obtained from the ecoinvent database version 3. This data is region-specific to South Africa. Two datasets were taken from the ecoinvent database. These were titled, “electricity, high voltage, production mix,” which was used as the electricity mix for the LCA and “electricity production, hard coal” which was used as the marginal electricity consumption dataset for the LCA. The production mix dataset was based on the mix of electricity production in South Africa for the year 2008. “Electricity production, hard coal” represents high voltage electricity production in South Africa for 2008 in an average, hard coal power plant (Treyer, 2014).

5.2.1.3 Waste Chemical Composition

The EASETECH database created at the Technical University of Denmark (DTU) has a detailed elemental analysis of many waste fractions. Similar waste fractions to those identified in the NLM waste stream were used for the LCA calculations. DTU sorted and sampled their MSW. Each fraction was studied in the laboratory for a variety of data including elemental composition, energy and ash content, total and volatile solids and carbon content.

5.2.1.4 PET Recycling Facility

This technology was modelled using the EASETECH database. It accounts for the processes required to reprocess the plastic bottles into hollow woven fibres. This includes washing, shredding, grinding, drying, granulating and reprocessing procedures. Furthermore, it accounts for the substitution of virgin material, at 81%, which includes the extraction of raw materials, transportation, production and disposal of waste products. External processes, for which South African data was available, were substituted for the default data such as marginal electricity.

5.2.1.5 Landfill and Leachate

The landfill technology is split into a range of processes including construction and operation, landfill gas generation and treatment or non-treatment, oxidation in the soil top cover, leachate generation and surface water runoff, as well as carbon storage. This technology was modelled using the EASETECH database; however, the necessary adjustments were made where possible to create a process that is reliable and similar to the landfill in Newcastle.

5.2.1.6 Collection Vehicle and Diesel Usage

This process was modelled using the EASETECH database of vehicle types. A collection vehicle was selected that was of a similar age to many of the Newcastle waste management trucks and that had a similar capacity and engine size. Diesel usage was calculated to be 0.001773 litres per kilogram of total wet weight. This was calculated from data collected from Newcastle. The municipality collects data on the amount of diesel used by a vehicle, the tonnage of waste it is carrying and the distance it has travelled.

5.2.1.7 Composting and Fertiliser Substitution

This treatment technology was modelled using the EASETECH database. A composting model similar to the one in use at Newcastle was selected. This is an open-windrow composting facility that treats garden waste. Large impurities are removed before the waste is shredded. Windrows are trapezoidal in shape and are approximately four metres high and nine metres wide. There is no emission control for the gases being released. Compost is sold to private citizens as a fertiliser substitute. The data used to create the technology model in EASETECH was from a composting plant that has a similar climate, soil and precipitation as Newcastle.

5.2.1.8 Reprocessing Plants

The reprocessing plants were modelled using the EASETECH database. Where possible, adjustments were made to the external processes to improve the geographical correlation. This included substitutions for the marginal electricity and electricity mix and the removal of district heating. Material substitution values were obtained from the EASETECH database, which was built by studying and analysing similar plants and technologies. Five technologies were modelled. Recovered paper and cardboard is to be reprocessed into a mix of different paper materials. The substitution of virgin material is set to approximately 90%. Plastic materials, excluding the PET plastic bottles, are to be reprocessed into granulated plastic foam, with a virgin substitution of 81% and a material grade loss of 10%.

Glass cullets are reprocessed into new bottles. The pre-sorted glass from the MRF is melted and used for the production of bottles with an assumed material loss of 0% and a loss of material grade of 0%. Scrap metal is shredded and reprocessed into steel sheets. Virgin material is substituted at 87%. The fifth reprocessing plant is for aluminium scrap, which is melted and reprocessed. The loss of material grade is 0% and there is a material loss of 21%.

5.2.1.9 Anaerobic Digestion Plant

The AD plant was modelled using the EASETECH database. The selected biological technology treats municipal organic solid waste including garden waste, food waste from restaurants and stores and household organic waste. It is a one stage “wet” thermophilic anaerobic digestion plant. In this process, the initial hydrolysis and acidification takes place in the same vessel as the methanogenesis phase. It models biogas generation for electricity production and digestate for fertiliser substitution. This model represents a hypothetical average digestion plant. This is because the data used for this technology was collected from a range of plants and the literature. It represents solid organic waste digestion technology developed in Western Europe.

5.2.1.10 Waste-to-Energy Plant

The WtE plant uses grate incineration technology with a wet flue gas cleaning system. It treats mixed MSW, removing the need for a MRF. The outputs of the incinerator are fly ash, bottom ash, iron scraps, aluminium, waste water and cleaned flue gas. This technology model included a district heating output, which was removed and marginal electricity production was substituted for the South African dataset. The fly and bottom ash are both sent to a bottom ash landfill that treats hazardous waste and includes a wastewater treatment plant for the leachate.

5.2.2 Dataset Quality

Data quality assessment is necessary to ensure the reliability and accuracy of the results. Data quality can be assessed in five categories. These are set out in ecoinvent version 3 and were first developed by B.P. Weidema from DTU (Weidema and Wesnæs, 1996). The categories are, "reliability, completeness, temporal correlation, geographic correlation and technological correlation." Each category is divided into five quality levels, ranging from 1 to 5 (Weidema et al., 2011). Further description of these categories and quality levels can be seen in Table 5-1.

Table 5 - 1: Data Quality Assessment Criteria and Guidelines

Indicator Score	1	2	3	4	5
Reliability	Verified data based on measurements	Verified, partly based on assumptions	Non-verified, partly based on qualified estimates	Qualified estimate	Non-qualified estimate
Completeness	Representative data from all relevant sites	Representative data from >50% of relevant sites	Representative data from <50% of relevant sites	Representative data from only one relevant site	Representative-ness unknown
Temporal Correlation	<3 years before study year	<6 years before study year	<10 years before study year	<15 years before study year	Data age unknown or >15 years old
Geographic Correlation	Data from study area	Average data from larger area in which study area is included	Data from area with similar conditions	Data from area with slightly similar conditions	Data from unknown or distinctly different area
Technological Correlation	Data from the process/tech.	Data from process/tech. under study but from different enterprise	Data from process but from different technology	Data from similar, related process/tech.	Data from laboratory or from different technology

Table 5-2 presents the data quality assessment relevant to the case study. Using the guidelines for quality assessment presented by Weidema and Wesnæs (1996), as described above, each inventory dataset is evaluated accordingly. Each dataset is assigned a score out of 25, with the ideal being the lowest score of 5. Information on each dataset was gathered from the source.

Table 5 - 2: Data Quality Assessment

Data	Source	Reliability	Completeness	Temporal Correlation	Geographic Correlation	Tech. Correlation	Sum
Waste Composition	NLM	1	1	1	1	1	5
Diesel usage	NLM	1	1	1	1	1	5
Electricity mix	ecoinvent	1	1	1	2	2	7
Marginal electricity	ecoinvent	1	1	1	2	2	7
Vehicle	EASETECH	1	2	3	4	3	13
PET recycling	EASETECH	2	2	4	4	3	15
Landfill and leachate	EASETECH	2	2	3	4	2	13
Composting and fertiliser substitution	EASETECH	1	2	3	3	2	11
Paper reprocessing	EASETECH	2	2	3	4	2	13
Plastic reprocessing	EASETECH	2	2	4	3	2	13
Metal reprocessing	EASETECH	2	2	3	4	2	13
Aluminium reprocessing	EASETECH	2	2	4	4	2	14
Glass reprocessing	EASETECH	2	2	5	3	2	14
AD Plant	EASETECH	2	1	3	4	2	12
WtE Plant	EASETECH	2	2	1	3	2	10
Waste chemical composition	EASETECH	1	2	1	3	3	10

Table 5-2 shows the results of the quality assessment. Datasets collected from NLM were evaluated for quality. The municipality collected this data from all relevant sites within the last three years. The ecoinvent database yielded relatively high quality datasets. This can be attributed to the fact that the datasets were based on actual measurements from the South African energy market. The ecoinvent database is widely considered by the LCA community to be reliable and to provide high quality datasets (Wernet, 2013). The final source of data, EASETECH, yielded data of satisfactory quality. Many of the processes and technologies in EASETECH have already been assessed according to these guidelines. The primary concern with using the EASETECH database is the geographic correlation. Technologies had to be chosen from similar climates as NLM. To confirm the reliability of the model utilising the EASETECH database, a sensitivity analysis was conducted on the largest contributors to each impact category. This can be seen in the Interpretation.

5.3: Life Cycle Impact Assessment

This phase of the LCA takes the inputs and outputs from the LCI phase and converts them into impact indicator categories that are linked to the natural environment, human health and resource depletion (JRC-IES, 2011b). The impact categories characterised for the LCA, based on the ILCD recommended methods for life cycle impact assessment (JRC-IES, 2011a), with the corresponding unit of measurement are presented in Table 5-3.

Table 5 - 3: LCIA Categories and Methods

Impact Category	LCIA Method	Abbreviation	Unit
Climate Change – Global Warming Potential	IPCC Baseline Model of 100 years	GWP	Kg CO_2-eq
Stratospheric Ozone Depletion	EDIP	SOD	Kg CFC-11-eq
Photochemical Oxidant Formation	ReCiPe	POF	Kg NMVOC
Terrestrial Acidification	ReCiPe midpoint	TA	Kg SO_2-eq
Eutrophication Potential	CML 2001	EP	Kg NO_x-eq
Freshwater Eutrophication	EUTREND model, implemented in ReCiPe	FE	Kg P-eq
Depletion of abiotic resources	CML 2013	DAR	Kg Antimony
Human Toxicity, Carcinogenic	USEtox model	HTC	CTU
Human Toxicity, Non-carcinogenic	USEtox model	HTNC	CTU
Depletion of abiotic resources, fossil	CML	DARF	MJ
Particulate Matter	RiskPoll model	PM	Kg PM2.5-eq
Ecotoxicity	USEtox model	ET	CTU

After selection of the impact categories, the inventory data is assigned to the relevant category through classification. Each output from the LCI is, then, characterised through multiplication of a characterisation factor. For example, methane is classified to climate change and has a characterisation factor of 25, to convert kilograms of methane into kilograms of CO_2 equivalents.

5.3.1 Characterised Impacts

This section details the characterised impacts and highlights the largest contributors to the result of each scenario.

5.3.1.1 Global Warming Potential

The climate change impact category is characterised by global warming potential in carbon dioxide equivalents. As Figure 5-8 illustrates, Scenario 4 performs best in this category with a low impact of -36.08 million kg CO2-eq. This result can be attributed to the WtE plant in the scenario, which has a GWP of -29.37 million kg CO2-eq.

The baseline scenario performs worst in this category, with a GWP of 15.56 million kg CO2-eq. This is credited mainly to the methane gas that is not oxidised in the top cover of the landfill and is released into the atmosphere, due to a lack of landfill gas collection. This process accounts for about 44.97 million kg CO2-eq, which is primarily countered by the storage of carbon in the soil due to leachate from the landfill. This is valued at -29.43 million kg CO2-eq.

Scenarios 1, 2 and 3 are similar to the baseline, as the highest environmental impacts can be attributed to the release of non-oxidised methane into the atmosphere and the most beneficial impact can be attributed to the carbon storage occurring from the leachate. In comparison with the baseline scenario, these scenarios contribute towards mitigating climate change, i.e., they have advantageous global warming potential of -9.46 million, -10.12 million and -16.32 million kg CO2-eq, respectively. The main difference is that due to the flare in these scenarios, the harmful impacts are much reduced, i.e., all are below 20 million kg CO2-eq.

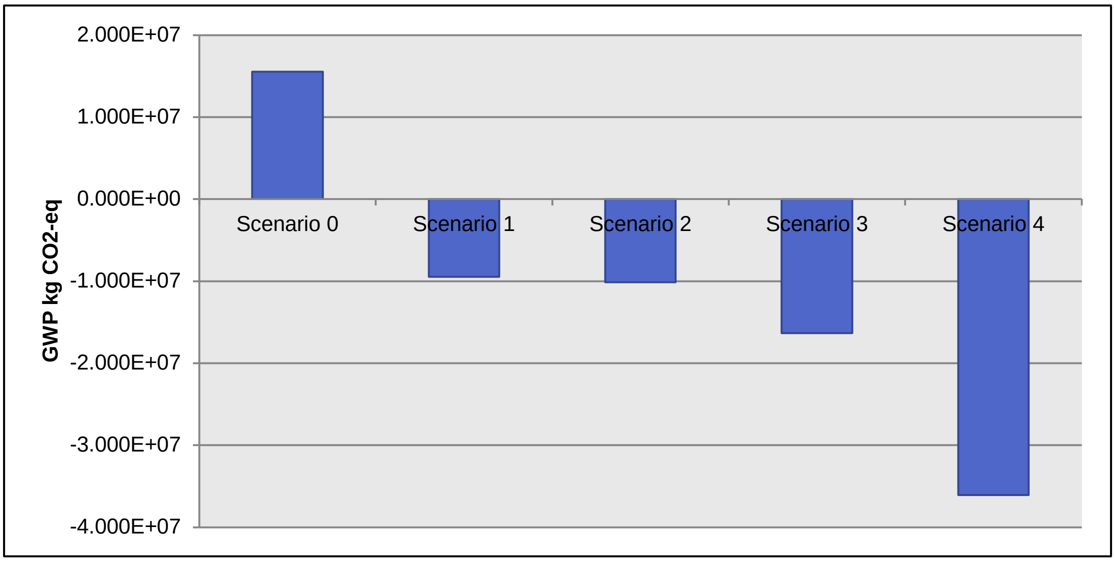

Figure 5 - 8: Global Warming Potential

5.3.1.2 Stratospheric Ozone Depletion

As can be seen in Figure 5-9, all four scenarios had a favourable impact for stratospheric ozone depletion. Scenario 4 performed best with an impact of -0.1485 kg CFC-11-eq, while Scenario 2 performed worst with an impact of -0.0715 kg CFC-11-eq. Scenarios 0 and 1 had the same impact: -0.0795 kg CFC-11-eq, while Scenario 3 performed second best with an impact of -0.09688 kg CFC-11-eq.

The beneficial impacts of this category can be attributed to the PET recycling facility, which provided an impact of -0.1031 kg CFC-11-eq for each scenario. This was the highest contributing impact in all the scenarios. In comparison, the removal of foreign items for the composting provided a harmful impact of 0.02225 kg CFC-11-eq for Scenarios 0, 1 and 2. This was the most significant destructive impact from any stage of the scenarios.

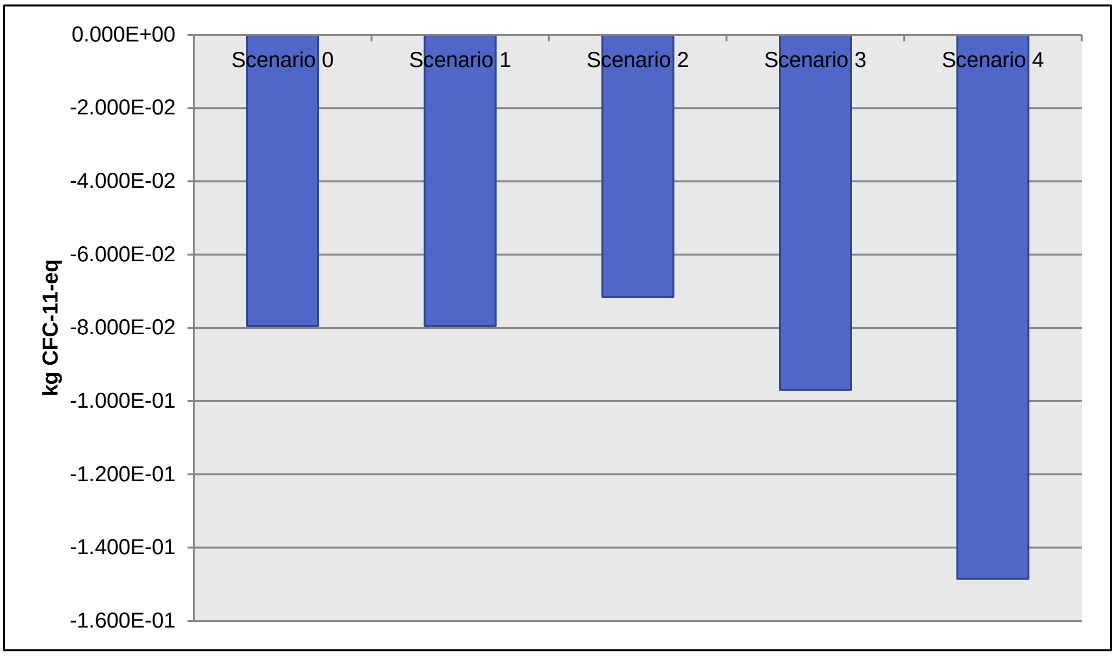

Figure 5 - 9: Stratospheric Ozone Depletion

5.3.1.3 Photochemical Oxidant Formation

The addition of the MRF to Scenarios 2 and 3 has a large impact on photochemical oxidant formation. Scenario 2 performs worst with the highest POF impact of 192 700kg NMVOC. Scenario 3 is second worst with a POF impact of 177 700 kg NMVOC. Scenario 4 is the only scenario to have a favourable impact on POF: -12 950 kg NMVOC. Scenarios 0 and 1 perform similarly with impacts of 32 530 and 25 570kg NMVOC, respectively.

