A Life Cycle Based Energy and Greenhouse Gas Emission Assessment of C&D Waste and Container Glass Recycling in the City of Cape Town

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I hereby declare this dissertation is my own work. I understand what plagiarism is, and where I have used the ideas of others, I have referenced these correctly.

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Abstract

Society's current approach to the production, consumption, and disposal of goods is likely unsustainable. The rate at which the world is consuming energy is growing, and with climate change an immediate concern (Stern, 2006), it is incumbent for the global society to find alternate ways of fuelling human activity. Along with greater energy use, global development is also generating ever-greater quantities of waste. Landfill space is becoming increasingly scarce and the assimilative capacity of Earth is reaching its limits.

The goal of this research is to assess the difference in cumulative energy demand (CED) and greenhouse gas (GHG) emissions for two waste management options: landfilling and recycling for the two materials of C&D rubble and container glass. It will do so by performing LCA on three scenarios per waste material. The C&D waste scenarios are 1) landfilling C&D waste and producing aggregate from virgin material; 2) recycling C&D waste offsite; and 3) recycling C&D waste onsite. Because recycling C&D rubble can possess such different crushing and transportation characteristics, two recycling scenarios were considered. The container glass scenarios consist of 1) landfilling with virgin-material production; 2) recycling with a theoretical 100% recycled content; 3) recycling with 80% recycled content. In practicality only about 80% of new container glass input can be cullet (U.S. EPA, 2011), so two recycling scenarios were created for evaluation: one that is theoretically based at the 100% recycled content level and one that shows a more realistic maximum recycled content level of 80%.

Local data was sourced to populate the life cycle inventory values. The merit of replacing generic data with system specific data is a model representative of local processes and characteristics, directly applicable to the City of Cape Town. The LCA results were assessed using Monte Carlo simulation for uncertainty characterisation and sensitivity analyses were performed on the most impactful parameters.

The C&D waste analysis concluded that recycling onsite is the most preferable option with an energy and GHG emissions savings of almost 90% compared to the landfilling scenario. The recycling offsite scenario's performance compared to landfilling was inconclusive; and sensitivity analysis showed it was only definitively lower in CED and GHG emissions when haulage distance was kept to a minimum.

The container glass LCA resulted in clear and significant savings of energy and GHG emissions for the recycling scenarios. While the 100% recycled content scenario performed the best, the 80% recycled content scenario still showed significant savings of 27% of the energy requirement of landfilling and 37% of the GHG emissions. The benefit of recycling glass comes largely from the reduced heating requirement, and thus reduced energy requirement, in the melting process of glass manufacture. Transportation has a much smaller impact than it does in C&D waste recycling, and the glass results were not highly dependent on waste glass collection methods.

In a comparison of the two materials, the absolute savings were significantly higher for container glass than C&D rubble. Recycling one kilogramme of waste glass saves six times the energy and almost 25 times the GHG emissions than recycling one kilogramme of C&D waste.

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Acronyms and Abbreviations

btu	British Thermal Units
C&D	Construction and Demolition
CBD	Central Business District
CCT	City of Cape Town
CED	Cumulative Energy Demand
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalents
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EU	European Union
FEL	Front End Loaders
FIFA	Fédération Internationale de Football Association
GDP	Gross Domestic Product
GER	Gross Energy Requirement
GHG	Green House Gas(es)
GJ	Giga Joule
GTL	Gas-to-liquid
GWh	Giga Watt Hours
GWP	Global Warming Potential
IPCC	International Panel on Climate Change
ISO	International Standards Organisation
kg	Kilogramme
km	Kilometre
kWh	Kilo Watt Hours
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
MJ	Mega Joules
MRF	Materials Recovery Facility
MSW	Municipal Solid Waste
NEU	Net Energy Use
NWMS	National Waste Management Strategy
OECD	Organization for the Economic Cooperation of Development
PREA	Promoting Renewable Energy in Africa
REL	Rear End Loader
SD	Standard of Deviation
SETAC	Society of Environmental Toxicology and Chemistry
UN	United Nations
UNEP	United Nations Environment Programme
WARM	Waste Reduction Model
WRAP	Waste and Resources Action Plan

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Introduction

Society's current approach to the production, consumption, and disposal of goods is not sustainable. The methods employed to supply, utilise and dispose of these goods act irreverently towards the basic environmental building blocks and natural processes required for life. Human activity directly impacts these environmental assets and overuse impairs their ability to provide continued life-supporting systems (AEPI, 1998). These impacts come in many forms, including climate changes due to increased concentration of greenhouse gases (GHGs) in the atmosphere, resource depletion from overuse of limited materials such as fossil fuels and minerals, and loss of assimilative capacity due to large amounts of disposed waste.

Evaluating how to avoid or dispose of waste in more environmentally respectful ways has become critical to waste management. The rate of energy consumption is growing, and with climate change an immediate concern (Stern, 2006), it is incumbent on our global society to find alternate ways of fuelling human activity. Along with greater energy use, global development is also creating ever-greater quantities of waste. Landfill space is becoming increasingly scarce and the assimilative capacity of Earth is reaching its limits. This thesis explores some aspects of the intersection between the energy and waste systems by performing a comparative life cycle assessment (LCA) on the energetic requirements and the GHG emissions of two waste management options: landfilling and recycling. This is performed by considering two waste streams: construction and demolition (C&D) waste and container glass, within the boundaries of the City of Cape Town (CCT).

The thesis begins by providing a background on the foundational concepts of the research in chapters one through five. Within these chapters, an international literature review was conducted with three main objectives: 1) provide a well-rounded awareness of the main concepts in Sustainability, Waste Management, Life Cycle Assessments (LCAs), as well as an overview of the life cycles for the studied materials and the characterisation of the waste system in the CCT; 2) establish current academic knowledge on the application of LCA to waste management alternatives, specifically recycling; and 3) identify similar studies for guidance and comparison with regard to the methodology and results applied in this project. Chapter Six presents the methodology applied in the LCA, and Chapter Seven reports the data inputs. Finally, the paper closes with the results, discussion and conclusion in Chapters Eight, Nine and Ten.

Chapter 1: Sustainability

Since the 1970's, a growing concern that economic development was being fuelled by an unsustainable use of the world's resources has prompted increased discussion of human-induced impacts on the environment (Ayres, 1993). This concern began a couple of decades of discussion around what is actually meant by the term "sustainability." Despite these years of research, the literature still claims a number of definition variations, many of which are in conflict (Swilling, 2010; Turner, 1993).

This conflict appears to be caused by the level, or degree, of sustainability meant by the use of the term. Firstly, it must be recognized that there are existing "assets" that support life and societies; these assets can be categorized as material, referring to man-made goods often mentioned in economic discussions; social, denoting the institutions that make up societies and cultures; human, indicating the health and education of the population; and finally natural, encompassing the environmental provisions of nature (Goodland & Daly, 1996). Unsustainable activities degrade the stock of these assets, while sustainable activities maintain or increase the measure of total assets. The degree of sustainability is determined by how much substitution exists between the assets being maintained. Strong sustainability is based on a concept of non-substitutability; it requires that the level of each asset be individually held constant (Blengini, 2009; Turner, 1993). Weak sustainability, on the other hand, requires that only the overall stock of assets should remain constant, allowing one asset to reduce in favour of another, because the other asset may be used instead (Turner, 1993).

There is thus a full range of options existing between the two extremes of weak and strong sustainability. A "guarded optimist," for example, believes that while much substitution for scarce resources is possible, minimum levels of protection on some assets is desirable while a "guarded pessimist" still admits the allowance of substitutability, but with less reliance. They desire higher levels of protection for individual assets or groups of assets (Kahn, et al., 1976). The question then becomes, where along the continuous scale of substitutability rests the most suitable meaning of the term "sustainable" as applied to environmental discussions?

Weak sustainability is criticized as "scientifically unreliable" because it disregards the value of diversity and the necessity of complementary systems (Turner, 1993). Likewise, very strong sustainability, referred to as absurdly strong by Goodland and Daly (1996), is equally inappropriate because it would not allow any use of a finite resource and doesn't recognize possible flow between different assets. Only the middle ground then remains, and the best definition is likely one that allows for some variability in the level of individual assets, as long as depletion of one is compensated by an increase in another that is a suitable replacement, e.g. use of oil for energy should be complemented by new technologies that harness energy in some other way than through oil resources (Goodland & Daly, 1996). The United Nations (UN) chooses to express this as providing for the needs of the present without impairing the ability of future generations to do the same (United Nations, 1987).

1.1 Current Sustainability Situation

Based on the above definition of sustainability, it is clear that the human race has not yet achieved a sustainable state. There are a number of environmental assets being depleted without clear and acceptable substitutes (United Nations, 2010), and initiatives such as the UN's Framework Convention on Climate Change acknowledge the need to change current practices. This section reviews the strain placed on the environment by human activity. It does so by examining three aspects that pertain most closely to the topic of this research. Firstly, this section will establish the current patterns of energy use and why they are unsustainable. Secondly, it will discuss global resource use, complementing the energy discussion with regard to fossil fuels but also establishing environmental concerns around other resource extraction trends. Thirdly, it will discuss the growth of waste and how this growth cannot be managed by the assimilative capacity of the planet.

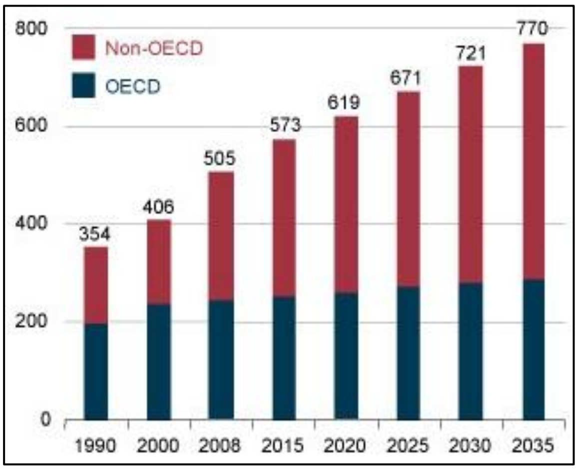
1.1.1 Energy

Currently, the world uses more than 500,000 PJ of energy annually, which if it all took the form of oil would fill 22 billion of the world's largest oil tankers. This value is still expected to increase by more than 50% over the next 25 years (U.S. EIA, 2011). The growth is primarily driven by the developing world, as shown below in **Error! Reference source not found.**. While the OECD countries have stable economies nd a low GDP growth rate of 2.1% per annum, the non-OECD countries have a much higher economic growth rate of 4.6% per annum (U.S. EIA, 2011). Because energy consumption is positively correlated with GDP, as the non-OECD countries reach ever higher levels of GDP, energy consumption will continue to rise.

This increase in energy demand by the developing world is important to sustainability discussions because it is expected that non-OECD nations continue to rely on fossil fuels to support fast growth in energy demand, resulting in an almost 80% growth in carbon emissions by these countries between 2008 and 2035 (U.S. EIA, 2011). Environmental concerns, such as climate change and air pollution, are linked to fossil fuel energy use (Stern, 2006), and whereas concern about the environmental impacts of fossil fuels is contributing to the increased use of renewables in some countries, non-renewable fuels continue to be important energy in many countries. Fossil fuels, i.e. oil, coal and natural gas, comprise 85% of global energy consumption. Renewable sources make up only 10% and the remaining 5% comes from nuclear sources (U.S. EIA, 2011).

Figure 1: World Energy Consumption

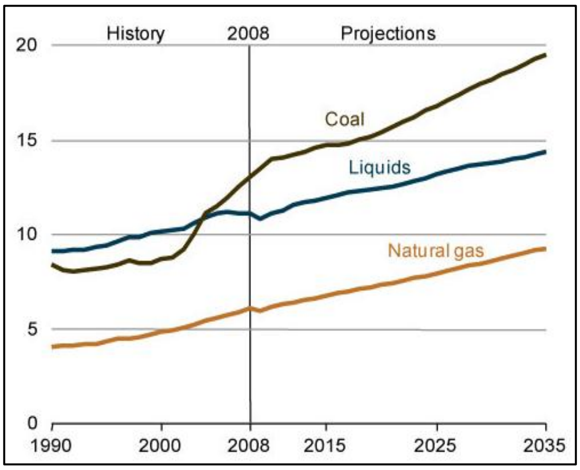
(Quadrillion Btu)



(U.S. EIA, 2011)

Figure 2: World CO_2 Emissions

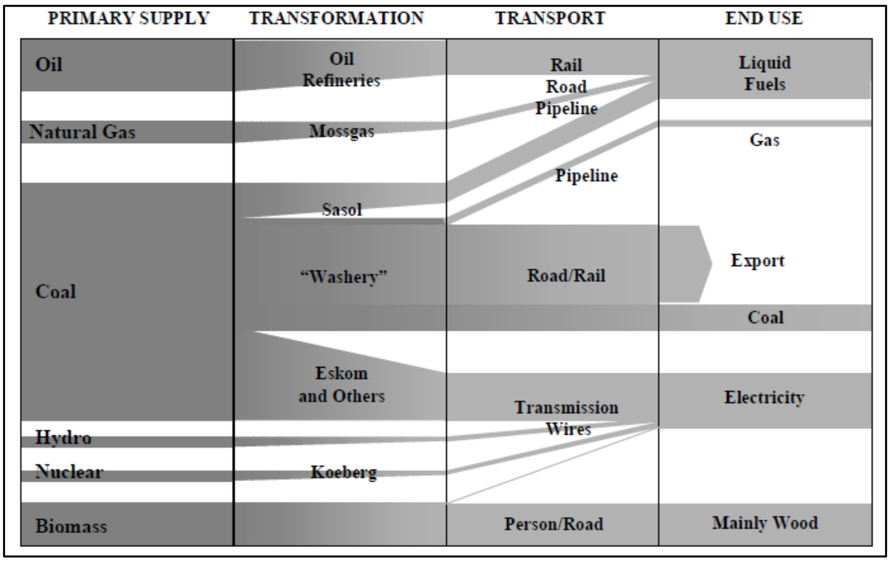
(Billion tonnes)



(U.S. EIA, 2011)

South Africa is an especially large consumer of fossil fuels because 61% of its primary energy supply comes from coal (City of Cape Town, 2011e). In South Africa, coal is plentiful and inexpensive by international standards; for this reason it is used as the main supply source for electricity generation and is used to supply oil via coal-to-liquid technology (Republic of South Africa, 2003b). Figure 3 clearly depicts the country's dependence on coal, as well as other non-renewable energy sources. Coal possesses the highest carbon dioxide emission intensity of all the fossil fuels and is the largest contributor of carbon dioxide (CO_2) emissions globally (U.S. EIA, 2011). Due to its reliance on coal, South Africa has one of the highest per capita CO_2 emissions in the world at seven to nine tonnes CO_2 per capita (Republic of South Africa, 2003; Republic of South Africa, 2007). This is double the world average of 4.3-5.5 (Flavin, 2008; MacKay, 2009) and similar to European countries with higher levels of GDP, such as the U.K. and Italy (Republic of South Africa, 2003).

Figure 3: South Africa's Energy Supply Flow



(Republic of South Africa, 2003b)

The carbon dioxide and other greenhouse gases (GHGs) released into the atmosphere have caused global temperatures to climb, and climate change has become a real concern. Scientific evidence on this is growing in strength; if not halted, climate change will reduce fresh water supply and crop yields, increase acidification in the ocean, and likely cut global GDP by five to twenty per cent (Stern, 2006). The atmospheric concentration of carbon dioxide has not been greater than 300 parts per million in the past five hundred thousand years of Earth's history, but the use of fossil fuels to provide the increasingly large quantities of energy required has since the industrial revolution lifted this concentration to more than 430 parts per million. The Intergovernmental Panel on Climate Change has recommended atmospheric carbon dioxide concentration levels must remain below 450 parts per million to maintain the climate of Earth as we know it; but the current emissions trajectory will take levels above 650 parts per million by year 2100 (IPCC, 2007b). While carbon dioxide carries much of the responsibility for climate change, methane and nitrous oxides are also contributing substances. To quantify and compare the effect each gas has on climate change, they are often cited in carbon dioxide equivalents. Methane, for example, over a 100 year time frame, is equivalent to 25 units of carbon dioxide (IPCC, 2007b).

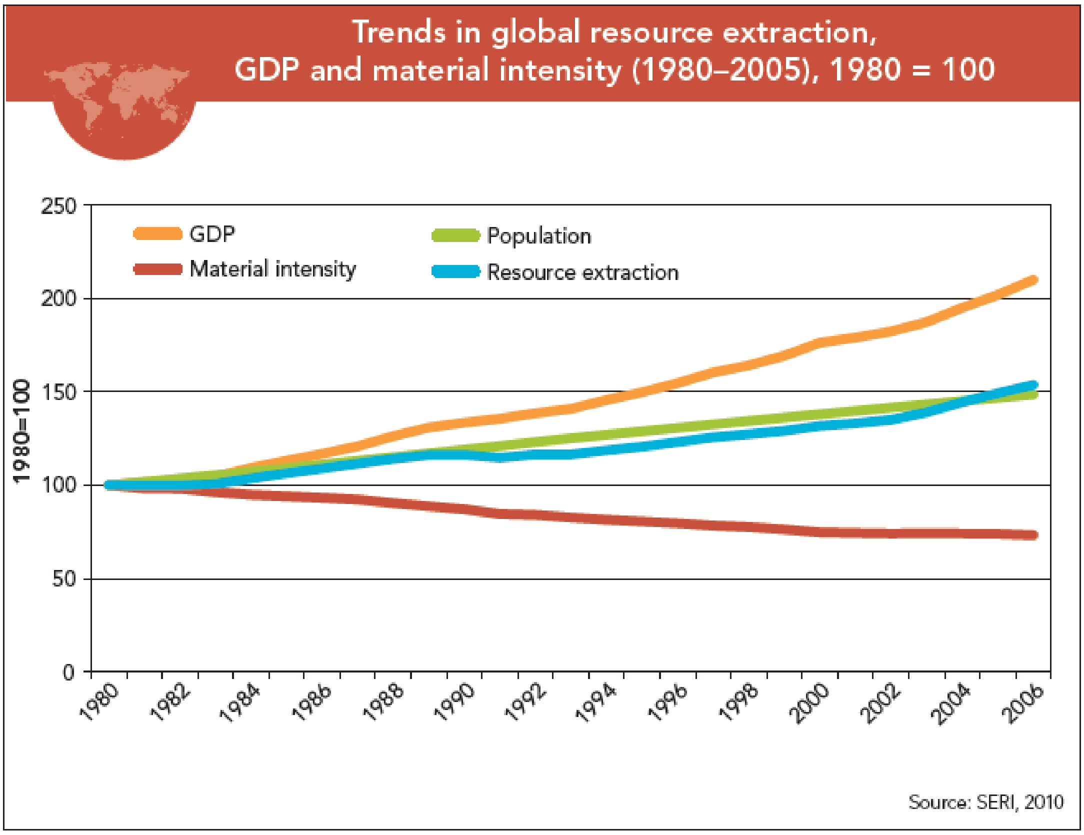
In conclusion, energy use is growing significantly and is often linked to global warming because of the high reliance on fossil fuels as supply sources. South Africa, and thus the City of Cape Town by default, is particularly dependent on coal, making it also a significant contributor to GHG emissions.

1.1.2 Resource Use

Fossil fuels are not only the primary energy source for human activity today, they are also finite natural resources along with other valuable materials such as minerals and metal ores. These resources are being extracted at a significant rate, which is expected to continue (United Nations, 2010). The Worldwatch Institute suggests there is little evidence of the "consumption locomotive" braking, despite growing evidence that the current pattern levels of consumption will "degrade our planet beyond recognition" if not restrained (Worldwatch Institute, 2011). The UN Environment Programme (UNEP) also reports that humans are extracting more resources than the earth can replenish (UNEP, 2011).

Despite technological improvements reducing material intensity, absolute extraction rates are still climbing due to population growth and increased incomes (United Nations, 2010). This suggests that while technology is improving our efficiency at harvesting and using natural resources, it is not resulting in a savings of those resources, but rather allowing us to consume even more. Figure 4 clearly shows the increasing trend of resource extraction, resulting in a dangerously unsustainable path.

Figure 4: Trends in global resource extraction



(United Nations, 2010)

Extracting and using these minerals, metals and energy supplies generate environmental impacts beyond just the depletion of the resources. The process of extraction and processing is often highly energy intensive, resulting in even more demand for fossil fuels and high emissions of GHGs. Secondly, historical mining took little, if any, note of environmental protection in the past, and toxic leaks, dead vegetation zones, and landscape scars such as mining waste dumps and abandoned open-pit mines remain (Youngquist, 1997). Thirdly, these resources are located where they were geologically formed, not necessarily where humans have settled. This means that often the extracted material is transported long distances at the great environmental cost of burnt liquid fuel (Youngquist, 1997). Finally, much of the mining done today occurs in less developed parts of the world, i.e. Africa, and exploitation of local societies and environment takes place where mining codes are not specific enough to provide a sound basis for broad environmental control programmes (UNECA, 1998).

The rising extraction rate of natural resources is thus worrisome for a number of different reasons. The following quote from the UN, in its Johannesburg Plan of Implementation 2002, concludes concisely. “Fundamental changes in the way societies produce and consume are indispensable for achieving global sustainable development” (United Nations, 2010, p. 2).

1.1.3 Waste

Continuing the theme of high growth rates in human production and consumption requirements, waste generation is also growing alongside them. Waste generation is positively correlated to population growth, gross domestic product (GDP), private consumption, and per capita energy consumption (Bogner, et al., 2007; UNEP, 2010b). These correlations are so strong that waste generation estimates are often made by proxy based on GDP growth (IPCC, 2007).

There are currently more than two billion tonnes of municipal solid waste (MSW) generated annually around the world in 2006 (UNEP, 2009). The amount per capita varies from 90kg/capita for non-OECD countries to 650kg/capita for OECD countries, and Monni, et al. (2006) projected an increase of at least 30% over the next 40 years for the IPCC 4th Assessment Report.

The correlation between GDP and waste generation is especially pertinent for South Africa because its relatively high GDP growth rate of 3.2% per annum indicates that without effective minimisation actions, the country's waste generation will continue to climb (Statistics South Africa, 2011). Table 1 provides a demonstration of how waste generation is linked to GDP. The richer countries are characterised with higher rates of waste generation, while the low-GDP countries generate much smaller amounts. The table lists the amount of municipal solid waste (MSW) for three different levels of country GDP; South Africa is currently a medium-GDP country (UNEP, 2010b).

Table 1: Waste Generation Correlated with GDP

	Low-GDP countries	**Medium-GDP countries**	**High-GDP countries**
Example country	India	Argentina	EU-15
GDP US$/capita/year	<$5,000	$5,000 - $15,000	>$20,000
MSW kg/capita/year	150-250	250-550	350-750

(UNEP, 2010b)

In the majority of countries around the world, landfilling is the dominant choice for disposing of waste, which for developing countries is a recent progression from open dumping or burning (de Wit, 2011; United Nations, 2011d; Williams, 2005; Monni, et al., 2006). Contained landfills are environmentally preferable to open dumping, but still pose a number of health and environmental threats associated with air and soil emissions (White, et al., 1995). The European Union is slightly different to the rest of the world, as it is leading the change to other management practices that minimise waste to landfill (UNEP, 2010b), but UNEP estimates there are still almost 100,000 closed and active landfill sites in the U.S. and Europe alone. With increasing urbanisation, land near metropolises is a valuable commodity; finding space for waste is an increasingly common problem (Leao, et al., 2004). In Cape Town, the three currently-open landfills collectively have less than ten years of capacity, which is one third less than the recommended buffer of fifteen years by international standards (City of Cape Town, 2011).

1.1.4 Conclusion

The review above shows that energy consumption is expected to continuously rise in the future, with fossil fuels remaining a large component of the source of supply. Resource extraction and patterns of over-consumption are also rising, especially as developing nations gain greater standards of living and greater personal wealth. Finally, it was shown that with increased wealth comes increased waste and despite minimisation efforts, landfill capacity issues are likely to continue in the future. Throughout the review a consistent message of over-consumption and non-sustainability exists.

Chapter 2: Waste Management

Waste management is considered to be the collection, separation, disposal, and monitoring of waste materials (Jenkins, 1993), and the way in which these steps are performed have different energy requirements, use different types of fuel, occupy different amounts of space and result in different levels of emissions. This section will review the various terms and concepts associated with the management of waste. It will begin with a comprehensive definition of the waste materials relevant to this study and continue with a discussion of waste management methods. The objective of this section is to provide a solid base for understanding the remainder of the paper, which applies energy demand and global warming potential (GWP) as assessment criteria to waste management options in the City of Cape Town (CCT).

2.1 Definition

Definitions of waste vary considerably around the world (Bogner, et al., 2007; UNEP, 2010b) and depending on one's point of view, waste may be a hazardous and costly consequence of a process, a useless by-product, or a valuable input material to another process. Due to the variation in waste definitions by geography as well as point of view differences, the first objective of this section will be to define waste as it will be used in this paper. The applicable legal definition of waste was found in the Waste Management Act of South Africa (Republic of South Africa, 2008, p. 16).

> "Any substance, whether or not that substance can be reduced, reused, recycled and recovered –
> a) That is surplus, unwanted, rejected, discarded, abandoned or disposed of
> b) Where the generator has no further use of for the purposes of production, reprocessing or consumption,
> c) That must be treated or disposed of or
> d) That is identified as a waste by the Minister, but
>   1) a by-product is not considered waste, and
>   2) any portion of waste, once reused, recycled and recovered ceases to be waste."

In addition to this definition, waste can have nomenclature relating to its physical state, such as whether it is a solid or a liquid; its original use (e.g. packaging waste); its material composition (e.g. glass or paper); its physical properties (e.g. combustible); its origin, such as generating from industrial or household activities; or finally, its safety level, such as hazardous or non-hazardous waste (White, et al., 1995). This research project limits its focus to two types of waste material: construction and demolition (C&D) rubble and container glass, so only applicable classifications and their characteristics will be discussed further.

Both materials reviewed in this research are classified within general waste as inert substances. General waste usually encompasses all waste materials that are not hazardous or the result of a specialized activity with individualized waste management, such as mining. Inert substances are waste materials that will not decompose and do not pose a significant health threat or toxicity; they can be described as relatively "benign" wastes. There are still adverse effects associated with the disposal of inert materials that should be noted, however. Inert waste takes up landfill space and with regards to concrete, there can also be small amounts of chemical leachate from concrete, impacting the toxicity of the surrounding soil and water (Zhao, et al., 2010), and an odorous gas emission of hydrogen sulphide contributing to soil and water acidification (Zhao, et al., 2010). Perhaps the largest impact of all though, is the opportunity cost associated with the depletion of resources extracted and used to make new, replacement products despite the ability to make replacement products from the disposed, inert material.

C&D Rubble is often considered a waste category itself, but container glass, on the other hand, falls within the category of municipal solid waste (MSW), which encompasses household and commercial waste (Williams, 2005). MSW is managed by local authorities and has a range of materials that fluctuate seasonally (White, et al., 1995). Both C&D waste and container glass are discussed further in Chapter Four.

To conclude on the definition, waste is any material that no longer has value to the user. It may be reclaimed as a useful material by adding value via recycling for example, at which point it leaves the auspices of waste management and becomes an input material to a new process. Moreover, while waste can be classified into many different types, this research refers to just two: container glass, an inert waste found in MSW, and C&D rubble, also an inert waste which constitutes a category of its own.

2.2 Waste Management Methods

The introduction to this chapter mentioned that different waste management options affect the environment in different ways. This section reviews the concept of integrated waste management (IWM) and a number of waste management options, such as landfilling with and without gas harvest, incineration, composing and recycling.

2.2.1 Integrated Waste Management

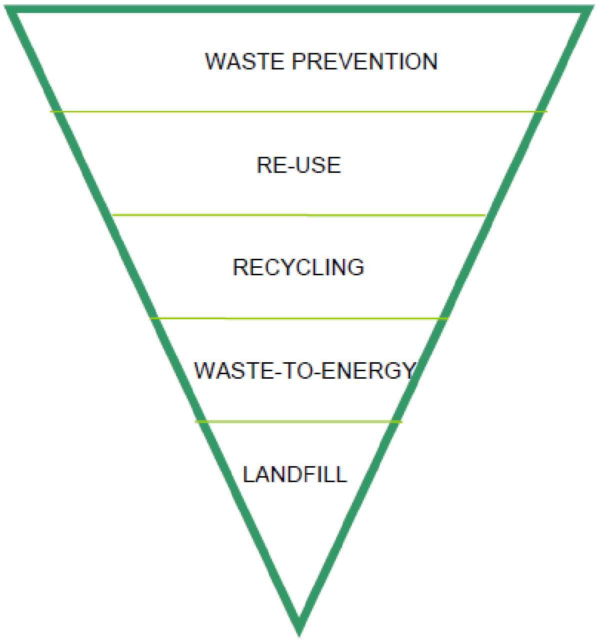
Before discussing IWM, it is useful to establish the basic processes of waste management first. Waste management, as mentioned in the introduction to this chapter, is the collection, separation, disposal and monitoring of waste. Each step has a number of sub-processes that may require significant amounts of energy. Some of these are reviewed below (White, et al., 1995).

1) Collection, for example, includes the transportation of waste from the generation source, e.g. households or businesses, to final disposal. This takes place via municipal or contractor waste trucks making kerbside and drop-off point collection, and possible train or barge transport if landfills are far from the generation site or recyclable materials are far from a viable market. The energy requirement in this step is often liquid fuel, i.e. diesel.
2) Separation is the act of removing usable or dangerous material from the general stream. This can be done at source, such as a homeowner having three different bins for types of recycling, or in a materials recovery facility (MRF), which usually employs conveyor belts, compactors, baling machines and manpower to divide the waste into more accessible fractions. These processes usually require energy in the form of electricity.
3) Disposal often means landfilling, but it can also refer to other ways of eliminating waste, such as incineration or recycling. It *consumes* energy in activities that contain and monitor the harmful effects of waste or to re-process the waste into another usable form, but it can also be a *source* of energy via incineration or landfill gas harvesting. These alternatives are discussed further below.

The South African Waste Act refers to the possible transition from waste to useful product when value is found within the waste material (Republic of South Africa, 2008). This occurs when the relevant waste material is separated and made available as an input to another process, at which point it ceases to be waste. An integrated waste management system is one that considers this possibility, as well as other waste minimization options, before acting on simplistic, end-of-life waste disposal means. It is a holistic approach that links waste management to other systems, such as the manufacture of new materials or energy generation. It differs from traditional waste management in that the “end of pipe” outlook is discarded and a more cyclical approach is employed (White, et al., 1995; Williams, 2005). Questions such as “How else can this waste be handled?” and “What other systems are impacted by the chosen disposal method?” drive IWM.

A key tool for this approach is the waste hierarchy, which essentially structures waste handling options into a prioritised funnel, where the final and least desirable option is the ultimate disposal of waste in a landfill (DEAT, 2011; Demirbas, 2011; U.S. EPA, 2011). See Figure 5 for an example of the waste hierarchy and its prioritized options for waste management.

Figure 5: The Waste Hierarchy



(UNEP, 2010b)

While a cornerstone of IWM, the hierarchy is sometimes challenged because of its overly simplistic approach (WRAP, 2006). In some situations, waste management options higher in the order might actually result in greater negative environmental impacts than options lower in the order and should not be prioritised. In a recent review of 20 waste strategy analyses, Cleary (2009) found that only half of the analysed scenarios confirmed the waste hierarchy. The studies ranged in geographical focus covering the European, Asian and American continents and varied in methodological choice; some reviewed MSW in its entirety, while others analysed just one waste material. One study found that when the recycling scenario included a high proportion of drop-offs, rather than kerb-side collection, the global warming potential (GWP) of recycling rose above that of landfilling (Beigl & Salhofer, 2004). Others resulted in a preference for incineration over recycling or composting in at least one category if not all the categories evaluated in the LCA (Chaya, 2007; Eriksson, et al., 2005; Hong, et al., 2006). Others were inconclusive on the clear placement of the waste management options due to different scenarios resulting in different results or unclear results because of an inability to separate management actions in a mixed treatment situation (Beigl & Salhofer, 2004; Buttol, et al., 2007; Consonni, et al., 2005).