Scenario 2 and 3's high impact can be partially attributed to the aluminium scrap reprocessing plant, which contributes 169 900 kg NMVOC to both scenarios and 164 000 kg NMVOC to scenario 4. The WtE plant in Scenario 4 provides a beneficial impact of -181 200 kg NMVOC, while the utilisation of biogas in Scenario 3 provides a beneficial impact of -12 562 kg NMVOC. Figure 5-10 illustrates the impacts for this category.

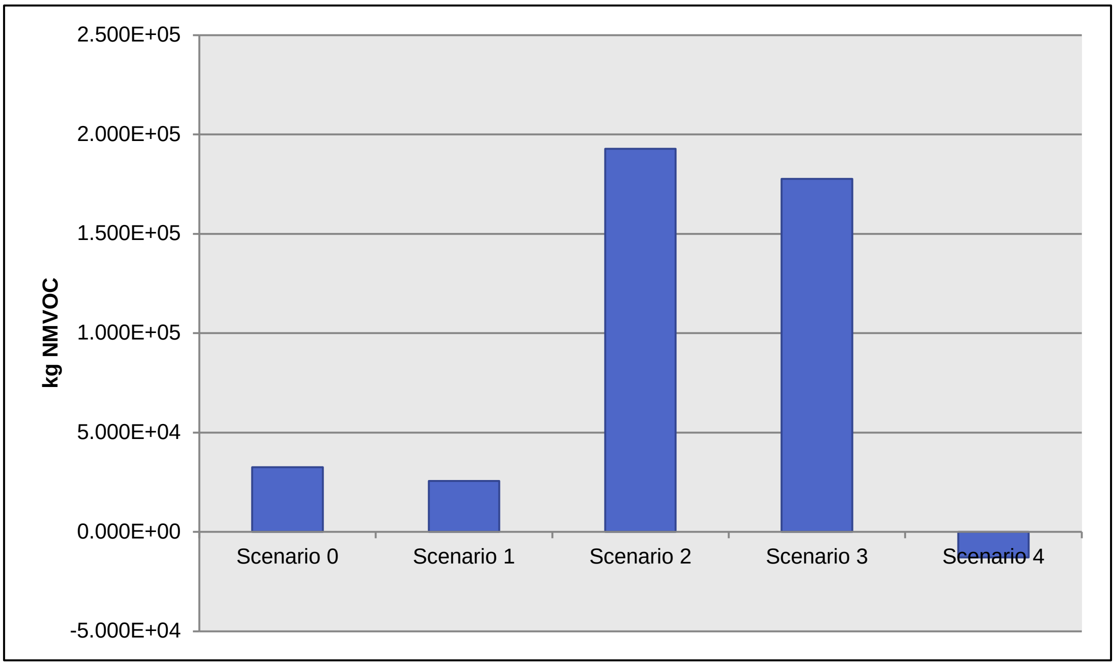

Figure 5 - 10: Photochemical Oxidant Formation

5.3.1.4 Terrestrial Acidification and Eutrophication Potential

These two impact categories follow similar trends for each scenario. This trend is also observable in the photochemical oxidant formation impact category. Figures 5-11 and 5-12 show relatively high harmful results for Scenarios 2 and 3 compared with Scenarios 0 and 1, which are comparatively lower. Scenario 4 is the only system that has an advantageous result.

Scenario 2 has the highest destructive impact in both categories: 372 600 kg SO2-eq for TA and 213 500 kg NOx-eq for EP. Scenario 3 had the second highest, with 341 000 kg SO2-eq for TA and 191 000 kg NOx-eq for EP. Scenario 4 provided the only favourable result with -129 693 kg SO2-eq for TA and -23 560 kg NOx-eq for EP. The baseline resulted in an impact of 22 000 kg SO2-eq for TA and 30 900kg NOx-eq for EP. Scenario 1 performed slightly worse than the baseline with an impact of 27 600kg SO2-eq for TA and 30 900kg NOx-eq for EP.

Scenario 2 and 3's high impact for both impact categories can be attributed to the aluminium scrap reprocessing plant, which contributes 163 800kg NOx-eq to the EP category for both scenarios, 372 600kg SO2-eq to the TA category for scenario 2 and 311 200kg SO2-eq to the TA category for scenario 3. The WtE plant in scenario 4 contributes -189 700kg NOx-eq in the EP category and -432 200kg SO2-eq in the TA category.

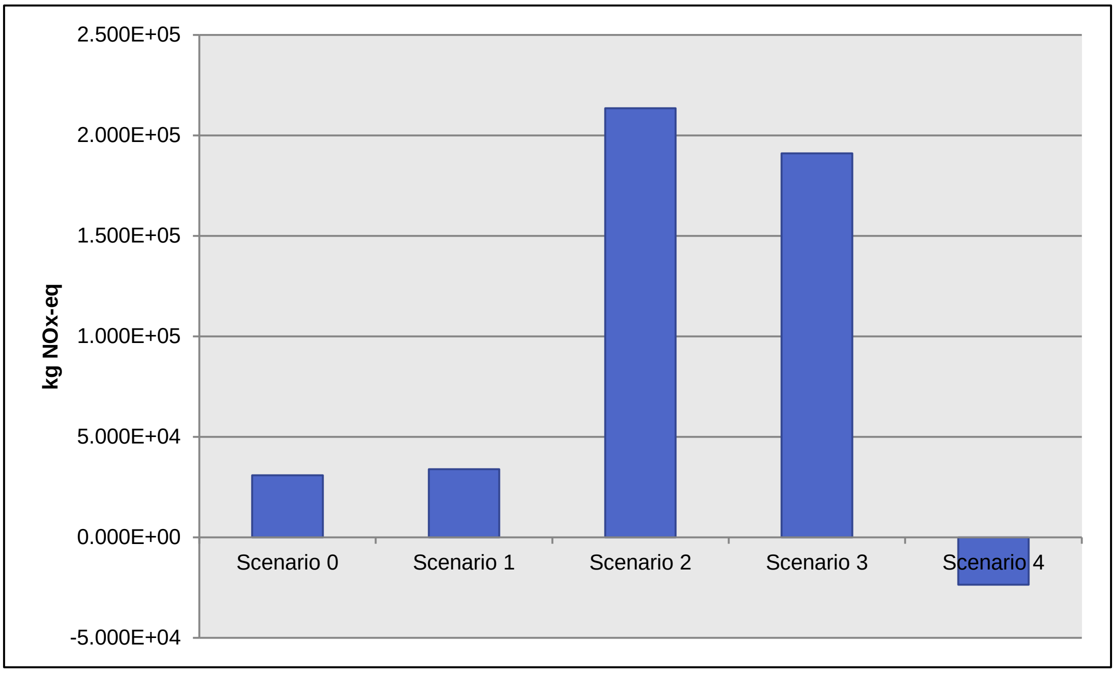

Figure 5 - 11: Eutrophication Potential

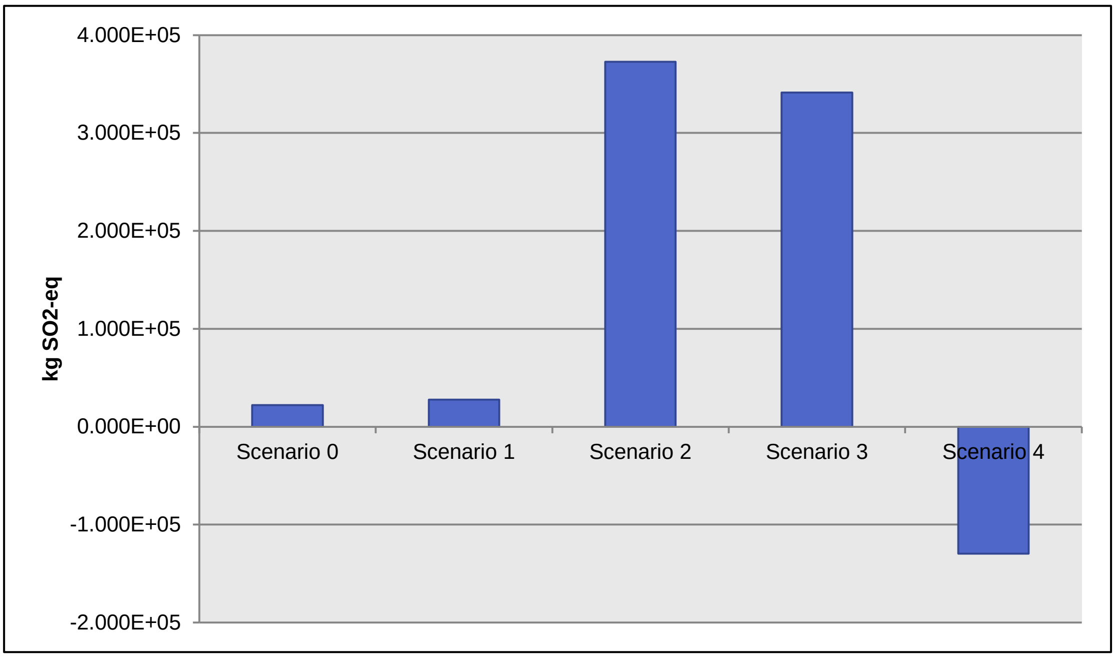

Figure 5 - 12: Terrestrial Acidification

5.3.1.5 Freshwater Eutrophication

The baseline and Scenario 1 have the same result for this impact category (see Figure 5-13), i.e., -166 kg P-eq. Scenario 3 has the largest favourable impact, -726kg P-eq, which can be largely attributed to the addition of the AD plant. The substitution of fertiliser in Scenario 3 contributes -620 kg P-eq to the FE impact category result. In comparison, the substituted fertiliser from the composting in Scenarios 0, 1 and 2 contribute -166 kg P-eq to the result for each system. Scenario 2 has a total impact of -271 kg P-eq for the freshwater eutrophication, while Scenario 4 has an almost zero result of 0.153 kg P-eq.

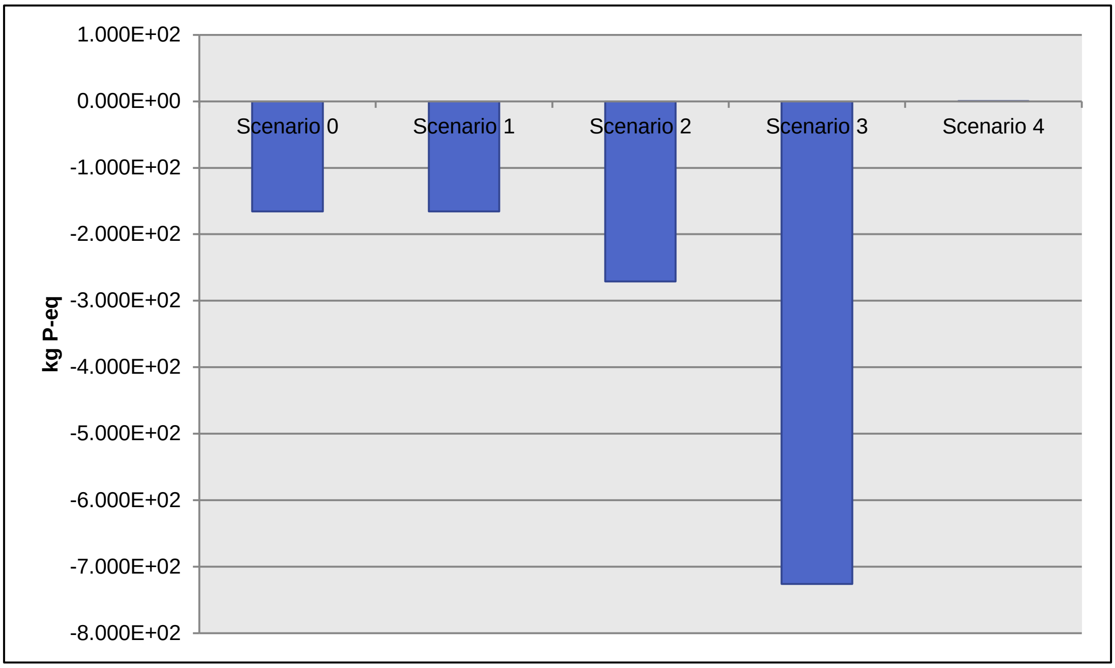

Figure 5 - 13: Freshwater Eutrophication

5.3.1.6 Ecotoxicity

Ecotoxicity, measured in comparative toxic units (CTU), provides an estimate of the fraction of species that may be potentially affected by the chemicals emitted. Scenarios 2, 3 and 4 resulted in similar beneficial impacts. Scenario 3 had the highest favourable impact of -6.44 million CTU, followed by scenario 2 with an impact of -5.77 million CTU and scenario 4 with an impact of -5.64 million CTU. Both the baseline and Scenario 1 have impacts of approximately 720 000 CTU.

The uncollected leachate that enters the surface water contributes 915 600 CTU to both the baseline and Scenario 1. Furthermore, it contributes 605 930 CTU to Scenario 2 and 551 530 CTU to Scenario 3. The aluminium scrap reprocessing plant contributes -4.987 million CTU to Scenarios 2 and 3 and -4.814 million CTU to Scenario 4. Fertiliser substitution contributes -188 400 CTU to the baseline and Scenario 1. Figure 5-14 summarises the environmental scores for this impact category for the scenarios investigated.

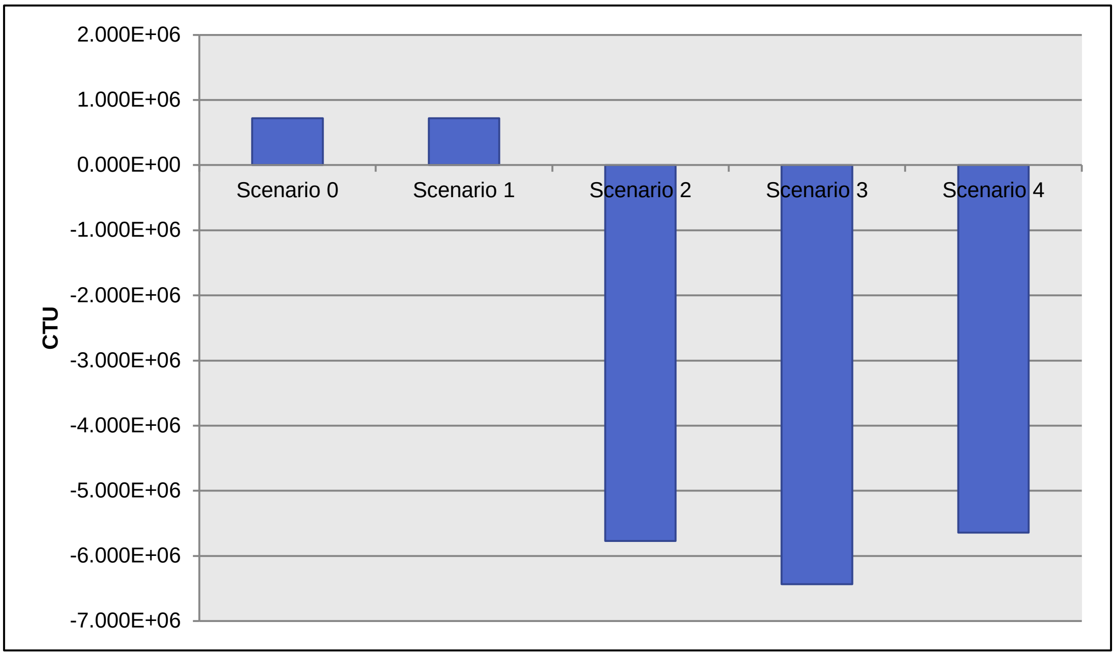

Figure 5 - 14: Ecotoxicity

5.3.1.7 Human Toxicity

Human toxicity consists of two categories, carcinogenic and non-carcinogenic human toxicity. Both are characterised in CTU, which measures the estimated increase in morbidity for the total human population for the chemicals emitted. Both categories follow similar trends as can be seen in Figures 5-15 and 5-16. The ecotoxicity category also has a similar trend.

Scenarios 2, 3 and 4 have relatively high favourable impacts for both categories. Scenario 2 results in an impact of -2.6 CTU for HTC and -310 CTU for HTNC. Scenario 3 results in an impact of -2.61 CTU for HTC and -311 CTU for HTNC. Scenario 4 is similar to the previous two and results in an impact of -2.56 CTU for HTC and -300 CTU for HTNC.

The aluminium scrap reprocessing plant contributes significantly to these results. Scenarios 2 and 3 are attributed -2.6 CTU for HTC and -310 CTU for HTNC, respectively, from the aluminium scrap reprocessing plant, while scenario 4 is attributed -2.5 CTU for HTC and -299 CTU for HTNC. In comparison, Scenarios 0 and 1 have very minimal impacts of 0.002 CTU for HTC and -0.21 CTU for HTNC. The major contributor to these results is the substitution of fertiliser, which contributes -0.335 CTU in the HTC category for both scenarios. Figures 5-15 and 5-16 present the environmental scores for this impact category for each scenario.

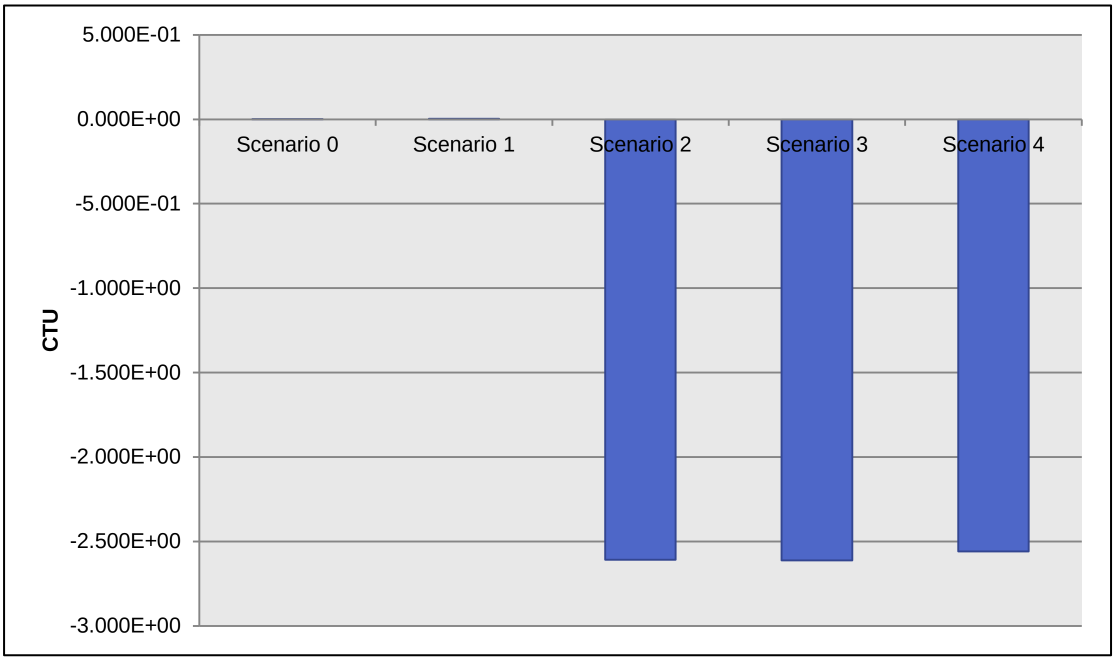

Figure 5 - 15: Human Toxicity, Carcinogenic

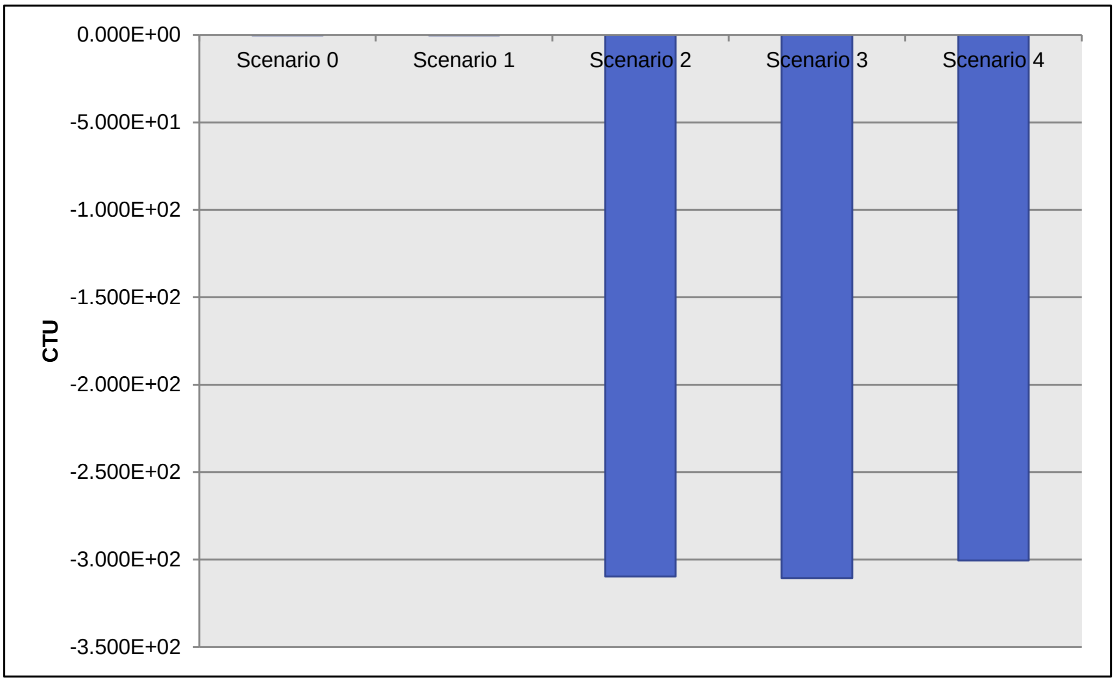

Figure 5 - 16: Human Toxicity, Non-Carcinogenic

5.3.1.8 Particulate Matter

Scenario 4 also outperforms the other scenarios in this impact category (see Figure 5-17). Compared with the other scenarios, this is the only advantageous impact, with a value of -32 620 kg PM2.5-eq. This is primarily due to the WtE plant, which contributes approximately -37 340 kg PM2.5-eq to this category. It is reduced, in part, by the aluminium scrap reprocessing plant, which has a harmful impact of 4 292 kg PM2.5-eq. The aluminium scrap reprocessing plant has a similar effect on Scenarios 2 and 3 with a value of 4 446 kg PM2.5-eq for both.

Scenario 2 performs worst with a total impact of 10 750 kg PM2.5-eq, followed by Scenario 3 with an impact on 8 482 kg PM2.5-eq and Scenarios 1 and 0, which have impacts of 1 643 kg PM2.5-eq and 1 269 kg PM2.5-eq, respectively. The process of the waste management system that affects the baseline and Scenario 1 the most is the PET recycling facility, which contributes 613.6 kg PM2.5-eq to the PM category for both scenarios.

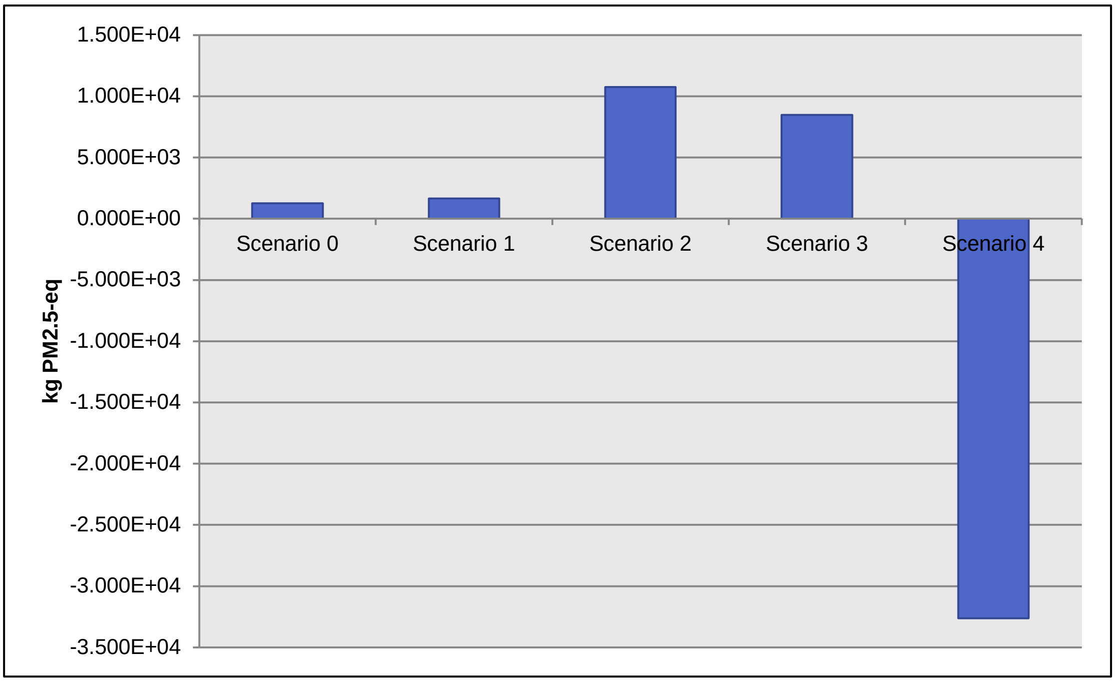

Figure 5 - 17: Particulate Matter

5.3.1.8 Depletion of Abiotic Resources

The DAR category assesses the loss of availability of natural resources, while the DARF category quantifies the loss of available fossil energy. These results follow similar trends as can be seen in Figures 5-18 and 5-19.

Scenario 2 has the highest harmful impact in both categories with an impact of 1.07kg Antinomy-eq for DAR and 89 500 700 MJ in DARF. Scenario 4 has the largest beneficial impact in both categories with a result of -3.17 kg Antinomy-eq for DAR and -762 million MJ for DARF. The baseline and Scenario 1 had similar results for both categories with 0.536 kg Antinomy-eq for DAR and 81 million MJ for DARF. Scenario 3 had an impact of 0.483 kg Antinomy-eq for DAR and 37 million MJ for DARF.

The WtE plant contributed -785 million MJ to DARF and -3.28 kg Antinomy-eq to DAR for Scenario 4. The removal of foreign items in Scenarios 0, 1 and 2 contributes 0.384 kg Antinomy-eq to the DAR category. The largest contributors to the DARF category for the baseline and Scenario 1 are the construction and operation of the landfill, 59 million MJ and the PET recycling facility, -36.9 million MJ. For Scenarios 2 and 3 the paper recycling plant contributes 40.4 million MJ and the plastic recycling plant contributes -67.4 million MJ.

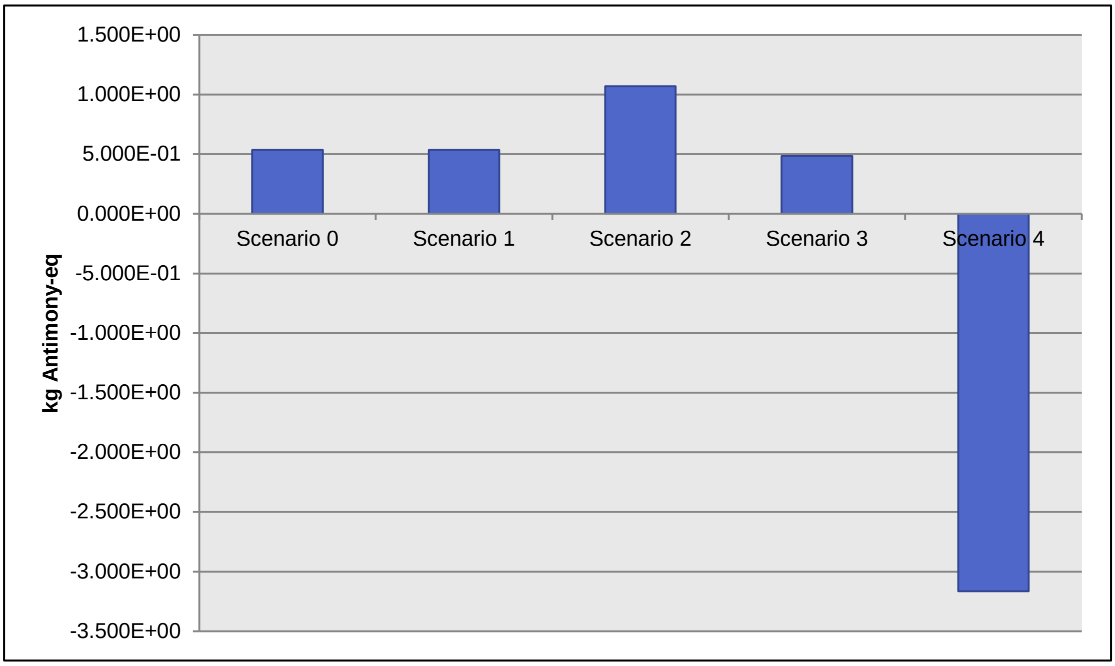

Figure 5 - 18: Depletion of Abiotic Resources

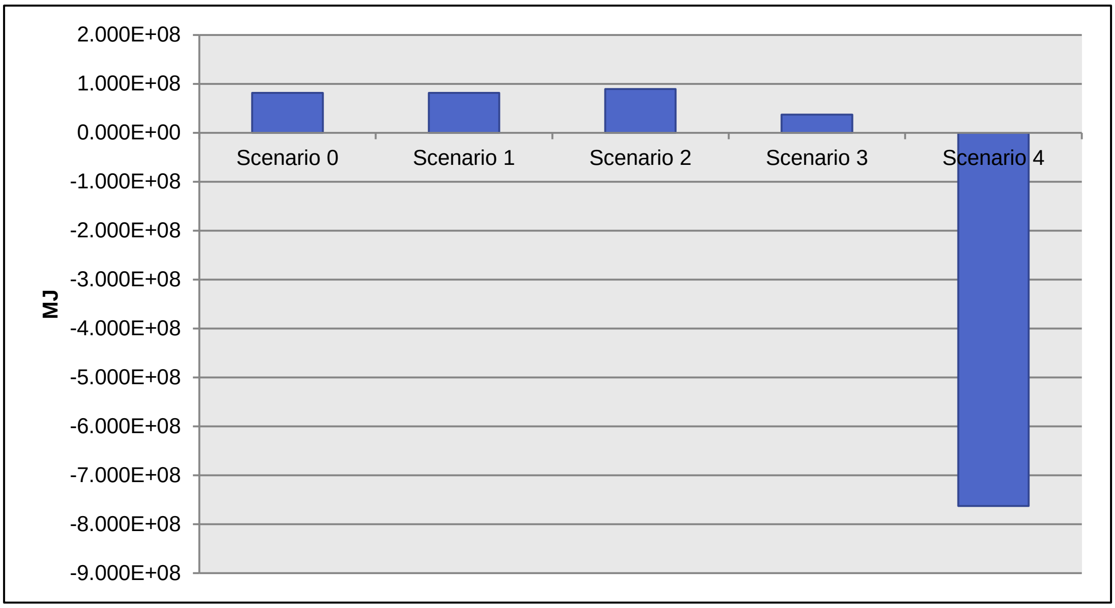

Figure 5 - 19: Depletion of Abiotic Resources, Fossil

5.3.2 Summary of Characterisation

Table 5-4 summarises the results of the LCIA for each impact category and scenario for ease of reference.

Table 5 - 4: Characterised Impacts per Scenario

Impact Category	Unit	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4
GWP	kg CO2-Eq	1.56E+07	-9.46E+06	-1.01E+07	-1.63E+07	-3.61E+07
SOD	kg CFC-11-Eq	-7.95E-02	-7.95E-02	-7.15E-02	-9.69E-02	-1.49E-01
POF	kg NMVOC	3.25E+04	2.56E+04	1.93E+05	1.78E+05	-1.29E+04
TA	kg SO2-Eq	2.20E+04	2.76E+04	3.73E+05	3.41E+05	-1.30E+05
EP	kg NOx-Eq	3.09E+04	3.39E+04	2.14E+05	1.91E+05	-2.36E+04
FE	kg P-Eq	-1.66E+02	-1.66E+02	-2.71E+02	-7.26E+02	1.53E-01
DAR	kg antimony-Eq	5.36E-01	5.36E-01	1.07E+00	4.83E-01	-3.17E+00
HTC	CTU	1.95E-03	2.14E-03	-2.61E+00	-2.61E+00	-2.56E+00
HTNC	CTU	-2.10E-01	-2.09E-01	-3.10E+02	-3.11E+02	-3.01E+02
ET	CTU	7.21E+05	7.22E+05	-5.77E+06	-6.44E+06	-5.64E+06
DARF	MJ	8.12E+07	8.12E+07	8.95E+07	3.71E+07	-7.62E+08
PM	kg PM2.5-eq	1.27E+03	1.64E+03	1.08E+04	8.48E+03	-3.26E+04

5.3.3 Normalised Impacts

Normalisation allows the impact categories to be compared with one another, by normalising each impact to a standard unit. The unit in this study is person equivalents (PE) set to a global average. Figures 5-20, 5-21 and 5-22 allow for an evaluation of the scenarios as a whole, considering all the characterisation impact categories discussed in the previous section. Normalisation also allows one to see the impact categories that have the largest effect on the environmental impact of the scenario in comparison with the other impact categories.

Figure 5-20 illustrates the impact categories for each scenario normalised and set to 100%. This figure clearly shows that in the baseline scenario, GWP has the largest harmful impact followed by DARF. The GWP in Scenario 1 is the largest beneficial impact and DARF is the largest harmful impact. In Scenarios 2, 3 and 4 it can be seen that the HTNC has the largest influence on the environmental impact, followed by HTC. This is a direct result of the aluminium reprocessing plant and the substitution of virgin material.