Research by Bjorkland & Finnveden (2005) found that occasionally recycling was more detrimental in terms of energy use and GHG emissions than other waste management strategies. These differences were usually attributed to the type of material being replaced or the source of energy used or displaced. For example, recycling plastic to replace an originally wood-derived product and recycling container glass into aggregate are not more beneficial than landfilling (Bjorkland & Finnveden, 2005; WRAP, 2006). They suggest it is necessary to draw conclusions for a specific time and place based on the key factors affecting that particular process, rather than establishing a universal rule in favour of recycling. These factors include the transportation distances, the type of transportation technology, the type of production technology and the energy mix applied.

Another review of published LCAs found that in 15% of the scenarios comparing recycling and incineration, the incineration option was less impactful than recycling and another 13% of the scenarios had no clear preference (WRAP, 2006). Additionally, the Australian government published a report in 2006 that “busted” recycling myths, including a refutation of the assumption that reuse is always better than recycling. They used the example of print cartridges, which were often collected and refilled by manufacturing companies, instead of collected and re-processed into new cartridges. Many of the companies practicing this had difficulties with quality control which resulted in leaking cartridges and damaged printers. The series of environmental impacts caused by this failure offset the advantages in landfilling the original cartridge (Planet Ark, 2006). These findings suggest that the middle layers of the hierarchy are most at risk for misapplication, but even the highest echelons of the hierarchy are not faultless.

2.3 IWM Disposal Options

There are a several different ways to manage waste, and each impacts the environment in unique ways. This section focuses primarily on landfilling and recycling being the two most pertinent to this research.

2.3.1 Landfilling

Landfilling is still the most common method of managing waste (United Nations, 2011d; Williams, 2005; Monni, et al., 2006). The objective of a landfill is to safely dispose of solid waste for a long timeframe as it is actually a long-term storage of inert waste and a place of decomposition for biodegradable waste. This decomposition means emissions are inevitable and controlling these is an important aspect of the landfilling process (White, et al., 1995).

Modern landfill operation is more complex than simply dumping waste into a predetermined location. Landfills are constructed by first preparing the land to be used by installing a special lining made of several layers to the ground. This prevents much of the harmful leakages from the decomposing waste into surrounding soil and water reserves. Gas pipes and water pipes are also constructed to give relief to built-up gas and liquids within the landfill. They control gaseous odours and emissions as well as liquids that need to be treated before being released (Williams, 2005). Figure 6 provides a visual of what these pipes look like on a closed section of landfill.

Figure 6: Gas pipes at Coastal Park Landfill

Landfill operations require the use of many land-moving machines, such as dump trucks, compactors, and bull dozers. These are applied to the tasks of distributing the waste appropriately, packing it down to conserve space, and constructing access roads on the dump sites. These machines are also used to apply a daily cover to the waste, in the form of sand or construction rubble, to limit as much as possible odour release and the attraction of rodents and birds. Figures 7 and 8 show these machines in operation at Coastal Park Landfill in the CCT.

Figure 7: Bulldozer at Coastal Park Landfill

Figure 8: Operations at Coastal Park Landfill

The main environmental concerns of landfills are three-fold. Firstly, they take up space that could otherwise have been used in a more environmentally safe and productive way. In a contained landfill, deprived of oxygen and water, even organic substances degrade very slowly, thus landfills occupy the land long after they close (Demirbas, 2011). Secondly, they leak chemicals, called leachate, into the surrounding ground water, contaminating a much larger area via the flow and seepage of unclean water. This water can then be harmful to both plant life and animal life, including humans (Williams, 2005). As discussed above, the leachate is contained as much as possible by landfill design and construction, but accidents do occur, as well as the ultimate breakdown of the lining, so the perfect system has not yet been built (Kannemeyer, 2011; White, et al., 1995). Finally, landfills also emit dangerous gases. The most commonly produced gas from landfill is methane, which has a large GWP: one kilogramme of released methane gas is equivalent to 25 kilogrammes of carbon dioxide in the atmosphere (IPCC, 2007). The rest of the gas is mainly made up of carbon dioxide plus trace amounts of over 100 other volatile compounds (White, et al., 1995). Worldwide, landfills emit 37 million tonnes of carbon dioxide equivalents per year (U.S. EPA, 2002), which is approximately equal to the emissions of a small to medium sized country, such as New Zealand or Slovakia (UNFCCC, 2011).

Some landfills are now harvesting the gas emissions for use in energy production, which prevents its escape into the atmosphere as a greenhouse gas (GHG), as well as reduces the requirement for the extraction of fossil fuels to supply energy. The gas is harvested via a piping system and then used to as an input to gas turbines, making electricity or heat which can then be fed to the electricity grid or used in a nearby industrial process. C&D rubble and container glass are both inert substances, as stated Section 2.1 and as such do not emit gases when landfilled. This component of waste treatment will thus not be discussed further in this paper.

2.3.2 Composting and Incineration

Unlike landfilling, there are waste management options that immediately breakdown the waste material. Biological treatment is the decomposition of biodegradable components of waste, including paper, while incineration is the combustion of waste, often referred to as thermal treatment (Demirbas, 2011). Both methods reduce the volume of waste going to landfill and can be used as alternative disposal means.

The two materials discussed in this research project are also not feasible options for composting or incineration; they are non-biodegradable and do not burn. Neither incineration nor composting is thus discussed further within the scope of this paper.

2.3.3 Recycling

Recycling, simply stated by Demirbas (2011), is the extraction of value from waste. It has been recognized globally as an important strategy to divert resources sent to landfill as waste and has a number of environmentally positive impacts, which will be discussed below.

The simple definition of recycling given in the paragraph above can be expanded to demonstrate its full position in IWM. The South African Waste Act of 2008 defines it as "reclaiming waste for further use; involving a separation from the waste stream and the processing of that separated material as a product or raw material" (Republic of South Africa, 2008, p. 16). This is quite a comprehensive definition, as it clearly shows the necessity of recovery *and* utilization (Uiterkamp, et al., 2011). Recycling has a unique role in IWM, as once a material has been separated and recognized as a recyclable product, it exits the boundary of the waste management system and joins another system as an input substance. Because it acquires value as a useful input, it ceases to be a waste (White, et al., 1995). This waste management option is highlighted within the United Nations Environment Programme's (UNEP) waste management strategies, the South African National Waste Minimisation strategy and the White Paper on Integrated Pollution and Waste Management for South Africa.

Recycling requires energy to collect and transport it from its source to the processing centre. It can also consume energy by using sorting machines, such as conveyor belts, when comingled recyclables need to be separated. Finally, the processing aspect also uses energy for crushing, heating or compacting. These energy consumptions are offset by the savings in energy experienced by not having to extract, transport and process the raw materials replaced by the recycled material. Generally, it is believed that the savings are greater than the incurred energy use (Blengini, 2009; Craighill & Powell, 1996; Crawford, 2009; Lino, et al., 2010; Morris, 1996; Bjorkland & Finnveden, 2005). Recycling has benefits in addition to saving energy as well; it reduces the requirement for landfill and associated pollution as well as the depletion of raw materials (White, et al., 1995).

Due to these benefits, recycling is often considered the most environmentally beneficial alternative for waste management except avoiding the creation of waste in the first place or reuse, which avoids the need for re-processing; this is depicted by the waste hierarchy discussed above in Section 2.2.1. Despite the general belief that recycling is a preferred waste management option, there remains the concern that recycling is not always beneficial. According to Blengini & Garbarino (2010) this is likely true for products that do not require a large amount of energy during primary production. Aggregate, which is often the product of recycled C&D rubble, is a prime example of this as producing aggregate from raw material is not an energy-intensive process (Hammond & Jones, 2011). There are a number of other studies that also conclude recycling is not preferred in certain circumstances. Many of these studies were reviewed above in Section 2.2.1.

2.4 Waste Management Conclusion

Waste generation is linked to population growth and rising income levels; as the world continues to develop economically, these factors rise, resulting in increased waste. Landfills are no longer a desirable waste management option, as they take up valuable land for a very long time and harm the nearby environment via leachate and emissions. Alternatives, such as incineration and composting have thus grown in prevalence, but inert materials, such as C&D rubble and container glass, are not suited to treatment by these methods. Recycling, on the other hand, is one of the most preferred options for all waste types according to the waste management hierarchy. Some doubts have been expressed, however, and some international research supports the need for further investigation before it is more broadly applied.

Chapter 3: Life Cycle Assessment

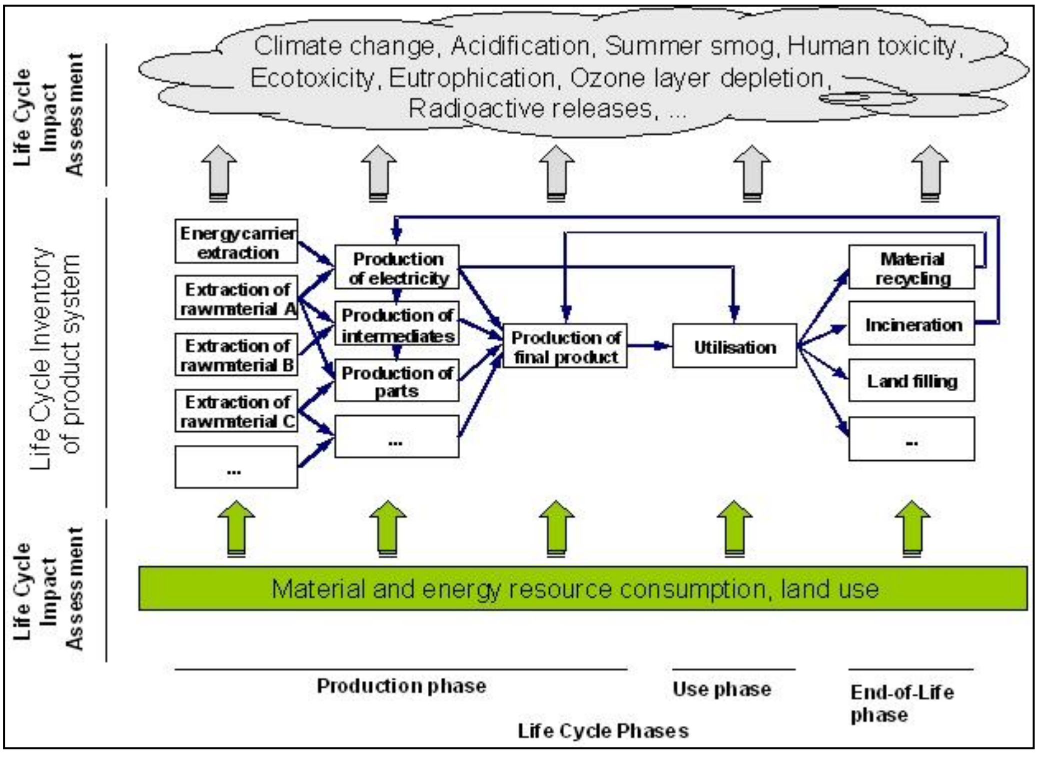
Life cycle assessment (LCA) is an approach to calculate the environmental burden associated with a material, product, or service (WRAP, 2006). It can be used to determine a preferred waste management option because it is a tool used to holistically measure and compare the environmental effects of all inputs and outputs when producing, using and disposing of a particular product. This section will review the main components of LCA and explain its applicability to the evaluation of the energy use and global warming potential of the emissions generated by a material or technique in waste management strategies.

3.1 The Definition and Components of LCA

LCA is a methodological tool that applies a holistic and quantitative review of activities relating to a good or service throughout its entire life, including inputs and outputs arising from its disposal. It essentially accounts for all materials going in and out of any defined system and enables the estimation of cumulative environmental impacts (Curran, 1996). The full life cycle, often referred to as a "cradle to grave" analysis represents all the phases in a product's life, from extraction of raw materials through to the end of its life. In each phase, all the inputs, such as energy and raw materials, and all the outputs, such as emissions to the air and soil, are evaluated for environmental impact (SAIC, 2006). Figure 9 graphically depicts a generic LCA.

There is an emerging movement to support cradle to cradle consideration of products, which promotes the idea of a constantly sustainable material flow, instead of assuming an end of life for the product. Cradle to cradle theory is an optimization approach that asks the decision makers to optimize, rather than limit, ecological effects (MBDC, 2010). This approach has been pioneered by William McDonough, and in a rare case of science and popular media converging, he was selected as one of *Vanity Fair*'s 2010 most influential people of the year for his activity in sustainability (Vanity Fair, 2010). This cradle to cradle approach is relevant to IWM because they share similar conceptual underpinnings and LCA has been the springboard for ideas like these to emerge (MBDC, 2010).

Figure 9: Life Cycle Assessment of a Generic Product



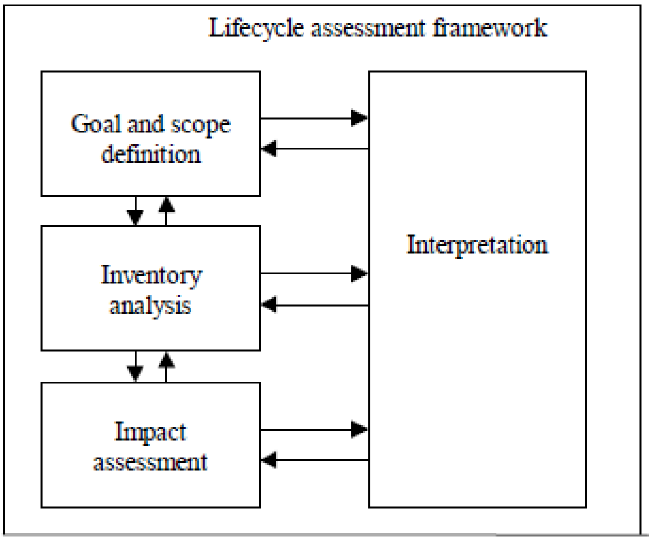
(European Commission, 2010)

There are four stages to every LCA, and these stages are standardised by the ISO 14040 group (Curran, 1996; SAIC, 2006). These four stages are explained below and their interaction is shown graphically in Figure 10.

1) Goal definition and scoping: this stage establishes the reason and boundaries for a particular study.
2) Inventory analysis: this stage quantifies inputs and outputs. The inputs are requirements of the process and indicated by the green rectangle below the flow chart in Figure 9. The outputs are substances released or produced by the process under review. These inputs and outputs have impacts on the environment and these impacts are identified and quantified in this step.
3) Impact analysis: this stage assesses the effects of the environmental loadings identified in the inventory. Characterization, normalization, and weighting all occur here. Characterization groups the impacts by category, while normalization gives scale and comparability to them. Weighting is a subjective measure that assigns relative values to the results. This is used to give more emphasis to the environmental impacts that are considered "worse" than the others based on the goal and situation of the LCA. In an area with intense smog, for example, further release of air particulates may be weighted more heavily than land use. The impact analysis results in a single indicator reflecting the entire environmental burden of the product. Because of the subjectivity inherent in the weighting process, LCAs can avoid this step by simply showing the results by impact category instead of weighting them for a single score. Examples of impact categories are shown in the grey cloud above the flow chart in Figure 9.
4) Improvement analysis or interpretation of results: this stage systematically evaluates the needs and opportunities to improve the product and reduce environmental burdens. This step includes the identification of significant issues, completeness and consistency checks, sensitivity analyses, and the recommendations that arise from the interpretation of results.

These four stages are the skeleton of any LCA. Combined, they ensure a comprehensive evaluation of the specified product, but even abbreviated LCAs can be valuable evaluation tools, as many LCAs apply a cradle to gate boundary or limit the number of impacts studied (Pieragostini, et al., 2012). A cradle to gate LCA cuts the process off before the use and disposal stages of the life cycle, which while not complete, ensures a focus on the impacts of production, and some impact methodologies, for example, consider only a single category, such as the global warming potential (GWP) of a product's emissions.

Figure 10: Life Cycle Assessment Framework



(ISO, 1997)

As part of the fourth step, LCA results should be checked for reliability, as there are a number of sources of uncertainty and variation in such analysis (Lo, et al., 2005; Sonneman, et al., 2003). Some are based on the inherent variability of the real world, such as technological progressions or weather disturbances, and some are due to data uncertainties, such as inaccurate measurements, incomplete data, or poor model assumptions (Sonneman, et al., 2003). The uncertainties of a model can be characterised for further insight into the reliability of its results; Monte Carlo is a widely used tool to do this (Lo, et al., 2005). Monte Carlo analysis is a simulation technique that performs multiple iterations of the model with different randomly selected values for each parameter based on their assigned probability distributions. By doing this, a sample of the possible results and their probability distribution is created. An estimation of the actual probability distribution of the results can then be made with increasing confidence as the number of iterations increase. This can then be used to provide uncertainty characteristics for the LCA results, further assessing their reliability.

3.2 Use of LCA as an Assessment Tool

The original attempts at LCA were performed in the 1960s and 70s during the first oil crisis in the form of net energy analyses by the US Department of Energy (Curran, 1996). It then became a popular tool late in the last century, and today, many different interest groups use it for product comparison and process improvement identification (Curran, 1996; U.S. EPA, 2011). With the evolution of the waste management hierarchy, discussed above in Section 2.2.1, waste management researchers also began to use LCA as an assessment method (Manfredi, et al., 2011). Currently, LCA is used for several different facets within waste management forums: national strategies and policies (e.g. waste tax evaluation), technology optimisation, municipal waste plans, and evaluation of climate change options amongst others (Christensen, 2009). LCA is particularly useful when comparing the manufacture of a product from recycled material versus production from virgin material because it helps the researcher expand system boundaries beyond just waste management (Ekvall, et al., 2007; Williams, 2005). LCA is also often applied to determine the best option among available waste management strategies, as evidenced by the volume of research using LCAs in published literature on the subject. Over 85 studies that use LCA were identified in the literature review (Bovea, et al., 2010; Cleary, 2009; WRAP, 2006).

In addition to the academic literature, many eco-label schemes (services that publically verify the environmental performance of a product or service) require an environmental LCA in order to be certified (Big Room Inc, 2010). WARM, a U.S. EPA model that provides decision makers with the energy and GHG implications of waste management options by material or product also uses LCA (U.S. EPA, 2011). There are a growing number of LCA instruments on the market, and the U.S. EPA (2011b) website lists over 30 software tools and databases, at least seven of which are dedicated to the review of waste management. From all of these examples and applications of LCA, it is a clear choice for environmental evaluation of products or waste management alternatives.

Its popularity is due to a number of substantial benefits, such as preventing the phenomena known as the "shifting of burdens" (SAIC, 2006). It is not a perfect measure, however, and the following sections further explain not only the benefits but also the limitations of using LCA.

3.2.1 The Benefits of LCA

The main benefit of LCA is its facility to encompass all the stages in a product's life. By doing this, it captures the full environmental impact and eliminates the shifting of burdens. This phenomenon occurs when a product improves in one area, e.g. energy use, only to deteriorate in another, e.g. toxicity (Curran, 1996; European Communities, 2006). If only one stage of the process was considered, for example the use stage, a decision maker may choose the components that use the least amount of electricity during operation, believing it to be the best environmental option. It may be, however, that producing those components requires five times the raw materials and electricity used by the process creating standard components, thus cancelling the benefits experienced in the use stage. This kind of well-meaning, but ultimately poor, decision making can be avoided by the proper use of LCA.

LCA is also used to gain stakeholder understanding or acceptance of a decision because it has the ability to quantify the environmental impacts arising from each process in the life cycle. This allows the researcher to identify the major contributors, and sensitivity analysis can then be applied to demonstrate trade-offs based on different scenarios. It provides a sound method of comparing the impacts of competing processes or identifying the impacts of one specific environmental area of concern (SAIC, 2006).

LCA also characterises and normalizes the results for easier comprehension and comparability. This is performed in the third stage of LCA, where the impact analysis establishes the actual impact of the inputs and outputs. For example, what is worse for the environment: 25 thousand tonnes of carbon dioxide or 13 tonnes of methane[1]? By characterising both of these outputs as values representing their global warming potential (GWP), LCA makes the comparison much more meaningful (SAIC, 2006).

3.2.2 The Limitations of LCA

Despite its many benefits, there are some critiques and issues of which one should be aware when applying LCA as an evaluation tool. Because the inventory requires large amounts of data, often difficult to obtain, the accuracy of the input data may be compromised by high levels of uncertainty (Finnveden, et al., 2009). Comparing different impacts on a single scale is a subjective and difficult task that could give wrong impressions about the overall environmental performance of product. Finally, methodological choices can greatly influence the results and hinder comparability, a main application of LCA (Ayres, 1995; SAIC, 2006). These concerns are discussed more fully below, aiming to recognize the limitations, but also to show how they can be ameliorated.

The first concern rests on data accuracy. The inventory and analysis sections are heavily dependent on the input data, which is often difficult to obtain and/or verify (Ayres, 1995). This data is usually proprietary information owned by the manufacturing companies and not easily shared, making thorough external review difficult (SAIC, 2006). This concern is somewhat overcome by the growing number of standard life cycle inventory databases that now provide generally accepted input data (Finnveden, et al., 2009). These databases, such as *ecoinvent* which is used in this research project, provide input and output values for typical and commonly used processes in life cycle analyses. While often not particular to the system under investigation, the data can be used as a close representation if system attributes are similar. For example, *ecoinvent* contains all the environmental impacts associated with operating an excavator in the European Union, which could be applied as an approximation of excavator use in an LCA based elsewhere. The establishment of these databases has been assisted by a joint project between the United Nations and the Society of Environmental Toxicology and Chemistry (SETAC), called the Life Cycle Initiative. This project began in 2002 and one of its primary goals is to improve the data and the indicators used in LCAs globally (SAIC, 2006).

In spite of these advances in accessible and reliable data, there remain issues with using these databases. Firstly, there is still a concern that because the data is not exactly the same as the performance of any particular machine or process, it may under-represent the burdens associated with older or less efficient technology (Osses de Eicker, et al., 2010). Secondly, there is the issue of geographical differences. To further expand on the example of the excavator above, while the standard input data may be a suitable representation of environmental performance in Europe, it may be a poor representation of performance in Africa, where the make and maintenance and thus operational performance of the excavator used may be very different. A 2006 SETAC paper reports that there are no publically available LCA inventories in Africa and only a few, decentralized academic workings in Egypt, Mauritius and South Africa (Curran & Notten, 2006). This means that any LCA scoped with African boundaries will not be able to apply geographically representative data unless sourced by the researcher. This limitation was recently explored in a study of Brazilian LCAs by Osses de Eicker et al (2010). Similar to the approach taken to populate the LCI in this study, they created a “modified” European dataset that adjusted the electricity mix, transportation distances, and oil production to reflect the Brazilian situation. This data set was then compared to the European LCI and a local Brazilian LCI. He concluded that a modified European LCI from the *ecoinvent* database is applicable to a Brazilian LCA, and may pose a better option than using a 100% local Brazilian LCI as limited data and experience have made it less complete than its European counterparts.

A second issue of LCA is the subjectivity inherent in the impact analysis stage: how does one compare different environmental impacts? A 1980’s example of this was the debate around disposable diapers (nappies) versus cloth diapers. A disposable would use 90% more landfill space than cloth, but a cloth diaper would use ten times the water and three times the energy in its life cycle (Ayres, 1995). Some may

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[1] Methane is 25 times more powerful as a global warming agent than carbon dioxide (IPCC, 2007); 13 tonnes of methane is much “worse” as it is approximately 325 tonnes of CO_2 equivalents.

weigh the use of energy heavily while others may be much more concerned with landfill capacity, meaning that two LCAs on these products, using the exact same input and output values could end up with opposing recommendations based on the valuation of the impacts. Ayres used this example to demonstrate the danger in assigning weights or valuation to different types of impacts. He then goes on to propose that this is less of a concern than the lack of verifiable data, as even without a fool-proof comparison of impacts, greater understanding of the environmental effects of the process is still achieved. Today, valuation is still acknowledged as the least developed stage of LCA and one that is most likely to come under attack when evaluating the integrity of an analysis (SAIC, 2006). Because values and goals change over time and geographies, it is important to transparently state what weighting methodology is applied in any LCA. With transparent documentation of the weighting factors, users are able to determine the outcome's applicability for their situation and thus reduce the possibility of incorrect conclusions. Similar to the development and establishment of input databases, there are also existing methods of impact assessment which have become commonly understood and accepted ways to analyse LCA results (SAIC, 2006).

Finally, there are a number of different methods and assumptions that researchers apply in LCA, making it difficult to quickly compare results across different studies. In 2009, Cleary reviewed 20 LCAs of MSW published in peer-reviewed journals. He found great variability in many foundational aspects of the analyses; the studies scoped boundaries differently and were not clear in stating methodological assumptions. This lack of transparency was found to hamper the interpretation and comparison of results (Cleary, 2009). Some of the common methodological choices required in a LCA are reviewed below.

1) The choice of boundaries is an important methodological choice and involves the inclusion or exclusion of processes linked to the study. In comparative studies, like this project, sub-processes contained within the lifecycle may be excluded when they are exactly the same in both compared cycles (SAIC, 2006). Boundaries also refer to the inclusion or exclusion of impacts associated with manufacturing the capital equipment of the system or the impacts associated with less significant processes. ISO 14044 recommends excluding an input or output if it is below a minimum threshold set by the researcher, but this is difficult in practice because one doesn't know if an input has a significant impact on the results until after the inventory and analysis stages (Finnveden, et al., 2009; SAIC, 2006). Because IWM systems cross territories into other systems, such as other product manufacturing processes due to recycling, LCAs involving waste generally need to expand to include the impacts, both negative and positive, on the integral, linked systems (Bjorkland & Finnveden, 2005). An example of this can be demonstrated by the choice to include the mining of aggregates in this research project, even though it is not a part of waste management.
2) The functional unit is a unit of reference decided by the researcher that forms the basis for understanding and comparing the LCA results (Consonni, et al., 2005). The unit may be based on mass, volume, space or any other practical element for comparison, but it must be clearly defined and measurable (ISO, 2006). It can also include a temporal aspect, e.g. "one tonne of MSW treated per year" (Cleary, 2009, p. 1259).
3) The allocation method is another key methodological choice, especially for evaluation of waste recycling (Chen, et al., 2010). Allocation procedure refers to how the inputs and outputs of a process have been assigned to a particular product when the process involves multiple products. There is not one dictated method of doing this; it can be performed on the basis of mass, chemical composition, economic value, or any other characteristic that is feasible and appears intuitively fair (Chen, et al., 2010; Curran, 1996). Allocation determines the share of burden taken up by the product in question. An example of this is the percentage of landfill impacts assigned to a single type of waste. For waste material LCAs it is common to begin the life cycle with the generation of waste and assign it a "zero burden" allocation of impacts at its entry to the process and begin to assign burdens with its disposal (Cleary, 2009; Finnveden, et al., 2009; Ozeler & Demirer, 2006).
4) Another methodological choice is the decision to apply average or marginal data input. Marginal effects are the changes associated with an incremental increase or decrease in the production of a good or service. This is often associated with electricity source: does the researcher apply the average, existing mix of energy or a choice of marginal energy, e.g. the least efficient fuel type, the peaking supply fuel type, or the near future fuel mix. This choice may reflect whether the researcher desires to design an attributional LCA, one that describes a system for better

understanding of the current system, or a consequential LCA which is one that determines the consequences of decisive action (Ekvall, et al., 2007).

3.3 Life Cycle Assessment Conclusion

In conclusion, LCA is a well-respected approach to fully evaluate the environmental performance of waste management options. It is made up of four steps, namely establishing the goal and scope, creating a data inventory of inputs and outputs, assessing those inputs and outputs with respect to environmental impact, and interpreting the results. The primary benefits of LCA are the avoidance of shifting burdens and the comparability of results across product life stages, processes, or even different products. To fully make use of these benefits though, the limitations of LCA must be addressed and methodological assumptions must be transparently reported. LCA has been a popular tool since the 1990's, and while still developing as a truly global tool with established norms, it has successfully been applied to a number of waste management studies.

Chapter 4: Life Cycles of the Selected Materials

This chapter presents the relevant processes to be analysed via LCA for the two selected materials of C&D rubble and container glass in this research project. It will fully define each material and highlight the main steps and key energetic aspects of their recycling and production processes. By the end of this chapter, the reader should have a clear grasp of the main steps involved in both virgin-material production and recycled-material production for the selected materials as well as an awareness of other LCA research on these materials.

4.1 C&D Rubble

C&D waste is a classification based on the origin activity (i.e. construction and demolition) and can be a composite of many different materials (see Table 2 below). C&D rubble is an inert waste with the following definition in South Africa:

> "Building and demolition wastes means waste, excluding hazardous waste, produced during the construction, alteration, repair or demolition of any structure, and includes rubble, earth, rock and wood displaced during that construction, alteration, repair or demolition (Republic of South Africa, 2008, p. 11).

Concrete is by far the largest component as it makes up 80% of the total mass of a building shell and the produced rubble (Robinson & Carville, 2008; Blengini, 2009). Many of the other components are stripped from the building either before demolition (e.g. wood door frames) or directly after (e.g. steel framing) (Johnston, 2011). The fully stripped rubble that consists primarily of concrete, masonry and asphalt is called clean rubble, and constitutes the meaning of the term C&D waste in this research.

Table 2: Components of C&D Waste

Material Components	Content Examples
Wood	Forming and framing lumber, stumps/trees
Drywall	Sheetrock (wallboard)
Metals	Pipes, rebar, flashing, wiring, framing
Plastics	Vinyl siding, doors, windows, flooring, pipes, packaging
Roofing	Asphalt, wood, slate, tile shingles, roofing felt
Masonry	Cinder blocks, brick, masonry cement
Glass	Windows, mirrors, lights
Miscellaneous	Carpeting, fixtures, insulation, ceramic tile
Cardboard	From newly installed items such as appliances and tile
Concrete	Foundations, driveways, sidewalks, floors, road surfaces (all concrete containing portland cement)
Asphalt	Sidewalks and road structures made with asphalt binder

(U.S. EPA, 2003)

While C&D waste can be recycled into new concrete mixes[2] only a small percentage is used in this way (6% in the U.S.) and the vast majority of it is recycled into aggregate (U.S. EPA, 2011). This kind of recycling, where a secondary product is fashioned from the waste of a primary product, is referred to as open loop recycling. LCAs that evaluate products with open loop recycling processes actually compare the lifecycle of the *secondary* product. This means that C&D waste recycled into aggregate is compared to aggregate produced from virgin material. This ensures that the systems being compared offer identical services to society, i.e. supply of aggregate. Aggregate is crushed rock and sand that is used as a foundation material for buildings, pipe beds, or roads (ASPASA, 2006-2011; CMRA, 2011).

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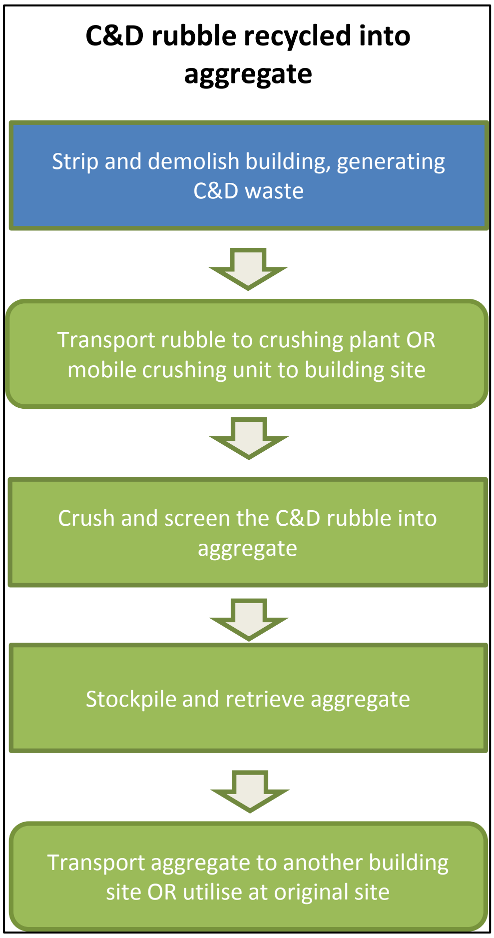
[2] This figure is based on U.S. data and can be considered a representative figure for the CCT, as no specific data is available locally. It corresponds to an indication provided by the manager of Cape Bricks that they receive approximately 7% of the crushed rubble in the CCT to fashion into concrete bricks and pavers.

4.1.1 The Process of Recycling C&D Rubble

Producing aggregate from recycled C&D waste is a fairly simple and straightforward process. Once a building is stripped and demolished, the clean rubble, which is made up of large chunks of concrete and asphalt, is either transported to a crushing plant or crushed onsite with a mobile crushing unit. The crushing and screening machines are self-contained units able to process quarry stone or demolition waste (Terex-Finlay, 2010; FINTEC, 2005). If the rubble is transported to an offsite crushing facility, diesel is burned by the road transport and electricity is burned by the stationary crushing unit. If crushed on site, diesel is burned to fuel the mobile crusher, and there is no energy expenditure related to transport of the rubble, but there is some burden for transporting the mobile crushing unit to the demolition site (SBM, 2009-2011).

The C&D waste goes through multiple iterations of crushing and screening to reach the desired size and quality aggregate. This process is followed by a stockpiling of the aggregate, either by direct dump from the crushing unit or by removal with front-end loaders (FELs), and possibly using dump trucks as well. The stockpiled aggregate must then be retrieved when required for use; this is also performed by FELs. Then, depending on the location of the crushing, it may need to be transported to the next construction site, or it can be used onsite in the construction of a replacement structure (Lennon, 2005). Figure 11 provides a graphical representation of the life cycle for recycling C&D waste applied to this project. The blue square denotes an identical step in all scenarios and as such, was excluded from the LCA.

Figure 11: Life Cycle Process for Recycled Aggregate



4.1.2 The Process of Landfilling C&D Rubble and Producing Aggregate from Raw Material

C&D rubble is not usually included in MSW collection (City of Cape Town, 2011); instead it is transported from the generation site to landfill by dedicated trucks. As part of landfilled waste, it must also bear a proportion of the energy consumed by landfill management activities. This includes the electricity used by support offices and pumping systems, as well as the diesel used by the earth-moving machines as discussed above in Section 2.3.1. Some of it, however, is used in landfill engineering such as covering the waste and making landfill access roads and should not be apportioned the environmental burdens of the landfill operation (White, et al., 1995).

In conjunction with landfilling C&D rubble, aggregate is then produced from raw material. The production of aggregate is not unlike the process of recycling C&D rubble with a few additional steps. The first step is creating the quarry itself. This constitutes energy-consuming activities such as ridding the location of topsoil and overburden[3]. Overburden blasting is done progressively throughout the life of the quarry as the site grows and requires further expansion. In addition to blasting the overburden, explosives are also used to break the required rock away from the land. This quarry blasting occurs only occasionally, with the time between used for excavating, loading, and hauling the blasted rock out of the quarry. Excavators and FELs are used to transfer the blasted rock into dump trucks or onto a conveyor belt for transportation to the crushing unit. The crushing unit then performs a number of sizing and screening iterations to produce the right size and mix of aggregate, just as it does in the recycling process. Primary crushing is performed by a jaw crusher, followed by secondary and possibly tertiary crushing, often performed by vertical shaft or funnel crushers. These machines are identical to the ones used in crushing C&D rubble and are all powered by electricity. Following the crushing process, the resulting product is again loaded, often by chutes which drop the aggregate into dump trucks for transportation to the stockpiles. From the stockpiles, the final product is retrieved by FELs and then transported to the customer by road haulage or train depending on distance and local system characteristics (NCGS, 2011). See Figure 12 for a picture of an aggregate mine in the CCT and Figure 13 for an overview of the process.

Figure 12: Quarry located in the City of Cape Town

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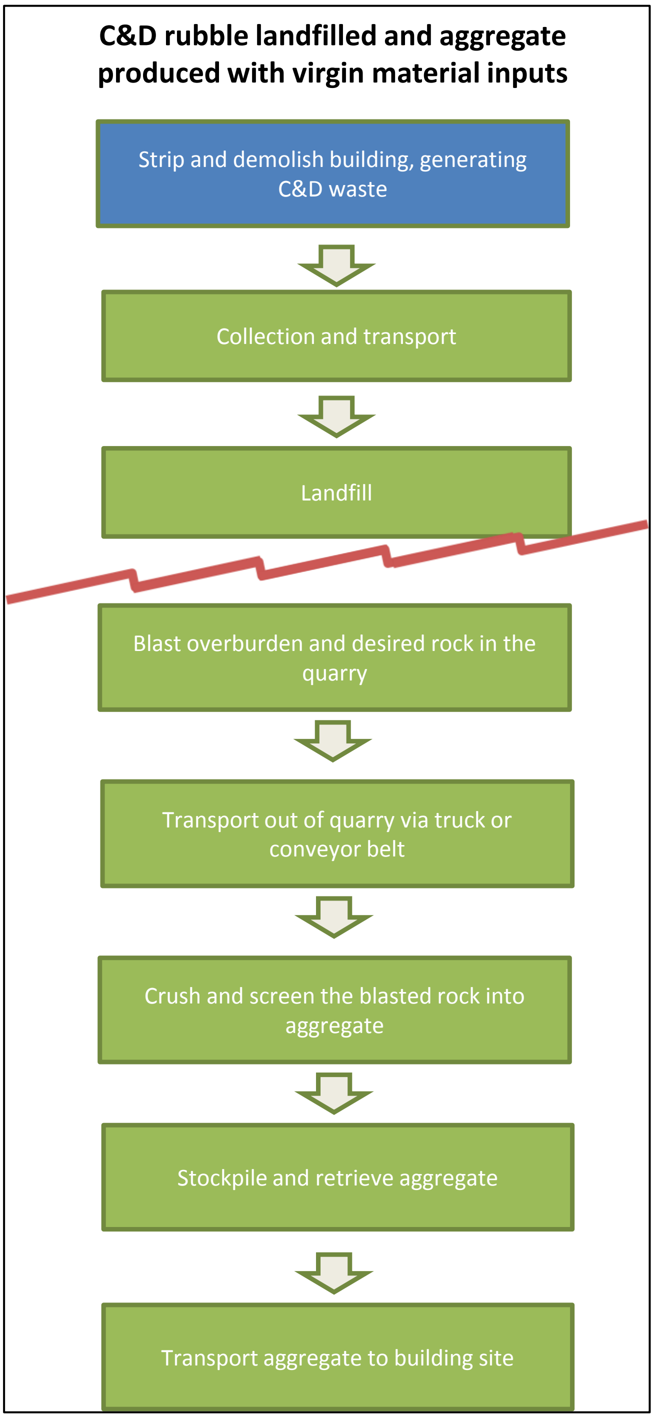
[3] Overburden is the top layer of soil and rock that needs to be excavated in order to reach the layers used for aggregate production.

Figure 13: Life Cycle Process of Landfilling C&D Waste and Producing Aggregate from Raw Material



4.1.3 Previous Research on Recycling C&D Waste

Recycling C&D rubble is generally considered a positive environmental action, and many developed countries have high recycling rates for this material. There is, however, enough dissent in the international literature to warrant more research, especially with respect to the localised evaluation of options.

Substantial activity with regards to recycling C&D waste can be found around the world. The U.S. identified C&D rubble as one of its key paths to resource conservation and is currently recycling about

70% of its C&D concrete (U.S. EPA, 2011). The U.K. also identified C&D rubble as one of seven waste minimisation priority materials; it currently recycles about 60% of its C&D rubble (WRAP, 2006). Switzerland has one of the highest rates of recycled C&D rubble at 90%, and some Nordic countries also reach above 80% (Spoerri, et al., 2009). There are thus a fair number of developed countries actively practicing and promoting the recycling of C&D rubble.

Despite many countries prioritising it in their waste management strategies, there are a couple of concerns around the assumed benefits of recycling C&D rubble. These include a lack of academic review and continued uncertainty around transportation energy use. WRAP, the U.K. study that reviewed global literature on waste management LCAs for seven products, found only two C&D studies for review. This incidence of international studies of C&D waste was low compared to the nine or more studies found for five of the other materials, and the lack of literature was commented on by the authors of the report as a primary concern for this material (WRAP, 2006). In addition to the WRAP research, another study from Italy and a database from the U.S. were also sourced to provide a range of previous findings on the energy and GHG emission savings linked to recycling C&D waste. A number of other associated studies were also examined for methodology, but none explicitly provided energy or GHG emission savings per unit of aggregate. In support of the WRAP finding, sourcing comparison research papers for this project was difficult.

In the few studies that were accessed, however, recycling C&D waste was found to be preferable to landfilling when assessing energy use and global warming potential (GWP). Reported energy savings for recycling C&D rubble compared to landfilling were in the range of 130 - 250 MJ per tonne of aggregate (Blengingi & Garbarino, 2010; Craighill & Powell, 1999)[4], and the associated carbon dioxide equivalent savings were in the range of 1-14 kg per tonne of aggregate (Blengingi & Garbarino, 2010; U.S. EPA, 2011; WRAP, 2006). These amounts are marginal when compared to the savings achieved by other materials, such as glass, which can reach savings of up to 3700 MJ and 500 kg of CO_2e per tonne of material (WRAP, 2006). Part of the reason savings are low in absolute terms is simply because the total amount of energy used in producing aggregate is low; Blengini (2009), the author of a number of journal articles about C&D recycling in Italy, expressed the concern that because aggregate production from virgin materials is not energy intensive, it is likely that the energy used in transporting and processing recycled material is higher than the energy used in the virgin material production process[5]. WARM, the U.S. EPA's carbon modelling tool, shows that the transportation energy of supplying aggregate is more than twice as much as the energy consumed in the processing of it (U.S. EPA, 2011). These values indicate the significance of the transportation characteristics of any aggregate production under evaluation for CED. Finally, the authors of one of the WRAP reviewed studies, Craighill & Powell (1999), contribute to the debate by pointing out that while recycling may use more diesel, it saves on electricity and because electricity is less efficient than liquid fuel, the net primary energy use was still less in the recycling process. All of these sources indicate the potential downside to recycling C&D aggregates is linked to the amount of energy consumed by the transportation required.

Based on the available published research, it appears that energy and GHG savings from recycled aggregates has positive, but marginal results. In some cases, transporting recycled aggregate may outweigh the benefits of avoiding raw material extraction. The global market is encouraging the practice of recycling C&D waste, but academia appears to still have some reservations based on the limited number of studies available and the relatively small savings that may be compromised further by specific system characteristics.

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[4] One study, the U.S. EPA's WARM, resulted in an outlier of 732 MJ per tonne of aggregate; 513MJ of this is attributed to avoided landfill burden, which is a very high estimate of landfill burden for C&D rubble when compared to the other studies.

[55] Blengini later performed a study on aggregates and these results are included in the range given earlier in the paragraph. For the case study performed on Turin, Italy, recycling did indeed result as the preferred option when considered energy use and GWP. This author and an associate found, in fact, that the recycling distance would have to at least double before the environmental impacts of recycling would outweigh its benefits (Blengingi & Garbarino, 2010).

4.2 Container Glass

Container glass, also called packaging glass, is the product used for packaging primarily food products; it is one of four main types of glass. The other three are flat glass such as window panes, pressed or blown glass such as tableware and lighting elements, and finally fibrous form glass used for insulation purposes (EMT-India, 2011). Each type of glass has different physical properties, and the other types cannot be included with container glass recycling because they would not mix well, causing defects in the re-processed material (Vellini & Saviola, 2009). Container glass comes in three different colours, each of which requires a slightly different mix of input materials, albeit only in the trace ingredients. These are called flint (white), amber (brown), and green, and are produced in separate batches, but with the same process (Vellini & Saviola, 2009).

Glass is distinctive in its claim to be 100% recyclable (The Glass Recycling Company, 2011; Glass Packaging Institute, 2010). This means that its life cycle can be repeated endlessly without any waste. While not exactly accurate, the U.S. EPA assigns a loss rate of only 2.4% to container glass which represents the unusable portion of collected and separated waste glass (U.S. EPA, 2011). Because container glass, when recycled, is made into container glass once more, it is considered a closed-loop recycling process (U.S. EPA, 2011).

4.2.1 The Processes of Recycling Container Glass

Container glass waste can be used instead of raw material as input for the manufacture of new glass. It can be mixed with raw materials or theoretically used as the only input for new glass manufacture, although in practicality only about 80% of new container glass input can be cullet, which is crushed glass used as an ingredient in glass manufacture (U.S. EPA, 2011). Before it is ready to be included in the production process, it needs to be separated by colour. Recyclers also need to ensure all other materials, like plastic or wood, are removed before adding it to the production mix. The cullet is then crushed and ready to be added as an ingredient to the glass production. Some of the separation and preparation is performed by manual labour and the rest of it makes use of automated separation machines, which consume electricity (Hischier, 2007). Once the cullet is prepared and ready to melt, it joins the process for making glass from raw materials; all the following process steps are exactly the same as the steps in the virgin-material production process, discussed below.

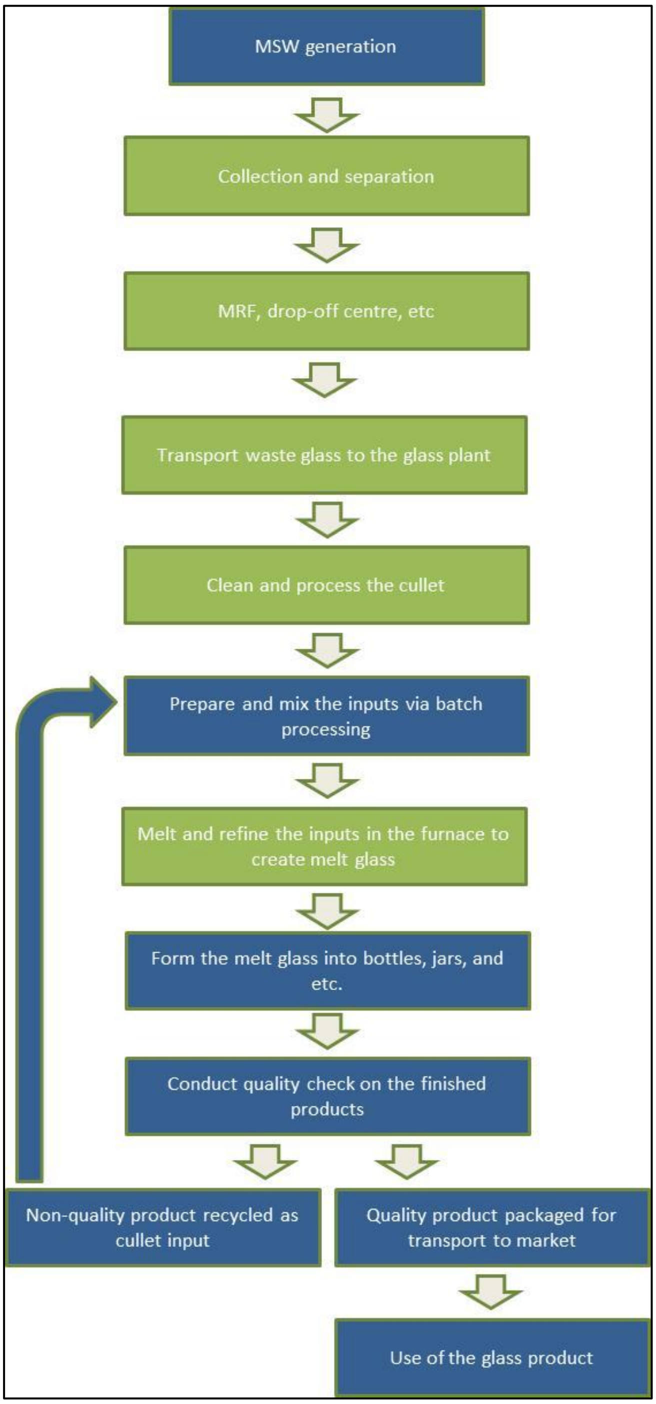
Transportation has an interesting role in the process of recycled glass because the collection can follow a number of different paths from its point of becoming waste to its delivery at the glass plant. Collection can be accomplished via kerbside pick-up, drop-off points, or place of business pick-up. Kerbside collection requires the public to separate the recyclables from the rest of their solid wastes at home. These recyclables are then placed in specialized bins or bags and placed on the kerb for pickup; this is referred to as source separation because the recyclables are separated from the general waste at the source of generation, e.g. the household (White, et al., 1995). After collection, the comingled recyclables are then taken to a materials recovery facility (MRF) for further division by material, i.e. glass, paper, plastic. Figure 14 shows the operation of the Kraaifontein MRF in the CCT.

Figure 14: Material Recovery Facility (MRF) in Cape Town

Drop-off points, on the other hand, are centralized locations that accept recyclables dropped off by the public. These require members of the public to privately transport the recyclables to the drop-off point, where it is later collected for transportation to the glass plant. The glass coming from these centres does not usually go via a MRF, as the glass is already separated in "igloos" or "skips," which are either closed or open top containers for temporarily storing the waste (White, et al., 1995). Finally, recycled glass can also be collected directly from large glass waste generators, such as restaurants or bars and transported to the glass plant for cleaning and crushing.

The life cycle process for recycling glass is shown below in Figure 15. The first step, or cradle of the LCA, begins directly after the creation of waste and the last step portrayed is the use of new, replacement container glass. The boxes shaded blue represent the processes that are the same in both the recycling and the landfilling life cycles, and as such, are excluded from this LCA study.

Figure 15: Life Cycle of Recycled Container Glass

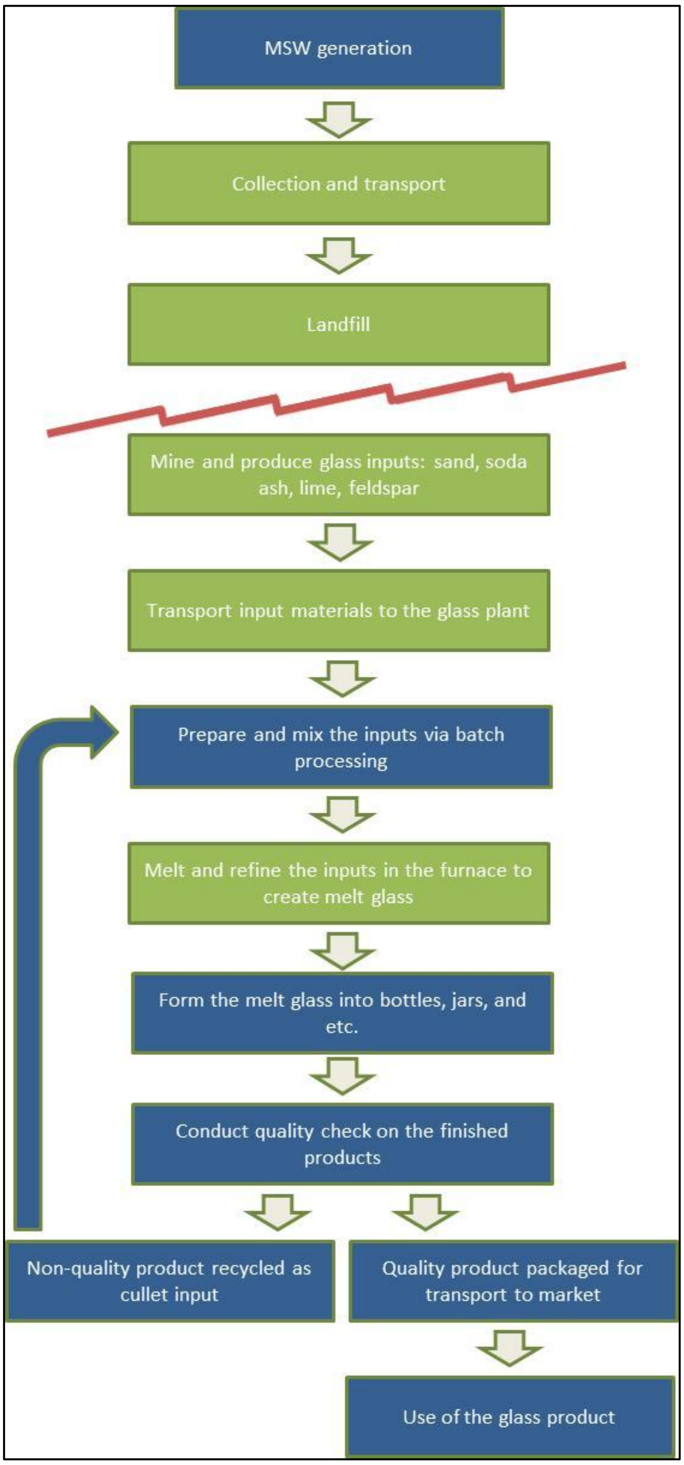


4.2.2 The Process of Landfilling and Producing Container Glass from Raw Materials

Glass is a common material found in MSW, and as such, is collected and landfilled along with other household and light trade waste (DEA DP, 2007). The secondary process of manufacturing new container glass from virgin materials is then undertaken.

Glass manufacturing is essentially made up of four main steps: batch preparation, melting and refining, forming, and post-forming. Batch preparation entails the blending and preparing of the raw materials for the furnace. The main inputs are high quality sand (silica), soda ash, and limestone (Fredericks, 2011). The melting and refining step occurs in a large furnace under extremely high temperatures (approximately 1500 degrees Celsius) (EMT-India, 2011). This step melts the ingredients and ensures the resulting substance is smooth and ready for forming. Heating carbonates, such as soda ash and limestone, releases carbon dioxide into the atmosphere, which contributes non-energy GHG emissions to the total GWP of container glass production (GTS, 2007). There are no carbonates in cullet, so using recycled materials significantly decreases the GHG emissions of the process. The third step, forming, then creates the shape of the container with moulds and the final step, post-forming, is where inspection and packaging occur. The imperfect glass that doesn't pass inspection is looped back to the cullet crushing plant and used as input again (EMT-India, 2011). In practice, almost all glass production uses some cullet as input, even without a large recycling drive because the plant always has imperfect glass it uses to supplement the raw material input (European Communities, 2001; U.S. EPA, 2011). The largest energy consumer in the process of manufacturing glass is the furnace, which often runs off a combination of fuel oil and natural gas (Hischier, 2007). A graphic representation of the full life cycle of glass made from raw materials is shown below in Figure 16. Again, the blue-shaded boxes represent processes that are identical to the life cycle of recycling container glass.

Figure 16: Life Cycle of Landfilled Container Glass



4.2.3 Previous Research on Container Glass

Recycling container glass is, in adherence to the waste hierarchy, also believed to have less environmental impact than landfilling it. This is primarily due to the lower temperatures required to melt cullet as opposed to raw materials. The energy savings experienced by recycling glass are supported by a number of international research projects, but concerns emerge around the type of energy saved and the site-specificity of data. It is important to note that in addition to recycling, glass can be reused. This is the most preferred environmental option according to the waste hierarchy, as reused glass is simply cleaned and used again in the same form, without the need to process it into cullet and then melt and form it again. This is not always an option however, due to the diversity of glass containers and the number of products used on the market (White, et al., 1995). Re-use is considered out of scope for this research project.

Unlike C&D rubble, container glass almost always has a closed-loop recycling process, meaning the new product exactly replaces the original product. Occasionally container glass has an open-loop recycling process to produce aggregate, but because aggregate production uses much less energy than glass production, the additional benefit from that recycling process is not as high as recycling it into container glass (European Communities, 2001). One of the largest advantages of recycling glass is the significant reduction in fuel required to melt the input material for container glass (Nampak Limited, 2010; White, et al., 1995). The energy used in the melting step makes up 60-70% of total production energy requirements, thus even a small savings in this section of the process can have a large impact on overall embodied energy for glass (EMT-India, 2011). The next sizeable saving usually occurs with the reduction in extraction and transportation of raw materials. These savings can be significant, and act as another motivating force for recycling glass (Hischier, 2007).

WRAP, the U.K. study already mentioned above, reviewed 11 LCAs on waste management options for packaging glass. Six of these studies, containing a total of 25 scenarios, dealt directly with the comparison of recycling and landfill and found that where closed loop recycling options were evaluated, the results always favoured recycling over landfilling. The amount of savings realised ranged from 0.9 GJ to 5.0 GJ per tonne of glass in a review of the literature of WRAP plus other sources (Lino, et al., 2010; U.S. EPA, 2011; White, et al., 1995; Morris, 1996), but results tended to converge towards the value of 3.5 GJ per tonne. WRAP raised the concern that many of the reviewed studies used generic data sources instead of data obtained from specific glass manufacturing sites. WRAP's conclusions also noted that the studies were neither as uniform in their boundary selections nor as transparent about their assumptions as could be desired for easy comparability. This was especially looked-for with respect to interactions with the energy system, such as the type of energy used in the glass production process and raw material extraction and transport. Finally, the studies were not always transparent in the recycled content of the produced glass; WARM, for example, explained that the glass manufactured from virgin materials in their model included 5% recycled content (U.S. EPA, 2003).

Avoided GHG emissions are primarily from reduced fuel in the furnace, reduced transportation for raw materials and reduced release of carbon from heating raw materials such as soda ash and limestone (U.S. EPA, 2011). The sourced literature found GHG emissions avoided by recycling to be between 0.3 and 1.1 kg CO_2e per kilogramme of glass. Craighill & Powell (1996) did not report clearly on energy savings, but their GHG assessment results were among the highest at 1.1 kg CO_2e per kilogramme of glass. The other studies reviewed by WRAP resulted in an average GHG savings of 0.58 kg CO_2e per kg of glass (WRAP, 2006), and the EU's Waste Management Options and Climate Change report (European Communities, 2001) states savings of only 0.3 kg CO_2e per kg of glass, half of the average of the studies reviewed in WRAP. This is likely due to EU study comparing a base case scenario with 25% cullet and a recycling scenario with 59% cullet, rather than comparing larger recycled content ranges. The wide range of results may also stem from differences in the sources of energy, technology or transport distances. The WRAP study concluded that most of the environmental impact categories were related to energy, however, and thus the energy system assumptions were found to be the most meaningful. Despite it having the most impact on the results, many of the reviewed LCAs failed to clearly specify the energy sources applied (WRAP, 2006).

In conclusion glass recycling is a closed-loop recycling process likely to result in significant energy and GHG emission savings when compared to other waste management strategies. LCAs that clearly specify system characteristics, such as the energy source and site-specific technology, are not plentiful in the international literature however, and further progress in these areas may be desirable.

Chapter 5: Background Information on the City of Cape Town

The City of Cape Town (CCT) is a growing metropolis with particular characteristics and issues that affect its waste and energy systems. With high population and GDP growth rates, these systems are under increased strain. Waste minimisation and energy efficiency measures have only recently been introduced in the City of Cape Town, and recycling is not yet a main-stream activity. This chapter will illustrate the relevant features of the city, giving context to the specific processes analysed in this research project.

5.1 Growth, Energy and GHG Emissions in the City of Cape Town

The CCT is the capital of the Western Cape province of South Africa. It has a population of 3.7 million inhabitants with one of the highest growth rates in the country at 3% (Accelerate, 2009; City of Cape Town, 2011b). In addition to the high population growth rate, the CCT also has a high GDP growth rate of 4%[6] which outperforms the national average by half a percentage point (Accelerate, 2009). As discussed earlier in Section 1.1.3, waste generation is closely linked with population and GDP growth, making high waste growth a reality for the CCT. Prior 2008, the historical waste growth rate in Cape Town was above 7% per annum; it has, since then, slowed to 2.5 - 4% per annum (Muller, 2011). Due to a lack of data, it is unclear if the decrease in waste generation growth is due to the economic downturn or the implementation of waste minimisation measures, although a number of current recycling initiatives appear to be effective (Engledouw, 2011). Despite the uncertainty around why the waste growth rate has declined in recent years, it remains a fact that that its growth, while lower than in the past, is still significant and may again climb to higher values in conjunction with the city's strong economic and population growth rates.

To fuel its economic activities and provide for its ever-increasing population, the CCT requires 128 billion MJ of energy per annum (City of Cape Town, 2011e). Oil, in the form of liquid fuel such as diesel, constitutes half of this, followed by electricity at 33%, coal at 10% and the remaining 7% is made up of wood and gas (City of Cape Town, 2007). The liquid fuel demand is primarily met by the oil refinery in Milnerton, a suburb of Cape Town, with oil sourced from the Middle East and shipped by tanker to Saldanha Bay, where the country's largest oil storage facilities are located (City of Cape Town, 2011e). For its electricity, the City of Cape Town accesses the national grid, and so despite having Koeberg, a nuclear facility that feeds the national grid, within city limits, the energy consumed locally is supplied by the national system, which is 87% generated by inefficient coal-fired power (City of Cape Town, 2006; Republic of South Africa, 2003b). Electricity shortages were experienced by the City of Cape Town in 2008 when the country's reserve margin dropped to 5.6%, much lower than the international standard minimum reserve of 15% (City of Cape Town, 2011e).

Because Cape Town's energy supply is almost entirely provided by fossil fuels, the city also emits substantial volumes GHGs. Direct emissions have been quantified at 27 million tonnes CO_2e per annum, or almost eight tonnes per capita[7] (City of Cape Town, 2011e). The city's landfills contribute 2.7 million tonnes, and electricity consumption contributes nearly 15 million tonnes (City of Cape Town, 2011e). The per capita emission rate is almost double the world average, which runs between 4.3 and 5.5 tonnes (Flavin, 2008; MacKay, 2009). Future projections by the city's Energy Futures report show energy use quadrupling by 2050 and carbon emissions more than doubling. To prevent a variety of risks associated with this forecast, such as vulnerability in a high carbon society and the opportunity cost of losing marketing value related to being a "green" city, the CCT has published a number of strategy documents that identify actions to mitigate future impacts. The CCT's Energy and Climate Strategy lists goals of energy efficiency and reduced dependency on fossil fuels (City of Cape Town 2005) and the Energy Futures Report lists electricity efficiency followed by transportation efficiency as two key actions (City of Cape Town, 2011e). The most relevant objective from the CCT's strategies, however, may be objective number four in the Energy and Climate Action Plan which is to, "build a more compact, resource-efficient city" (City of Cape Town, 2011e, p. 54).

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[6] Calculated from 1995-2005.

[7] This figure includes emissions from landfills, aviation, and maritime activities. Without these, the carbon footprint per capita is 5.88 tonnes CO_2 equivalents.

5.2 Integrated Waste Management in Cape Town

From the preceding section, it is clear that the CCT is a growing metropolis with significant challenges (and ambitions) to manage its growth in an environmentally sensitive way. In some aspects, the waste management system is coping well with the growth of the city, but in other ways, it is failing to reach sustainable practices.

5.2.1 The City of Cape Town Waste Management Framework

In South Africa, the national government is responsible for providing an overall waste management strategy, including leadership and guidance through the development of legislature and policy, the sharing of information, and auditing. The provincial governments are responsible for the implementation and enforcement of pollution and waste management issues, while the local municipalities are provided with the authority and responsibility of providing waste disposal services in promotion of a safe and healthy environment (Republic of South Africa, 2000). The previously discussed waste hierarchy has helped drive the current South African IWM policy, which moved from an end-of-pipeline to waste minimisation strategy with the White Paper on Integrated Pollution and Waste Management in 2000 (DEAT, 2011; Republic of South Africa, 2000). The City of Cape Town's IWM Policy, adopted in 2006, reinforces the city's adhesion to the waste management hierarchy as stated by the National Waste Management Strategy (NWMS). It also commits to waste minimisation, which it describes as any action that prevents or reduces the volume or environmental impact of waste in its generation, treatment, storage or disposal (City of Cape Town, 2006, p. 27).

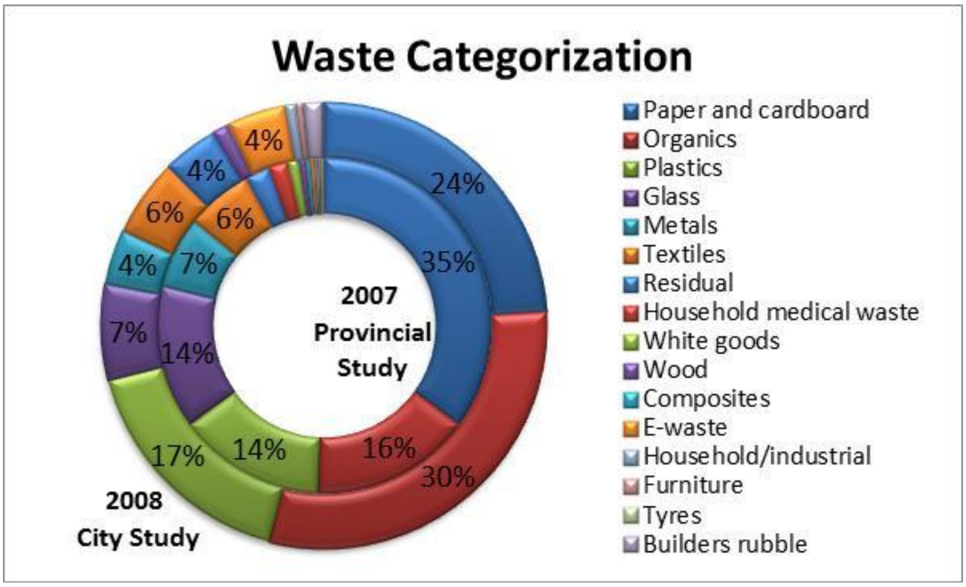
The CCT thus possesses a clear framework for IWM activities; the next section shows how this framework has translated into practical service thus far. It gives a summary of the waste generated and its composition, as well as some key characteristics of the waste management system's infrastructure. Finally, it briefly comments on the alternative waste management techniques practiced in the CCT.