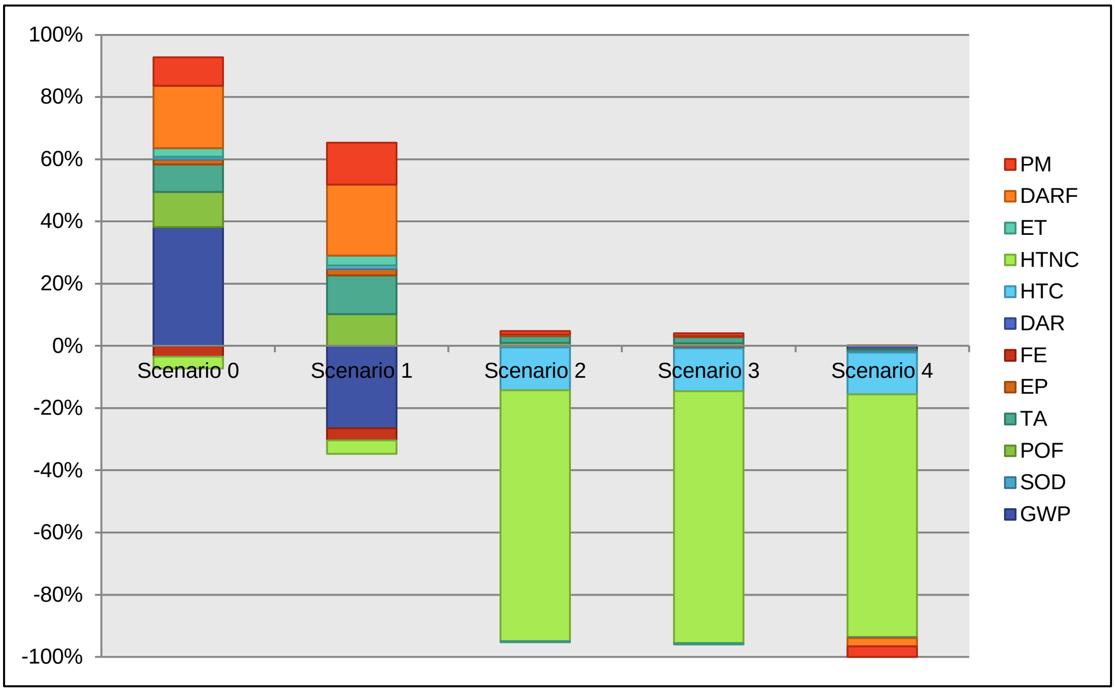

Figure 5 - 20: Impacts per Scenario set to 100%

Figures 5-20 and 5-21 illustrate similar information; however, Figure 5-20 presents the normalisation of each impact category as a portion of the total (100%) environmental impact of the scenario, while Figure 5-21 presents the impact categories for each scenario in PE. It clearly shows that Scenarios 2, 3 and 4 perform the best environmentally as they have the largest advantageous impacts. These large impacts are mainly attributable to the human toxicity impact categories. In comparison with the human toxicity categories, the other categories have a relatively small impact. The DARF category in Scenario 4 also contributes to the strong environmental profile of this scenario; this is due to the substitution of hard coal for waste as the electricity fuel source.

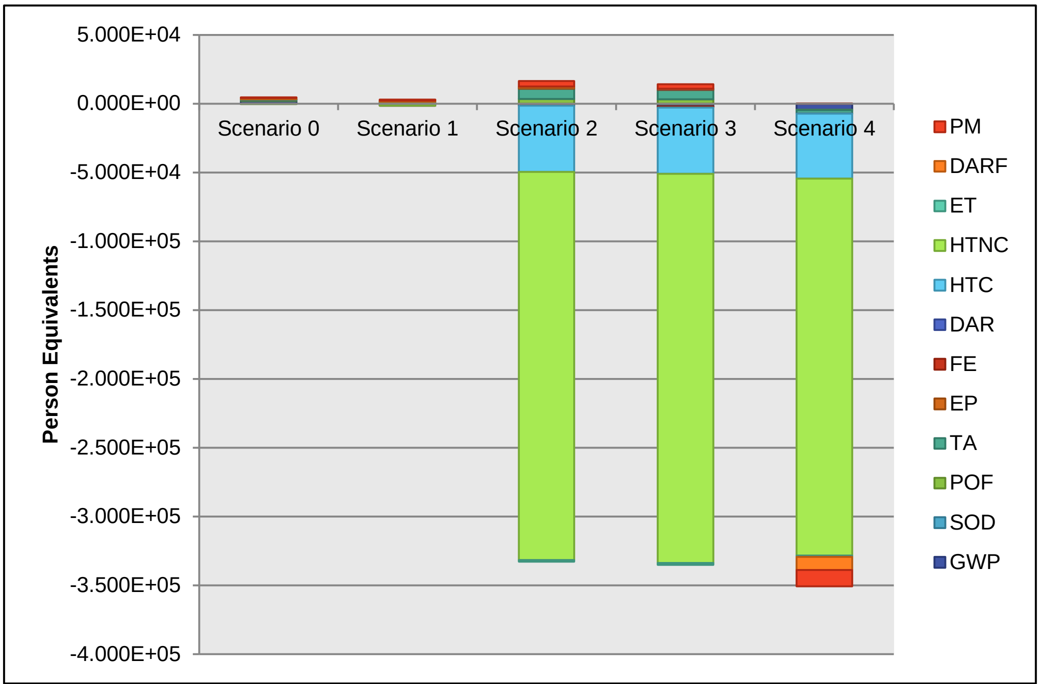

Figure 5 - 21: Normalised Impacts per Scenario

Figure 5-22 presents a ranking of the scenarios for each impact category. Each scenario is apportioned a percentage of the total combined impact for that category. It can be seen that for GWP, SOD, FE, HTC, HTNC, and ET, all the scenarios that include the MRF and reprocessing plants have highly beneficial results.

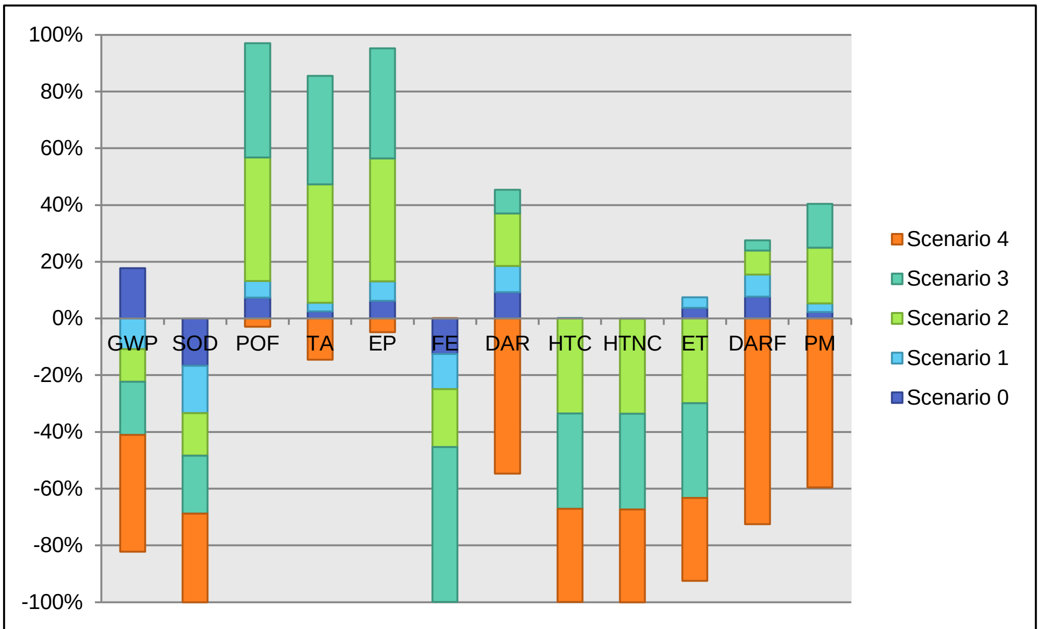

Figure 5 - 22: Normalised Impacts per Category

5.4 Interpretation

This section interprets and discusses the results from the LCI and LCIA and draws conclusions based on the objectives set out in the goal and scope definition. The first section examines each scenario and their respective environmental profiles, considering the possible causes of good or poor performance of the impact categories. The second section details the sensitivity analysis on the largest contributors to each impact category, in order to test the robustness and reliability of the results.

5.4.1 Environmental Profile of the Scenarios

The LCIA classified and characterised the impacts for each scenario as per the results of the LCI. Through the characterisation and normalisation of each impact category, the scenarios can be compared with one another other and the scenario with the lowest environmental impact can be identified. The list below ranks the scenarios from least environmental impact to most, based on the normalisation.

1. Scenario 4
2. Scenario 3
3. Scenario 2
4. Scenario 1
5. Baseline Scenario

From a life cycle perspective, the current Newcastle MSW management system has the highest environmental impact in comparison with the other scenarios. These impacts are quantified in Table 5-4. The GWP of the baseline is the only scenario that has a harmful impact. GWP contributes about 40% of the overall impact of the baseline scenario. This impact is mainly due to the methane generation in the landfill and its release into the atmosphere without being oxidised through the top cover. The baseline has the second lowest impact for TA, EP and PM. This is mainly attributable to the substitution of fertiliser, which reduces the need for chemical fertiliser production. The baseline scenario leaves much space for the growth and development of the IWMS of NLM.

Scenario 1 has the second highest environmental impact of all the scenarios. There is little difference between the baseline and this scenario, except for the addition of the landfill gas collection and flare system. It performs similarly to the baseline but has the worst impact in the toxicity categories: HTC, HTNC and ET. Scenarios 2, 3 and 4 significantly outperform the baseline and Scenario 1 in the aforementioned categories, primarily due to the reprocessing plants, particularly aluminium reprocessing.

Scenario 2 increased the source separation to four streams and added a MRF to the IWMS. This scenario has the highest impact in the SOD, POF, TA, EP, DAR, DARF and PM categories. Even though it has such large impacts in many of the LCIA categories it is still ranked as the third best scenario overall. The aluminium scrap reprocessing plant contributes the most to the high impacts in the TA, EP and PM categories. This could be due to the release of chemicals in the melting and reprocessing procedures. Although the aluminium reprocessing plant contributes highly to the TA, EP and PM categories, it also contributes to low impacts in the toxicity categories: HTC, HTNC, and ET, in which Scenario 3 has the lowest impact.

Scenario 3 is similar to Scenario 2, except for the substitution of an AD plant for the composting plant. The AD plant treats a mix of garden waste and food waste. Food waste is source separated in this scenario, adding another stream to the system. As previously noted, Scenario 3 has the lowest impact in the toxicity categories; it also has the lowest impact in the FE category. Overall, Scenario 3 has the second best environmental profile. The substitution of virgin aluminium production is the main contributor to the low impact in the toxicity categories. The AD plant substantially pays off in the FE category as the substitution from the fertiliser contributes the most to the low impact of Scenario 3. Comparing Scenario 2 with Scenario 3, the contribution of the AD plant is clear. Scenario 3 outperforms Scenario 2 in most categories, i.e. POF, TA, EP, DAR and PM, with help from the biogas utilisation from the AD plant.

Scenario 4 is significantly different from all the other scenarios. There is little source separation in this scenario. All waste, except for PETs, is sent to the WtE plant. The ash outputs from this plant are sent to a bottom ash landfill, while the iron and aluminium scraps are sent to their respective reprocessing plants. This comparative study identifies the WtE scenario as having the least environmental impact, due primarily to the substitution of coal as the primary source of fuel for electricity generation. Scenario 4 performs outstandingly in most of the categories including, GWP, SOD, POF, TA, EP, DAR, DARF and PM. The WtE plant is the main cause of the environmental profile of this scenario having such a low score. This is possibly due to the air pollution control system that is part of the WtE plant and the strict regulations that define the outputs of such a system. This scenario also has the worst impact in the FE category, which could be caused by the hazardous nature of the ash waste being landfilled and the leachate generated at the landfill.

The WtE plant in Scenario 4 produces 44 million kWh per annum, from a total energy of 720 million MJ. The hard coal is substituted at an efficiency of 22%, which results in a 5MW WtE plant that could be installed in NLM and powered by the MSW.

Overall, for effective decision support to occur, the feasibility of the scenarios has to be taken into consideration. The scenarios were built with the waste hierarchy in mind. From Scenario 3 to the baseline, the results are in line with the waste hierarchy. As more reduction, re-use and recycling is added to the system, the environmental impact decreases. While having the lowest environmental impact, Scenario 4 does pose a few problems. WtE plants have a large capital cost and require highly technical skills. In addition, an incineration plant is not in line with the National Waste Management Strategy. Newcastle is a relatively small municipality, which may be unable to afford a WtE plant or attract the required skills to maintain and operate the plant. With these factors in mind, the best scenario, from an environmental perspective, for Newcastle to implement is Scenario 3. In similar fashion to the PET recycling facility, the paper, plastic, aluminium, metal and glass reprocessing facilities could be privatised to reduce capital costs. Substituting the composting plant with an AD plant would provide the municipality with a form of renewable energy and result in a better quality digestate for fertiliser substitution.

Scenario 3 may cause some problems, as it requires many streams of waste to be separated at the source. However, NLM have proven themselves capable of educating their citizens and running a successful source separation programme. In time, this could be up-scaled to the required level of source separation. In examining the environmental profiles of the scenarios, it is clear from Figure 5-21 that the toxicity categories, primarily human toxicity, have the biggest influence on the environmental impact of the scenarios. The normalisation figures show that Scenarios 3 and 4 provide a similar reduction in the environmental impact of the MSW management system in NLM. As the chosen option, Scenario 3 will offer significant improvement in the environmental impact of the MSW management system in comparison with the baseline system.

5.4.2 Sensitivity Analysis

A sensitivity analysis tests a model's sensitivity to changing parameters. To evaluate the data used for the LCA a sensitivity analysis was run through the EASETECH model. This was carried out by systematically changing the input parameters. Table 5-5 details the inputs that were considered critical for sensitivity analysis. The sensitivity analysis was run on the external processes and inputs that contributed the most to each impact category. For example, for SOD, Scenario 2 performed the worst, and the process of lubricating oil production from the composting module made the highest contribution to this performance. Therefore, a sensitivity analysis was run by increasing the value of the lubricating oil production by 10% in order to ascertain the change in the characterisation for SOD. Each value under consideration is increased by 10% to determine the effect that process has on the scenario. If the impact category result increased by more than 10%, it would indicate that the model is highly sensitive to that parameter.

The sensitivity ratio (SR) gives an indication as to how the change in the parameter affected the overall change in result. The equation used to calculate SR is as follows.

$$SR = \frac{\frac{\Delta result}{initial\ result}}{\frac{\Delta parameter}{initial\ parameter}}$$

Table 5 - 5: Sensitivity Analysis for NLM

Impact Category	Scenario	Contributor	Sensitivity Ratio
Global Warming Potential	Baseline	Carbon from dirty cardboard	0.59
Stratospheric Ozone Depletion	2	Lubricating oil production	0.31
Photochemical Oxygen Demand	2	Aluminium melting	0.92
Terrestrial Acidification	2	Aluminium melting	0.91
Eutrophication Potential	2	Aluminium melting	0.80
Freshwater Eutrophication	4	Phosphorous from animal food waste	0.44
Depletion of Abiotic Resources	2	Lubricating oil production	0.36
Human Toxicity, Carcinogenic	1	Electricity production using hard coal	0.65
Human Toxicity, Non-Carcinogenic	1	Arsenic from food cans	0.06
Ecotoxicity	1	Zinc from plastic products	0.008
Depletion of Abiotic Resources, Fossil	2	High voltage electricity production mix	2.87
Particulate Matter	2	Aluminium melting	0.47

Table 5-5 shows that, with a 10% increase in the highest contributing processes or inputs, most of the impact categories are changed by less than 10%. For example, HTC had a sensitivity ratio (SR) of 0.65, which indicates a 6.5% increase in the result, due to a 10% increase in the marginal electricity value. For GWP, FE, HTC and ET the respective waste fraction was increased by 10% and the waste generation composition normalised to 100%. This is an indication of the sensitivity of the model for those contributors.

The only impact category to have a high SR is DARF. The SR of 2.87 indicates a 28.7% increase due to a 10% increase in the electricity production mix value. A 20% increase in electricity production mix resulted in a SR of 5.74. This indicates that DARF is highly sensitive to the electricity mix and a high level of accuracy is required for this parameter for reliable LCA results. As a large portion of the South African electricity mix comes from hard coal and DARF is concerned with the loss of fossil energy, its sensitivity to the electricity parameter can be expected. However, the electricity data used were of relatively high quality and, therefore, the sensitivity of the model to changes in the electricity mix parameter should not be of major concern.

6: DISCUSSION AND CONCLUSION

6.1 Discussion

This section extrapolates the findings from the single case study to inform the development of waste LCA as a decision support tool for South African municipalities. It also discusses the dissemination of LCA results to South African municipalities. One of the research objectives of this study is to assess EASETECH as a LCA tool for modelling MSW management in South Africa. Based on the results of the Newcastle waste LCA and the reliability of those results, this section analyses the applicability of EASETECH as a tool for waste LCA in South Africa. Furthermore, this chapter highlights the uncertainty and limitations inherent in this study and in waste LCAs in general and discusses ways to mitigate these shortcomings.

6.1.1 Decision Support for South African Municipalities

The assessment of integrated MSW scenarios is a complicated exercise. Waste management is a dynamic field that incorporates a multitude of variables and interest groups. In the selection of technologies that will promote sustainable development, it is important that projects have efficient and comprehensive decision support. The literature indicates that the assessment of environmental impacts (through a LCA approach) of different MSW management scenarios should be amongst the first steps in decision support for stakeholders, i.e., municipalities, project developers, technology vendors and civil society. However, scenario analysis should encompass more than an assessment of environmental impacts. The STA (Sustainable Technology Assessment) methodology discussed in Section 2.5 can support reliable decision support through the use of a basket of tools and indicators, including a social impact assessment, economic and financial modelling and a technology audit. In addition, utilising MCDA will enable decision makers to reduce the difficulty of assessing the complex situation of MSW management.