5.2.2 Waste System Characteristics for the City of Cape Town

Cape Town generates at least two million tonnes of waste per year, or between 0.2 and 2.0 kilogrammes of waste per capita, depending on economic status. Of this, it sends 1.6 million tonnes to landfill, while the remainder is reused, recycled or otherwise disposed. Approximately half of this landfilled waste is from households, while 23% is classified as trade waste, another 23% is C&D rubble, and the final 4% is hazardous (City of Cape Town, 2011). The MSW from households has been further studied to determine its composition.

Two recent studies provide a summary of waste by type for the CCT (City of Cape Town, 2008; DEA DP, 2007). It is difficult to draw non-debatable conclusions from these studies, as the results, while possessing some similarity, were by no means equivalent. The four largest fractions in both surveys were paper and cardboard, organics, plastics, and glass. These four totalled 78% of the MSW in both surveys, but the order of contribution was different in each. For example, glass was 14% of total collected waste in the 2007 study, but only 7% of collected waste in the 2008 study. Conversely, organics were 16% in the 2007 survey, but almost double that in the 2008 survey. This variance in composition is consistent with established literature's opinion that MSW is very difficult to characterise (White, et al., 1995; Williams, 2005). It is sufficient to take away from these composition studies that glass, while not the largest component of MSW, is a sizeable element of MSW in Cape Town. Figure 17 shows the categorization for both studies; the inner ring represents the 2007 provincial study and the outer ring represents the 2008 city study.

Figure 17: Waste Composition in the City of Cape Town



To collect, separate, process and dispose of this waste, the CCT has a capital infrastructure that includes over 150 trucks, three active landfill sites, four transfer stations, and more than 20 drop-off areas. It spends more than R1.8 billion each year and services 96% of its households, a laudable figure as other developing countries are in the 50-80% range (City of Cape Town, 2011b; UNEP, 2010b). Appendix A provides a map of the city's solid waste land assets.

The CCT waste management division has disclosed that landfill capacity is down to ten years or less (City of Cape Town 2011b), no longer meeting the international guideline for airspace provision of 15 years (City of Cape Town 2011). A fourth landfill is planned to open near Atlantis, more than 40 kilometres from the central business district (CBD), replacing all existing landfills by 2017 and adding additional transport considerations for waste collection (City of Cape Town, 2011c; Muller, 2011). None of the landfills harvest gas, despite the Coastal Park facility being approved to do so in 2008 (Kannemeyer, 2011). There are no municipal waste incineration plants or composting plants.

Formal waste minimisation efforts are relatively recent in the CCT and have not yet saturated the system, although some progress has been realised. Recycling is presently done voluntarily, and the municipality has focused its efforts on the "Think Twice" programme. It is a free kerb-side recycling service that began in 2008 with just three suburbs of the city. It has now spread to a number of other areas, including the most recent addition of the Northern suburbs in August of 2011 (City of Cape Town, 2011). In the six months prior to the Northern suburbs joining the programme, Think Twice was diverting from landfill about one thousand tonnes of waste per month. Annualising this tonnage and comparing it to the previous year shows that waste diversion increased by 5%, which in turn was an increase of 5.3% on 2008 (City of Cape Town, 2011c). The Think Twice programme's growth rate is thus currently higher than the rate general waste growth.

The amount of glass recycled in the CCT is difficult to determine, but the estimate by a major glass manufacturer is 30%, which correlates with the nationally reported figure of 33% by The Glass Recycling Company[8] (The Glass Recycling Company, 2011). When compared to the waste composition figures and the cullet purchases by the glass manufacturer though, the estimate appears high and a more conservative figure would be closer to 15% or 20%.

In addition to Think Twice, the city also recently began C&D rubble crushing, to be performed at the municipality's landfills and transfer stations. It achieved some success in 2010, but failed to agree terms with a contractor for 2011 and no rubble crushing at the landfills has taken place since December 2010

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[8] This rate is based on 2010 reported values.

(City of Cape Town, 2011d; Johnston, 2011). For a more detailed discussion on the status of C&D waste and container glass recycling, see Sections 5.2.3 and 5.2.4.

While it may be difficult to quantify the waste diversion by material, the City of Cape Town currently diverts 27% of its generated waste from landfill. Approximately 18% of the diversion is from commercial and industry recycling and reuse efforts, while 9% is derived from MSW recycling efforts (City of Cape Town 2011). Comparatively, the UK and the US divert about half their waste from landfills by using not only recycling and composting, which is applied to about 35% of generated waste, but also incineration, which is used on the remaining 15% (UN 2011[9]). The city estimates a further 25% of the waste to landfill can be diverted through actualizing recycling more fully (City of Cape Town, 2011).

Finally, it should be noted that informal recyclers also contribute to waste minimisation in the CCT. Wilson et al (2006) denote four possible types of informal sector involvement in the waste system: itinerant waste buyers, bin pickers, MSW solid waste crew and waste picking from dumps. The most visible and common type of salvaging performed in Cape Town is picking from bins and dumps. These activities likely divert 2% of the waste stream from landfills (DEA & DP, 2007), but are often dangerous and unhygienic (Wilson, et al., 2006).

5.2.3 C&D Recycling in the City of Cape Town

Given the statistics reported above on the waste composition in the CCT, almost 350 thousand tonnes of C&D rubble are landfilled per annum. Of this landfilled rubble, 10% is actually required for landfill engineering such as the daily covering of waste and the creation of haul roads within the landfill (City of Cape Town, 2011). This 10% should not be considered waste nor take any of the burdens associated with landfilling, as it is a necessary input material to the infrastructure of the landfill. This is a relatively low figure when compared to the 24% applied by Craighill & Powell in their 1999 study of C&D waste recycling (Craighill & Powell, 1999).

Publically available information on demolition figures, rubble crushing, and aggregate demand is limited in the CCT. Additionally, construction and demolition companies sometimes do their own crushing for aggregate use in the same location, which is essentially unmeasured C&D recycling (Grace, 2011). Only two of the interviewees would make an estimate as to the amount of rubble generated annually in Cape Town, but both of them agreed a figure of about one million tonnes[10]. The CCT, therefore, currently recycles about 65% of its C&D rubble, uses 4% in landfill engineering and the remaining 30% ends up as waste in the landfills or illegally dumped.

A small portion of the recycled C&D rubble is transported to Cape Bricks and used as an input material for concrete blocks and pavers. The managing director of Cape Bricks estimates that he takes approximately 70 thousand tonnes per year, which is about 10% of the recycled mass. Because evaluating this small proportion of the rubble would require the analysis of a separate closed loop recycling process, it has been omitted from the scope of this paper.

5.2.4 Container Glass Recycling in the City of Cape Town

Applying the statistics stated above with regard to the recycling rates of glass and the composition of waste, it can be calculated that the CCT produces between 150 and 300 thousand tonnes of waste glass per year, recycling about 20 to 60 thousand tonnes of it. There are two glass manufacturers in the CCT, one of which is a dominant player with approximately 75% of the market. These producers supply the city's demand for container glass and receive the recycled glass returned. With the recycled glass, the glass manufacturer can reduce raw material input, which is obtained from a variety of locations. Sand is supplied from Philippi, a suburb of the city, soda ash is imported from the U.S.A., lime is purchased from Saldanha, which is approximately 120km from the CCT, and feldspar is sourced from Springbok, which is

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[9] The UN regularly reports on country statistics, including waste diversion, but regrettably, there was no waste information for many developing countries, including South Africa, Brazil or India (commonly comparable nations).

[10] Sources withheld for confidentiality reasons; please contact writer if verification is necessary.

approximately 500 km from the CCT. Other than the soda ash which is railed and then shipped by ocean freight from the States, all are hauled by road.

5.3 Conclusion

This concludes the background information on the CCT. In summary, the city puts 1.6 million tonnes of waste per year in its three landfills. Of this, C&D rubble makes up 23% and glass 7-14%. Significant levels of recycling are being achieved on both materials, but there is still ample room for improvement. The CCT's waste and energy systems are under increasing strain from the growth of the city, and carbon emissions per capita are well above the global average. The city has the ambition to remain, or rather become, "green," but needs to reach some significant goals in resource and energy efficiency to achieve this.

Chapter 6: Methodology

The preceding chapters presented an introduction to the value of studying the intersection of the waste management and energy systems. They provided background on the increasing demands that waste generation and energy consumption, with associated GHG emissions, have on the environment. They demonstrated that while studying human impact on the environment has been a common research topic in the past twenty years, there is still a knowledge gap with respect to how individual system characteristics, especially transportation, affects the preference order of waste management options.

This research project attempts to further explore this facet of waste management and energy research by performing a life cycle assessment (LCA) on two waste materials in the City of Cape Town, South Africa. Life cycle assessment is a well-accepted method for evaluating environmental impacts and has been used extensively over the past ten years by the scientific community to compare waste handling options, as discussed in Section 3.2. This study applies the LCA software, *SimaPro 7*, which has also been used by a number of other researchers internationally (Blengingi & Garbarino, 2010; Chen, et al., 2010; Christensen, 2009) to evaluate waste management options.

To explain the methods used in this research project, each stage of the LCA will be reviewed below. First, the goal and scope of the project will be explained. In this subsection, the problem will be clearly defined, the project's scope is established and the boundaries are presented. Next, the life cycle inventory (LCI) stage will address the techniques used to obtain data. The final section will assert what impact assessments have been applied to the LCI. The interpretation stage is essentially the discussion of results and can be found in Chapters Eight and Nine.

6.1 Goal and Scope

The inspiration for this research project came from a query raised in discussion about energy efficiency in the Energy Research Centre of the University of Cape Town: Can Cape Town not only save landfill space, but also save energy by recycling its waste? The breadth of this question was too large to be addressed by a single study, so this thesis has investigated a restricted version: can recycling result in net energy savings with respect to C&D waste and waste glass?

6.1.1 Problem Statement and Hypothesis

There is strong international evidence that recycling is environmentally beneficial, an understanding that is very much driven by reduced energy requirements in recycling systems versus landfilling plus virgin-material manufacturing systems. There is also evidence, however, that refutes the claim that every recycling system results in lower energy use than landfilling. This project attempts to determine whether this claim is true for two materials (C&D rubble and container glass) for the City of Cape Town. The principal hypothesis is that both C&D rubble recycling and container glass recycling will require less energy and emit fewer GHGs than landfilling and creating product from virgin material.

6.1.2 Goal

The goal of this research is to assess the difference in cumulative energy demand (CED) and GHG emissions for two waste management options: landfilling and recycling for the two materials of C&D rubble and container glass. It will do so by performing LCA on three scenarios per waste material. The C&D waste scenarios are 1) landfilling C&D waste and producing aggregate from virgin material; 2) recycling C&D waste offsite; and 3) recycling C&D waste onsite. Because the onsite and offsite recycling scenarios possess such different crushing and transportation characteristics, two recycling scenarios were considered. The onsite crushing scenario involves transportation only for conveying the crushing machine and associated equipment to the construction site, while the offsite crushing scenario requires transportation of the rubble to the offsite facility as well as transportation of the produced aggregate to the final site. Additionally, onsite crushing uses diesel-powered crushers, while off-site crushing employs electrically-powered, stationary crushers.

The container glass scenarios consist of 1) landfilling with virgin-material production; 2) recycling with a theoretical 100% recycled content; 3) recycling with 80% recycled content. In practicality only about 80% of new container glass input can be cullet (U.S. EPA, 2011), so two recycling scenarios were created for evaluation: one that is theoretically based at the 100% recycled content level and one that shows a more realistic maximum recycled content level of 80%.

6.1.3 Scope

The scope of this LCA has been defined by the following boundaries in order to best achieve the stated goal. The subsections below will elucidate the reasons for choosing the location, impact categories, and major LCA methodological choices that shaped the main structure of the model.

Research Scope

The spatial boundary of the LCA is global with a focus on Cape Town; all inputs and outputs associated with the studied process steps were included, regardless of where they were incurred. Electricity production in South Africa, for example, is performed mostly in Mpumalanga, close to the coal mines (Eskom, 2011), but all the impacts associated with the production and distribution of electricity have been quantified and included in the study. Similarly, the extraction and production impacts of soda ash and feldspar, for example, have been included in the container glass life cycle, despite being mined outside the limits of Cape Town. Recycling methods and haulage distances for the waste system have been based on the characteristics of the CCT, however.

This study considers two of the many possible environmental impact categories available with LCA: cumulative energy demand (CED) and global warming potential (GWP). It does not include an evaluation of other impact factors, such as acidification, eutrophication, land use or water use among others. This restrictive focus hones in on the most relevant indicators for this particular study: the intersection of energy and waste management.

Material Choice

Two materials are reviewed in this study: C&D rubble and container glass. This provided a comparative aspect of more than one material, which was considered valuable. The materials have some shared characteristics that make them feasible for the review and some dissimilar characteristics that make them interesting for comparison.

Within the CCT, both materials are significant fractions of landfilled waste; as discussed in Section 5.2.2, C&D rubble is estimated to be 23% of landfilled waste by mass, and container glass is estimated to be in the range of 7% - 14% (City of Cape Town, 2011; City of Cape Town, 2008; DEA DP, 2007). They are both inert substances; disposal in landfill takes up space and prevents their reuse as the same, or another, product. Neither is a likely candidate for incineration or composting, which supports the decision to evaluate only recycling and landfilling as the waste management options reviewed in this study. Furthermore, both of these materials are heavy substances; the transportation requirements for these materials is therefore intensified and because it was established in Chapter 4 that transportation may play a significant role in the evaluation of recycling, assessing the impacts for these materials is especially interesting. Finally, both materials are also supplied by producers within the CCT, making the results relevant to the City.

There are differences in some characteristics of the two materials as well. Making aggregate from raw material requires relatively modest amounts of energy, while container glass, on the other hand, has a very energy-intensive production process (Blengini, 2009; Vellini & Saviola, 2009). Comparing the effect of transporting such heavy material for a low energy intensive process like aggregate to a high energy intensive product like glass manufacture is worthy of exploration. The collection and separation methods for the two materials are very different; C&D waste is an “easy” stream to single out and often travels to landfill by individualised loads (Wise, 2012). Container glass is part of MSW, and as such is collected along with other household waste. It is of prime interest to explore what, if any, effect different collection and separation methods have on the results for these two materials.

Boundaries

The cradle of this LCA is considered to be the moment waste is generated, and the grave is considered to be the point at which its value has been fully restored as a replacement product or the point at which a replacement product has been manufactured via raw material production. This is true even for the landfilling scenario, where the traditional "grave" of disposal to landfill is followed by the raw material production of a replacement product so that a comparison can be made with recycling. Please refer to Figure 13 and Figure 16 in Chapter 4 for a graphical representation of the life cycles analysed in this study. Processes which are the same in both the recycling and landfilling scenarios were excluded from the analysis (e.g. the use stage of container glass), and the absolute values for the resulting CED and GWP are not meaningful or representative of the full life cycle of an individual product.

The system boundaries have been set to exclude infrastructure impacts. For instance, while the operation of a truck for road transport will be included, the energy used in manufacturing the truck itself will be excluded. This is a common methodological choice applied in LCA (Cleary, 2009) and it was additionally viewed acceptable to deselect capital equipment in this study because much of the equipment used in the two waste management options for the selected materials is similar (see Chapter Four).

The allocation of inputs or outputs has been apportioned by the physical property of mass, chosen because both materials are relatively high density commodities making mass a practical choice. It is also the most commonly applied method of allocation according to Lundie et al (2007) in a report on LCA inventory methodology for the UNEP-SETAC Life Cycle Assessment Initiative.

Following the allocation of burdens, this study did not set any input threshold in advance; instead it applied a practical interpretation to the inclusion or exclusion of LCI data and then checked the importance of these inputs in the results. This follows the approach described by Lindfors et al. and quoted by Finnveden et al. (2009)as a feasible way to handle the difficulty of deciding the significance of certain processes or burdens in advance. It also corresponds to the approach employed by the *ecoinvent* database (Frishknecht, et al., 2007). There were two input exclusions that demonstrate this and should be noted here. Firstly, the explosives used in mining aggregate were assumed to contribute a very small portion of the energy requirement in the total process. Blasting only occurs a couple times a year to create many thousands of tonnes of aggregate, and the blasting step was not included for mining gravel in the generic database process either; this input has been excluded from the production of aggregates from virgin material. Secondly, the glass manufacturing process excludes a number of trace ingredients, such as dolomite, potassium carbonate and borax. These materials together make up less than 3% of the mass of inputs (EMT-India, 2011; Fredericks, 2011), and their exclusion was recommended by the local glass manufacturer interviewed; feldspar at 4% of the raw material input to glass is the smallest glass ingredient quantified in the LCI. The emissions caused by heating carbonates were quantified as a total amount in the model and includes the carbonation of the smaller quantity ingredients, however. It has also been determined that the production of the glass ingredients are background processes; they are included in the LCA but updated with localised data only when applicable and readily obtained. Instead, the focus on sourcing local data was scoped to the foreground processes demonstrated in the life cycle flow charts in Chapter 4.

This study applies two functional units: a kilogramme of waste material, i.e. C&D waste or container glass, and a kilogramme of produced material, i.e. aggregate or container glass. The results are presented in terms of the final product used in the marketplace, but inherent in that is the assessment of the waste unit landfilled or recycled. For example, the calculation of CED for one kilogramme of aggregate produced from virgin material includes the energy required to landfill one kilogramme of C&D rubble. Any losses that occur throughout the process are accounted for in the kilogramme of final product.

The data collected for the LCI was obtained from the most recent local sources available; usually an average of values for the year 2010-2011, or from the *ecoinvent* database which is discussed further below. The LCA impact assessment was conducted on a 100 year basis for GWP, which is an often-chosen time frame for emissions consideration (Chen, et al., 2010; Manfredi, et al., 2011; Shen, et al., 2010; Vellini & Saviola, 2009) and discussed further below in Chapter 6.4.

6.2 Data Inventory

The LCI for this study was populated by local primary and secondary data, as well as generic, international data. The inputs and outputs were obtained via interviews, company reports, and a generic LCI database.

6.2.1 Attaining the Data Values

Locally-sourced information was of paramount importance to accurately model the system and make relevant conclusions regarding the waste system in the CCT. The inputs that make up the foreground processes, those that are directly a part of the studied material's life cycle, were thus all sourced locally. These include the amount of electricity used by the crusher in making aggregate, for example. The background process inputs, those that are part of the life cycle of supporting materials or ingredients, were obtained from generic sources. These include inputs such as the energetic requirements for the production of soda ash and lime.

The foreground inputs were obtained by conducting a number of semi-structured interviews. Over one hundred people from relevant organisations were contacted to provide a solid cross-referenced database of interviewees. Sixteen of those contacted participated in full length interviews, while another 32 provided information through shorter, more concise and structured interviews or requests. The remainder directed the researcher to one of those interviewed or declined to participate in the study. The full-length interviews were mostly conducted face-to-face and an outline of questions was prepared in advance for each interviewee. The interviews contained both open and close-ended questions to ensure precise parameter values were gathered, but also allowed the interviewee to volunteer additional information. Clarifying questions if a new point was raised and verification of the interviewees' responses were performed immediately if the quality of data was an issue. These quality checks took the form of comparing one interviewee's response to another's response for corroboration. If the range of values was wide, the interviewee was asked for an explanation on why the given value was so different to other responses; this occurred both during the interview and in follow-up questions by email or phone. Appendix B contains record of the interviews conducted.

Many of the interview questions required the interviewees to provide quantitative data about their processes, including statistics on the amount of energy used per kilogramme of product processed. The way in which the interviewees responded was varied. Only a few felt comfortable sharing internal company reports; most answered verbally while looking at company data on their computers, and some gave educated estimations due to lack of data records. Wherever possible, the researcher asked for the most recent 12 months of data to ensure a representative average value was used.

The background processes were populated with generic data from the LCI database, *ecoinvent*, and updated with South African values were possible. *Ecoinvent* was developed by the Swiss Centre for Life Cycle Inventories and is a comprehensive database widely used in LCA studies around the world (Chen, et al., 2010; Finnveden, et al., 2009; Osses de Eicker, et al., 2010; Shen, et al., 2010; Tunesi, 2011; Blengini, 2009). The database values are mostly based on an average of technologies used in the Swiss or European markets in the year 2000; updates to the transportation and electricity processes were based on the year 2004/2005. In general, the emissions associated with processes are infinite, in that they include past emissions (from the creation of capital equipment), present emissions (from use) and future emissions (from decomposition). The geographical boundaries for the systems in *ecoinvent* encompass the entire world, as full review of imported materials and fuels are included (Frishknecht, et al., 2007).

6.3 Uncertainty

The Monte Carlo approach is an integrated tool within Simapro7 and was used in this research to ascertain the reliability of its results. Each scenario's result was assessed with a run of 300 simulations;

50 – 100 runs are enough to obtain reliable figures for the standard deviation, median, and mean, but higher numbers of iterations improve presentation of the graphs and make the statistical values more precise (Ecoinvent Centre, 2007).

It is a requirement of Monte Carlo that probability distributions are set for the uncertain parameters within the model. Because this research project sourced local data for the inventory, the sample sizes were small and the quantitative data was too limited to perform rigorous statistical investigation. The localised parameters were estimated based on interviewee responses or literature references.

6.4 Impact Assessment

The impact assessment has been conducted on a single-issue basis for both cumulative energy demand (CED) and global warming potential (GWP). The CED assessment used in this study was developed by *ecoinvent* and can provide a characterisation of energy in five different categories: non-renewable, fossil fuels; non-renewable, nuclear; renewable, biomass; renewable, wind, solar, geothermal; and renewable, water. It consolidates all primary energy consumed, which means, for example, it is not the electricity consumed that is added to CED, but the amount of primary energy needed to supply the required electricity. It does not employ a normalisation step and applies a weight of one to each category.

The GWP assessment used in this study is the IPCC 2007 method with an assessment time frame of 100 years. It was developed by the International Panel on Climate Change and characterises the results by converting all the global warming potential of air emissions to the common unit of carbon dioxide equivalents, or CO_2e. There is no normalisation or weighting with this method of assessment. The IPCC provides CO_2e for horizons of 20, 50 and 500 years; the 100 year option was considered a suitable middle ground that does not give undue weight to either the short term or long term effects. Because the 100 year time horizon is also a commonly used evaluation factor (Finnveden, et al., 2009), comparison to other studies is more readily accomplished.

Chapter 7: Data Inputs

In order to compute the values needed to populate the LCI, a number of calculations and data checks were applied to locally sourced data. The general assumptions and calculations that apply to both LCAs are reviewed below, followed by the calculations applied to the inventory values for C&D waste and then container glass.

7.1 General Data

Electricity consumption in the model references the South African electricity mix which was provided by the local agent for *SimaPro*, The Green House. The electricity inventory is based on relevant *ecoinvent* v2.2 datasets (Ecoinvent Centre, 2007) updated to be more relevant to South Africa, primarily with data from Eskom (2011). This was considered a key replacement because the local electricity supply mix is considerably different to its European counterpart. Some background processes deep in the process tree still refer to a generic electricity mix, but these rest below the practical input threshold.

The liquid fuel data obtained from local sources was often reported in units of volume for transportation activities, i.e. litres, or units of energy for the glass melting activity, i.e. kilocalories. To convert these data values into a common unit of mass, the following fuel densities and calorific content were applied throughout the inventory process. These conversion values were obtained from the International Energy Agency's *Energy Statistics Manual* (OECD/IEA, 2005).

Table 3: Liquid fuel densities and energy content

Type	kg/litre	MJ/kg
diesel	0.844	45.66
oil, low sulphur	0.925	42.18
petrol	0.741	47.10

7.2 Transportation

Most of the transportation used in the model's foreground processes was conducted by road; only the importation of soda ash from the U.S. required the use of a train and ship. For these two legs, the generic data in *ecoinvent* was applied. For all other specified transportation, localised road transport figures were used.

For each transportation leg modelled, the LCI included data on the distance travelled and the fuel consumed. Both of these were adjusted to match local characteristics in this project. The following sections discuss in detail how these parameter values were determined.

7.2.1 Transportation - Distance

Transportation distances for loaded hauls were determined by either mapping specific points with Google Maps when the origin and destination locations were known, or by halving the roundtrip distance estimated by interviewed company representatives. It was then assumed that every tonne of material needed to travel that distance, and the tonne-kilometres were entered into the model.

The model then links fuel consumption to the unit of tonne-km by applying a demand factor, which is based on the average load for the entire lifetime of the truck. By using this demand factor, the burden associated with the truck's empty loads, i.e. return trips, maintenance loads and less-then-full-capacity loads is also included, and the underestimation of transportation burden by considering only the fuel used by the truck when it is fully loaded is prevented. The generic demand factors from *ecoinvent* were used and in most cases, the demand factor appeared conservative, for the lifetime average load size was usually less than half the capacity of the truck. The application of this factor is demonstrated below in Chapter 7.2.2.

Table 4 provides the key distances used in the models and provides a brief comment on the approach used to determine the applicable haulage distance. It also includes the uncertainty values assigned to each parameter: 2SD is two times the standard of deviation and is applied to either side of the inventory value to specify the 2.5 – 97.5 interpercentile range.

Table 4: Key Distances

Material	Transportation Type	Distance (km)	Comments	Uncertainty Distribution	2SD (km)	2.5-97.5 percentiles range (km)	Comments
Glass	MSW collection to landfill	28.8	Based on the CCT MSW collection distances	Normal	1.4	27.3 - 30.2	Low uncertainty because single data source with high confidence of correct reported figures
Glass	Kerbside collection to MRF	20.0	Based on average of kerbside recyclers' distances	Normal	10.0	10 - 30	High uncertainty because recyclers in CCT are mostly informal without clear strategies or reporting on distances travelled
Glass	Businesses to glass plant	15.0	Practical average	Normal	4.5	10.5 -19.5	Medium-high uncertainty based on range of responses from all interviewees
Glass	Drop-offs to glass plant	15.0	Practical average	Normal	4.5	10.5 -19.5	Medium-high uncertainty based on range of responses from all interviewees
Glass	MRF to glass plant	13.9	Mapped distance	n/a	n/a	n/a	No uncertainty; mapped distance
Glass	Private Car use to Drop-offs	6.0	Based on drop-off locations per the CCT coverage strategy	n/a	n/a	n/a	Uncertainty embedded with special car trips
Glass	Raw Materials	Varies	Mapped distance	n/a	n/a	n/a	No uncertainty; mapped distance
C&D Rubble	C&D rubble to landfill	15.0	Practical average	Normal	4.5	10.5 -19.5	Medium-high uncertainty based on range of responses from all interviewees
C&D Rubble	C&D rubble to crushing plant	15.0	Practical average	Normal	4.5	10.5 -19.5	Medium-high uncertainty based on range of responses from all interviewees
C&D Rubble	Recycled aggregate to final site	15.0	Practical average	Normal	4.5	10.5 -19.5	Medium-high uncertainty based on range of responses from all interviewees
C&D Rubble	Virgin-manufactured aggregate to final site	15.5	Based on quarry to site delivery distances	Normal	0.8	14.7 - 16.3	Low uncertainty: all quarry managers provided reported values with confidenc and little variation between interviewees

7.2.2 Transportation – Fuel Consumption

The fuel efficiency parameters for road transportation were determined by using the average fuel consumption for the appropriate size and type of truck. The general fleet consumption rates were obtained from two independent, local transporters with significant experience. These values were averaged and found to be somewhat less efficient than the European general fleet, which was expected due to an older average fleet age in South Africa (ERC UCT, 2011). These parameters were assumed have normally distributed uncertainty with the 95% confidence interval estimated based on the span of individual truck averages as provided by the transporters; values are shown in Table 5.

The recycling trucks' consumption rates were obtained from seven independent, local recyclers who provided their average fleet efficiencies, and these values were classified by the type of collection performed by the recycler, i.e. kerbside or business/skip pickups. These parameters were assumed to have normally distributed uncertainties and the ranges within which 95% of the values exist have been estimated based on the span of averages provided by the recyclers. Values are shown in Table 6.

The waste compactor truck's fuel consumption was sourced from the CCT's Waste Management Department and represents 74% of the MSW collection performed in the CCT. Very little uncertainty was assigned to this parameter because it represented the actual average currently experienced by the municipality, which comprises most of the collection performed in the CCT.

The private vehicle efficiency was sourced from Edwards and Schelling's transport analysis (1999), which while old, was very thorough in that it gave a range of efficiencies for cold and warm engine trips, depicting the difference in fuel consumption for short distances if the car was just started or already warm from other driving. The National Association of Automobile Manufacturers of South Africa (NAAMSA, 2011) was accessed to corroborate the private vehicle fuel assumption. These values were in the range of 6.2 – 21.7 kilometres per litre, which encompassed the range of 11.6 – 15.9 kilometres per litre in Edwards and Schelling (1999), so the bottom of their range was chosen as a conservative average estimate for private vehicle fuel use (see Table 6).

Table 5: Road Transportation Fuel Consumption

General fleet	**Fuel Consumption**		**2SD**	**2.5 - 97.5 percentiles range (kg/km)**
<10 tonnes	0.1964	kg/km	0.029	0.16 - 0.22
11-20 tonnes	0.3516	kg/km	0.08	0.27 - 0.43
21-30 tonnes	0.4453	kg/km	0.075	0.37 - 0.52
>30 tonnes	0.3601	kg/km	0.13	0.23 - 0.49
Total Average	0.2789	kg/km	0.17	0.11 - 0.45

Table 6: Road Transportation Fuel Consumption II

Specific Use Road Transportation	**Fuel Consumption**		**2SD**	**2.5 - 97.5 percentiles range (kg/km)**
Waste Compactors	0.8439	kg/km	0.042	0.8 - 0.88
Kerbside Recycling Trucks	0.1777	kg/km	0.045	0.13 - 0.22
Business & Dropoff Recycling Trucks	0.3455	kg/km	0.17	0.17 - 0.52
Private Vehicles (petrol)	0.0641	kg/km	0.013	0.05 - 0.07

Similar to the calculation for distance, the truck size of any given type of transport was obtained by averaging the capacity of the trucks as given by the interviewed company representatives. This average was then matched to the fuel consumption for that size truck, which in conjunction with the demand factor mentioned above, ensured an appropriate amount of fuel was allocated to each tonne of material. The fuel consumption for a particular transport leg was thus calculated as follows:

Fuel per tonne of material for a transport leg = Tonne-kilometres × demand factor × fuel consumption

To demonstrate, the sand input for glass travels 17 kilometres from the sand mine to the glass manufacturing plant. The transportation leg makes use of the largest trucks, i.e. greater than 30 tonne carrying capacity. The fuel consumption for these trucks in the CCT was set per transporters' data at .36 kilogrammes per kilometre as shown in Table 5. These trucks have a demand factor of .0856, indicating an average lifetime load of 11.7 tonnes. The following calculation was performed to obtain the fuel consumption used in supply one tonne of sand to the glass plant.

17 tonne-km × 0.0856 km/tonne-km × 0.3601 kg/km = 0.52 kg of diesel

7.2.3 Emissions

The impact assessment assumes that the carbon content of the liquid fuels used in the CCT is not significantly different to the fuels used in Europe. The Euro 3 emissions standard, which is the oldest and most conservative, i.e. highest GHG emitting, level available in *ecoinvent* was used to define the type and amount of emissions given by the consumed fuel in each type of truck. This is the same assumption applied to the national energy model developed by the Energy Research Centre of UCT (ERC UCT, 2011)

7.3 Landfill Parameters

There are two types of energy used in landfilling in the CCT: electricity and diesel fuel. For the electricity used in landfilling, the Waste Management division of the CCT provided the total cost of electricity for 2010. By applying the average of the rates in the Megaflex Municipality plan by Eskom, it was estimated that the waste management system in Cape Town consumed 4.8 million kWh in 2010. This amount was divided by the total annual tonnage landfilled to result in an average kWh/tonne value of 2.83 for inclusion in the LCI. Detailed electricity figures and calculations are shown in Appendix D, and the values used in the LCI are shown in Table 7.

Table 7: Landfill Energy Requirements

	Parameter Value	2SD	2.5 - 97.5 percentiles range
Diesel (kgs of diesel/tonne of material)	0.37	0.1	0.27 - 0.47
Electricity (kWh/tonne of material)	2.83	1.1	1.83 - 3.83

Unlike electricity, which is controlled centrally, each waste facility manages its own diesel consumption. To determine the diesel used in landfilling, the average consumption per tonne of waste at the Coastal Park Landfill was used to represent the consumption of all three landfills in the City of Cape Town. The landfill provided received tonnage for the six and a half month period of April – mid October 2011. The tonnage was increased by 33% to account for the additional free tonnage received by the landfill, but not recorded as per city officials free waste makes up 25% of total landfilled waste (City of Cape Town, 2011d; Muller, 2011). The corresponding diesel consumed in the same period was used to obtain the average diesel consumption per tonne of waste[11]. This resulted in a parameter value of 0.37 kg/tonne. This value was compared to another calculation result based on actual diesel consumption for the full year of 2010 and the verbal estimate of annual waste landfilled by the site superintendent. The second value was found to be significantly less at 0.34 litres/tonne. The original calculation was used as a

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[11] Note: Fuel purchase and delivery is made once a month; occasionally a month was skipped due to inventory management. The difference in inventory levels from the beginning of the period reported to the end was negligible (approximately 6000 litres for both start and end values), so it was assumed that the fuel purchased is equal to the fuel consumed for the period.

conservative value for the model, and the uncertainty distribution was set to reflect the difference in the two calculations. Detailed diesel consumption figures and calculations are shown in Appendix E.

7.4 C&D Waste and Aggregate Inputs

7.4.1 Recycled Aggregate Inputs

Two local crushing companies plus one manufacturer of recycled bricks that also crushes C&D waste were interviewed to obtain electricity and fuel usages per tonnage of recycled aggregate for onsite and offsite recycling. These companies did not provide historical data but gave internal calculations of the electricity and diesel used per tonne. The values were verified by comparing them to crusher manufacturer claims and individualized process requirements from the quarry managers. The diesel used by the excavators and support vehicles for onsite and offsite recycling are shown in Table 9. The range provided by the interviewees was quite wide, but Company C's data was considered an outlier and discarded from the calculation due to data inaccuracy. The average of the other two was used as the parameter value in the LCI. The electricity used by the crusher in recycling offsite is equal to the electricity used by the crusher in raw material production and is shown in Table 11 along with virgin manufactured aggregate inputs.

The density of C&D rubble at 1.47 tonnes per cubic meter was determined by averaging the density values used by local companies, with the closely corresponding figure found in the literature of 1.5 tonnes per cubic meter (City of Cape Town, 2011).

Table 8: C&D rubble density

Company	Company F	Company E	City of Cape Town	**Parameter Value**
Tonnes/cubic meter	1.4	1.5	1.5	**1.47**

Table 9: Excavation Fuel Use in Recycling C&D Rubble

kg/cubic meter	Company C	Company D	Company E	**Parameter Value**	Uncertainty	2SD	2.5 -97.5 percentile range
Excavators	0.01	0.23	0.31	**0.27**	normal	0.08	0.19 - 0.35

The diesel used by the mobile crusher was also determined by the interviews, and this parameter's calculation is shown in Table 10.

Table 10: Mobile Crusher Fuel Use

kgs/tonne	Company C	Company D	Company E	**Parameter Value**	Uncertainty	2SD	2.5 -97.5 percentile range
Crusher	n/a	0.33	0.31	**0.32**	normal	0.01	0.31 - 0.33

Only one company was able to provide an average job size for onsite recycling and thus this amount of 3666 tonnes was used to allocate the burden arising from transporting the excavator and mobile crusher to the building site (Dix, 2012). A sensitivity analysis on this parameter later explores the dependency of the model results on this value.

7.4.2 Raw Material Aggregate Production

Three quarry managers, covering 87% of the market, were interviewed for energy consumption in the manufacture of virgin material aggregate. All three gave the most recent 12 months of production data, and one company supplied two previous years of data as well. These values were averaged for the kWh and litres of diesel used per tonne of aggregate and can be found in Table 11.

Table 11: Raw Material Aggregate Production LCI Inputs

Mining Fuel Use	Company A Year 1	Company A Year 2	Company A Year 3	Company B	Company C	Parameter Value	Uncertainty Distribution	2SD	2.5 - 97.5 Percentile Range
Diesel (litres per tonne)	0.63	0.74	0.88	0.60	1.00	**0.77**	Normal	0.23	0.54 - 1.00
Electricity (kWh per tonne)	3.34	3.37	3.25	3.60	1.82	**3.07**	Normal	1.26	1.81 - 4.33
Haulage Distance (km)	17.5	17.5	17.5	14	15	**15.5**	Normal	0.8	14.7 - 16.3

The uncertainty distributions for these parameters were set to normal with the 2.5 to 97.5 percentile range of plus or minus 30% for diesel use and 41% for electricity use. These large uncertainty ranges were considered the best, and conservative, representation because of the large differences reported in average fuel use by company.

7.5 Glass Specific Input Assumptions

7.5.1 Manufacturing Parameters

Firstly, there are some losses that must be specified when manufacturing glass from recycled waste glass. The model in this research assumed a loss rate of 13% in the tonnage from kerbside collections, 0% for tonnage from drop-offs and business, and 2% in cullet preparation. The cullet preparation loss rate was an average of the three values found in the literature and mentioned above. The reason for the choice of collection loss rates lies in the collection methods employed. Kerbside collection in Cape Town consists of source-separated, comingled recyclables that are further separated by the MRFs. To obtain a local loss rate to the collection of waste glass, a local MRF provided data on the total amount of comingled recyclables received and the amount not able to be recovered; the loss rate for the whole MRF was extremely high at 42%. In discussion with the company's recycling manager, it was concluded that this rate could not be realistically applied to glass and a loss rate of 13% was agreed. This was somewhat similar to the figure of 10% used by the U.S. EPA (2011), and if not accurate, errs on the conservative side with a lower collection efficiency rate than experienced in the U.S. Because the waste glass collected from the drop-offs and businesses are transported directly to the glass manufacturer, there was not assumed any loss rate in their collection. Appendix F provides the background data on MRF recovery performance. The 2% cullet preparation loss rate was the practical average from comparison studies (Edwards & Schelling, 1999; European Commission, 2006; U.S. EPA, 2011)

Secondly, to manufacture raw material glass, four main ingredients were obtained from a number of different locations, as discussed above in Chapter Four. These ingredients were found to have the following procurement characteristics.

Table 12: Raw Material Input Supply Characteristics

Material	Transport Type	Distance (kilometres)
Sand	32+ tonne truck	17
Soda Ash	Train and Ocean Container Ship	15717
Limestone	32+ tonne truck	151
Feldspar	32+ tonne truck	563

Following the supply of ingredients, there are parameters to establish for the melting process. The primary glass manufacturer in the CCT, with more than 75% of the market, provided fuel requirements for their furnaces. The company has four furnaces that run more or less equally in time and output. The fuel requirements for the highest and lowest performing furnaces were provided for each level of cullet use. These two values were then averaged as a representation of the energy consumed by any given batch of glass production. Fuel oil makes up 85% of it, while electricity provides the rest. This split was a verbal estimate by the company representative, but supported by an analysis of the actual fuel consumption on a typical day for all four furnaces. The proportion of fuel oil to total energy requirement varied from 81% to 87%, but the average was 84.7%, satisfyingly comparable to the given value of 85%, and used to determine the split of fuel oil and electricity consumed. The parameter values included in the LCI are provided in Table 13. The uncertainty of the fuel requirements was determined to be best described by a triangular distribution because the interviewee provided the values for the highest and lowest performing furnaces, which thus collars the possible average values.

Table 13: Furnace Fuel Parameter Values

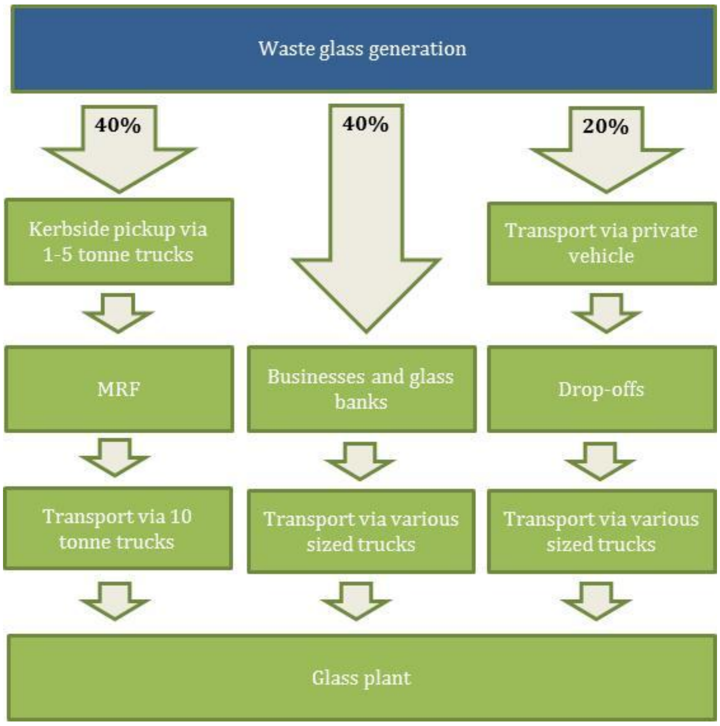
Fuel type	0% Cullet	80% Cullet	100% Cullet
Oil (kcal/kg)	1 033	853	808
Electricity (kcal/kg)	182	151	143
Normal Uncertainty Distrubtion: 95th percentile range			
Oil (kcal/kg)	997-1069	817-889	772-844
Electricity (kcal/kg)	175-189	144-157	136-149

Finally, glass production also releases non-energy GHGs from the heating of soda ash and limestone. This study applied the same carbon dioxide emission rate as the U.S. EPA's rate of 0.185 kg CO_2e per kilogramme of glass manufactured from virgin materials (U.S. EPA, 2011). This is the same value used in a study by Glass Technology Studies but somewhat different to the value of 0.15 assumed by the World Bank Group in its Environmental, Health and Safety Guidelines (GTS, 2007; IFC, 2007). This parameter was assigned a uniform uncertainty distribution with these two internationally applied values for carbonation given as the maximum and minimum of the range. The uniform distribution was chosen because both values came from respected sources and there was no reason to believe that any particular value between the two would be more likely to occur than another. This parameter value decreased proportionally to the increase of cullet input in the recycling scenarios.

7.5.2 Glass Collection Parameters

The collection of container glass for recycling can be complex because of the multiple paths available to recyclers. Figure 18 below shows the collection scenario used in the model. Note that 40% of the recycled glass is collected via kerbside pickup and is processed through a MRF. Another 40% comes via business and glass banks, and the final 20% comes via the city's drop-off centres. The kerbside proportion was determined by comparing the amount of glass collected by the Think Twice programme in 2010 to the total tonnage of recycled glass bought by the glass manufacturer in the last fiscal year (July 2010 – June 2011). The proportion collected via the drop-off centres was calculated by the tonnage collected by the drop-off centres for the year of 2011 compared to the total tonnage of recycled glass bought by the manufacture in its last fiscal year. The remaining amount was assumed to come via businesses themselves or their hosted glass banks.

Figure 18: The Collection of Recycled Glass in the City of Cape Town



It was also assumed that the glass from businesses and glass banks had no first collection transportation burden, as it either didn't need to travel (e.g. a skip was placed at the restaurant where the wine bottles were used) or it was assumed the person dropping the recyclables at would have made that trip anyway (e.g. glass banks at schools are accessed when picking up a child). Some transportation burden was assigned to the drop-off centres, however, because they are not located at a place of business or other institution and it is likely that some of the waste glass arrives by special trip. The CCT has a strategy to ensure drop-offs centres are located five to seven kilometres from any given residence, and this has been largely achieved (see Appendix C for a map of drop-offs and their seven kilometre ranges). An estimate of six kilometres for distance travelled from waste generation to drop-off centre was thus used in the LCI.

Determining the per cent of drop-offs that should be assigned this transportation burden was more difficult to determine. Some LCAs avoid this issue by simply not assigning any transportation burden to the transport of glass from its source to a waste management facility (Cleary, 2009; European Communities, 2001; Manfredi, et al., 2011; Vellini & Saviola, 2009). There was one published study by Edwards and Schelling (1999), however, that used data from a survey of recyclers in the U.K to create a formula to calculate the percentage of dropped recyclables arriving by special trip. This formula was also applied by Krivtsov et al (2004), and used here to estimate per cent of special trips. The function is as follows:

$$N_{st} = \alpha_{st} exp(-L \div \beta_{st})$$

where
N_{st} = *percentage of trips made primarily for recycling*
α_{st} = *0.45*
L = distance to drop-off
β_{st} = *0.95 (Edwards & Schelling, 1999).*

With a distance of 6 kilometres, 24% of the drop-offs were assumed to be made primarily for recycling. There is very little literature on this parameter however, and it is unknown how similar or dissimilar consumer behaviour is in the CCT compared to the survey location in the U.K, so uncertainty for this parameter is high and quantified at the end of the section.

It was further assumed that each journey to the drop-off centre carried 4.5 kilogrammes of recyclables; the burden of the private transportation was then allocated by mass to obtain a burden per kilogramme of recyclable material, be it glass or another recyclable. This figure was also sourced from the Edwards and Schelling (1999) paper, but corresponded to a practical estimate based on three interviewed drop-off operators' opinions on size of load as well as research by Finnveden et al. (2005) which assumed five kilogrammes of recyclables per drop-off. The range of possible values for this variable is, however, large with much variation as the interviewed operators also cited small businesses dropping off up to 300 kilogrammes of recyclables in a single load. Table 14 gives the average load sizes sourced during the research.

Table 14: Average Quantity of Recyclables per Drop-off

Source	Kilogrammes
Edwards & Schelling (1999)	4.5
Finnveden et al (2005)	5
Drop-off Facility A	5-10
Drop-off Facility B (based on private dropoffs)	1
Drop-off Facility B (based on commercial dropoffs)	5-7

To conclude the process step of dropping off waste glass, each of these factors discussed above were used to model an average distance burden per kilogramme of dropped off recyclables.

$$\textit{Drop-off burden} = (\textit{Ave distance} \times \textit{per cent of special trips}) \,/\, \textit{average load size}$$

$$\text{Drop-off burden} = (6\text{ km} \times 24\%) / 4.5\text{ kg} = 0.32\text{ km per kg}$$

It was estimated that any variable in this calculation has an uncertainty range of plus or minus 33%, so a normal distribution with a standard deviation of 0.05, or a range of 0.21 – 0.43, was assigned. The uncertainty assigned may still not represent the full uncertainty of this parameter, but it will be further investigated with sensitivity analyses.

7.6 Conclusion

Sourcing reliable data is often a difficult and onerous task; this research project found it to be no different. While it is recognised that the parameter values used are not always beyond challenge, the intention to source the best practical input directed the decision-making and uncertainty distributions were conservatively set to account for data inconsistencies or misinformation.

Chapter 8: Results

In this chapter, the LCA results are presented by material and impact factor. The uncertainty ranges for the results are discussed alongside and a review of the sensitivity analyses follows the CED and GWP impact analyses for each material. The chapter concludes with a quantification of the possible savings for the City of Cape Town, given its current waste-to-landfill amounts.

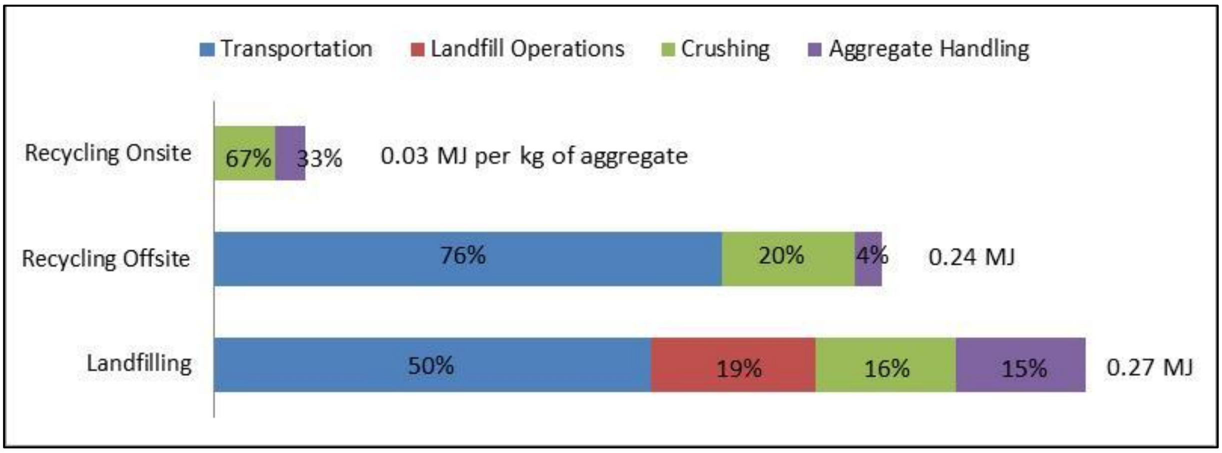
8.1 C&D Waste

The C&D waste scenarios contained input and output data for all the steps in their life cycles because each process differed in some way between the scenarios. The C&D waste results can thus be viewed in terms of total absolute energy requirement as well as in terms of the differences between the processes.

8.1.1 Cumulative Energy Demand Results

The CED for each scenario and its main contributing processes are shown below in Figure 19. The best performing scenario in the CED impact analysis was recycling onsite; it had the lowest CED of the three C&D waste scenarios, with an energy savings of almost 90% compared to landfilling.

Figure 19: CED Process Contribution Results for C&D Waste

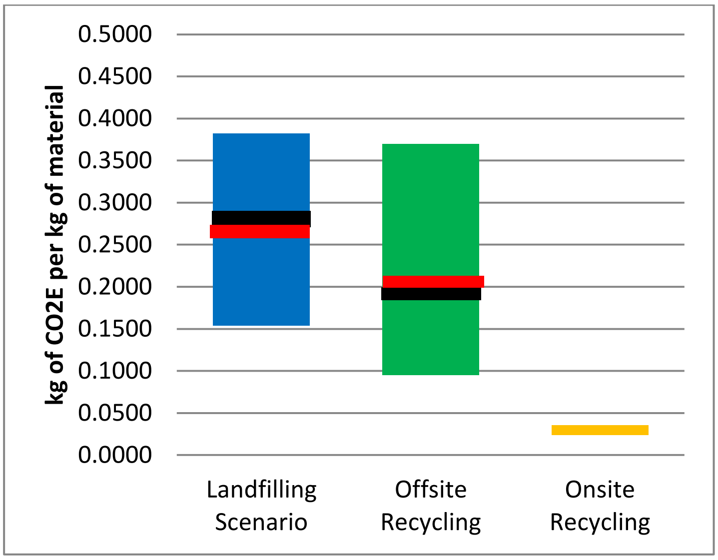


Result Values and Uncertainty Ranges

The landfilling scenario resulted in a CED of 0.27 MJ per kg of aggregate with a 95 per cent confidence interval of 0.15 – 0.38 MJ. The offsite recycling scenario resulted in a 24% reduction in CED, equal to 0.21 (0.10-0.37) MJ per kg of aggregate, and the onsite recycling scenario resulted in a 89% reduction in CED, equal to 0.03 (0.024-0.036) MJ per kg of aggregate. There is a considerable amount of uncertainty associated with the results that can be largely explained by the uncertainty assigned to the transportation legs and the electricity use in the crusher, both of which had medium to high uncertainty and together comprise most of the CED. Despite having a result less than the landfilling scenario, due to the uncertainty ranges for these results, the offsite recycling scenario cannot be said to be more beneficial; individual situations with minimal uncertainty should be evaluated to determine the preferred option.

Figure 20 shows the range for each scenario within which it is 95% confident the true values are placed. The red lines denote the result values determined by this study and given above; the black lines denote the median value of the Monte Carlo simulations; and the coloured bars denote the range.

Figure 20: Uncertainty Analysis for C&D Waste CED Results



The onsite recycling scenario has much less uncertainty in its results; its 95% confidence interval for it is bounded on the low side at 15% below the model result and 27% above it. While its relatively low value for CED prevents it from being presented in detail on the same scale as the other two scenarios, it definitively demonstrates the superiority of onsite recycling for these impact factors, however. Graphical results for the Monte Carlo simulations are shown in Appendix H.

Table 15 provides a summary of the results and uncertainty characteristics for each scenario. From this summary, the least favourable difference between the scenarios can be determined by subtracting the highest likely value of the recycling range from the lowest likely value of the landfilling range. For recycling offsite, this calculation shows a net gain in CED of 0.22 MJ per kg of aggregate, demonstrated by the negative savings value in the table. The most beneficial outcome can also be determined by subtracting the lowest likely value of offsite recycling from the highest likely value of landfilling, which results in a net savings of 0.29 MJ per kg of aggregate. This means that while offsite recycling cannot be determined as preferable to landfilling, the upside is slightly higher than the downside.

Table 15: Summary of Results for CED of C&D Waste

	CED in MJ per kg of Aggregate				
	Landfilling	**Offsite Recycling**	**Onsite Recycling**	**Offsite Savings (Difference between Landfilling and Offsite Recycling)**	**Onsite Savings (Difference between Landfilling and Onsite Recycling)**
LCA Result	0.27	0.21	0.02	0.06	0.21
Monte Carlo Mean	0.27	0.20	0.03	0.07	0.20
Monte Carlo Median	0.27	0.19	0.03	0.08	0.19
2.5 percentile	0.15	0.10	0.02	0.06	0.10
97.5 percentile	0.38	0.37	0.04	0.01	0.37
Lowest Likely Savings*				**-0.22**	**0.12**
Highest Likely Savings**				**0.29**	**0.36**
* Lowest likely savings calculated by subtracting the 97.5 percentile value for offsite recycling from the 2.5 percentile value for landfilling. This actually resulted in a net rise in CED, as shown by the negative savings.					
**Highest likely savings calculated by subtracting the 2.5 percentile value for offsite recycling from the 97.5 percentile value for landfilling. This resulted in a net savings of 0.77MJ per kg of aggregate.					

Process Contribution

Transportation is the largest consumer of energy in the C&D scenarios (see the blue sections of the bar graph in Figure 19); by avoiding this requirement, except in the transport of the crusher and excavator, onsite recycling uses much less energy than the other scenarios[12]. The landfilling scenario includes both the delivery of the rubble to landfill and the delivery of the virgin material aggregate to the final site, and the recycling offsite scenario includes both the delivery of the rubble to the crushing facility and the delivery of the aggregate to the final site. Recycling onsite, however, avoids both of these haulage legs.

Demonstrated by the length of green coloured bar in the Figure 19, the process step of crushing the aggregate is also a major contributor to all three scenarios. In the recycling onsite scenario, the crusher makes up a large percentage of the CED, but its absolute values is less than half the CED for crushing in the other scenarios. This is explained by the change in fuel type. Electricity is an inefficient fuel compared to oil-based fuels or natural gas; according to the Renewable Energy and Energy Efficiency Partnership, 50 to 70 per cent of primary energy supply is lost during fossil fuel power plant generation (REEEP, 2008) and more is lost during transmission and distribution. One megajoule of South African electricity at the grid requires 3.73 MJ of CED, but supplying one megajoule of diesel requires only 1.18 MJ of CED (Ecoinvent Centre, 2007; TGH, The Green House, 2011). So, while crushing still requires a substantial portion of the CED in recycling onsite, the absolute energy saved by changing fuel type is significant.

8.1.2 Global Warming Potential Results

The GWP results echo those of CED because there are no non-energy carbon emissions in the production of aggregate; they differ slightly due to changes in technologies and types of fuels used. Figure 21 provides the total GHG emissions and the main contributing processes for the C&D Waste scenarios.

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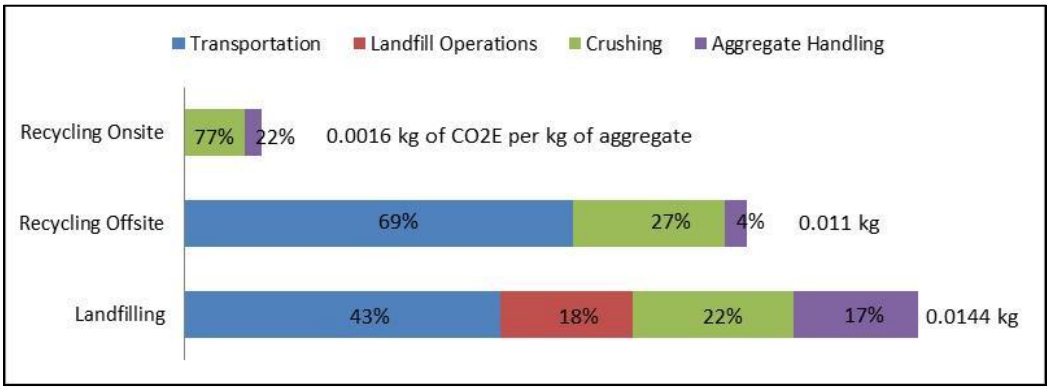
[12] The transportation of the equipment for recycling onsite does not appear on the graph because the energy requirement is too insignificant.

Figure 21: GWP Process Contributions for C&D Waste Scenarios



Results and Uncertainty

The landfilling scenario resulted in total emissions of 0.014 kg of CO_2e per kilogramme of aggregate with a 95 per cent confidence interval of 0.009 and 0.021 kg of CO_2e. The offsite recycling resulted in 24% fewer emissions at 0.011 (0.007 - 0.02) kg of CO_2e per kilogramme of aggregate, and onsite recycling resulted in 89% fewer emissions at 0.0016 (0.0014 – 0.0020) kg of CO_2e. The uncertainty range is again large for the landfilling and the offsite recycling scenarios because of the transportation variability and offsite recycling cannot be said to be definitively better than landfilling.

Table 16 provides a summary of the uncertainty characteristics for each scenario. Again, the offsite recycling scenario does not always prove beneficial over landfilling within the 95th percentile confidence ranges, but onsite recycling is absolutely a preferred option to landfilling.

Table 16: Uncertainty for C&D Waste GWP Results

	GHG Emissions in kg of CO2E per kg of Aggregate				
	Landfilling	**Offsite Recycling**	**Onsite Recycling**	**Offsite Savings (Difference between Landfilling and Offsite Recycling)**	**Onsite Savings (Difference between Landfilling and Onsite Recycling)**
LCA Result	0.014	0.011	0.002	0.003	0.011
Monte Carlo Mean	0.022	0.011	0.002	0.011	0.011
Monte Carlo Median	0.021	0.010	0.002	0.011	0.010
2.5 percentile	0.012	0.006	0.000	0.006	0.006
97.5 percentile	0.039	0.022	0.002	0.017	0.022
Lowest Possible Savings*				**-0.010**	**0.010**
Highest Possible Savings**				**0.033**	**0.039**

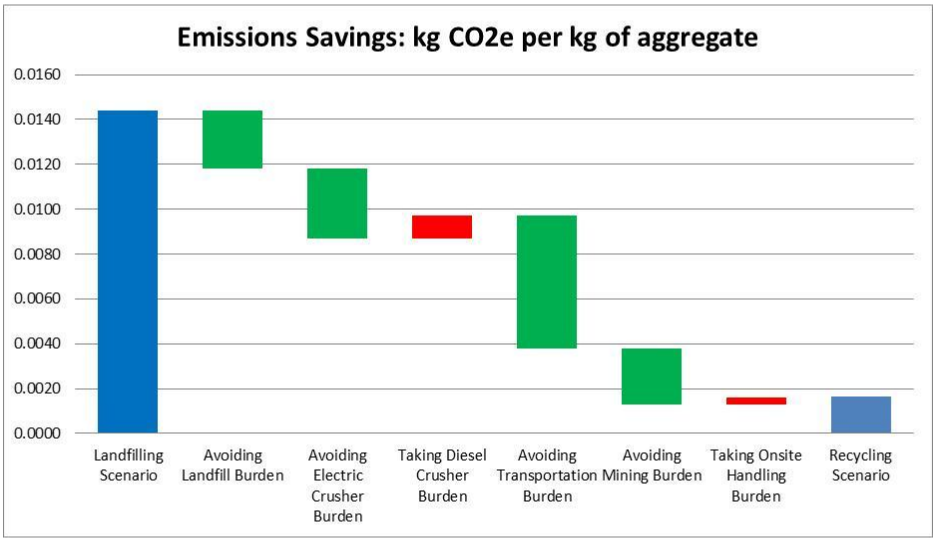
* Lowest possible savings calculated by subtracting the 97.5 percentile value for offsite recycling from the 2.5 percentile value for landfilling. This actually resulted in a net rise in emissions, as shown by the negative savings for offsite and an onsite savings of 0.01 kg CO2E.

**Highest possible savings calculated by subtracting the 2.5 percentile value for offsite recycling from the 97.5 percentile value for landfilling. This resulted in a net savings of 0.033 kg of CO2E per kg of aggregate for offsite recycling and 0.039 kg of CO2E for onsite recycling.

Process Contribution

To further explore the contribution each process has on the GHG emissions of the waste management options, Figure 22 “bridges the gap” between landfilling and recycling onsite emissions by showing the reductions and increases of main contributing processes. The first bar shows the total GHG emissions for the landfilling scenario. The following green bars show the reductions in GHG, while the red bars show the additional GHG emissions arising from process differences between the scenarios. Again, the dominance of transportation is clearly demonstrated, while the remainder of the savings are fairly equally spread between the avoidance of landfill, the change of crusher technology, and the reduction in mining/handling requirements.

Figure 22: Bridging the GWP Difference between Recycling Onsite and Landfilling



The effect of changing fuel types in the LCA can be seen by the crusher process in this graph as demonstrated by the second and third bridges. The avoided GHG emissions by not using an electric crusher far exceed the incurred burden associated with using a diesel-powered crusher, showing the lower GHG intensity of diesel to electricity. One mega joule of electricity emits 0.268 kg of CO_2e, while one mega joule of diesel used in the crusher emits 0.086 kg of CO_2e or approximately one third of the GHG emissions of electricity (Ecoinvent Centre, 2007; TGH, The Green House, 2011).

8.1.3 Sensitivity Analysis

As shown in the previous section, the largest contributing processes to the C&D waste recycling scenarios were the transportation legs. Because the transportation is such an impactful aspect to this comparison, a deeper review of these processes was completed with sensitivity analyses.

There are a number of parameters relating to transportation that can be tested by sensitivity analysis. The aspects selected for further analysis were 1) the distance to landfill, representing the upcoming change when the City of Cape Town (CCT) commissions the new regional site, 2) the transportation distances in the recycling offsite scenario to test the extent to which its priority level is dependent on the haulage distance, 3) the size of onsite recycling jobs over which the transport of the crusher and excavator are allocated, 4) the type of truck used to transport the aggregate, which affects fuel consumption.

Sensitivity 1: Distance to landfill

This sensitivity analysis was conducted to show the future scenario facing the waste management system of Cape Town when the city commissions the new regional landfill site, which is likely to be placed 40 kilometres further than current landfill options. Changing this parameter resulted in dramatically increased results of 56% greater CED and 43% more GHG emissions.

Table 17: Sensitivity on landfill site distance

Impact Category	**Original Landfill**	**Landfill at 15+40 = 55 kms**	**Comment**
CED: MJ per kg of aggregate	0.27	0.42	Disposal now makes up 62% of the total CED - with the transportation to landfill contributing 49% of life cycle CED.
GWP: kg of CO2E per kg of aggregate	0.0144	0.0206	Again, the largest contributor, with 42% of the GHG emissions, is the transport to landfill.