LCA is a tool that should be used as a part of a highly integrated approach to technology selection. It is a component of a decision support framework especially in the case of sustainable technology selection and diffusion in emerging economies. Waste LCA can be used in the early stages of assessing feasibility. It is a powerful tool that allows practitioners to compare the environmental impact of different scenarios for waste management. Furthermore, waste LCA has gained acceptance as a reliable method for planning and policy making for waste management (Ekvall et al., 2007). Scenario analysis should be conducted in accordance with the waste hierarchy, which as a rule of thumb provides reliable guidelines to improve the environmental impact of waste management (Finnveden et al., 2005). This is evident from the results of the LCA presented in the previous chapter.

Waste LCA is an uncommon approach for decision support in South African municipalities. This is as a result of various constraints, namely, time, financial resources, human resources, data resources and a general lack of awareness of the benefits of LCAs amongst decision makers. Furthermore, LCA expertise in South Africa is scarce. This hinders the development of LCA as a decision support tool for South Africa as the LCA methodology is not mainstreamed. Owing to this lack of skills and awareness, a high level of interaction between LCA practitioners and stakeholders is required for LCA results to be properly leveraged. While the simplicity of presenting the results in the form of a single score may seem appealing, this leads to a loss of transparency and information. A more comprehensive alternative would present a basket of key categories to make the results more communicable. Categories such as GWP, toxicity and eutrophication may be of significant relevance to stakeholders and could thus be the main categories for presentation. Furthermore, stakeholders could apply a weighting to the categories prior to the results being produced.

Waste management stakeholders in South African municipalities encompass a wide range of individuals in the private and public sectors and civil society. Conflict is common between stakeholders with different interests. A participatory approach should be entrenched in the goal and scope definition stage of the LCA to reduce conflict and arrive at solutions that are acceptable to all parties (Blengini et al., 2012). Figure 6-1 embeds the research and conceptual approach within the real world. It shows how the discussion that is built from the LCA and the lessons from the case are reported back to stakeholders, in this case, the public sector, i.e., NLM. The findings can then be used to influence and inform public policy, which may lead to further, purposeful trans-disciplinary research and development of the LCA methodology in South Africa.

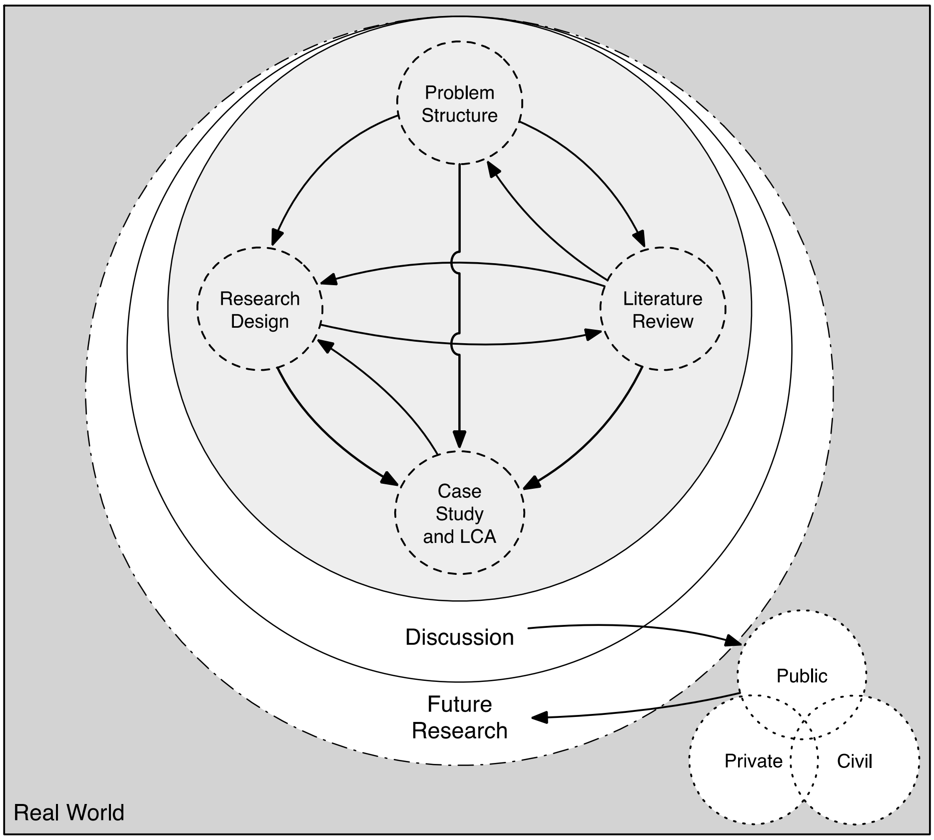

Figure 6 - 1: Conceptual Approach 2.0

6.1.1.1 Waste LCA and EASETECH in South Africa

The EASETECH LCA model is an intuitive and user-friendly tool that provides robust and verifiable LCA results specifically for waste management. The outcome of the case study analysis has led to an understanding of the strengths and weaknesses of utilising EASETECH as a waste LCA modelling tool in the South African context. In order to corroborate these findings more waste LCAs for South African municipalities should be conducted using EASETECH.

EASETECH has many features and strengths that make it suitable for modelling waste management in the South African context. First and foremost, not much primary data is required to produce a relatively reliable model of an IWMS. This is highly beneficial to many South African municipalities, where little data has been gathered on waste management and few municipalities are utilising waste treatment technologies such as MRFs, from which data can be collected. According to the programme developers and LCA experts at DTU, the MSW physical composition (i.e., the waste fractions) provides a good starting point to construct an IWM model in EASETECH. The large database of chemical compositions of waste fractions and waste treatment technologies already available in EASETECH can be utilised to construct a model that is specific to an individual municipality.

EASETECH provides a relatively easy to understand user interface. With adequate training, a user with a strong understanding of LCA theory and methodology can extract a highly detailed LCI and run an impact assessment utilising their desired LCIA method. The LCIA allows for characterisation at many levels, from the whole model to just a single process. This allows for in depth analysis of the impacts of each scenario. In addition, EASETECH utilises Sankey diagrams, which provide a flow diagram where the width of the arrows are proportional to the quantity of the flow. The Sankey diagram is built off a feature, which allows the user to determine the elemental composition of the waste at any point in a scenario. EASETECH has a customisable interface and database, which allows the user to adjust or create technologies and material properties to best suit their area of study. Therefore, with an accurate dataset, a model can be built with an intrinsic accuracy to assess the environmental impact of a MSW management system.

Waste LCAs can be used as decision support tools to supplement multiple trans-disciplinary decision support frameworks. Understanding the environmental impact of MSW management is vital to decision support. Through EASETECH a practitioner can construct more detailed scenarios, using a variety of technology combinations to find the waste management system that has the least environmental impact. After building a range of scenarios, the LCA practitioner can understand the environmental impact that the substitution of virgin material, through recycling and reprocessing, has on a system. Furthermore, the practitioner can identify opportunities for electricity or energy substitution and the impact this would have on the environmental profile of a system. EASETECH provides information to calculate the amount of energy that can be extracted from the system. Moreover, the energy flow through the system can be followed, i.e., EASETECH gives the user information on the energy input, output and throughput. Understanding energy consumption and generation is particularly important in South Africa, where the primary energy supplier, Eskom, is unable to meet country's electricity demand.

Decision support requires a deep contextual understanding of the system under consideration. Waste LCA provides stakeholders with a holistic comprehension of the environmental impact of a MSW management system. As awareness of waste LCA grows, the need for it as part of decision support will increase. The need to truly understand the environmental impact of waste management will drive better data collection by municipalities. High quality data is a prerequisite to produce an accurate and reliable LCA. To improve the applicability of the LCA results for the respective municipality, the datasets should originate from the study area and the technologies under study. Furthermore, in accordance with certain criteria, i.e., the availability, accessibility and quality of waste datasets, EASETECH can be a useful tool that has many benefits for conducting waste LCAs for MSW in South Africa.

The lack of waste LCA skills and stakeholders’ low levels of awareness of the benefits of waste LCAs in South Africa create a barrier to the wide scale (i.e., national) deployment of EASETECH. For EASETECH to be utilised to its full potential, policy makers, practitioners and municipal waste managers need to attend the training course at DTU. This adds to the cost of conducting a waste LCA, which can be an expensive undertaking. Waste management departments in many municipalities in South Africa do not have sufficiently large budgets to accommodate the cost of conducting a waste LCA on their current MSW management system. This is exacerbated when one considers the other assessments that are required for effective decision support. Lack of awareness, arguable lack of political will (policy and practice), a shortage of skills, and the high cost of LCAs can prevent waste LCA from becoming an important piece in the decision support puzzle. However, if these barriers are overcome a crucial piece in conducting a successful waste LCA will be the collection of high quality datasets.

EASETECH has a built-in database of technologies, processes and material properties. As the previous chapter showed, this proxy data can be used to conduct a relatively reliable LCA. However, as noted above, it is more advisable to use data from the study area to limit uncertainty. Proxy data can be used to streamline the LCA. The EASETECH database is built on data collected from waste management in European municipalities. These are highly developed technologies and processes. This data, from a developed country can be applied to a municipality from a developing country with some reliability. However, there will be an inherent inaccuracy if only the technologies are transferred from the European countries into South African municipalities. The relevant skills also need to be transferred. Training needs to occur in South Africa to build the skills required to efficiently operate and maintain the transferred technologies.

The LCI is paramount to the results of a waste LCA being precise, robust and reproducible. Data may be unavailable for waste LCAs of South African municipalities. As far as possible, LCA practitioners should rely on the ecoinvent database to supplement datasets in EASETECH. Ecoinvent provides LCA practitioners with LCIs for a wide range of processes for their specific country of study, such as marginal electricity production or the electricity mix, both of which were used in this study. Ecoinvent provides trustworthy LCI data; however the database is not comprehensive and more contextual data will still need to be collected to conduct a waste LCA for a South African municipality.

South African municipalities need to start collecting detailed data on their waste management systems. This will enable LCA practitioners to construct a high quality LCIs. The data should comply with the data quality requirements for reliability, completeness, and temporal, geographic and technological correlation. Data should be based on measurements with few assumptions and with no qualifications required to complete and explain the dataset. It should be collected from all parts of the municipal waste management system under consideration and should be collected regularly, i.e., at least once a year. This will ensure that recent, reliable data is used to build the LCI and conduct a waste LCA. A thorough waste LCA can contribute to the development of a detailed and comprehensive IWMP for municipalities that will ensure that their waste management and growth is sustainable.

There are advantages and disadvantages to using EASETECH as a LCA tool to assess waste management in South African municipalities. This section highlights the gaps and opportunities for development in this field. As awareness and understanding of the LCA methodology improves in South Africa, skilled LCA practitioners will drive the need for better data collection. While the misuse of proxy data may lead to results that are highly sensitive to input parameters, this study has shown that a relatively reliable model could be built primarily using the EASETECH database and substituting as much relevant available South African data as possible. EASETECH is globally lauded as one of the most sophisticated scientific software modelling tools available to conduct waste LCAs. With its customisable databases and interfaces, it can allow South African municipalities to transition towards the adoption of state-of-the-art technical frameworks for technology decision support.

6.1.2 Uncertainty in LCA

All LCA studies are subject to a level of uncertainty. This can arise from inaccurate measurements, variability of data, incorrect estimations, unrepresentative or missing data and modelling assumptions (Clavreul et al., 2012). These uncertainties or limitations are not unique to LCAs; similar problems are present in a range of environmental assessments (Ekvall et al., 2007). Uncertainty can typically propagate in three forms: model uncertainties, scenario uncertainties and parameter uncertainties. Model uncertainties arise from attempting to represent real life in the form of a linear mathematical equation. Moreover, model uncertainties can be identified in the models used for waste collection and transport, where idling is not taken into account, or in the LCIA, which attempts to quantify substance fate and the pathways through the environment (Clavreul et al., 2012).

Scenario uncertainties arise from decisions made in the construction of the scenarios. This can include the system boundaries, which should cut-off at the point where there is little environmental relevance of the excluded impact (Clavreul et al., 2012). In addition, scenario uncertainties can arise from the choice of technologies and how well this represents the area under study. Technology choices have to have reliable temporal and geographic correlation to reduce uncertainty (Clavreul et al., 2012). Furthermore, uncertainties related to the waste composition and time horizon of the inventories and the impact characterisation are considered scenario uncertainties. Finally, parameter uncertainties arise from each specific input parameter, which has inherent variability. This can range from waste fractions, to diesel consumption, to sorting efficiencies and characterisation factors (Clavreul et al., 2012).

When conducting a LCA, it is important to attempt to minimise uncertainty as far as possible. Clavreul et al. (2012) suggest a four-step method; beginning with step 0, a contribution analysis, followed by step 1, a sensitivity analysis, step 2, uncertainty propagation, step 3, uncertainty contribution analysis and step 4 combined sensitivity analysis. This is a tiered approach, which will provide a quantitative assessment of the uncertainty in the waste LCA model. The approach suggested by Clavreul et al. (2012) begins as a rough evaluation and evolves into a more precise assessment of the uncertainty in the LCA as the steps are followed. It is suggested that, with limited time and resources, at least a sensitivity analysis be conducted as this requires no additional data (Clavreul et al., 2012). This study included a sensitivity analysis to reduce uncertainty as detailed in the Interpretation phase of the LCA.

6.1.3 Comparison with International Studies

This study is the first LCA on MSW management in South Africa using EASETECH. As a result, it could not be compared with results from similar local municipalities in the country. LCAs have been widely conducted in the international waste management field, particularly in Western, developed nations. The literature review in Chapter 2 presented two international waste management LCA studies from developing countries, namely China and Indonesia. This section presents a brief comparison of the LCA on NLM and these two international studies.

The Chinese study restricted the impact assessment to GWP (Zhao et al., 2009). This limits the comparison of the results as this study (NLM) assesses each scenario in 12 categories. The Chinese study found their integrated scenario, including a MRF, AD plant, incineration plant and landfill to have the lowest GWP. In this study, focusing only on the GWP category, Scenario 4 has the lowest impact, followed by Scenario 3. Scenario 3 is similar to the integrated scenario in the Chinese study incorporating a MRF, AD plant and landfill with LFG utilisation to treat the MSW. The NLM LCA incorporated the substitution of electricity production and virgin materials, while the Chinese study only included the substitution of virgin materials within its system boundary. Taking this factor into account, the results of the Chinese study are conservatively comparable to that of the NLM LCA. That is, the integrated scenarios involving recycling, reprocessing, AD and LFG technologies both have low GWPs.

Gunamantha and Sarto (2012) studied MSW management scenarios for the KARTAMANTUL region in Indonesia. Their study focused on treating MSW to create energy; hence, all their scenarios included WtE technologies. Furthermore, the Indonesian study included avoided emissions from marginal electricity production and assessed the scenarios in four impact categories that are similar to four of the impact categories in this study. In the Indonesian study, the direct gasification of all MSW resulted in the lowest or second lowest impact for all the categories (GWP, acidification, eutrophication and POF). This is a mass burn technology, which can be compared with the WtE Scenario 4 in the NLM LCA. Scenario 4 also had the lowest impact in the four categories of GWP, TA, EP and POF.

In summary, the results of this LCA on waste management in NLM can be compared with international studies to a limited extent. Despite the differences between the three studies, a similar pattern emerges when comparing the results of international studies with those of the Newcastle LCA.

6.2 Conclusion

This study aimed to provide decision support for NLM on their MSW management system. Five objectives were designed to achieve this aim. An environmental assessment of five scenarios for managing MSW was conducted from a consequential life cycle perspective. In the first scenario, the environmental impact of the current (baseline) MSW management system in NLM was evaluated, while the other four scenarios were constructed in accordance with the waste hierarchy, modelling alternative configurations of waste treatment technologies. The environmental impacts of all the scenarios were evaluated utilising EASETECH (waste LCA software) and the reliability of the results was tested through a sensitivity analysis. Finally, EASETECH was assessed as a waste LCA tool to improve decision support for MSW management in South African municipalities; this was addressed in the above discussion.

An IWMS was sought that provided a reduction in the environmental impact of MSW management in NLM in comparison with the current baseline. The baseline scenario proved to have the worst environmental impact. In particular, it had a high impact in the GWP category with a characterisation of 15.5 million kg CO_2-equivalents, compared with the other scenarios, which all had mitigating GWPs. Scenario 4 performed particularly well, with a beneficial GWP of 36.1 million kg CO_2-equivalents. All the scenarios ranked as would be expected, i.e., according to the waste hierarchy. The more recycling, reduction and re-use the scenario entailed, the lower the environmental impact. The only thermal treatment for waste under consideration was in Scenario 4, which outperformed all the other scenarios due to its air pollution control system and electricity substitution, which replaced hard coal for MSW as the fuel source.