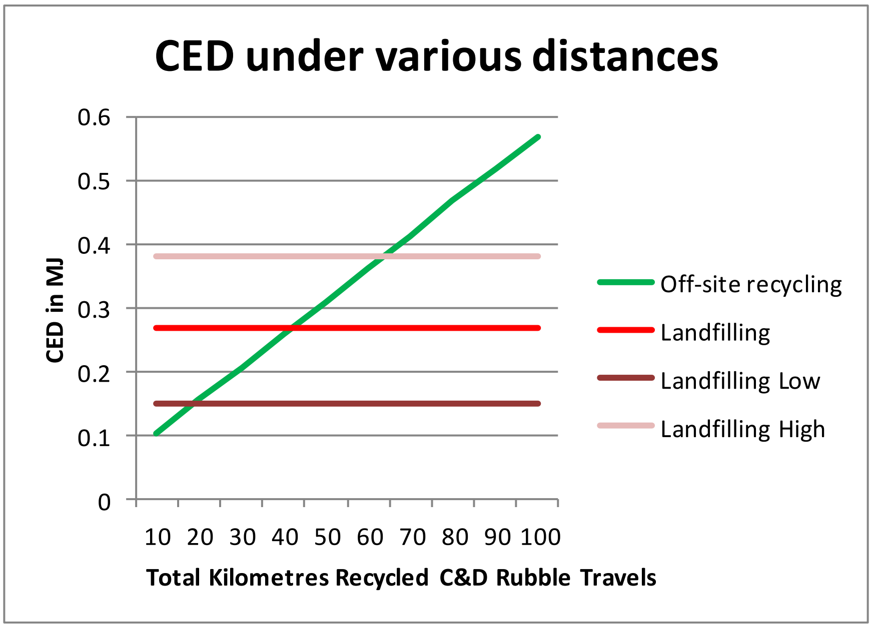
If the same coefficients of variance from the original landfilling scenario results are applied to these results, offsite recycling is still not definitively better than landfilling, although the overlap of ranges is less. It is 95% confident that landfilling would result in a CED of 0.24 - 0.60 MJ per kilogramme of aggregate, while offsite recycling still has a range of 0.10 – 0.37 MJ.

Sensitivity 2: Haulage distances for offsite recycling

This sensitivity analysis was applied to test the extent to which offsite recycling's priority level is dependent on the haulage distance. The original results show the offsite recycling scenario as requiring 22% less CED than the landfilling scenario. By increasing the total travel distance in the recycling offsite scenario, the limit to its preferred status was determined.

The landfilling scenario was held constant and shown in Figure 23 as the middle line. The range of likely values was also depicted by horizontal lines for the 2.5 percentile and 97.5 percentile values. The recycling offsite scenario was then shown as a linear function of the total haulage distance. The figure demonstrates the points at which recycling offsite CED exceeds that of landfilling. Based on the model's original assumptions, this occurs at a total transport distance of 42 kilometres in the offsite recycling scenario. This tipping point reduces to 19 kilometres for the low range value of landfilling and increases to 63 kilometres for the high range of landfilling.

Figure 23: The Effect of Transportation Distance on C&D Waste Recycling



Before concluding this sensitivity analysis, the uncertainty of the recycling result should also be considered. When that is considered, the offsite recycling scenario is only absolutely preferable to the landfilling scenario, when the haulage distance is less than 6.5 kilometres. The best case scenario, if all uncertainty is favourable towards recycling, recycling offsite may be beneficial up to a maximum transportation distance of 162 kilometres. The details for this calculation are provided in Appendix G. This sensitivity analysis shows that the offsite recycling's priority status has a strong dependency on the haulage distance involved, but also the effect of high uncertainty.

Sensitivity 3: Onsite Recycling job size used for transportation allocation

In this sensitivity analysis, the impact of progressively smaller job sizes was explored to assess the dependency of the onsite recycling results to the tonnage of waste processed. It was found to have a very small impact, as the average job size is sufficiently big that even reducing job size by 90% does not significantly affect the results. This sensitivity also identified the point at which transporting the crusher and excavator to the site becomes more burdensome than transporting the waste to an offsite recycling facility. This occurs at a demolition job size of 4.8 tonnes, or 0.1% of the average job size applied in the model for CED and a slightly larger job size of 5.4 tonnes for GHG emissions.

Table 18: Sensitivity 3 Results

Job size (tonnes)	Size of Job (tonnes)	CED: MJ per kg of aggregate	GWP: kg of CO2E per kg of aggregate	Comment
Original Landfilling	N/A	0.269	0.0144	
Original Recycling Onsite	3666	0.0282	0.0016	
50% of Original	1833	0.0285	0.0017	rounding of .00168
25% of Original	916	0.0291	0.0017	rounding of .00171
100 tonnes	100	0.0310	0.0023	
10 tonnes	10	0.1440	0.0086	
6.5 tonnes	6.5	0.2070	0.0123	
5.6 tonnes	**5.4**	**0.2440**	**0.0145**	tipping point for GHG emissions
4.8 tonnes	**4.8**	**0.2710**	**0.0158**	tipping point for CED

Sensitivity 4: Truck Size for hauling aggregate

This sensitivity explores the model's reaction to adjusting the size of truck used to transport the C&D waste or aggregate. Because some percentage of C&D waste is a hauled by small "bakkies" instead of 10 tonne lorries, this sensitivity explores the dependency of results on the size of truck used. For each scenario requiring transportation (landfilling and recycling offsite), the percentage of material traveling by small loads (i.e. less than 7.5 tonnes) was progressively increased from the original assumption that all loads were an average size of approximately 10 tonnes and 0% were specified as small. This sensitivity showed significant increases in CED and GHG emissions. Smaller loads are less efficient and when the number of small loads in aggregate transportation increased, the overall energy requirement and GHG emissions also increased.

The percentage of material travelling by large loads (i.e. greater than 16 tonnes) was also progressively increased, with the result that some small reductions in CED and GHG emissions were experienced. Larger loads are more efficient, and when the number of large loads in aggregate transportation increased, the overall energy requirement and GHG emissions dropped, but not as steeply as they climbed when using smaller vehicles. This indicates that while there are some savings to be had by increasing load size of transportation vehicles, it is more of a risk factor because of the greater negative change associated with smaller vehicles. There is not much of an upside to increasing the size of the load, but there is a significant downside to decreasing the size of the load. Table 19, Figure 24 and 25 show the results of this sensitivity analysis.

Table 19: Summary of Sensitivity Results for Truck Load Size

Sensitivity		Landfilling		Offsite Recycling	
		CED: MJ per kg of aggregate	GWP: kg of CO2E per kg of aggregate	CED: MJ per kg of aggregate	GWP: kg of CO2E per kg of aggregate
Increasing per cent large loads	50%	0.261	0.0138	0.190	0.0097
	40%	0.263	0.0139	0.198	0.0101
	30%	0.264	0.014	0.201	0.0104
	20%	0.266	0.0142	0.204	0.0106
	10%	0.268	0.0143	0.208	0.0108
Original Model		**0.269**	**0.0144**	**0.206**	**0.0108**
Increasing per cent small loads	10%	0.307	0.0158	0.254	0.0127
	20%	0.355	0.0177	0.297	0.0142
	30%	0.397	0.0193	0.339	0.0158
	40%	0.44	0.0209	0.382	0.0174
	50%	0.47	0.022	0.425	0.0190

Figure 24: CED Impact for Variation in Truck Load Size

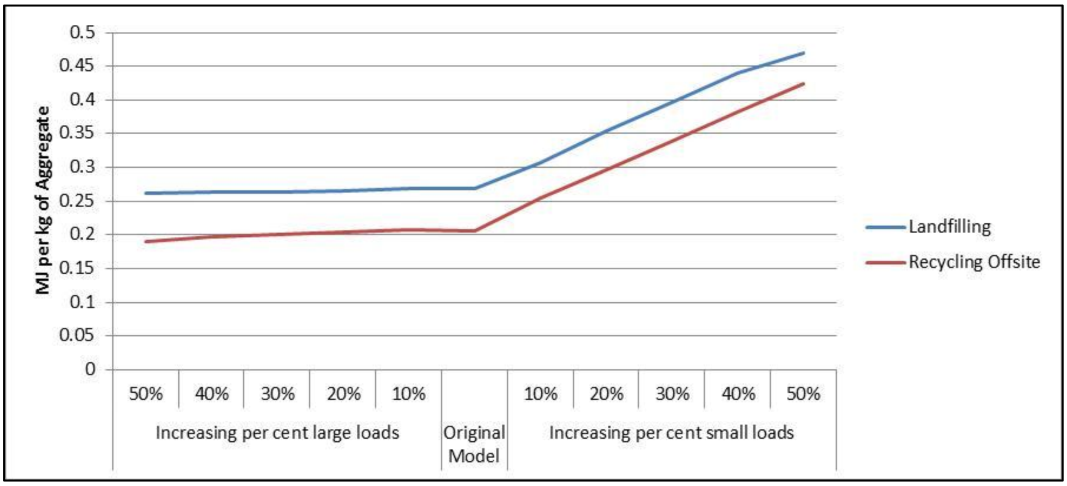
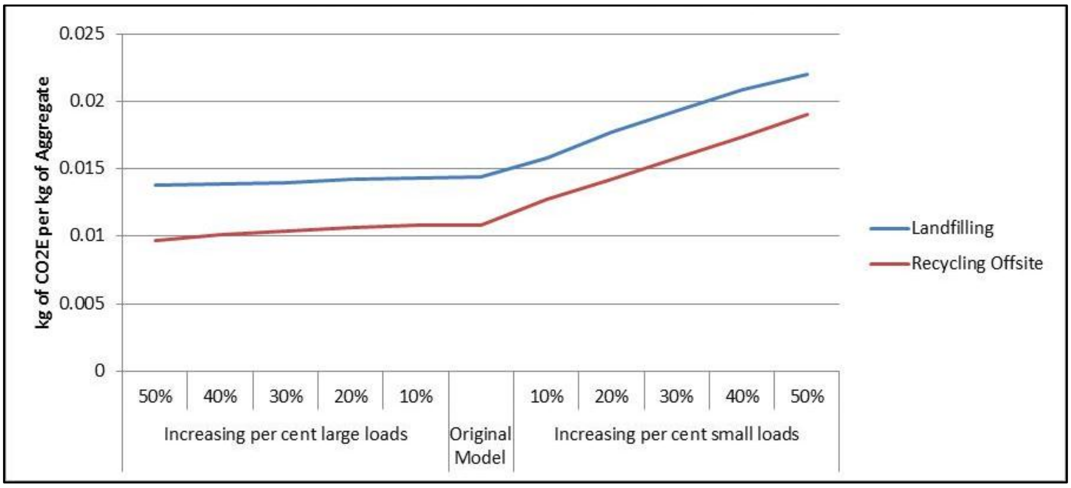


Figure 25: GWP Impact for Variation in Truck Load Size

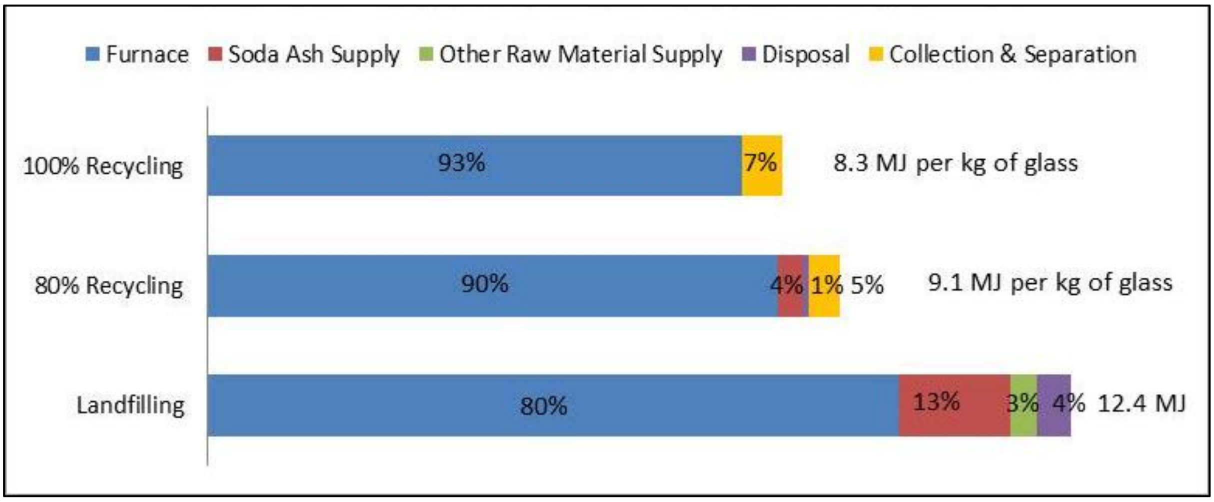


8.2 Container Glass

8.2.1 Cumulative Energy Demand Results

Unlike the LCA for C&D waste, the evaluation of container glass did not encompass every step of the life cycle because it excluded those steps that were the same in all scenarios. For this reason, the absolute CED and GWP values can only be used to compare the differences in the life cycles and should not be interpreted as representative of the full life cycle of recycling or raw manufacture of glass. Figure 26 shows the results and process contributions for the container glass scenarios

Figure 26: CED Process Contributions for Container Glass Scenarios



Results and Uncertainty

The practical, 80% recycling scenario resulted in a CED that was 27% lower than the landfilling scenario with a savings of 3.32 MJ per kilogramme of container glass. The theoretical 100% recycling scenario required 33% less energy, or 4.15MJ per kilogramme of glass, and while interesting to note, because it is not a realistically achievable scenario[13], the remainder of the results discussion will refer to the 80% recycling scenario when discussing the recycling of container glass.

These results have also been characterised for uncertainty, but with much tighter ranges than experienced in the C&D waste analysis. This is because the largest contributing process, the melting step, does not have the same high levels of uncertainty associated to the transportation distances. The 95% confidence intervals are demonstrated graphically in Figure 27 below. The landfilling total CED (for the processes included in the LCA) resulted in a value of 12.44 and a range of 11.4 – 14 MJ per kilogramme of glass. The recycling scenario had a total CED of 9.12 (8.3 – 10.1) MJ. These ranges result in a definitive conclusion that recycling container glass performs better than landfilling with regard to the impact category of CED. See Table 20 for a summarised table of comparison between recycling and landfilling CED results.

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[13] For further explanation, please refer to Chapter Four.

Figure 27: The 95% Confidence Interval for Container Glass CED Results

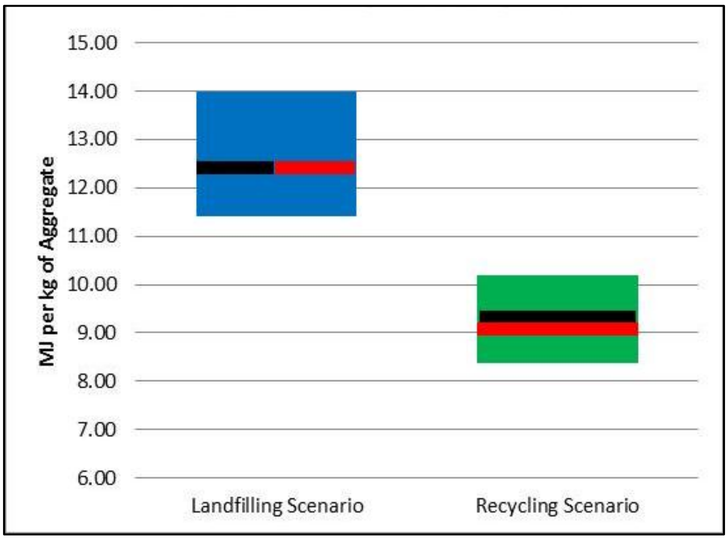


Table 20: Uncertainty for container glass CED Results

	CED in MJ per kg of Glass		
	Landfilling	**Recycling**	**Recycling Savings (Difference between Landfilling and Recycling)**
LCA Result	12.44	9.12	**3.32**
Monte Carlo Mean	12.40	9.22	3.18
Monte Carlo Median	12.40	9.24	3.16
2.5 percentile	11.40	8.28	3.12
97.5 percentile	14.00	10.10	3.90
Lowest Likely Savings*			**1.30**
Highest Likely Savings**			**5.72**
* Lowest likely savings calculated by subtracting the 97.5 percentile value for recycling from the 2.5 percentile value for landfilling.			
**Highest likely savings calculated by subtracting the 2.5 percentile value for recycling from the 97.5 percentile value for landfilling.			

Process Contributions

As seen in
Figure 26 above, it is shown that the largest contributor to energy requirement in the recycling and production of glass is, unsurprisingly, the melting step. The second largest contributor is the supply of soda ash. Soda ash is the third greatest ingredient, by mass, in the production of virgin manufactured glass, but surpasses the other raw materials in energy requirement not only because of its production process, but also because of the great transportation requirement incurred by importing it from the U.S.A. Supplying the other raw materials of sand, limestone and feldspar make up another 3% and finally, the disposal process for container glass contributes 4% to the CED.

The recycling CED is also dominated by the furnace, but is then followed by the collection and separation of cullet, at 5%. The remaining 5% of CED can be attributed to the fraction not recycled as it is made up of raw material supply and disposal. A more detailed description of the main life cycle processes and their contributions is provided in Table 21.

Table 21: Tabulated CED Process Contributions for Container Glass

Process	Landfilling		Recycling	
	MJ per kg	Per cent	MJ per kg	Per cent
Furnace - heat from Fuel Oil	6.57	52.8%	5.39	59.1%
Furnace - heat from Electicity	3.36	27.0%	2.79	30.6%
Soda Ash Production	0.95	7.6%	0.18	2.0%
MSW collection	0.40	3.2%	0.08	0.9%
Soda Ash transport by train	0.36	2.9%	0.07	0.8%
Soda Ash transport by ship	0.34	2.7%	0.07	0.8%
Limestone production	0.21	1.7%	0.05	0.5%
Production & transport of Sand	0.10	0.8%	0.02	0.2%
Production & transport of Feldspar	0.10	0.8%	0.02	0.2%
Landfill operations	0.06	0.5%	0.03	0.3%
Consumer drop-offs of recyclable glass	0.00	0.0%	0.21	2.3%
Kerbside Collection to MRF	0.00	0.0%	0.08	0.9%
Separation and transport from MRF	0.00	0.0%	0.05	0.5%
Cullet Preparation	0.00	0.0%	0.08	0.9%
Total	**12.44**	**100.0%**	**9.12**	**100.0%**

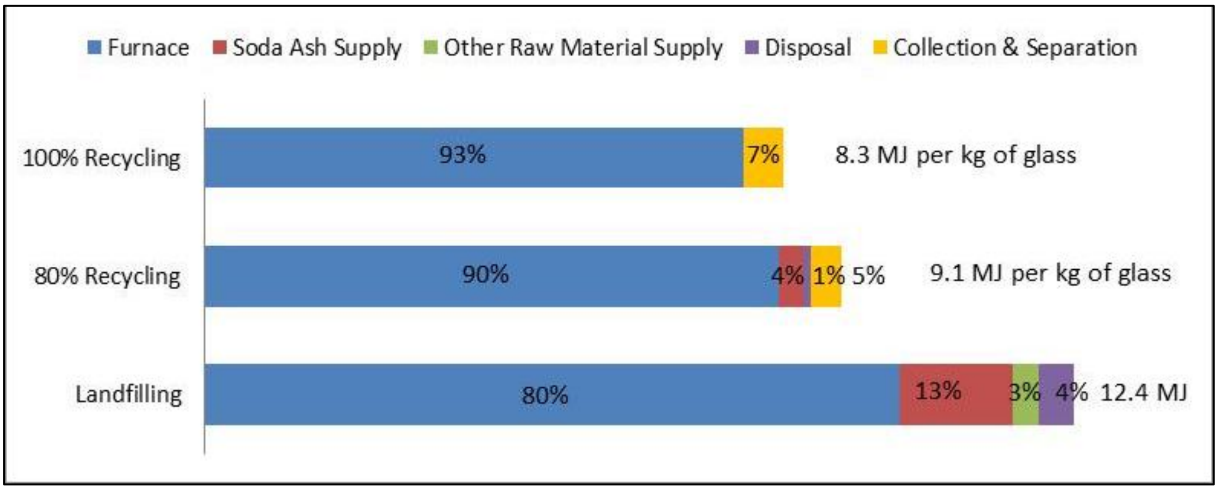
By disaggregating the collection step, it becomes evident that the use of private vehicles to drop-off recyclables is the main contributor. The kerbside collection and MRF separation, if taken together because they are currently linked processes in the CCT's collection methods, is not far behind. While these processes are not very significant in comparison to the furnace, which has readily defensible argument for its large CED contribution, the variability in the method of collection makes them interesting for further exploration. Two sensitivity analyses were thus applied to the method of collection and separation in the recycling scenario. Because these sensitivities also explored the impact to glass' GWP, the review can be found below in Chapter 8.2.3.

Soda ash production while also a large contributor has not been further investigated because the production of it is a background process and as such is out of the scope of this research project. This reason is also relevant to the other raw materials of sand, limestone and feldspar.

8.2.2 Global Warming Potential Results

The GWP assessment results echo the CED results, but with increased savings due to the non-energy carbon emissions associated with glass manufacture. As seen below in Figure 28, the CO_2e released by the 80% recycling scenario is 37% less than the emissions of the landfilling scenario.

Figure 28: GWP Process Contributions for Container Glass Scenarios



Results and Uncertainty

The landfilling scenario resulted in GHG emissions of 1.05 kg CO_2e per kilogramme of glass with a 95% confidence interval of 0.97 to 1.13 kg of CO_2E. The 80% recycling scenario resulted in GHG emissions of 0.66 (0.60 -0.72) kg CO_2e per kilogramme of container glass, and the theoretical 100% recycling scenario has GHG emissions that are 46% less than the landfilling option, at 0.56 (0.53-0.63) kg of CO_2e per kilogramme of glass.

The 95% confidence interval for recycling and landfilling is shown below in Figure 29. It is clear that recycling container glass is also definitively preferred with regard to GHG emissions. This can also be seen in the tabulated summary in Table 22, where recycling likely saves between 0.25 and 0.53 kg of CO_2e per kilogramme of glass.

Figure 29: The 95% Confidence Interval for Container Glass GWP Results

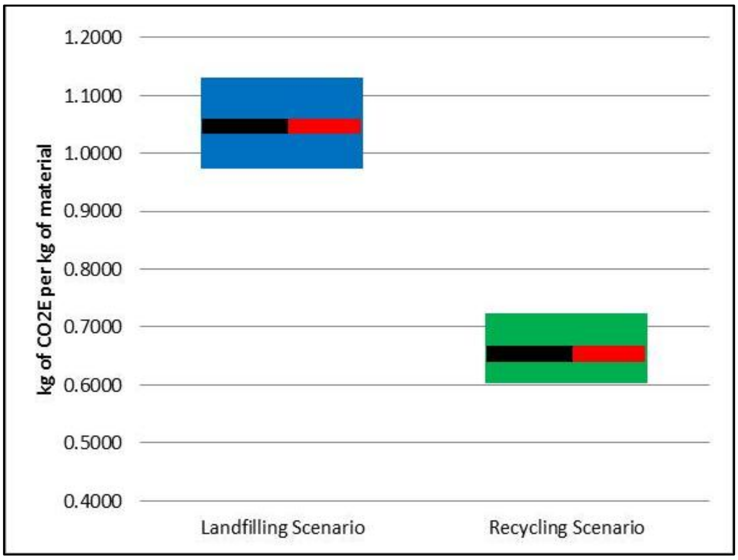


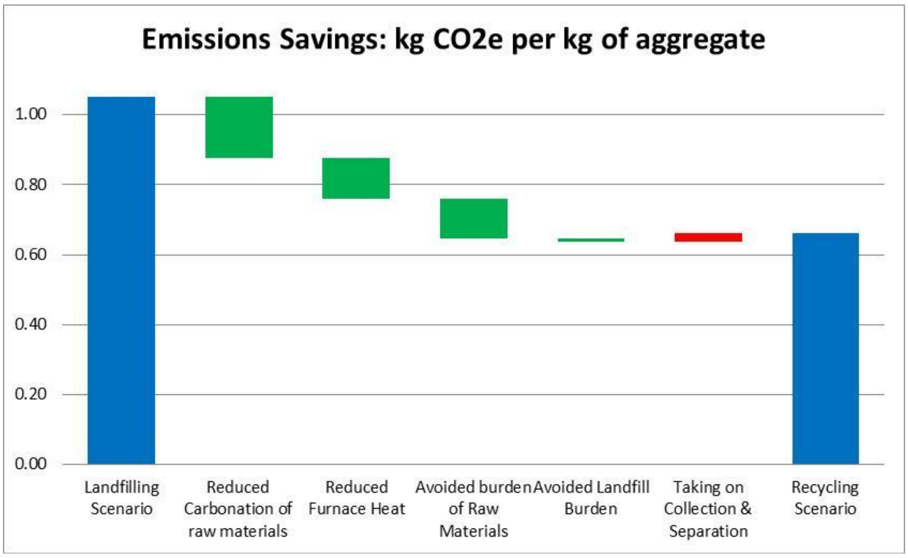
Table 22: Uncertainty for container glass GWP Results

	GWP in kg of CO2E per kg of glass		
	Landfilling	**Recycling**	**Recycling Savings (Difference between Landfilling and Recycling)**
LCA Result	1.05	0.66	**0.39**
Monte Carlo Mean	1.05	0.66	0.39
Monte Carlo Median	1.05	0.66	0.39
2.5 percentile	0.97	0.60	0.37
97.5 percentile	1.13	0.72	0.41
Lowest Likely Savings*			**0.25**
Highest Likely Savings**			**0.53**
* Lowest likely savings calculated by subtracting the 97.5 percentile value for recycling from the 2.5 percentile value for landfilling.			
**Highest likely savings calculated by subtracting the 2.5 percentile value for recycling from the 97.5 percentile value for landfilling.			

Process Contribution

The furnace is again the largest contributor to GHG emissions in all three scenarios, and in the case of the landfilling scenario, its contribution is significantly higher than in the CED results due to the non-energy carbon emissions of the soda ash and limestone as they heat in the furnace. The effect of carbonation can be seen more clearly in the following bridge graph, showing what processes make up the difference in GHG emissions between recycling and landfilling.

Figure 30: Bridging the GWP Difference between Recycling and Landfilling



8.2.3 Sensitivity Analysis

Despite it being the most impactful process step, the furnace has not been selected as a process for sensitivity analysis because its uncertainty and variability is limited. As discussed above, the collection method is of some interest, however and three sensitivity analyses have been performed by adjusting the assumptions around collection path, private vehicle use, and amount of glass per drop-off.

Sensitivity 1: Collection Method

The first sensitivity varied the collection method by changing the proportion of glass received from each collection path. This was performed by changing the percentage of glass collected via kerbside, while allowing the percentage of glass collected via the drop-offs to counter-adjust; business collections were held constant as it was felt to be a different category of consumer and less likely to change with increased kerbside or drop-off collections. A description of the adjustments and the resulting outcomes are summarised in Table 23. The extreme cases were so named because they allowed a change in the per cent collected from businesses, rather than just allowing a trade-off between kerbside and drop-off.

Table 23: Sensitivity on Collection Methods for Glass Recycling

Sensitivity Adjustments	Kerbside Collections	Dropoff Collections	Business/Glass Bank Collections	CED	Savings	GWP	Savings
Landfilling	N/A	N/A	N/A	12.44		1.050	
Recycling with original assumptions	40%	20%	40%	9.12	27%	0.662	37%
Increase kerbside by 10%	50%	10%	40%	9.03	27%	0.656	38%
Increase kerbside by 20%	60%	0%	40%	8.94	28%	0.650	38%
Extreme kerbside	80%	0%	20%	8.99	28%	0.652	38%
Decrease kerbside by 10%	30%	30%	40%	9.20	26%	0.668	36%
Decrease kerbside by 20%	20%	40%	40%	9.29	25%	0.674	36%
Extreme dropoffs	0%	80%	20%	9.68	22%	0.700	33%

Some interesting conclusions arose from this sensitivity analysis. Firstly, it was noted that the while increasing the kerbside collections resulted in increasingly better environmental performance (see green arrows on table), the extreme case results reversed that trend by showing a small increase over the 20% increased kerbside adjustment (see the red circles on the table). This shows that the business collection is the least impactful option, which intuitively makes sense, as this glass has only one transportation leg compared to the other options which have two[14]. The second conclusion identifies the least preferred option of collection as the drop-offs. The extreme drop-off sensitivity resulted in the lowest savings for both impact categories. In this sensitivity, the private vehicle transportation process increased in importance to the overall LCA result, for a contribution of 8%, which climbed from 2.3% in the original recycling scenario.

Sensitivity 2: Private Car Transportation

The contribution of the private car transportation to CED and GHG emissions was surprisingly high. This circumstance, along with the poor performance of the extreme drop-off sensitivity completed above, warranted a deeper evaluation of the use of private vehicles in the drop-off collection method. The original model estimated that 24% of the recyclable glass from the drop-off was transported by special trip, and thus assumed the environmental impact for that trip. The following sensitivity analysis adjusted the percentage of glass dropped by special trip.

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[14] Refer Figure 18 in Chapter Seven for an overview of the collection process steps.

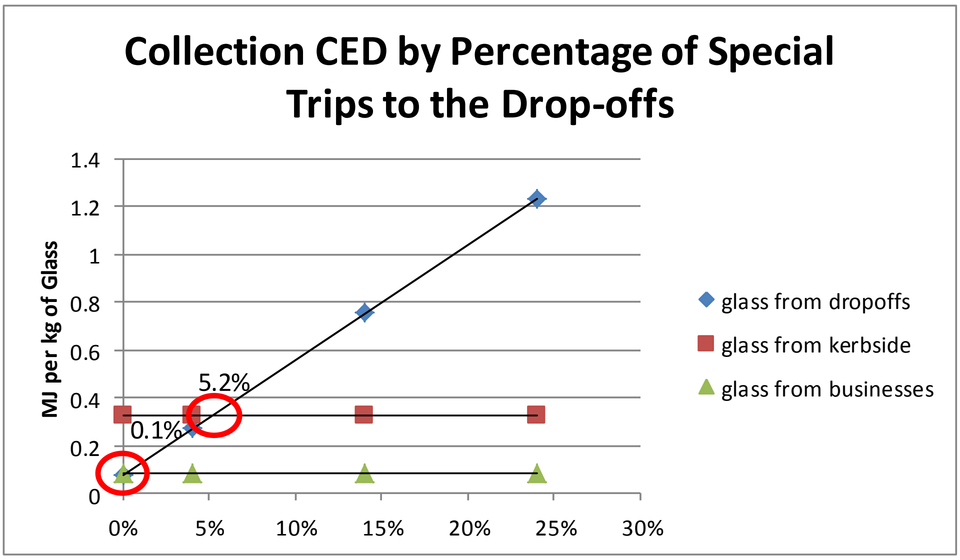
Table 24: Glass Recycling Savings Response to Changes in Private Car Drop-offs

Sensitivity Adjustments	Percent Special Trips	CED	Savings	GWP	Savings
Landfilling	N/A	12.44		1.050	
Recycling with original assumptions	24%	9.12	27%	0.662	37%
Decrease by 10 percentage points	14%	9.02	28%	0.656	38%
Decrease by 20 percentage points	4%	8.93	28%	0.650	38%
Extreme decrease - 0%	0%	8.90	28%	0.647	38%
Increase by 10 percentage points	34%	9.20	26%	0.667	36%
Increase by 20 percentage points	44%	9.29	25%	0.673	36%
Extreme Increase - 70%	70%	9.52	23%	0.688	34%

With decreasing percentages of recycled glass delivered at the drop-off by special trip, the burden associated with the transportation by private vehicle use decreases, resulting in higher achievement of savings (see the green arrows in Table 24). There thus exists a point at which the benefits associated with the drop-off collection method perform better than the impacts of kerbside recycling, which in the original model is preferred over drop-off collections. Similarly to the transportation analysis performed above in the results of C&D waste, the CED for the various levels of special car trips in the sensitivity analysis were plotted to a graph. A trend line was then fitted and the tipping point was determined to be at 5.2% of the glass delivered by special trip. This infers that drop-off centres are more energetically efficient than kerbside recycling programmes only if 5.2% or less of the glass arrives via special trip. This can be seen by the meeting of the drop-off trend line and the business collection trend line at 5.2% in Figure 31.

The drop-off collection method, when it is assumed not to bear any burden associated with the transportation of the drop-off, essentially becomes the same as the collection of glass from businesses and glass banks. In this case, there is no transportation burden in mass collection of the recycled glass, and there exists only the single haul from the collection centre to the glass plant. This can be seen by the meeting of the drop-off trend line and the business collection trend line at zero in Figure 31.

Figure 31: The Limit of Special Car Trips for Drop-offs as Preferred Collection Method



Sensitivity 3: Amount of Glass per Trip at the Drop-off centres

The collection of waste glass via drop-offs is also dependent on the amount of glass (or recyclables) dropped with each trip. This sensitivity tests the significance of the drop-off load size. The original drop-off size of 4.5 kilogrammes was adjusted larger and smaller in 10% increments; results are summarised in Table 25.

Table 25: Summary of Sensitivity Results for Drop-off Load Size

Adjustments to Drop-off Size	**Drop-off Load Size (kgs)**	**CED (MJ per kg of Glass)**	**Savings**	**GWP (kg of CO2E per kg of Glass)**	**Savings**
Landfilling	n/a	12.44		1.050	
Recycling with Original Values	**4.5**	**9.12**	**27%**	**0.662**	**37%**
Increase by 10%	4.95	9.10	27%	0.660	37%
Increase by 20%	5.4	9.08	27%	0.659	37%
Increase by 30%	5.85	9.06	27%	0.658	37%
Increase by 40%	6.3	9.05	27%	0.657	37%
Increase by 50%	6.75	9.04	27%	0.655	38%
Decrease by 10%	4.05	9.13	27%	0.663	37%
Decrease by 20%	3.6	9.16	26%	0.665	37%
Decrease by 30%	3.15	9.20	26%	0.667	36%
Decrease by 40%	2.7	9.25	26%	0.671	36%
Decrease by 50%	2.25	9.32	25%	0.675	36%

From the summary, it can be seen that decreasing the load size does impact the overall efficiency of the recycling system and erode the savings potential, but not with great impact. Even if the average load size is halved, the savings realised by recycling only decreases by two percentage points. This concludes the sensitivity analyses and results for container glass.

8.3 Overall Results for the City of Cape Town

The big-picture possibilities for the CCT were assessed by applying these results for one kilogramme of waste material to the amount of waste landfilled annually in the CCT. If it was chosen to be recycled onsite, the C&D waste currently going to landfill and not being used in the operation of the landfill can save up to 75 million MJ of energy and four thousand tonnes of CO_2 equivalent could be realised per annum. Comparatively, container glass has a much larger unit savings, with a maximum potential saving of 371 million to 743 million MJ per annum. This is up to ten times the savings potential of C&D rubble, and equal to 1% of the CCT's total energy demand. It can also save 43 to 87 thousand tonnes of CO_2e which is 1% to 1.5% of the city's GHG emissions. A summary of the quantitative results is compiled in Table 26.

Table 26: Summary of Results

Results by Impact Category		**Impact per kg of material**		**Savings per kg of material compared to landfilling**		**Annual Landfilled**	**Potential Savings Based on Currently Landfilled Volumes**	
Waste Material	**Scenario**	Cumulative Energy Demand (MJ)	Global Warming Potential (kg CO2e)	Cumulative Energy Demand (MJ)	Global Warming Potential (kg CO2e)	Max Amount that can be recycled (tonnes)	Cumulative Energy Demand (MJ)	Global Warming Potential (kg CO2e)
C&D Rubble	Landfilling	0.27	0.014			315 thousand		
	Recycling offsite	0.21	0.011	0.06	0.004			
	Recycling onsite	0.03	0.002	0.24	0.013		75 million	4 thousand
Container Glass*	Landfilling	12.44	1.050			110-220 thousand		
	Recycling at 80% content	9.12	0.662	3.32	0.388		743 million	87 thousand
	Recycling at 100% content	8.29	0.565	4.15	0.485			

* Container glass life cycles are not complete; because the forming, postforming, and use stages were identical in the landfilling and recycling scenarios, they were not included. CED and GWP values represent only the included life cycle stages of raw material extraction and prodcution, melting, and disposal.

8.4 Summary of the Results

The conclusions that can be gathered from these results support an affirmation of the hypotheses that recycling C&D waste and container glass in the CCT saves both energy and GHG emissions, with the exception of offsite recycling of C&D waste. This scenario and the C&D waste landfilling scenario both had large uncertainty ranges, preventing a definitive conclusion in favour of one over the other at the 95% confidence level. Compared to landfilling, recycling C&D rubble onsite, however, saves up to 90% of the energy and GHG emissions. Recycling glass saves up to 27% of the energy and 37% of the GHG emissions of landfilling it.

Transportation was found to play a very significant role in the prioritisation for C&D Waste, but was less impactful for container glass simply because of the extremely large influence of the furnace operations. Collection methods and transportation did not have a significant role in glass recycling however. Scenarios that minimised the number of transportation legs performed best. The collection method of direct business to glass plant has the lowest impact compared to the other collection methods, as there is only one transport leg from the place of business to the glass plant. The glass is transported in large, bulk loads thereby spreading the burden of the transportation amongst a large quantity, thereby reducing the impact per kilogramme of glass. Kerbside collection is the next preferred option, and the worst-performing method is collection via drop-off centres, primarily due to the assumption that 24% of the drop-offs were made by special trip. Drop-off centres begin to perform better than kerbside collection as special trips are reduced and drop-off load size is increased, however. When special trips make up less than 4.8% of the glass dropped (at a load size of 4.5kg), the drop-off centre collection path is preferred to kerbside recycling.

It can be concluded that recycling one kilogramme of glass saves six times the energy and almost 25 times the GHG emissions than recycling one kilogramme of C&D waste. It is particularly more impactful in the savings of GHG emissions due to the decomposition and release of carbon in the manufacture of glass from raw materials.

Chapter 9: Discussion

9.1 Validity of Results within International Context

Due to restricted visibility of the boundary decisions and data input assumptions used by other studies, it was difficult to place these results in an exact position amongst other studies. Tables 27 and 28 provide an overview of the international context in comparison with the results from this research project. From this review, it can, however, be concluded that the results are similar to others, and the outcomes of this LCA are generally within range of previous research.

Table 27: Results (as savings) for C&D Waste within International Context

Study	MJ per kg of aggregate	kg CO2E per kg of aggregate	Comments
Blengini & Garbarino	0.250	0.014	Recycling case is a combination of stationary, semi-mobile, and mobile crushers. Transportation distances of recycling scenario 30% less than distance in landfilling scenario.
Craighill & Powell	0.132	0.001	Based on eight case studies of recyclers, builders, and road maintenance companies. This result based on a 100% onsite recycling scenario, but they also reviewed other combinations with offsite and landfilling.
WARM	0.732	0.011	Savings arose by avoiding virgin material process and transportation in almost equal parts. Very little transparency of assumptions; assumed 0% loss rate in concrete to aggregate recycling.
This Study	**0.24**	**0.013**	**These savings relevant to onsite recycling.**

Table 28: Results (as savings) for Glass within International Context

Study	MJ per kg of glass	kg CO2E per kg of glass	Comments
Edwards & Schelling	3.3-3.7, 4.0	0.47	Recycling rates were in the range of 65% to 72%, with maximum recycled rate of 83%, shown as the third value in the energy savings column. Collection methods were not included in GHG emissions and no range provided.
WARM	2.8	0.31	Little transparency with respect to assumptions. Recycled content was set at 100%, but virgin material content contained 5% cullet.
EU Commission	2.8	0.30	Also not very transparent, but does specify a very limited change in recycling rates (25% - 68%), which may explain the relatively low savings values.
Lino et al	3.40-3.57	N/A	Glass was just one component of a general MSW study; no transparency with respect to glass-specific savings; production process energy based on other sources. Transportation energy calculated directly.
This study	**3.3**	**0.38**	**Applied a "practical maximum" recycled content of 80%.**

9.2 Implications for the City of Cape Town

As presented in the conclusion of the previous chapter, despite high levels of uncertainty in some aspects of the model, recycling C&D waste onsite and recycling container glass are definitively preferable to landfilling when assessing the energy requirement and GHG emissions for these materials in the City of Cape Town (CCT). The study results affirm the waste hierarchy in application to the local situation for these two recycling scenarios. The relative significance of the two wastes suggests that should prioritisation be needed, the CCT should choose to focus on container glass before C&D waste because of the higher unit savings that can be achieved when considering energy and climate change impacts. This decision should be supported by further analysis of other factors, such as cost, other environmental impacts, available technologies, and etcetera.

9.2.1 Transportation

The transportation and collection burdens have been rigorously analysed by sensitivity analyses in this research. For container glass, it was found that collection method choice does not significantly impact the net savings. This indicates that the CCT should strongly encourage glass recycling for energy and GHG savings, even if collection methods have not been optimised. Transportation for C&D rubble, on the other hand plays a very significant role, and further research can be performed to minimise uncertainty levels and establish more clear haulage distance limits to its preferred status.

Finally, the transportation of raw materials plays a not insignificant role in the total CED and GHG emissions of glass manufacture in the CCT. A large portion of this burden is due to the importation of soda ash from the U.S.A, despite closer resources available. BotAsh, for example, is a soda ash supplier located in Sowa, Botswana, only two thousand kilometres from the CCT, instead of the more than 15 thousand kilometres currently travelled by the American supply. Even though ocean freighters are the least polluting form of mass transport (IEA, 2012), a quick calculation of energy requirements in the LCA software shows that it is environmentally preferable to rail the soda ash from Botswana than ship it from the U.S. If trucked from Botswana, however, the savings margin narrows to almost zero. The transport of soda ash in the current model has a CED of 3.5 MJ per kilogramme of soda ash delivered, while transporting it from Botswana by rail has a CED of 1.2 MJ per kilogramme and by truck a CED of 3.4 MJ. While these savings may not accrue directly to the CCT because the combustion occurs outside municipality limits, they still decrease the embodied energy and carbon footprint of the product.

9.2.2 Fuel Source

Fuel type was also identified as an impactful parameter in both materials; the change from using an electric crusher to using a diesel-powered crusher accounted for a savings of 0.002 kg CO_2e per kg of aggregate, equal to 15% of the avoided GHG emissions. This agrees with a number of international research reports that site fuel source as a critical parameter (Christensen, 2009; Eriksson & Baky, 2010; WRAP, 2006). The furnace step in glass production is another process that may benefit from a review of energy sources. The European furnaces use natural gas, a cleaner and more efficient fuel than oil or electricity (Hischier, 2007).

9.2.3 Market Forces

The findings of this research also suggest that even though the CCT is already recycling at least 60% of its C&D rubble, more recycling, if performed on site or at relatively low distances offsite, would further benefit the city. This obviously depends somewhat on the market for recycled aggregate, however. While the CCT recently experienced a boom in the demand for aggregate due to a number of public projects associated with hosting the 2010 FIFA World Cup which are now complete and the market has been low in the past year, the construction industry is still the fastest growing in the Western Province at 7% per annum and the generation of rubble and the demand for aggregate will likely continue. At least two interviewees shared the concern of deficiency in the demand for recycled aggregate, however. The CCT's public roads do not currently use recycled aggregates as base material due to quality concerns (Grace, 2011; Johnston, 2011). This, while not unfounded, can be overcome. The reason for the quality concerns is that aggregate from rubble that is not properly cleaned contains materials like clay and plastic. These materials behave differently under stress than clean rubble and can affect the performance of the aggregate (Grace, 2011; Johnston, 2011). Proper cleaning and standard specifications that allow recycled aggregate to be audited can ensure the performance of the aggregate is within acceptable bounds.

Aggregates have a low unit-value and are considered a bulk commodity where the cost to supply it is highly influenced by the expense of transporting it (Wilburn & Goonan, 1998). Robinson et al (2004) found that the difficulty of developing and permitting new sites for virgin aggregate production increases the cost of transport because it often forces the virgin material aggregate to be mined and produced a great distance from its marketplace. This creates a market incentive for using locally produced C&D waste to contain the costs of aggregate (Wilburn & Goonan, 1998). This market force is missing in the CCT because at least two of the quarries have about 50 years of production still available in their present locations, which are quite close to the CBD of Cape Town. This suggests that the CCT should not rely on market forces alone to drive increased recycling of C&D waste, and in fact, according to the interviewed rubble crushers, one of the main obstacles to publically serviced rubble crushing is a lack of market demand.

9.3 Limitations to the Study

There are certain limitations that must be recognised when interpreting this research. These limitations have been overcome as much as possible by methodological choice, additional research, impact analysis or qualitative assessment.

9.3.1 Limitations in the Data

The acquisition of data is rarely an easy task, and obtaining quantitative data for this project was difficult. A few interviewees referred to the National Waste Information Site for historical statistics, but the resources available online did not contain enough detail to be useful. This seems to be a recurring theme in IWM, as it was listed as the number one concern in a survey of Western Province waste stakeholders as well as cited by the United Nations as a difficulty in providing waste statistics globally (DEA DP, 2010; United Nations, 2011d).

Additional difficulty in obtaining representative data was due to the limited market size of the materials reviewed. There were very few players and as is the case with oligopolistic markets, sharing information was somewhat viewed with mistrust. Some contacted company representatives also promised information that never materialised, and many of the companies involved in recycling were found to be more relaxed organisations with minimal record-keeping as a common feature. Despite these difficulties, at least 70% of the aggregate and glass manufacturing markets were represented by participating interviewees.

A substantial part of the value in this project stems from the use of local data in the LCA. This, as described in the methodology, was used to populate the LCI for the foreground processes. There are however a great number of background processes supporting them; more than 1500 process steps exist in each model and more than 66% of the variables still refer to generic data sources. One study, reviewed in the literature review explicitly tested this and found that a modified European LCI was a suitable representation for a Brazilian LCA (Osses de Eicker, et al., 2010). So, while it is recognised that a number of processes in this study's LCA does not reflect South African characteristics, the processes that have a large impact on the results do refer to local features and the LCI is likely a reasonably valid representation of the system in the CCT.

The allocation method used in this study apportioned burden by mass. This is a commonly applied measure and in fact, almost all of the reviewed international studies used mass (Blengingi & Garbarino, 2010; Bovea, et al., 2010; Craighill & Powell, 1996; Edwards & Schelling, 1999; European Commission, 2006; Vellini & Saviola, 2009). It can be argued that mass is not the most suitable allocation basis for these materials with respect to landfill burden, however. Both C&D waste and container glass are inert materials that do not require the same level of disposal management as other landfilled material. For example, the electricity used to manage the pump stations on the landfill sites is not relevant to the disposal of inert materials, because inert materials don't emit gasses or leachate that needs to be pumped. Both glass and C&D waste are also high density materials. The landfill space occupied by these materials is proportionally less for the same amount of mass as the space occupied by other materials, such as plastic. For these reasons an alternative allocation method, based on either chemical properties or volume, may be more representative than the allocation by mass. Changing the allocation principle to allow less of a landfill burden would result in lower CED requirements for the landfilling scenarios and shrink the margin of benefit experienced by the recycling scenarios. When applied to this model, it was clear that this only significantly affected the C&D waste. The C&D landfilling scenario results decreased in CED by 15% to 0.229 MJ/kg of aggregate, not quite obliterating the likely savings from offsite recycling at 0.21 MJ/kg of aggregate; the glass landfilling scenario changed by less than 1%. The comparison of landfill burden assigned in this model, however, was not unduly large when compared to international sources. The generic European landfill in *ecoinvent* has a CED that is 0.02 MJ/kg higher than the CED for landfilling in this model. This does not completely clear the model from the charge of overburdening C&D waste with disposal impacts though; because C&D waste is an inert waste material and does not require the full support and operation of a sanitary landfill, the model's disposal to landfill may instead be likened to a generic inert landfill. The *ecoinvent* inert landfill energy requirement is indeed 0.02MJ lower than this model's energy requirement. The CCT does not have a separated inert landfill, however, and because the variance in the European processes is large, but the absolute value of the energy demand is not, it can be concluded that this model's result, resting squarely in the centre of the two generic processes compared, is not excessive. It appears more significant simply because the overall energy requirement for producing aggregate is low.

9.3.2 Limitations to the Interpretation of Results

This study, while predominately bounded to the municipality of the City of Cape Town, also included global impacts arising from the processes. By reducing these impacts through recycling, some of the reported savings will be actualised in the source location of Springbok, South Africa or Wyoming, U.S.A for example.

This study found that transportation played a large role in the LCA of C&D waste, and there are a few considerations of liquid fuel in South Africa that should be noted. The emissions factor applied to the combustion of diesel, as mentioned in the methodology, was the EURO 3 standard. This is an older standard of allowable emissions, applied to vehicles in Europe about 10 years ago, and two more, EURO 4 and 5, have since come out (DieselNet, 2009). This was deemed to well-represent the fleet in S.A. as slightly older and less efficient than the current standard of European vehicles (ERC UCT, 2011). The emissions from transportation are also dependent on the fuel sources for the diesel used by the trucks. The liquid fuel industry in South Africa does not only create diesel from crude oil, but also from coal and gas; approximately 30% of the national liquid fuels are generated by using coal-to-liquid or gas-to-liquid technology (Republic of South Africa, 2007b). Because Secunda, a production facility near Johannesburg, is the only one using coal as its primary feedstock though, it is unlikely that this affects the diesel used locally in the CCT; the major concern for national transportation of liquid fuels is how to get the fuel inland, not the other way around (Republic of South Africa, 2007b). There is also a PetroSA gas-to-liquid plant in Mossel Bay that produces a diesel fuel blended from crude-derived diesel and gas-derived diesel. The plant services approximately 15% of the market, primarily in the Southern Cape and some of the Northern and Eastern Cape (PetroSA, 2011). Because Cape Town is not included in the Southern Cape district (Sadler, 2002-2012), it is again unlikely that a significant portion of the diesel used in the CCT would be supplied from GTL technology. As described in Chapter 5, liquid fuel supply for Cape Town is provided by the refinery in Milnerton, which receives crude oil by tanker to Saldanha Bay. This leads to another limitation of this research; the LCA applied generic data to the liquid fuel LCI inputs. More energy and associated GHGs should also be attributed to the supply of liquid fuels in the CCT because the transportation distance between the source of crude oil and South Africa may be longer than the average distance to Europe. Saudi Arabia and Iran account for 81% of the world's crude oil supply (Republic of South Africa, 2003b), and these countries are four thousand kilometres closer to the middle of Europe than to the tip of Africa. The impact of this, when explored, however, is so small as to be negligible. Ocean transport makes up only 1% of the CED of diesel fuel in Europe. Even doubling the transportation distance would not significantly affect the outcomes of this model.

9.4 Methodological Critique

The use of LCA for waste management strategy comparison is a commonly applied and suitable tool, as discussed in the literature review. It was especially useful in this research project to evaluate the expanded boundaries of the recycling systems, as it was quite straightforward to link processes from different systems. This included the specification of South African electricity from the energy system and the use of an excavator from the building products system in the single scenario of recycling offsite, for example. The use of LCA, and the associated methodological choices, had some impact on the interpretation of results, however; these are discussed below.

9.4.1 LCA and Software Choice

LCA is limited in application to non-linear relationships (Ekvall, et al., 2007); see Appendix I for a more detailed explanation of this phenomenon. The model in this research project thus applied a linear relationship to the collection of waste glass, even though it is likely that high recycling recovery rates necessitate greater environmental burdens (Ekvall, et al., 2007). If integrated in this research, this would deflate the savings experience by recycling glass, but only marginally as it was shown that collection methods do not significantly impact the results.

The use of *Simapro7.3*, while freely available for limited period to academic researchers in developing countries and user-friendly in navigation of its set-up, was not as useful as expected in its reporting facilities. It allows you to track the contribution of process steps in the network diagram, but it is very difficult to do the same in the inventory and assessment tables. This is may be due to a number of reasons: one being that it is simply difficult to show a cumulative flow in table form. It may also be due to the mixture of energy carriers and activities – all of which are considered "processes" – listed in the tabulated results. It would be better if the "used by" option was available in the impact analysis with a quantification of amount allocated to each following process using the process in question. Limited "save" features also required the exportation of results immediately to avoid re-runs, or in the case of Monte Carlo simulations, to avoid different results by another simulation run.

9.4.2 Methodological Choices

This study approached the LCA as an attributional analysis, and as such used average data inputs. This was usefully applied to understand the system and identify main contributors, areas of concern, and opportunities for improvement. It was sufficient to identify the current net impacts of recycling versus landfilling and thus answer the research question. It does not, however, assess the system's reaction to changes in the process, demand or supply of the materials reviewed. Recommendations or suggested actions may affect the system in such a way as to cause future savings to be different from those identified in this study.

The choice of impact assessment was made to be single-issue, i.e. CED and GWP, which again, was appropriate for the research question, but not a very broad application of LCA. When applying the results to a greater statement of full environmental impact, rather than simply energy and global warming potential, caution should to be exercised. A less abbreviated LCA would include impact assessments on other categories, such as acidification and land use. Some of these aspects are important to the CCT. Its population is growing and the Cape Floral Region has been designated one of the World Centres of Plant Diversity (UNESCO, 1999-2012); conserving space and protecting its valuable surrounding flora are pertinent considerations.

9.5 Recommendations for the City of Cape Town

Arising from this research are a number of recommendations that can be made to the City of Cape Town. These recommendations are based on the conclusions of this LCA and should be taken in the context of the limitations reviewed above.

Firstly, it was concluded that the amount of energy and GHG emission savings experienced by recycling one kilogramme of glass far exceeds the savings of recycling one kilogramme of C&D waste and therefore has a greater impact on the lowering the energy and carbon intensity of the CCT. The CCT should note this priority and schedule waste minimisation actions accordingly. It was further established that changes in collection methodology, while somewhat impacting the results, do not seriously erode the overall benefits of recycling glass, and as such, the city can continue to develop a variety of collection programmes with confidence. Educating the public on the impacts of recycling, both from a perspective of overall saving potential and from a perspective of driving the right behaviour, i.e. dropping recyclables on route, rather than as a special trip, is recommended. This action will also respond to the recent gap analysis of IWM in the Western Cape that listed information and education as the need with the highest priority (DEA DP, 2010).

Secondly, the glass manufacturers should be encouraged to support cullet use and also consider purchasing soda ash from a closer source. It would also be extremely beneficial to continue making progress on furnace efficiency as that process step makes up the majority of the energetic impact of glass manufacturing and recycling.

Thirdly, recycling C&D rubble onsite was also found to be environmentally preferable and should be encouraged. The CCT is already doing this by offering an urban development tax incentive for building owners that improve the condition of their building by recycling and reusing materials according to Patel at the Promoting Renewable Energy in Africa (PREA) workshop (Patel, 2006). This should be continued and can be supported by other measures such as increasing the tipping fees, which are paid to the landfill for each load dumped. This practice may however increase illegal dumping. The city is aware of this and currently has a pricing structure that includes one free load (up to 1.3 tonnes) of C&D waste per day to counter the practice of illegal dumping (Kannemeyer, 2011).

Fourthly, the CCT may consider opening inert landfills. This will be especially pertinent when the new regional landfill facility is in operation and average waste haulage distances more than double. Inert waste can then be diverted from the general landfills, thus saving precious resources, like landfill space and transport energy consumption. This recommendation is a second-best option to recycling, however.

Chapter 10: Conclusion

This research project began with the premise that society's current approach to the production, consumption and disposal of goods is not sustainable. This premise was based on the evidence of increasing energy and resource consumption as well as increasing waste generation around the globe. Additional evidence with respect to climate change and pollution issues exhibited Earth's limited ability to continuously provide resources and assimilate waste. Sustainability was then presented as a philosophy that protects the provision of Earth's assets, either in their current state or with acceptable substitutes, and it was suggested that a more sustainable approach is needed in society today.

Integrated waste management (IWM) helps drive a more sustainable production and disposal cycle. It considers the greater impact of waste by evaluating it in the context of other systems, such as manufacturing systems, bio-ecological systems, and energy systems to name a few. The waste hierarchy, which prioritises waste management options as follows: prevent, reuse, recycle, extract energy, and finally landfill, is a major underpinning for IWM, but it cannot be applied indiscriminately, as the preferred order may change when specific scenarios are considered.

This thesis explored some aspects of the intersection between the waste and energy systems by comparing recycling to landfilling in the City of Cape Town (CCT). This was performed by life cycle assessment (LCA) on the cumulative energy demand and greenhouse gas (GHG) emissions for two wastes, C&D rubble and container glass. The model was developed by using LCA software and modifying a generic database of life cycle inventory values. These modifications were representative of the processes and characteristics of the CCT which greatly increased the validity of the results as directly applicable to the CCT. Uncertainty was assessed by Monte Carlo simulation and sensitivity analyses were performed on key parameters to test for result dependency and explore their limitations.

Overall results showed that recycling is indeed preferred to landfilling for container glass and for onsite recycling of C&D rubble. Results for the offsite recycling of C&D waste, however, were inconclusive and highly dependent on haulage distance. Container glass recycling in the CCT showed significant energy and GHG savings of 27% and 37% respectively when compared to landfilling; while C&D recycling onsite showed very high savings of 89% in both energy and GHG emissions. Due to the energy intensity of glass manufacturing, the absolute values of its savings' are much greater than that of C&D waste savings. Six times more energy can be saved by recycling one kilogramme of glass versus one kilogramme of C&D waste and almost 25 times more GHG emissions.

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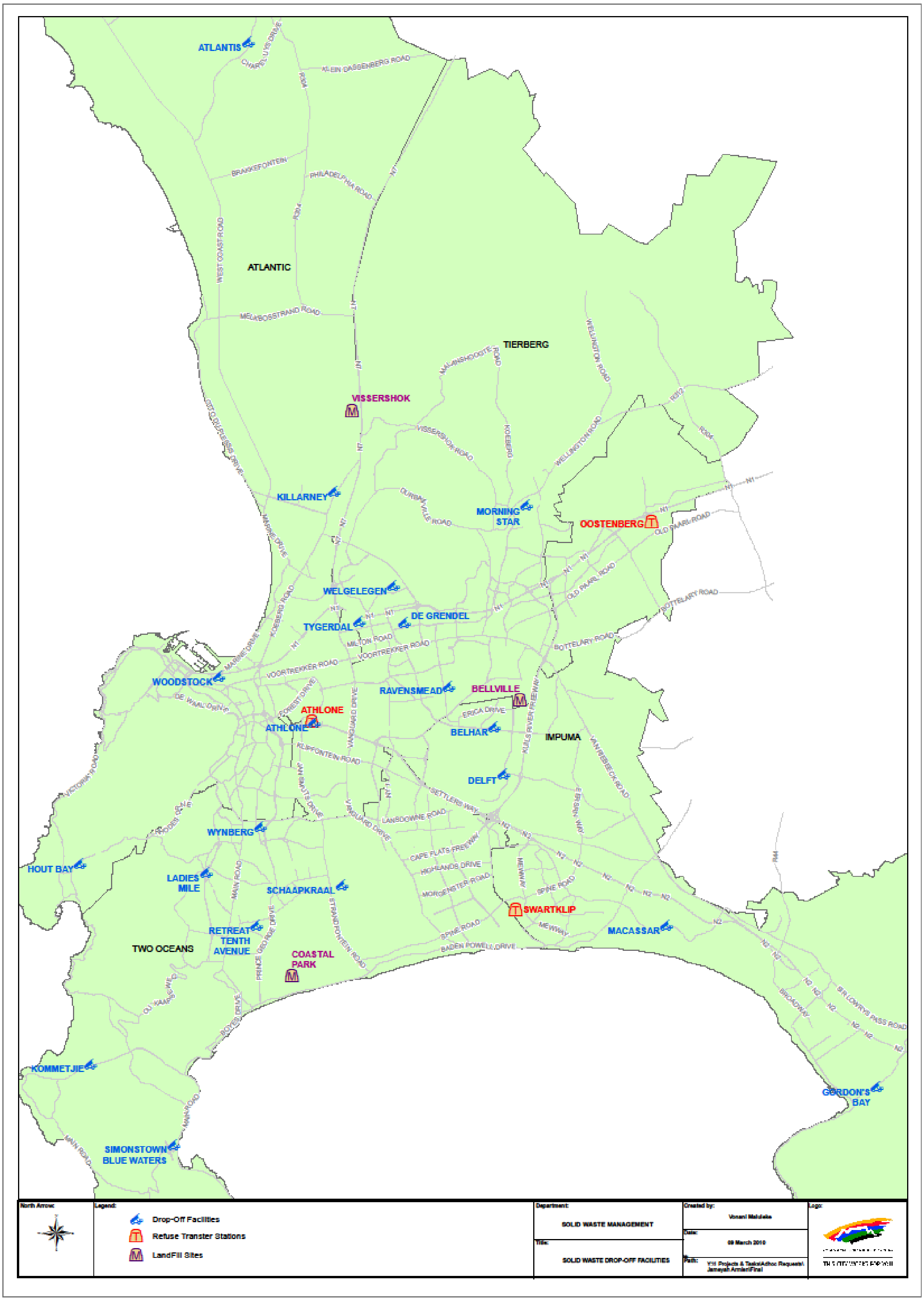
Appendix A

Map of Solid Waste Management Facilities in the City of Cape Town (City of Cape Town, 2011)



Appendix B

Interview Schedules and Notes

Interview Schedule – Aggregate Quarry Manager / Crushing Company Manager
Name:
Company / Title:
Date:

What per cent market share does your company have? How many tonnes aggregate (demolition crushing) are produced each year in the CCT?

How many tons of aggregate does your quarry / facility produce?

Is it your only product? If not, what other products and amounts are produced?

How do the processes vary between products (especially with respect to energy / fuel use)?

What is the total amount of fuel used to produce one tonne of aggregate?

Can you break this down by process step? Please describe the machinery used in each step of the process and provide fuel statistics if possible.

1. Blasting/Drilling?
2. Hauling?
3. Crushing/Screening?
4. Stockpiling?
5. Delivery to Customer?

What is the average distance (and/or range of distances) to your customer?

What is the average load size (and/or range of load sizes) to your customer?

Did you include the electricity to run the office and repair the trucks in your totals above?

Is there anything else that requires electricity, fuel oil, diesel, etc in your production process that was not discussed already?

Do you have any other comments/concerns you'd like to raise about this project and the operations of aggregate mining or rubble crushing?

Interview Schedule – Glass Manufacturers

Name:
Company / Title:
Date:

What per cent market share does your company have?

How many tons of container glass does your company produce?

Is it your only product? If not, what other products and amounts are produced?

How do the processes vary between products (especially with respect to energy / fuel use)?

What is the total amount of fuel used to produce one tonne of container glass?

Can you break this down by process step? Please describe the machinery used in each step of the process and provide fuel statistics if possible.

1. Preparation
2. Melting
3. Forming
4. Post-forming

What are the input materials, and what proportion of the ingredients does each make up?

How are these adjusted when cullet is used?

From where are the input materials sourced?

Did you include the electricity to run the office and provide ancillary services?

Is there anything else that requires electricity, fuel oil, diesel, etc in your production process that was not discussed already?

Do you have any other comments/concerns you'd like to raise about this project and the operations of glass manufacturing and recycling?

Interview Schedule – Recyclers and Transporters
Name:
Company / Title:
Date:

What kind and size of truck do you use?

What is the average distance travelled per trip?

What is the average fuel consumption (by truck size, if possible)?

In which suburbs do you operate? Do you perform kerbside, business, skip, or igloo pickups?

How many tons of recyclables have you collected in the past 12 months?

Do you have any other comments/concerns you'd like to raise about this project and the operations of recyclables collection?