Scenario 4 concluded that a 5MW WtE plant could be installed in NLM and powered by their MSW. This plant could provide part of the free basic electricity required for all NLM residents. While Scenario 4 had the lowest environmental impact overall, WtE is a relatively new technology in the South African MSW management landscape. In addition, WtE requires a high capital investment and highly technical skills for construction, operation and maintenance, hence rendering this an unsuitable technology option for a local municipality like Newcastle. The LCA identified Scenario 3 as having a similar normalised impact to Scenario 4.

Scenario 3 was preliminarily suggested as the most feasible for NLM. It builds on the current infrastructure in place in Newcastle. Scenario 3 increases the source separation streams and transitions from a composting plant to an AD plant to treat food and garden waste. In addition, it would require the construction and operation of a MRF to which all the recyclable waste will be routed. Sorted recyclables will be transferred to reprocessing plants. These improvements to the current MSW management system yield a significant reduction in environmental impact.

The sensitivity analysis was conducted on the largest contributor to each impact category. The low sensitivity of the scenarios to changes in the parameters indicated that the model is relatively reliable and accurate. However, while the scenarios were not highly sensitive to many of the processes and inputs that were tested, the sensitivity of more parameters should be checked to further reduce the uncertainty of the model.

This study on NLM provided initial evidence that EASETECH can be used as a tool for waste LCA modelling in South African municipalities. It has a customisable interface and database, which will allow LCA practitioners to use their personalised datasets in the modelling programme. By utilising EASETECH and waste LCA as decision support tools, stakeholders can be assured that the evaluation encompasses the whole environment; i.e., human health, ecological health and natural resources. For successful LCAs to be conducted on MSW management in South Africa, practitioners require more high quality data. The process of building the LCI is a core issue. As waste LCAs become more prevalent in South African municipal decision support tools, there will be a growing need for more detailed datasets. With a reliable and comprehensive dataset, practitioners can conduct LCAs for municipalities as part of a basket of decision support tools, including social impact assessment and economic feasibility.

6.2.1 Recommendations for Future Research

A contextualised standardised framework for decision support needs to be developed for stakeholders to select the appropriate configuration of technologies to treat MSW in the South African context. An integrated framework to construct IWM scenarios should include: economic and financial feasibility, social impact assessment, technology audits and LCA. This will promote reliable data collection by municipalities. In addition, decisions can be supported through the use of approaches such as MCDA to incorporate the multitude of viewpoints and interest groups that are inherent to MSW management.

The primary recommendation is that future research needs to focus on collecting primary LCI data from all types of South African municipalities (local, district and metropolitan). This data should encompass chemical composition of the waste and the emissions from waste treatment plants, like the open windrow composting in NLM. With robust and recent primary data, it is possible for LCA practitioners to construct accurate and reliable models with low uncertainty.

Moreover, this study has shown that future LCAs on MSW management in South African municipalities can be conducted utilising the EASTECH modelling programme to provide reliable results. To further corroborate these findings, it would be beneficial to conduct a waste LCA on NLM using the same data with another modelling tool, such as SimaPro and assess the sensitivity of the model to more parameters. A better understanding of how the data performs in another model will allow for comparison with the EASETECH model and the results. This would enable more concrete conclusions to be reached on the applicability of EASETECH as a waste LCA tool for South African municipalities.

Finally, more South African municipalities need to conduct waste LCAs, utilising EASETECH and/or other programmes. The increased demand for waste LCAs will lead to better data collection, enabling stakeholders to make more informed decisions based on state-of-the-art systems modelling methods.

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APPENDIX A: LCI OF BASELINE SCENARIO

In an effort to conserve paper, a portion of the LCI for the baseline scenario is detailed in this appendix. The full LCI would exceed 130 pages.

Name	Compartment	Sub compartment	Unit	Total	Composting air emissions Aarhus_[1]	Fertilizer substitution, MSW compost, Denmark, 2005	UOL direct emission, MSW compost, plant farming, East Denmark, loam soil, 2005	LFG - Oxidation in top cover (4c)	LFG - Oxidation in top cover (4c) - NLM	Leachate and soil - Storage of carbon and other pollutants (2b)	Leachate and soil - Storage of carbon and other pollutants (2b)_[1]	Leachate - Uncollected (3b) - Emissions to surface water and attenuation	Leachate - Uncollected (3b) - Emissions to surface water and attenuation - NLM	Removal of foreign items prior to shredding Aarhus_[1]	PET Recycling Facility, NLM Corrected	Collection and Transport of Waste, NLM, 2013	Collection and Transport of Waste, NLM, 2013, PET	Collection and Transport of Waste, NLM, 2013, Garden Waste	Construction and operation of landfilling, NLM	Construction and operation of landfilling, NLM_[1]
Radon-222	air	low population density, long-term	kBq	4.11E+06	0	0	0	0	0	0	0	0	0	0	2.99E+06	0	0	0	1.13E+06	0
Radon-222	air	low population density, long-term	kBq	3.49E+06	0	0	0	0	0	0	0	0	0	3.49E+06	0	0	0	0	0	0
Carbon dioxide, non-fossil	air	unspecified	kg	2.95E+06	2.19E+06	-3.76E+06	3.27E+06	1.24E+06	0	0	0	0	0	0	1.23E+04	0	0	0	0	0
Carbon dioxide, fossil	air	non-urban air or from high stacks	kg	1.85E+06	0	0	0	0	0	0	0	0	0	0	1.34E+06	0	0	0	5.05E+05	0
Methane, non-fossil	air	unspecified	kg	1.82E+06	1.83E+04	0	0	1.80E+06	0	0	0	0	0	0	0	0	0	0	0	0
Oil, crude, in ground	natural resource	in ground	kg	1.28E+06	0	0	1.99E+04	0	0	0	0	0	0	1.50E+05	-1.21E+06	9.96E+05	2.78E+04	8.87E+04	1.20E+06	0
Coal, hard, unspecified, in ground	natural resource	in ground	kg	1.10E+06	0	0	0	0	0	0	0	0	0	0	8.01E+05	0	0	0	3.02E+05	0
Noble gases, radioactive, unspecified	air	non-urban air or from high stacks	kBq	4.74E+05	0	0	0	0	0	0	0	0	0	0	3.45E+05	0	0	0	1.30E+05	0
Noble gases, radioactive, unspecified	air	non-urban air or from high stacks	kBq	4.00E+05	0	0	0	0	0	0	0	0	0	4.00E+05	0	0	0	0	0	0
Carbon dioxide, fossil	air	urban air close to ground	kg	3.11E+05	0	0	0	0	0	0	0	0	0	0	0	2.79E+05	7794	2.48E+04	0	0
Water, turbine use, unspecified natural origin	natural resource	in water	m3	1.68E+05	0	0	0	0	0	0	0	0	0	0	1.22E+05	0	0	0	4.61E+04	0
Water, turbine use, unspecified natural origin	natural resource	in water	m3	1.48E+05	0	0	0	0	0	0	0	0	0	1.48E+05	0	0	0	0	0	0
Radon-222	air	non-urban air or from high stacks	kBq	1.35E+05	0	0	0	0	0	0	0	0	0	0	9.79E+04	0	0	0	3.68E+04	0
Radon-222	air	non-urban air or from high stacks	kBq	1.01E+05	0	0	0	0	0	0	0	0	0	1.01E+05	0	0	0	0	0	0
Sulfate	water	ground-, long-term	kg	9.31E+04	0	0	0	0	0	0	0	0	0	0	6.76E+04	0	0	0	2.55E+04	0
Oil, crude, in ground	natural resource	in ground	kg	7.89E+04	0	0	0	0	0	0	0	0	0	7.89E+04	0	0	0	0	0	0
Gravel, in ground	natural resource	in ground	kg	4.79E+04	0	0	0	0	0	0	0	0	0	0	3.48E+04	0	0	0	1.31E+04	0
Gas, natural, in ground	natural resource	in ground	m3	4.46E+04	0	0	0	0	0	0	0	0	0	4.46E+04	0	0	0	0	0	0
Radon-222	air	low population density, long-term	kBq	4.03E+04	0	0	0	0	0	0	0	0	0	4.03E+04	0	0	0	0	0	0
Carbon dioxide, fossil	air	non-urban air or from high stacks	kg	3.56E+04	0	0	0	0	0	0	0	0	0	3.56E+04	0	0	0	0	0	0
Nitrate	water	surface water	kg	3.18E+04	0	0	3.18E+04	0	0	0	0	0	0	0	0	0	0	0	0	0
Carbon dioxide, fossil	air	urban air close to ground	kg	3.09E+04	0	0	0	0	0	0	0	0	0	3.09E+04	0	0	0	0	0	0
Calcium, ion	water	ground-, long-term	kg	2.12E+04	0	0	0	0	0	0	0	0	0	0	1.54E+04	0	0	0	5803	0
Hydrogen-3, Tritium	water	ocean	kBq	1.91E+04	0	0	0	0	0	0	0	0	0	0	1.39E+04	0	0	0	5230	0
Hydrogen-3, Tritium	water	ocean	kBq	1.64E+04	0	0	0	0	0	0	0	0	0	1.64E+04	0	0	0	0	0	0
Carbon dioxide, fossil	air	unspecified	kg	1.59E+04	0	0	0	0	0	0	0	0	0	0	1.15E+04	0	0	0	4346	0
Nitrate	water	ground-	kg	1.59E+04	0	0	1.59E+04	0	0	0	0	0	0	0.005121	-31.19	0.03399	0.0009504	0.003027	0.04111	0
Water	water	unspecified	m3	1.56E+04	0	0	0	0	0	0	0	0	0	0	1.13E+04	0	0	0	4269	0
Carbon dioxide, fossil	air	urban air close to ground	kg	1.40E+04	0	0	0	0	0	0	0	0	0	0	1.01E+04	0	0	0	3817	0
Sulfur dioxide	air	non-urban air or from high stacks	kg	1.36E+04	0	0	0	0	0	0	0	0	0	0	9850	0	0	0	3708	0
Occupation, forest, intensive	natural resource	land	m2*year	1.28E+04	0	0	0	0	0	0	0	0	0	0	9278	0	0	0	3493	0
Sodium, ion	water	ground-, long-term	kg	1.27E+04	0	0	0	0	0	0	0	0	0	0	9234	0	0	0	3476	0
Magnesium	water	ground-, long-term	kg	1.17E+04	0	0	0	0	0	0	0	0	0	0	8518	0	0	0	3207	0
Silicon	water	ground-, long-term	kg	1.13E+04	0	0	0	0	0	0	0	0	0	0	8207	0	0	0	3090	0
Coal, hard, unspecified, in ground	natural resource	in ground	kg	1.06E+04	0	0	0	0	0	0	0	0	0	1.06E+04	0	0	0	0	0	0
Radon-220	air	non-urban air or from high stacks	kBq	9752	0	0	0	0	0	0	0	0	0	0	7085	0	0	0	2667	0
Hydrogen-3, Tritium	water	surface water	kBq	8549	0	0	0	0	0	0	0	0	0	0	6211	0	0	0	2338	0
Potassium, ion	water	ground-, long-term	kg	8145	0	0	0	0	0	0	0	0	0	0	5918	0	0	0	2228	0
Water, river	natural resource	in water	m3	7807	0	0	-1.012	0	0	0	0	0	0	-7.626	7933	-50.61	-1.415	-4.507	-61.22	0
Carbon dioxide, in air	natural resource	in air	kg	7388	0	0	0	0	0	0	0	0	0	0	5367	0	0	0	2021	0
Nitrogen oxides	air	non-urban air or from high stacks	kg	7322	0	0	0	0	0	0	0	0	0	0	5319	0	0	0	2002	0

Calcite, in ground	natural resource	in ground	kg	7255	0	0	0	0	0	0	0	0	0	0	5271	0	0	0	1984	0
Chloride	water	ground-	kg	7253	0	0	0	0	0	0	0	0	0	0	5269	0	0	0	1984	0
Hydrogen-3, Tritium	water	surface water	kBq	6349	0	0	0	0	0	0	0	0	0	6349	0	0	0	0	0	0
Gravel, in ground	natural resource	in ground	kg	6147	0	0	0	0	0	0	0	0	0	6147	0	0	0	0	0	0
Water	water	unspecified	m3	5523	0	0	0	0	0	0	0	0	0	5523	0	0	0	0	0	0
Oil, crude, in ground	natural resource	in ground	kg	4842	0	0	0	0	0	0	0	0	0	0	3518	0	0	0	1324	0
Gas, natural, in ground	natural resource	in ground	m3	4672	0	0	0	0	0	0	0	0	0	0	3394	0	0	0	1278	0
Noble gases, radioactive, unspecified	air	non-urban air or from high stacks	kBq	4552	0	0	0	0	0	0	0	0	0	4552	0	0	0	0	0	0
Gas, mine, off-gas, process, coal mining	natural resource	in ground	m3	4469	0	0	0	0	0	0	0	0	0	0	3247	0	0	0	1222	0
Carbon dioxide, fossil	air	unspecified	kg	4305	0	0	0	0	0	0	0	0	0	4305	0	0	0	0	0	0
Water, river	natural resource	in water	m3	4292	0	0	0	0	0	0	0	0	0	0	3118	0	0	0	1174	0
Phosphate	water	ground-, long-term	kg	3609	0	0	0	0	0	0	0	0	0	0	2622	0	0	0	986.9	0
Hydrogen-3, Tritium	air	non-urban air or from high stacks	kBq	3573	0	0	0	0	0	0	0	0	0	3573	0	0	0	0	0	0
Ammonia	air	unspecified	kg	3113	3148	-115	91.72	0	0	0	0	0	0	0.04407	-13.13	0.2925	0.008179	0.02605	1.513	0
Methane, fossil	air	non-urban air or from high stacks	kg	3055	0	0	0	0	0	0	0	0	0	0	2219	0	0	0	835.5	0
Nitrogen oxides	air	unspecified	kg	2982	0	-381.8	46.67	0	0	0	0	0	0	346.5	91.52	0	0	0	2879	0
Chloride	water	ground-, long-term	kg	2894	0	0	0	0	0	0	0	0	0	0	2103	0	0	0	791.5	0
Nitrogen oxides	air	urban air close to ground	kg	2877	0	0	0	0	0	0	0	0	0	0	0	2575	72.01	229.3	0	0
Xenon-133	air	non-urban air or from high stacks	kBq	2660	0	0	0	0	0	0	0	0	0	0	1933	0	0	0	727.6	0
Iron, 46% in ore, 25% in crude ore, in ground	natural resource	in ground	kg	2656	0	0	0	0	0	0	0	0	0	0	1930	0	0	0	726.5	0
Sulfate	water	ground-	kg	2563	0	0	0	0	0	0	0	0	0	0	1862	0	0	0	700.9	0
Carbon monoxide, fossil	air	unspecified	kg	2525	0	-70.16	17.42	0	0	0	0	0	0	1776	26.88	0	0	0	775.3	0
Polonium-210	air	non-urban air or from high stacks	kBq	2364	0	0	0	0	0	0	0	0	0	0	1717	0	0	0	646.5	0
Particulates, > 10 um	air	non-urban air or from high stacks	kg	2329	0	0	0	0	0	0	0	0	0	0	1692	0	0	0	636.9	0
Occupation, mineral extraction site	natural resource	land	m2*year	2308	0	0	0	0	0	0	0	0	0	0	1677	0	0	0	631.1	0
Xenon-133	air	non-urban air or from high stacks	kBq	2273	0	0	0	0	0	0	0	0	0	2273	0	0	0	0	0	0
Iron, ion	water	ground-, long-term	kg	2230	0	0	0	0	0	0	0	0	0	0	1620	0	0	0	609.8	0
Carbon dioxide, non-fossil	air	urban air close to ground	kg	2061	0	0	0	0	0	0	0	0	0	0	1498	0	0	0	563.7	0
Occupation, dump site	natural resource	land	m2*year	2003	0	0	0	0	0	0	0	0	0	0	1455	0	0	0	547.8	0
Gangue, bauxite, in ground	natural resource	in ground	kg	1919	0	0	0	0	0	0	0	0	0	0	1394	0	0	0	524.7	0
Carbon-14	air	non-urban air or from high stacks	kBq	1894	0	0	0	0	0	0	0	0	0	1894	0	0	0	0	0	0
Coal, brown, in ground	natural resource	in ground	kg	1810	0	0	0	0	0	0	0	0	0	0	1315	0	0	0	495.1	0
Occupation, industrial area	natural resource	land	m2*year	1742	0	0	0	0	0	0	0	0	0	0	1265	0	0	0	476.3	0
Water, salt, sole	natural resource	in water	m3	1644	0	0	0.05706	0	0	0	0	0	0	0.4301	1637	2.854	0.07981	0.2542	3.453	0
Clay, unspecified, in ground	natural resource	in ground	kg	1438	0	0	0	0	0	0	0	0	0	1438	0	0	0	0	0	0
Coal, brown, in ground	natural resource	in ground	kg	1389	0	0	0	0	0	0	0	0	0	1389	0	0	0	0	0	0
Occupation, forest, intensive	natural resource	land	m2*year	1388	0	0	0	0	0	0	0	0	0	1388	0	0	0	0	0	0
Lead-210	air	non-urban air or from high stacks	kBq	1332	0	0	0	0	0	0	0	0	0	0	967.7	0	0	0	364.3	0
Sulfate	water	ground-, long-term	kg	1245	0	0	0	0	0	0	0	0	0	1245	0	0	0	0	0	0
Nitrate	water	ground-, long-term	kg	1218	0	0	0	0	0	0	0	0	0	0	884.7	0	0	0	333	0
Radon-222	air	non-urban air or from high stacks	kBq	1134	0	0	0	0	0	0	0	0	0	1134	0	0	0	0	0	0
Water, cooling, unspecified natural origin	natural resource	in water	m3	1090	0	0	0	0	0	0	0	0	0	1090	0	0	0	0	0	0
BOD5, Biological Oxygen Demand	water	surface water	kg	1086	0	0	0	0	0	0	0	0	0	0	1086	0	0	0	0	0
COD, Chemical Oxygen Demand	water	surface water	kg	1086	0	0	0	0	0	0	0	0	0	0	1086	0	0	0	0	0
Calcite, in ground	natural resource	in ground	kg	1085	0	0	0	0	0	0	0	0	0	1085	0	0	0	0	0	0

Clay, unspecified, in ground	natural resource	in ground	kg	1078	0	0	0	0	0	0	0	0	0	0	783.4	0	0	0	294.9	0
Carbon dioxide, fossil	air	non-urban air or from high stacks	kg	1061	0	0	0	0	0	0	0	0	0	1061	0	0	0	0	0	0
Manganese	water	ground-, long-term	kg	943.1	0	0	0	0	0	0	0	0	0	0	685.2	0	0	0	257.9	0
Xenon-135	air	non-urban air or from high stacks	kBq	895	0	0	0	0	0	0	0	0	0	0	650.2	0	0	0	244.8	0
Carbon dioxide, non-fossil	air	urban air close to ground	kg	880.8	0	0	0	0	0	0	0	0	0	880.8	0	0	0	0	0	0
Radioactive species, other beta emitters	air	urban air close to ground	kBq	855.8	0	0	0	0	0	0	0	0	0	0	621.8	0	0	0	234.1	0
Xenon-135	air	non-urban air or from high stacks	kBq	814.2	0	0	0	0	0	0	0	0	0	814.2	0	0	0	0	0	0
Chloride	water	surface water	kg	756.8	0	0	0	0	0	0	0	0	0	756.8	0	0	0	0	0	0
Water, cooling, unspecified natural origin	natural resource	in water	m3	751.5	0	0	0	0	0	0	0	0	0	0	546	0	0	0	205.5	0
Iron, 46% in ore, 25% in crude ore, in ground	natural resource	in ground	kg	751.2	0	0	0	0	0	0	0	0	0	751.2	0	0	0	0	0	0
Carbon dioxide, in air	natural resource	in air	kg	729.1	0	0	0	0	0	0	0	0	0	729.1	0	0	0	0	0	0
Nitrogen oxides	air	unspecified	kg	725.2	0	0	0	0	0	0	0	0	0	0	526.8	0	0	0	198.3	0
NMVOC, non-methane volatile organic compounds, unspecified origin	air	urban air close to ground	kg	694.6	0	0	0	0	0	0	0	0	0	694.6	0	0	0	0	0	0
Occupation, traffic area, rail/road embankment	natural resource	land	m2*year	694.4	0	0	0	0	0	0	0	0	0	0	504.5	0	0	0	189.9	0
Aluminium	water	ground-, long-term	kg	693.5	0	0	0	0	0	0	0	0	0	0	503.8	0	0	0	189.7	0
Volume occupied, reservoir	natural resource	in water	m3*year	674.6	0	0	0	0	0	0	0	0	0	0	490.1	0	0	0	184.5	0
Coal, hard, unspecified, in ground	natural resource	in ground	kg	633.7	0	0	0	0	0	0	0	0	0	633.7	0	0	0	0	0	0
Hydrogen-3, Tritium	air	non-urban air or from high stacks	kBq	591.7	0	0	0	0	0	0	0	0	0	0	429.8	0	0	0	161.8	0
Volume occupied, reservoir	natural resource	in water	m3*year	579.3	0	0	0	0	0	0	0	0	0	579.3	0	0	0	0	0	0
Occupation, traffic area, rail network	natural resource	land	m2*year	554.2	0	0	0	0	0	0	0	0	0	0	402.6	0	0	0	151.6	0
Chloride	water	surface water	kg	545.6	0	0	0	0	0	0	0	0	0	0	396.4	0	0	0	149.2	0
Phosphate	water	ground-	kg	519.6	0	0	0	0	0	0	0	0	0	0	377.5	0	0	0	142.1	0
Hydrogen chloride	air	non-urban air or from high stacks	kg	509.9	0	0	0	0	0	0	0	0	0	0	370.4	0	0	0	139.4	0
Gangue, bauxite, in ground	natural resource	in ground	kg	477.6	0	0	0	0	0	0	0	0	0	477.6	0	0	0	0	0	0
Radioactive species, other beta emitters	air	urban air close to ground	kBq	468.3	0	0	0	0	0	0	0	0	0	468.3	0	0	0	0	0	0
Sodium, ion	water	surface water	kg	455.9	0	0	0	0	0	0	0	0	0	455.9	0	0	0	0	0	0
Potassium-40	air	non-urban air or from high stacks	kBq	442.3	0	0	0	0	0	0	0	0	0	0	321.4	0	0	0	121	0
Calcium, ion	water	ground-, long-term	kg	440.7	0	0	0	0	0	0	0	0	0	440.7	0	0	0	0	0	0
Heat, waste	air	urban air close to ground	MJ	438.7	0	0	0	0	0	0	0	0	0	0	318.7	0	0	0	120	0
Occupation, traffic area, road network	natural resource	land	m2*year	431.2	0	0	0	0	0	0	0	0	0	0	313.3	0	0	0	117.9	0
Water, well, in ground	natural resource	in water	m3	423	0	0	0	0	0	0	0	0	0	0	307.3	0	0	0	115.7	0
Methane, fossil	air	non-urban air or from high stacks	kg	416.7	0	0	0	0	0	0	0	0	0	416.7	0	0	0	0	0	0
Carbon monoxide, fossil	air	urban air close to ground	kg	407.2	0	0	0	0	0	0	0	0	0	0	0	364.6	10.19	32.46	0	0
Strontium	water	ground-, long-term	kg	405.8	0	0	0	0	0	0	0	0	0	0	294.8	0	0	0	111	0
Calcium, ion	water	ground-	kg	389.1	0	0	0	0	0	0	0	0	0	0	282.6	0	0	0	106.4	0
Xenon-135m	air	non-urban air or from high stacks	kBq	383.9	0	0	0	0	0	0	0	0	0	383.9	0	0	0	0	0	0
Radium-226	water	surface water	kBq	372.7	0	0	0	0	0	0	0	0	0	372.7	0	0	0	0	0	0
Dinitrogen monoxide	air	unspecified	kg	366.3	0	-435.3	846.6	0	0	0	0	0	0	1.197	-58.72	0.6243	0.01746	0.05559	11.82	0
Radium-226	water	surface water	kBq	364.4	0	0	0	0	0	0	0	0	0	0	264.7	0	0	0	99.65	0
Radium-226	air	non-urban air or from high stacks	kBq	353	0	0	0	0	0	0	0	0	0	0	256.5	0	0	0	96.55	0
Xenon-135m	air	non-urban air or from high stacks	kBq	332.6	0	0	0	0	0	0	0	0	0	0	241.6	0	0	0	90.95	0
Actinides, radioactive, unspecified	air	non-urban air or from high stacks	kBq	329.6	0	0	0	0	0	0	0	0	0	0	239.4	0	0	0	90.13	0
Uranium-238	air	non-urban air or from high stacks	kBq	306	0	0	0	0	0	0	0	0	0	0	222.3	0	0	0	83.69	0
Thorium-228	water	surface water	kBq	292.8	0	0	0	0	0	0	0	0	0	292.8	0	0	0	0	0	0

Water	air	unspecified	m3	290.4	0	0	0	0	0	0	0	0	0	0	211	0	0	0	79.42	0
Aluminium	air	unspecified	kg	272.3	0	0	0	0	0	0	0	0	0	0	197.9	0	0	0	74.48	0
Carbon monoxide, fossil	air	unspecified	kg	258.9	0	0	0	0	0	0	0	0	0	0	188.1	0	0	0	70.81	0
Carbon-14	air	non-urban air or from high stacks	kBq	258.6	0	0	0	0	0	0	0	0	0	0	187.9	0	0	0	70.73	0
Heat, waste	air	unspecified	MJ	242.6	0	0	0	0	0	0	0	0	0	0	176.3	0	0	0	66.36	0
Occupation, traffic area, road network	natural resource	land	m2*year	226.5	0	0	0	0	0	0	0	0	0	226.5	0	0	0	0	0	0
Aluminium, in ground	natural resource	in ground	kg	217.6	0	0	0	0	0	0	0	0	0	0	158.1	0	0	0	59.5	0
NMVOC, non-methane volatile organic compounds, unspecified origin	air	non-urban air or from high stacks	kg	210.9	0	0	0	0	0	0	0	0	0	210.9	0	0	0	0	0	0
Barite, 15% in crude ore, in ground	natural resource	in ground	kg	199	0	0	0	0	0	0	0	0	0	199	0	0	0	0	0	0
NMVOC, non-methane volatile organic compounds, unspecified origin	air	urban air close to ground	kg	195.3	0	0	0	0	0	0	0	0	0	0	0	174.9	4.89	15.57	0	0
Magnesium	water	ground-, long-term	kg	192.5	0	0	0	0	0	0	0	0	0	192.5	0	0	0	0	0	0
Carbon monoxide, fossil	air	non-urban air or from high stacks	kg	191.5	0	0	0	0	0	0	0	0	0	0	139.1	0	0	0	52.36	0
Sulfur dioxide	air	urban air close to ground	kg	187	0	0	0	0	0	0	0	0	0	187	0	0	0	0	0	0
Dissolved solids	water	unspecified	kg	183.6	0	0	0	0	0	0	0	0	0	183.6	0	0	0	0	0	0
Occupation, industrial area	natural resource	land	m2*year	183.1	0	0	0	0	0	0	0	0	0	183.1	0	0	0	0	0	0
Hydrogen-3, Tritium	water	ocean	kBq	182.9	0	0	0	0	0	0	0	0	0	182.9	0	0	0	0	0	0
Nitrogen	natural resource	in air	kg	178.4	0	0	0	0	0	0	0	0	0	0	129.6	0	0	0	48.79	0
Water, river	natural resource	in water	m3	169.7	0	0	0	0	0	0	0	0	0	169.7	0	0	0	0	0	0
Water, turbine use, unspecified natural origin	natural resource	in water	m3	168.9	0	0	0	0	0	0	0	0	0	168.9	0	0	0	0	0	0
Silicon	water	ground-, long-term	kg	166.1	0	0	0	0	0	0	0	0	0	166.1	0	0	0	0	0	0
Suspended solids, unspecified	water	ocean	kg	165.4	0	0	0	0	0	0	0	0	0	165.4	0	0	0	0	0	0
Chloride	water	ocean	kg	163.8	0	0	0	0	0	0	0	0	0	163.8	0	0	0	0	0	0
Particulates, < 2.5 um	air	non-urban air or from high stacks	kg	161.7	0	0	0	0	0	0	0	0	0	0	117.5	0	0	0	44.24	0
COD, Chemical Oxygen Demand	water	surface water	kg	159.3	0	0	0	0	0	0	0	0	0	159.3	0	0	0	0	0	0
Sulfur dioxide	air	non-urban air or from high stacks	kg	158.6	0	0	0	0	0	0	0	0	0	158.6	0	0	0	0	0	0
Magnesium	water	ground-	kg	156.7	0	0	0	0	0	0	0	0	0	0	113.8	0	0	0	42.86	0
BOD5, Biological Oxygen Demand	water	surface water	kg	156.1	0	0	0	0	0	0	0	0	0	156.1	0	0	0	0	0	0
Occupation, dump site	natural resource	land	m2*year	154.5	0	0	0	0	0	0	0	0	0	154.5	0	0	0	0	0	0
Chloride	water	unspecified	kg	149.9	0	0	0	0	0	0	0	0	0	149.9	0	0	0	0	0	0
COD, Chemical Oxygen Demand	water	ocean	kg	148.1	0	0	0	0	0	0	0	0	0	148.1	0	0	0	0	0	0
Radium-228	water	surface water	kBq	146.4	0	0	0	0	0	0	0	0	0	146.4	0	0	0	0	0	0
BOD5, Biological Oxygen Demand	water	ocean	kg	144.9	0	0	0	0	0	0	0	0	0	144.9	0	0	0	0	0	0
Zinc, ion	water	ground-, long-term	kg	139.8	0	0	0	0	0	0	0	0	0	0	101.6	0	0	0	38.24	0
Nitrogen	natural resource	in air	kg	134.3	0	0	0	0	0	0	0	0	0	134.3	0	0	0	0	0	0
Nitrogen oxides	air	non-urban air or from high stacks	kg	129.6	0	0	0	0	0	0	0	0	0	129.6	0	0	0	0	0	0
Sodium, ion	water	ground-, long-term	kg	125.3	0	0	0	0	0	0	0	0	0	125.3	0	0	0	0	0	0
NMVOC, non-methane volatile organic compounds, unspecified origin	air	unspecified	kg	122.2	0	0	0	0	0	0	0	0	0	0	88.75	0	0	0	33.41	0
Potassium, ion	water	ground-, long-term	kg	116.7	0	0	0	0	0	0	0	0	0	116.7	0	0	0	0	0	0
Occupation, lake, artificial	natural resource	land	m2*year	116.4	0	0	0	0	0	0	0	0	0	116.4	0	0	0	0	0	0
Potassium-40	water	surface water	kBq	115.3	0	0	0	0	0	0	0	0	0	0	83.76	0	0	0	31.53	0
Chloride	water	ground-	kg	113.8	0	0	0	0	0	0	0	0	0	113.8	0	0	0	0	0	0
Radium-228	air	non-urban air or from high stacks	kBq	113.6	0	0	0	0	0	0	0	0	0	0	82.54	0	0	0	31.07	0
Nickel, ion	water	ground-, long-term	kg	109.6	0	0	0	0	0	0	0	0	0	0	79.63	0	0	0	29.97	0
Water, unspecified natural origin	natural resource	in water	m3	108.6	0	0	0	0	0	0	0	0	0	0	78.92	0	0	0	29.71	0
Sodium, ion	water	ocean	kg	108	0	0	0	0	0	0	0	0	0	108	0	0	0	0	0	0
Ammonia	air	unspecified	kg	106.7	0	0	0	0	0	0	0	0	0	0	77.51	0	0	0	29.18	0

Hydrogen-3, Tritium	water	surface water	kBq	106.4	0	0	0	0	0	0	0	0	0	106.4	0	0	0	0	0	0
Occupation, lake, artificial	natural resource	land	m2*year	105.2	0	0	0	0	0	0	0	0	0	0	76.45	0	0	0	28.78	0
Calcium, ion	water	surface water	kg	105.1	0	0	0	0	0	0	0	0	0	0	76.36	0	0	0	28.75	0
Transformation, to annual crop, non-irrigated, intensive	natural resource	land	m2	104.4	0	0	0	0	0	0	0	0	0	0	75.84	0	0	0	28.55	0
Dissolved solids	water	unspecified	kg	100.7	0	0	0	0	0	0	0	0	0	0	73.19	0	0	0	27.55	0
Dissolved solids	water	ground-	kg	97.46	0	0	0	0	0	0	0	0	0	0	70.8	0	0	0	26.65	0
Sulfate	water	ground-	kg	96.52	0	0	0	0	0	0	0	0	0	96.52	0	0	0	0	0	0
Gas, mine, off-gas, process, coal mining	natural resource	in ground	m3	96.45	0	0	0	0	0	0	0	0	0	96.45	0	0	0	0	0	0
Water	air	unspecified	m3	94.07	0	0	0	0	0	0	0	0	0	94.07	0	0	0	0	0	0
Transformation, from unspecified	natural resource	land	m2	93.47	0	0	0	0	0	0	0	0	0	0	67.9	0	0	0	25.56	0
Thorium-232	air	non-urban air or from high stacks	kBq	92.85	0	0	0	0	0	0	0	0	0	0	67.45	0	0	0	25.39	0
Water, unspecified natural origin	natural resource	in water	m3	92.47	0	0	0	0	0	0	0	0	0	92.47	0	0	0	0	0	0
Lead-210	water	surface water	kBq	91.84	0	0	0	0	0	0	0	0	0	0	66.72	0	0	0	25.12	0
Polonium-210	water	surface water	kBq	91.84	0	0	0	0	0	0	0	0	0	0	66.72	0	0	0	25.12	0
Xenon-138	air	non-urban air or from high stacks	kBq	90.45	0	0	0	0	0	0	0	0	0	90.45	0	0	0	0	0	0
Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	natural resource	in ground	kg	89.71	0	0	0	0	0	0	0	0	0	0	65.18	0	0	0	24.54	0
Heat, waste	water	surface water	MJ	88.98	0	0	0	0	0	0	0	0	0	0	64.64	0	0	0	24.33	0
Carbon dioxide, from soil or biomass stock	air	non-urban air or from high stacks	kg	87.36	0	0	0	0	0	0	0	0	0	87.36	0	0	0	0	0	0
Transformation, from forest, extensive	natural resource	land	m2	86.55	0	0	0	0	0	0	0	0	0	0	62.88	0	0	0	23.67	0
Transformation, to forest, intensive	natural resource	land	m2	85.86	0	0	0	0	0	0	0	0	0	0	62.38	0	0	0	23.48	0
Chloride	water	unspecified	kg	82.24	0	0	0	0	0	0	0	0	0	0	59.75	0	0	0	22.49	0
Heat, waste	air	unspecified	MJ	80.43	0	0	0	0	0	0	0	0	0	80.43	0	0	0	0	0	0
Sodium chloride, in ground	natural resource	in ground	kg	80.38	0	0	0	0	0	0	0	0	0	0	58.4	0	0	0	21.98	0
Xenon-138	air	non-urban air or from high stacks	kBq	78.04	0	0	0	0	0	0	0	0	0	0	56.7	0	0	0	21.34	0
Transformation, from annual crop	natural resource	land	m2	77.63	0	0	0	0	0	0	0	0	0	0	56.4	0	0	0	21.23	0
Thorium-230	water	surface water	kBq	77.13	0	0	0	0	0	0	0	0	0	0	56.04	0	0	0	21.09	0
Iron, ion	water	ground-, long-term	kg	75.71	0	0	0	0	0	0	0	0	0	75.71	0	0	0	0	0	0
Transformation, from seabed, unspecified	natural resource	land	m2	75.14	0	0	0	0	0	0	0	0	0	75.14	0	0	0	0	0	0
Occupation, seabed, drilling and mining	natural resource	land	m2*year	75.12	0	0	0	0	0	0	0	0	0	75.12	0	0	0	0	0	0
Transformation, to seabed, drilling and mining	natural resource	land	m2	75.12	0	0	0	0	0	0	0	0	0	75.12	0	0	0	0	0	0
Transformation, from annual crop, non-irrigated, intensive	natural resource	land	m2	74.85	0	0	0	0	0	0	0	0	0	0	54.38	0	0	0	20.47	0
Gypsum, in ground	natural resource	in ground	kg	74.34	0	0	0	0	0	0	0	0	0	0	54.01	0	0	0	20.33	0
Radium-224	water	surface water	kBq	73.21	0	0	0	0	0	0	0	0	0	73.21	0	0	0	0	0	0
Carbon dioxide, from soil or biomass stock	air	non-urban air or from high stacks	kg	72.61	0	0	0	0	0	0	0	0	0	0	52.75	0	0	0	19.86	0
Sulfur dioxide	air	urban air close to ground	kg	70.15	0	0	0	0	0	0	0	0	0	0	50.97	0	0	0	19.19	0
Water, salt, ocean	natural resource	in water	m3	66.45	0	0	0	0	0	0	0	0	0	66.45	0	0	0	0	0	0
Sodium, ion	water	ground-	kg	66.42	0	0	0	0	0	0	0	0	0	0	48.26	0	0	0	18.17	0
Thorium-230	water	surface water	kBq	65.39	0	0	0	0	0	0	0	0	0	65.39	0	0	0	0	0	0
Sodium chloride, in ground	natural resource	in ground	kg	65.04	0	0	0	0	0	0	0	0	0	65.04	0	0	0	0	0	0
Thorium-228	water	ocean	kBq	63.86	0	0	0	0	0	0	0	0	0	63.86	0	0	0	0	0	0
Thorium-228	air	non-urban air or from high stacks	kBq	63.45	0	0	0	0	0	0	0	0	0	0	46.09	0	0	0	17.35	0
Occupation, annual crop, non-irrigated, intensive	natural resource	land	m2*year	63.19	0	0	0	0	0	0	0	0	0	0	45.9	0	0	0	17.28	0
Nitrogen oxides	air	urban air close to ground	kg	63.02	0	0	0	0	0	0	0	0	0	63.02	0	0	0	0	0	0
Occupation, river, artificial	natural resource	land	m2*year	61.65	0	0	0	0	0	0	0	0	0	61.65	0	0	0	0	0	0

Occupation, annual crop	natural resource	land	m2*year	61.21	0	0	0	0	0	0	0	0	0	0	44.47	0	0	0	16.74	0
Transformation, to annual crop	natural resource	land	m2	59.8	0	0	0	0	0	0	0	0	0	0	43.45	0	0	0	16.36	0
Heat, waste	air	urban air close to ground	MJ	58.1	0	0	0	0	0	0	0	0	0	58.1	0	0	0	0	0	0
Solids, inorganic	water	ground-	kg	57.08	0	0	0	0	0	0	0	0	0	0	41.47	0	0	0	15.61	0
COD, Chemical Oxygen Demand	water	ground-, long-term	kg	55.38	0	0	0	0	0	0	0	0	0	0	40.23	0	0	0	15.15	0
Carbon dioxide, non-fossil	air	unspecified	kg	55	0	0	0	0	0	0	0	0	0	0	39.96	0	0	0	15.04	0
Oxygen	natural resource	in air	kg	54.59	0	0	0	0	0	0	0	0	0	0	39.66	0	0	0	14.93	0
Hydrogen fluoride	air	non-urban air or from high stacks	kg	54.49	0	0	0	0	0	0	0	0	0	0	39.59	0	0	0	14.9	0
Aluminium, in ground	natural resource	in ground	kg	54.16	0	0	0	0	0	0	0	0	0	54.16	0	0	0	0	0	0
Oils, unspecified	soil	forestry	kg	54.14	0	0	0	0	0	0	0	0	0	54.14	0	0	0	0	0	0
Sulfate	water	ground-, long-term	kg	53.49	0	0	0	0	0	0	0	0	0	53.49	0	0	0	0	0	0
TOC, Total Organic Carbon	water	surface water	kg	53.3	0	0	0	0	0	0	0	0	0	53.3	0	0	0	0	0	0
DOC, Dissolved Organic Carbon	water	surface water	kg	52.66	0	0	0	0	0	0	0	0	0	52.66	0	0	0	0	0	0
Krypton-85m	air	non-urban air or from high stacks	kBq	52.44	0	0	0	0	0	0	0	0	0	0	38.1	0	0	0	14.34	0
Calcium, ion	water	surface water	kg	51.41	0	0	0	0	0	0	0	0	0	51.41	0	0	0	0	0	0
Transformation, to industrial area	natural resource	land	m2	50.89	0	0	0	0	0	0	0	0	0	0	36.97	0	0	0	13.92	0
Water, salt, sole	natural resource	in water	m3	50.06	0	0	0	0	0	0	0	0	0	50.06	0	0	0	0	0	0
Radon-220	air	non-urban air or from high stacks	kBq	49.47	0	0	0	0	0	0	0	0	0	49.47	0	0	0	0	0	0
Radioactive species, Nuclides, unspecified	water	ocean	kBq	47.88	0	0	0	0	0	0	0	0	0	0	34.79	0	0	0	13.1	0
Krypton-85m	air	non-urban air or from high stacks	kBq	47.67	0	0	0	0	0	0	0	0	0	47.67	0	0	0	0	0	0
Barite	water	ocean	kg	46.8	0	0	0	0	0	0	0	0	0	46.8	0	0	0	0	0	0
Oils, unspecified	water	ocean	kg	46.79	0	0	0	0	0	0	0	0	0	46.79	0	0	0	0	0	0
Uranium-238	water	surface water	kBq	46.72	0	0	0	0	0	0	0	0	0	0	33.94	0	0	0	12.78	0
Radon-220	air	urban air close to ground	kBq	45.48	0	0	0	0	0	0	0	0	0	45.48	0	0	0	0	0	0
Oils, unspecified	water	surface water	kg	45.17	0	0	0	0	0	0	0	0	0	45.17	0	0	0	0	0	0
Sodium, ion	water	surface water	kg	44.06	0	0	0	0	0	0	0	0	0	0	32.01	0	0	0	12.05	0
TOC, Total Organic Carbon	water	ocean	kg	42.96	0	0	0	0	0	0	0	0	0	42.96	0	0	0	0	0	0
Sodium, ion	water	unspecified	kg	42.22	0	0	0	0	0	0	0	0	0	42.22	0	0	0	0	0	0
Strontium-90	water	surface water	kBq	42.21	0	0	0	0	0	0	0	0	0	0	30.67	0	0	0	11.54	0
Aluminium	water	ground-, long-term	kg	41.83	0	0	0	0	0	0	0	0	0	41.83	0	0	0	0	0	0
Occupation, river, artificial	natural resource	land	m2*year	41.83	0	0	0	0	0	0	0	0	0	0	30.39	0	0	0	11.44	0
Xenon-131m	air	non-urban air or from high stacks	kBq	41.69	0	0	0	0	0	0	0	0	0	41.69	0	0	0	0	0	0
DOC, Dissolved Organic Carbon	water	ocean	kg	41.64	0	0	0	0	0	0	0	0	0	41.64	0	0	0	0	0	0
Phosphate	water	ground-, long-term	kg	41.45	0	0	0	0	0	0	0	0	0	41.45	0	0	0	0	0	0
Oxygen	natural resource	in air	kg	41.13	0	0	0	0	0	0	0	0	0	41.13	0	0	0	0	0	0
Radioactive species, Nuclides, unspecified	water	ocean	kBq	40.6	0	0	0	0	0	0	0	0	0	40.6	0	0	0	0	0	0
NMVOC, non-methane volatile organic compounds, unspecified origin	air	non-urban air or from high stacks	kg	40.43	0	0	0	0	0	0	0	0	0	0	29.37	0	0	0	11.06	0
Uranium-234	air	non-urban air or from high stacks	kBq	39.34	0	0	0	0	0	0	0	0	0	0	28.58	0	0	0	10.76	0
Nitrogen oxides	air	urban air close to ground	kg	39.05	0	0	0	0	0	0	0	0	0	0	28.37	0	0	0	10.68	0
Water, lake	natural resource	in water	m3	39.05	0	0	0	0	0	0	0	0	0	0	28.37	0	0	0	10.68	0
Sulfate	water	surface water	kg	38.72	0	0	0	0	0	0	0	0	0	0	28.13	0	0	0	10.59	0
Xenon-131m	air	non-urban air or from high stacks	kBq	36.37	0	0	0	0	0	0	0	0	0	0	26.43	0	0	0	9.948	0
Occupation, traffic area, rail/road embankment	natural resource	land	m2*year	36.31	0	0	0	0	0	0	0	0	0	36.31	0	0	0	0	0	0
COD, Chemical Oxygen Demand	water	ground-, long-term	kg	35.78	0	0	0	0	0	0	0	0	0	35.78	0	0	0	0	0	0
Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	natural resource	in ground	kg	35.75	0	0	0	0	0	0	0	0	0	35.75	0	0	0	0	0	0
Uranium alpha	water	surface water	kBq	35.56	0	0	0	0	0	0	0	0	0	0	25.83	0	0	0	9.724	0

Barium	water	ground-, long-term	kg	35.4	0	0	0	0	0	0	0	0	0	0	25.72	0	0	0	9.682	0
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	natural resource	in ground	kg	35.23	0	0	0	0	0	0	0	0	0	35.23	0	0	0	0	0	0
Clay, bentonite, in ground	natural resource	in ground	kg	34.7	0	0	0	0	0	0	0	0	0	0	25.21	0	0	0	9.489	0
Xenon-133	air	non-urban air or from high stacks	kBq	34.33	0	0	0	0	0	0	0	0	0	34.33	0	0	0	0	0	0
Bromine	water	surface water	kg	33	0	0	0	0	0	0	0	33	0	0	0	0	0	0	0	0
Carbon monoxide, fossil	air	non-urban air or from high stacks	kg	32.78	0	0	0	0	0	0	0	0	0	32.78	0	0	0	0	0	0
Carbon monoxide, fossil	air	unspecified	kg	32.05	0	0	0	0	0	0	0	0	0	32.05	0	0	0	0	0	0
Radium-228	water	ocean	kBq	31.93	0	0	0	0	0	0	0	0	0	31.93	0	0	0	0	0	0
Uranium alpha	water	surface water	kBq	30.15	0	0	0	0	0	0	0	0	0	30.15	0	0	0	0	0	0
Chromium, 25.5% in chromite, 11.6% in crude ore, in ground	natural resource	in ground	kg	29.7	0	0	0	0	0	0	0	0	0	0	21.58	0	0	0	8.123	0
Water, well, in ground	natural resource	in water	m3	29.42	0	0	0	0	0	0	0	0	0	29.42	0	0	0	0	0	0
Occupation, mineral extraction site	natural resource	land	m2*year	29.26	0	0	0	0	0	0	0	0	0	29.26	0	0	0	0	0	0
Particulates, > 2.5 um, and < 10um	air	non-urban air or from high stacks	kg	29.11	0	0	0	0	0	0	0	0	0	0	21.15	0	0	0	7.961	0
Gravel, in ground	natural resource	in ground	kg	28.48	0	0	0	0	0	0	0	0	0	28.48	0	0	0	0	0	0
DOC, Dissolved Organic Carbon	water	ground-, long-term	kg	27.79	0	0	0	0	0	0	0	0	0	0	20.19	0	0	0	7.6	0
TOC, Total Organic Carbon	water	ground-, long-term	kg	27.79	0	0	0	0	0	0	0	0	0	0	20.19	0	0	0	7.6	0
Transformation, to annual crop, non-irrigated, intensive	natural resource	land	m2	27.31	0	0	0	0	0	0	0	0	0	27.31	0	0	0	0	0	0
Transformation, from forest, unspecified	natural resource	land	m2	26.96	0	0	0	0	0	0	0	0	0	26.96	0	0	0	0	0	0
Sulfur dioxide	air	unspecified	kg	26.72	0	0	0	0	0	0	0	0	0	26.72	0	0	0	0	0	0
Radium-226	water	ocean	kBq	26.26	0	0	0	0	0	0	0	0	0	26.26	0	0	0	0	0	0
Particulates, > 10 um	air	non-urban air or from high stacks	kg	25.87	0	0	0	0	0	0	0	0	0	25.87	0	0	0	0	0	0
Sulfate	water	surface water	kg	25.8	0	0	0	0	0	0	0	0	0	25.8	0	0	0	0	0	0
Chloride	water	ground-, long-term	kg	25.74	0	0	0	0	0	0	0	0	0	25.74	0	0	0	0	0	0
Radon-222	air	urban air close to ground	kBq	25.61	0	0	0	0	0	0	0	0	0	25.61	0	0	0	0	0	0
Dinitrogen monoxide	air	non-urban air or from high stacks	kg	25.59	0	0	0	0	0	0	0	0	0	0	18.59	0	0	0	6.998	0
Transformation, to mineral extraction site	natural resource	land	m2	25.01	0	0	0	0	0	0	0	0	0	25.01	0	0	0	0	0	0
Nitrogen oxides	air	unspecified	kg	23.87	0	0	0	0	0	0	0	0	0	23.87	0	0	0	0	0	0
Cobalt	water	ground-, long-term	kg	23.74	0	0	0	0	0	0	0	0	0	0	17.25	0	0	0	6.493	0
Sodium, ion	water	unspecified	kg	23.69	0	0	0	0	0	0	0	0	0	0	17.21	0	0	0	6.478	0
Krypton-85	air	non-urban air or from high stacks	kBq	23.28	0	0	0	0	0	0	0	0	0	0	16.91	0	0	0	6.366	0
Nitrate	water	ground-	kg	22.99	0	0	0	0	0	0	0	0	0	0	16.7	0	0	0	6.286	0
Sulfur dioxide	air	unspecified	kg	22.91	0	0	0	0	0	0	0	0	0	0	16.64	0	0	0	6.266	0
Transformation, to mineral extraction site	natural resource	land	m2	22.27	0	0	0	0	0	0	0	0	0	0	16.18	0	0	0	6.09	0
Particulates, < 2.5 um	air	non-urban air or from high stacks	kg	22.05	0	0	0	0	0	0	0	0	0	22.05	0	0	0	0	0	0
Gypsum, in ground	natural resource	in ground	kg	21.95	0	0	0	0	0	0	0	0	0	21.95	0	0	0	0	0	0
Strontium-90	water	surface water	kBq	21.93	0	0	0	0	0	0	0	0	0	21.93	0	0	0	0	0	0
Thorium-232	water	surface water	kBq	21.5	0	0	0	0	0	0	0	0	0	0	15.62	0	0	0	5.879	0
Peat, in ground	natural resource	biotic	kg	21.06	0	0	0	0	0	0	0	0	0	0	15.3	0	0	0	5.759	0
Clay, bentonite, in ground	natural resource	in ground	kg	20.91	0	0	0	0	0	0	0	0	0	20.91	0	0	0	0	0	0
Carbon monoxide, fossil	air	urban air close to ground	kg	20.33	0	0	0	0	0	0	0	0	0	20.33	0	0	0	0	0	0
Magnesium	water	surface water	kg	20.32	0	0	0	0	0	0	0	0	0	0	14.76	0	0	0	5.557	0
Magnesite, 60% in crude ore, in ground	natural resource	in ground	kg	20.26	0	0	0	0	0	0	0	0	0	0	14.72	0	0	0	5.542	0
Manganese, 35.7% in sedimentary deposit, 14.2% in crude ore, in ground	natural resource	in ground	kg	20.13	0	0	0	0	0	0	0	0	0	0	14.62	0	0	0	5.505	0