Interviewed	**Name**	**Email**	**Phone**	**Title / Company**
Yes	Barry Coetzee	XX	XX	City of Cape Town, Strategic Waste Management
Yes	Othelie Muller	XX	XX	Head of MIS and GIS for Solid Waste Planning, City of Cape Town
Referred	Jo-anne, Shaheed	XX	XX	City of Cape Town, Solid Waste Management
Yes	Lingley Skippers	XX	XX	Coastal Park Landfill
No Response	Sarah Ward	XX	XX	UCT
N/A	Martin de Wit	XX	XX	Stellenbosch
Limited	Susanne Ditka	XX	XX	Integrated Resource and Waste Minimisation Specialist
Limited	Chris Wise	XX	XX	Head of sustainability, Jeffares and Green
Limited	Sally-Anne Engledouw	XX	XX	Jeffares and Green
Limited	Alison Davison	XX	XX	City of Cape Town - Waste minimization
N/A	Ballim Ighsan	XX	XX	Head of solid waste business improvement
Limited	Tolane Kotsi	XX	XX	Knew about Waste Categorization Sheet
No Response	Bertie Lourens	XX	XX	Wasteplan
Referred	Michael Pienaar	XX	XX	Wasteman
Yes	Malcolm Smith	XX	XX	Wasteman Recycling Guy
No Response	Linda McDonald	XX	XX	Enviroserve
Referred	Duncan	XX	XX	Enviroserve, recycling solutions
Limited	Hein Fourie	XX	XX	Enviroserve, proj mgr, Energy savings
Limited	Lytton Malele	XX	XX	Enviroserve
Limited	Jacques	XX	XX	Enviroserve
N/A	Steven Chatham	XX	XX	Atlantic Plastic Recycling
No Response	Roy Moulton	XX	XX	Consul Glass
Referred	Andre Burger	XX	XX	Consul Bellville plant
Yes	Gerard Schrief	XX	XX	Consul energy/recycling
Yes	Oswin Fredericks	XX	XX	Melting manager, Consol
Yes	Grant Irlam	XX	XX	Finance manager, Consol
N/A	Philemon Nkosi	XX	XX	Consol melting & plant operations mgr
Referred	Jeanne Seal	XX	XX	Wasteman
Limited	Glass Recycling Co	XX	XX	The glass recycling company
No Response	Joe Prinsloo	XX	XX	Acelor Mittal
N/A	Douw Steyn	XX	XX	enquiries@plasfed.co.za
Referred	Lynn du Plessis	XX	XX	PET recycling Co
Limited	Jannie Wagener	XX	XX	City of Cape Town, Solid Waste Management
N/A	Annabe Pretorius	XX	XX	Propak
N/A	Dianne Blumberg	XX	XX	Plastics SA
Referred	N Khanyile	XX	XX	PPC cement
Referred	Nurshani Govender	XX	XX	PPC cement
Referred	Claudine	XX	XX	Afrisam
N/A	Nivashni	XX	XX	Afrisam
Yes	Andrew Wheater	XX	XX	La Farge Area Mgr
No Response	Megamix	XX	XX	Megamix
Yes	Craig and Braam	XX	XX	Ciolli Bros
Referred	Afrisam	XX	XX	Afrisam
Yes	Jaco Cockart	XX	XX	Afrisam Ops Mgr
Limited	Marlene Botha	XX	XX	Afrimat, accounts dept
Yes	Dave Johnston	XX	XX	Isuela Crushing MD
No Response	Skye demolition	XX	XX	Skye demolition
No Response	Duran	XX	XX	Skye demolition
Limited	Ross demolition	XX	XX	Ross demolition
No Response	Ivy and Robert Ross	XX	XX	Ross demolition
N/A	Bradis	XX	XX	Bradis
Limited	Speedy Plant Hire	XX	XX	Speedy Plant Hire
N/A	CSS	XX	XX	CSS
N/A	demolition	XX	XX	demolition
N/A	La Saka Construction	XX	XX	La Saka Construction
N/A	Cape demolition earthwor	XX	XX	Cape demolition earthworks plant
N/A	green building	XX	XX	green building
N/A	Minibins waste disposal	XX	XX	Minibins waste disposal
N/A	Cape Core Rubble	XX	XX	Cape Core Rubble

Interviewed	Name	Email	Phone	Title / Company
Yes	Anthony Grace (recomme	XX	XX	Cape Bricks
No Response	Think Twice	XX	XX	Think Twice
No Response	Damien	XX	XX	Think Twice
No Response	James	XX	XX	Think Twice
Limited	Clearer Conscience	XX	XX	Clearer Conscience
N/A	recyclefirst	XX	XX	Recycle First
Referred	Stephen de Jager	XX	XX	Sand plant (supplier to Consol) Consul Industrial Minerals
Limited	William Lilly	XX	XX	project mgr
No Response	Gerard	XX	XX	B&E Area manager (blasting of quarry rock)
N/A	BME	XX	XX	BME explosives
Limited	Wilna Gouws	XX	XX	Marko metals
Limited	Hennie Rasmus	XX	XX	Marko metals
Yes	Shaheed Kannemeyer	XX	XX	Site Superintendent, Coastal Park Landfill
Referred	Megan Rose	XX	XX	Nampak
No Response	Jacobus Steenkamp	XX	XX	nampak Wiegand Glass
No Response	Nomsa Bengani	XX	XX	nampak environmental affairs mgr
N/A	Lynne Kidd	XX	XX	nampak group compensation, benefits, and sustainability
Declined Partic	Dr. Anee Sieberhagen	XX	XX	Nampak business information mgr (R&D Epping)
Limited	Brian Roger	XX	XX	Glass recycling company, chairman
No Response	Suzall Timm	XX	XX	Criminology dept. Knows about informal recycling.
Limited	Rienie	XX	XX	Saldanha limestone
Limited	Henk	XX	XX	Cape Feldspar
Referred	Linda campbell	XX	XX	Institute of waste management
No Response	Victor Doyi	XX	XX	Wastemart domestic waste mgr
Limited	Bevan Peterson	XX	XX	Wastemart cullet recycling mgr
No Response	Samuel le roux	XX	XX	Wastemart transport mgr
Limited	Le-Roy Martin	XX	XX	Wastemart asst transport mgr
Yes	William Dix	XX	XX	Cidel Crushing
Limited	James	XX	XX	Waste Control
Limited	Franco Visser	XX	XX	Wasteplan Transport and Collection Manager
Yes	Gavin Grosch	XX	XX	Luk 4 Junk
N/A	Mary	XX	XX	Full Cycle
Limited	Ricardo	XX	XX	Greens Bottle Recyclers
N/A	Ika	XX	XX	Recycler
Limited	Dorah Mulidzi	XX	XX	City of Cape Town, Waste Minimisation
Limited	Jemima Birch	XX	XX	Houtbay drop off: Hout Bay recycling Primary coop
No Response	Carol Bruce	XX	XX	Tygerdal drop off: Graphe Agencies
Limited	Lydia Anderson - Jardine	XX	XX	Woodstock: WasteWant
Limited	Vanessa Paulse	XX	XX	Kommetjie: Mam Sebenzi
Limited	Mervin Steer	XX	XX	Gordons Bay: Shine the Way
Limited	Craig Daniels	XX	XX	Wynberg/ladies mile: Craigon Transport
Yes	Jeremy Nell	XX	XX	BB Transport
Referred	Carmen	XX	XX	Craigon
Limited	Johan Lamprecht	XX	XX	Hiregenix

Interview: Barry Coetzee
Company: City of Cape Town, Head of Strategic Waste Management
Date: July 28, 2011
Format: Face-to-face

Summary:
Discussed interesting ideas for the hypothesis and issues to consider; pointed to a number of other resources and gave overview of waste management system.

Notes from his input:
Assessing the energy requirements of certain recycling processes is interesting. We also need to consider the economic factors – i.e. the cost of the recovery logistics. And illegal dumping is also an issue to us. You can do a sensitivity analyses for the distances travelled because landfills are soon to be full and new site in operation. You can also consider different types of separation projects. I would suggest a hypothesis along the lines of "Is there a net energy savings achieved by recycling X?" Maybe also consider the GHG emissions associated? And/or the economic feasibility of it. Waste to energy also needs to be further explored.

There are 3 private companies that are contracted to assist the city with collection and separation of waste and recyclables: Enviroserve, Wasteman, and Wasteplan.

Othelie Muller is the head of information in solid waste division – from her you can get the types of trucks used, the distances hauled, etc.

Martin de Wit is a private consultant/economist and professor at Stellenbosch. He reviewed kerbside collection for an economic analysis.

Allison Davidson is the head of the Waste Minimisation division and has data on what waste has been accepted to landfill and diverted from landfill.

Jo-anne is in charge of the Coastal Park Landfill site (amongst other duties). You can contact her for a tour and information on the operations of landfills locally.

Interview: Othelie Muller
Company: City of Cape Town, Head of MIS and GIS for Solid Waste Management
Date: August 3, 2011
Format: Face-to-face

Summary:
Promised to follow-up with maps, reporting statistics, etc.

Notes from her input:
There are some statistics available, and I'd be happy to send you what we have. This will include:

1. Amounts of waste diverted by city recycling projects
2. Collection info – types and number of vehicles used, service points (i.e. households), distances travelled, etc.
3. The waste categorisation study
4. Some maps and general site information.

There's also a gentleman, Melumzi Nontangana, who's looking at waste – to – energy research for us. I can also put you in contact with the person who receives and pays the electricity bills.

Interview: Shaheed Kannemeyer
Company: City of Cape Town, Coastal Park Landfill Site Superintendent
Date: August 9, 2011
Format: Face-to-face

Summary:
Provided overview of landfill management; toured facility to verify and view machines.

Notes from his input:
Landfills are lined with several layers to prevent leachate pollution. We have good record for health and safety, but nothing is perfect. Landfills are also unsightly. This one should have a green berm around it, but previous manager did not arrange/plan for it.

We receive about 900-1200 tons of waste per day, occasionally reaching up to 2000 tonnes during the festive season.

Gas extraction plans were put in place in 2008, but nothing has happened on that yet. We also don't do any separation for recycling here, but we do have a drop-off facility. (Note: when I saw drop-off facility, it was clear it was not in active use however, as there were chairs and table stored there.) We do, however do accept separated greens for composting here. Palm tree waste should not be mixed in with the rest of it though because it ruins the blades and it should instead be transported to a compost plant in Phillipi. We also receive separated building rubble for crushing, but it's just stockpiling now because there the contractor has not set up operations yet.

We also use the C&D waste to cover the waste daily to minimise rodents and birds in the area. The steel is separated out with the magnets on the crusher and is probably sold to scrap dealers. It makes up about one third of the 900 tonnes received per day, but plastics take up the most space.

We fill a "finger" of about 2.5m by 30 m each week. We have a residents meeting every three months and we are regularly audited for safety measures, etc. I don't see the electricity bills, those are paid by someone in the city accounts department. The pump station does use some electricity, along with the support buildings, etc.

We have the following equipment:
2 bulldozers
1 road grader
2 FELs
2 dumpers
3 compactors
2 water trucks (for dust control).

Lindley Skippers is the guy in charge of the diesel used by these machines.

Interview: Susanne Dittke
Company: Envirosense
Date: 19 August 2011
Format: Face-to-face

Summary:
Confirmed glass would be interesting, along with plastic; although difficult to get information. Raised issue of illegal dumping. Provided some studies for reference sources.

Notes from her input:
Aluminium cans would be an interesting material to study – we get the bauxite from Australia. Maybe difficult to get all the necessary information though. Glass would also be interesting – with local production. Building rubble is a huge problem for the CCT. 80% of the illegal dumping that occurs in the city limits is made up of building rubble. We could make new building blocks out of it, but I think mostly it's used for aggregate. Plastics…mmm.. I have a study on the energy (calorific values) of the plastics. Let me know if you choose this material.

Chris Wise, at Jeffares and Green, would be a good contact to discuss the embodied energy of cement, LCA of products, etc.

The Waste Exchange website might be worth checking out, but I don't have any specific information on the kilometres covered during collection of recyclables or waste.

Interview: Dave Johnston
Company: Isuela Crushing
Date: October 6, 2011
Format: Face-to-face

Summary:
Crushing process pretty simple; provided records on energy requirements easily. Market is small and competitive.

Notes from his input:
He's approved contractor with the CCT for crushing at landfills plus transfer stations. Concerned however that city engineers won't purchase the recycled aggregate from him however. He said this is a nationwide issue; some municipalities will use it for infrastructure projects, such as road bed bases, but the CCT is not accepting it in place of virgin aggregate yet.

The aggregate he produces is G5 – no pebbles/gravel larger than 53 mm.

Confirmed process of recycled rubble crushing; advised that he uses a mobile jaw crusher that can be transported to site of construction or landfills on a lowbed truck. Size of crusher/screeners vary, but his are usually 14 tonne machines and can go up above 40 tonnes however. Most mobile crushers are no larger than 30 tonnes because transporting them to the construction site becomes inhibitive at sizes greater than that.

Customer locations vary in distance – anything up to 100kms.

Provided fuel consumption rates for his machines, and said the steel, glass, etc is usually removed manually by informal pickers, but the crusher also has a magnetic operation that can remove pieces of steel as well. The rubble must be clean, so sometimes I pay the informal pickers R120 to "clean out" the bits of wood, etc.

There are only 4 or so other crushers in Cape Town: Afrimat, Skye, Ross, and Bradis (now Cidel).
There are 5 virgin aggregate quarries: La Farge, Ciolli Brothers, Afrisam, Portland Cement, Megamix.

Interview: William Dix
Company: Cidel Crushing
Date: January 9, 2012
Format: Telephonic

Summary:
Provided records on energy consumption.

Notes from his input:
We use a static crusher at our site – we don't do mobile crushing. We also use an excavator, 2 front end loaders and a dump truck for moving the rubble and aggregate a max distance of 100m. Provided energy consumption and production figures.

Best guess at per cent of rubble recycled in Cape Town is 60-80% but believes only 10-20% of that is done on site.

There are also magnets on our machine to pick up any remaining steel; but it is minimal and done to protect the crusher rather than gather a quantity of steel for resale.

Interview: Malcolm Smith
Company: Wasteman
Date: October 17 and November 19, 2011
Format: Face-to-face

Summary:
Provided reported data figures and discussed process of collection and separation of glass.

Notes from his input:
We don't crush rubble, no do any glass recycling / cullet processing. We do only the collection and separation of comingled recyclables.

WasteMart, Wasteplan and Enviroserve are also collection companies that are contracted by the City.

We take domestic recyclables: glass, paper, cardboard, 7 types of plastic, cans, etc.
We use two rear-end loaders for collection: one does southern suburbs and one does northern suburbs. We collect primarily from business (e.g. golf courses). We also let out bins, or business hire skips, to collect the recyclables.

The trucks he originally thought were 19 tonners, but upon looking it up, he corrected himself to say they had 14tonne capacity. We handled over 4000 tonnes of comingled recyclables from July 2010 to June 2011. He then also provided figures that indicated the amount of glass processed was only about 1%. That didn't seem right, even to him, and he questioned the veracity of the numbers.

The operation has a conveyor belts that dumps the glass into a skip after it is separated from the other recyclables (manually). The paper products continue to the baling machine, which uses a lot of electricity. We don't have any metered electricity tracking, but the glass processing wouldn't use a large percentage of the total kWh consumed because it would just need its share of support use (e.g. lighting) and its share of the first conveyor belt. We employ 75 people – mostly female – for manual separation activities.

The skip at the end of the conveyor belt that collects the glass is taken to Consol, the glass manufacturer, by a roll-on/roll-off truck. It is a distance of about 10 kilometres. This transportation is contracted to Wastemart.

Provided fuel consumption rates for the rear-end loaders used to collect the comingled waste.

Electricity usage for three months in 2010 (for which Malcolm previously supplied tonnage figures) were given, as well as tonnage processed by the MRF.

Interview: Ashwen
Company: Clearer Conscience
Date: October 19 and November 27, 2011
Format: Telephonic

Summary:
Confirmed very small "bakkie" used for collection. Could not provide fuel consumption rate; unusual for a small business that relies on haulage. This supports other interviewee stating that the small recycling collector does not generally act professionally (or very efficiently).

Notes from his input:
Collect recyclables primarily from small businesses. We use just one truck, a 3 cubic meter TATA. I'll get back to you on diesel consumption.

Interview: Lindley Skippers
Company: the City of Cape Town, Coast Park Landfill
Date: August 8, 2011
Format: Face-to-face

Summary:
He shared the records of diesel purchases for the last year and quantified the amount of waste processed.

Notes from his input:
Keeping track of the materials used on this landfill site is not an easy job. We order diesel about once a month, and I keep a book of all the amounts purchased.

Below are the diesel values obtained from him; he also provided a printout of the weighbridge statistics for the six and a half months of April through mid-October, 2011.

Month	Diesel (litres)
Sep-11	6540
Aug-11	11238
Jul-11	14849
Jun-11	8090
May-11	12035
Apr-11	10062
Mar-11	11415
Feb-11	
Jan-11	9900
Dec-10	7975
Nov-10	
Oct-10	11002
Sep-10	8117
Aug-10	9728
Jul-10	11219
Jun-10	13263
May-10	11003
Apr-10	7879
Mar-10	10196
Feb-10	11932
Jan-10	8872

Interview: Braam le Roux
Company: Ciolli Brothers
Date: October 14, 2011
Format: Face-to-face

Summary:
Provided records on energy consumption and aggregate production. Toured facility.

Notes from his input:
We do mostly aggregates for cement, but about 10% of our output is aggregate for base materials.

Confirmed the process for mining. Said they save the top soil for spreading back over the mine at the end of its life. They use a subcontractor for blasting. Hauling the rock from the quarry uses 30 tonne articulated dumpers. They also use excavators and front end loaders. He provided the fuel consumption and productivity for each type of machine.

The crusher runs off electricity and he provided the kWh billed Jan-Nov, 2011. After crushing, about 65% of the aggregate is transferred to stockpile by truck. 20% is sold and collected straight from the bin, and remaining 15% is dumped at the end of the crusher immediately, without any transportation. This uses a 6 cubic meter Nissan truck and he provided the fuel consumption and productivity.

Aggregate's density is about 1.5 tonnes per cubic meter.

The transport from the mine to the final building site varies; but the farthest distance we go is 50kms. We use three 10 cubic meter trucks and two 16 cubic meter trucks. But customers also collect themselves or subcontract. 30 tonne trucks are not unusual either.

The support office is tiny; using about same amount of electricity as 1 household probably. 15 employed people for the mine. I've been working here for longer than you've been alive and there's at least another 50 years left in this quarry.

Interview: Gerard Schrief
Company: Consol Glass, Recycling Manager
Date: October 26, 2011
Format: Face-to-face

Summary:
Relatively new to the Consol team himself. Provided the cullet amounts purchased for the previous 12 months and discussed difficulties in estimating distances travelled.

Notes from his input:
Confirmed process of collecting glass, but could not tell what percentages were collected by what method. Could also not estimate distances hauled as each haulier has own processes and business models.

Wastemart identified as top contributor.

Shared frustration that the individual recyclers do not approach their businesses professionally. Minimal, if any, records are kept and they generally do not make efficient decisions about collection routes/strategies.

Interview: Andrew Wheater
Company: La Farge, Area Director
Date: October 12, 2011
Format: Face-to-face

Summary:
Provided reported figures on energy consumption and aggregate production.

Notes from his input:
We have two operating quarries in the area: Tygerberg and Eerste Rivier. About 50% of our output is used as base material aggregate.

Confirmed the process for mining aggregate. First we clear the overburden (about 20 m thick). This uses the same equipment and blasting technique as blasting the rock. We have excavators and dump trucks to haul rock out of the quarry. He provided fuel consumption per tonnage.

We use electricity to run the crusher (Samvic make); its bigger than is usually used in recycled rubble crushing, which just means it can handle larger pieces of rock (i.e. one square meter). Electricity consumption and productivity provided.

The stockpiling uses dump trucks and FELs. Delivery trucks sometimes pickup from the crusher and sometimes retrieve from stockpile. Amount that is not stockpiled varies up to 50%. Fuel consumption figures provided.

We also have other ancillary machines that consume diesel: water trucks, graders, light vans for passenger transport. This was also included in the productivity and consumption figures provided.

We have about 40% of the market in aggregates in the CCT (rough estimate). G5 sub base is usually what recyclers produce. G3,2,and 1 are strictly specified sub-base material also.

If the new toll road happens, that will be big business, as it will require 600 thousand tonnes of asphalt for the job.

Energy accounts for approx. 20% of production costs.

Interview: Jaco Cockart
Company: Afrisam, Operations Manager
Date: October 20, 2011
Format: Face-to-face

Summary:
Noted that Afrisam have an on-site R&D team as well. Provided printed company reports on energy consumption and aggregate production.

Notes from his input:
Confirmed the process for mining aggregate. Subcontracts the blasting, which uses some light vehicles and drill rigs. The load and haul legs use 4 articulated dump trucks, 2 excavators, 1 FEL and 1 water truck. We also have a few more machines as backup or for use in other processes. All fuel consumption and productivity figures were provided.

We use a jaw crusher that runs on electricity; it has six screens. Electricity consumption figures were provided.

Almost all the aggregate goes to stockpile; we use a 40 tonne dumper for this. Diesel consumption figures provided.

Transport from the quarry to the final site is subcontracted / arranged by the customer. The average distance is 17.5kms and uses all different size trucks.

We have about 35-40% of the market, as a guess. This mine still has lots of available space – and we can always lease more from the surrounding farmers also – there's probably at least 50 years of aggregate to be mined here; maybe the mine life is even as large as 200 years, and this one opened in the 60's. The pay for the farmers is good, and they can always convert the space into a dam or recreation area after the mining is complete.

Interview: Oswin Fredericks
Company: Consol Glass, Melting Manager
Date: October 26, 2011
Format: Face-to-face

Summary:
Discussed heating requirements and confirmed glass ingredients. Provided energy data and input requirements from company records.

Notes from his input:
Two of Consol's size plants nationwide accept cullet. The CCT location is one of them.

We have about 75%-80% of the market of container glass production. Nampak also makes glass, and in fact, makes the lightest glass bottle in the country. They concentrate more on specialised production.

The furnaces use oil and electricity (85% / 15% split). He provided daily use figures by accessing data on his computer and verbally responding to questions.

He also confirmed the process of making glass and the ingredients with their input proportions. Advised the place of supply for these ingredients as follows:

1. Sand from Phillipi
2. Lime from Saldanha
3. Feldspar from Springbok
4. Soda Ash from the U.S.A.

Estimated that about 15-20% of the input is cullet today. (Note: figures provided later gave a much higher figure of about 34%, which he also agreed with as it was in the reports.)

Interview: Grant Irlam
Company: Consol Glass, Finance Manager
Date: October 26 and December 11, 2011
Format: Face-to-face

Summary:
Provided electricity and productivity figures.

Notes from his input:
Confirmed input from Gerard and Oswin. Provided productivity figures and consumption figures by furnace. Tried to break the electricity use down by activity, but they don't have metered processes and he could only share budgeted amount. In the end, he recommended using the same electricity requirement applied internationally, as it was seemed feasible and he could not confirm specific local use.

Confirmed glass process and also confirmed that none of the processes after the melting differed based on cullet input proportion.

Interview: Anthony Grace
Company: Cape Bricks, MD
Date:
Format: Face-to-face

Summary:
Confirmed their activity in the market, and shared the worksheet he made up for embodied energy.

Notes from his input:
We use about 70% recycled content. The rubble usually comes to us after primary crushing and we apply secondary and tertiary crushing if needed. Cleaning the rubble is poorly attended to and one of our major issues. We purchase about 70,000 tonnes per year. The CCT probably recycles 60-70% of its building rubble, which is maybe 1 million tonnes per year.

Ross and Skye both do some of their own crushing and they have magnets on their crushers.

Interview: Wilna Gouws and Hennie Rasmus
Company: Marko Metals
Date: November 8, 2011
Format: Telephonic

Summary:
Willing to offer information, but precise records were not kept. Provided estimates on fuel consumption, loads, etc.

Notes from their input:
The trucks carry 8-9 loads per day, of which 2 are glass. Confirmed collection process from businesses – not kerbside or city drop-offs. Truck fuel consumption was provided.

Interview: Jeremy Nell
Company: BB Transport, Workshop Manager
Date: November 22, 2011
Format: Telephonic

Summary:
Provided average fuel consumption by truck size for a listing of about 25 vehicles.

Notes from his input:
Operates various sized trucks; 7 tonner and small bakkies for local deliveries, other larger trucks for heavy or long distance deliveries. Provided following information on fleet fuel efficiencies.

Size of truck (tonnes capacity)	Km/liter
7	4.16
7	4.77
7	5.15
7	4.29
8	3.8
8	3.9
8	4
15	2.4
25	1.87
28	1.9
28	1.6
30	2.15
30	1.62
30	2.23
32	2.18
32	2.22
32	1.77
32	2.21
36	2.8
37	3.94
38	1.8
38	1.97
38	2.2

Interview: Johan Lamprecht
Company: Hiregenix, Operations Manager
Date: November 22, 2011
Format: Telephonic

Summary:
Confirmed average fuel consumption calculated from other interviewed source.

Notes from his input:
Confirmed the fuel efficiencies provided by other transporters. Did not want to share individual truck records, but stated average consumption rate was 3 km per litre and that's what they use for in-house budgets and reporting.

Interview: Jannie Wagner
Company: City of Cape Town
Date: 7 September, 2011
Format: Email exchange

Summary:
Provided details on the MSW collection.

Notes from his input:
In-house trucks = 113 (983 lifts per truck per day)
Contracted trucks = 36 (1072 lifts per truck per day)
Total = 149 trucks per day at 1004 lifts per truck per day.

2500 kms covered per truck (compactor) per month. Compactors work 260 days per year. This works out to 115 km per day.

Fuel consumption is 1 litre per km. The compactors handle 10 tonnes per load. Or 19.9 kg per lift.

Interview: LeRoy
Company: Wastemart
Date: December 5, 2011
Format: Telephonic

Summary:

Wastemart personal very difficult to get hold of and get information from. Provided size of truck estimates for collection.

Notes from his input:

They use 16 tonne trucks to transport waste from Wasteman to Consol
They use a number of other, various sized, but also much smaller trucks to do other pickups (from drop-off points, business, etc).

Interview: Franco Visser
Company: Wasteplan, Transport and Collection Manager
Date: December 12, 2011
Format: Email

Summary:
Provided fuel consumption, distance, and truck size totals.

Notes from his input:
We use 1.6 tonne "bakkies" and 3-4 tonne trucks to collect recyclables.
I estimate approximately 70% of the glass is from drop-offs, glass banks, businesses, etc; approximately 30% of the glass arrives in the form of comingled recyclables.

Provided fuel efficiency of trucks, average distances travelled and total glass collected.

Interview: James Beasley
Company: Waste Control
Date: December 13, 2011
Format: Telephonic / Email

Summary:
Provided size, distance, and fuel consumption of recycling collection trucks.

Notes from his input:
Handles the deep South collections. We use 1.3 tonne "drop-side" trucks to collect recyclables. We transport it to the False Bay recycling "MRF" in Kommetjie. We do 100% kerbside recycling and no igloo or skip collections.
He provided fuel consumption, average distance travelled and total tonnage of glass in past 12 months.

Interview: Gavin Groesch
Company: luk4junk
Date: December 19, 2011
Format: Telephonic

Summary:
Provided fuel consumption, distance, and truck size for recycling collection.

Notes from his input:
Handles the Southern Suburbs and CBD areas. We sell to a small recycler in Lansdowne that in turn sells it to Consol. I have average load size of about 2 tonnes for the business pickups in town, but use a 5 tonne truck that is sometimes fully loaded. Wastemart has skips all over the place and services most of the recyclers with transport to Consol. They almost have a monopoly on buying/selling waste glass.

The price for recycled glass is low – about 20 cents/kg. For the co-mingled recyclables I pick up, we separate manually; no conveyor belts or other machines that use energy.

He provided fuel consumption, average travel distances, and average tonnage.

Interview: Hein Fourie
Company: Enviroserve
Date: December 19, 2011
Format: Telephonic / Email

Summary:
Enviroserve personnel difficult to make contact; provided average fuel consumption figure.

Notes from his input:
Provided fuel consumption figure.

Interview: Lydia Anderson
Company: Wastewant
Date: January 9, 2012
Format: Telephonic

Summary:
Provided estimation of consumer behaviour with respect to drop-off operations.

Notes from her input:
We handle the drop-off centres in Woodstock and Killarney. Assumes almost 70% of the drop-offs are special trips. People usually drop off 1 kg a week, but businesses also drop off and their loads are 5-7kgs.

The glass is separated into its own skip that carries 6 tonnes, which is pickup up by truck and transported to Consol by Heinbru.

Provided glass tonnage.

Interview: Vanessa Paulse
Company: Mam Sebenzi
Date: January 9, 2012
Format: Telephonic

Summary:
Provided input on consumer behaviour with respect to drop-off facilities.

Notes from her input:
Glass is 13% of recyclables dropped off. No opinion given on the percentage of trips made specifically for recycling drop-off. Wastemart picks up the glass in the skip, but each load only maybe three tonnes.

Interview: Mervin Steer
Company: Shine the Way
Date: January 10, 2012
Format: Telephonic

Summary:
Provided input on consumer behaviour with respect to drop-off facilities.

Notes from his input:
Glass is only 5% of drop-offs. Range of drop-off size is .5kg to 300 kg; won't make a guess for average or typical size. Wastemart picks up the skips – usually about two tonne loads.

Interview: Jemimah Birch
Company: Hout Bay Recycling Primary Co-op
Date: January 10, 2012
Format: Telephonic

Summary:
Admitted she could not be very helpful. Sells glass to Wastemart and provided a few opinions/estimates at the drop-off characteristics.

Notes from her input:
50% of the drop-offs are made by special trip. 5-10 kg at a time, of which 25% is glass.

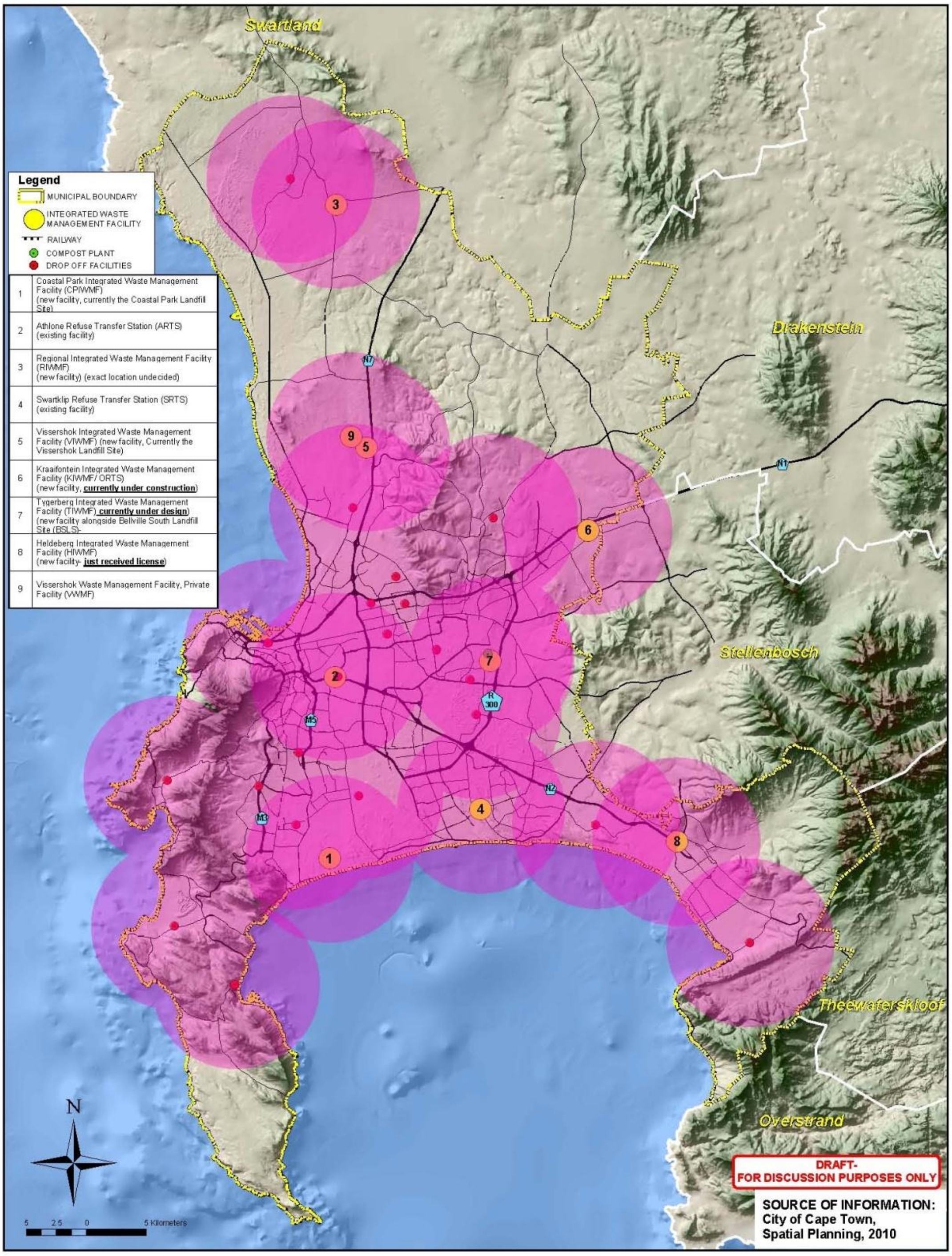
Interview: Bevan Peterson
Company: Wastemart
Date: December 19, 2011 and January 30, 2012
Format: Telephonic

Summary:
Unable to provide much assistance.

Notes from his input:
Confirmed the company did not keep record of distances travelled per collection trip. Said distance varied, as they do pickups in Atlantis as well as Gordon's Bay. Suggested I speak with Wasteplan – which I already have. Confirmed the transportation from MRF to Consol is a short distance, but lots of loads – about 250 tonnes per month.

Appendix C

Map of the drop-off locations in the City of Cape Town (City of Cape Town, 2011)



1	Coastal Park Integrated Waste Management Facility (CPIWMF) (new facility, currently the Coastal Park Landfill Site)
2	Athlone Refuse Transfer Station (ARTS) (existing facility)
3	Regional Integrated Waste Management Facility (RIWMF) (new facility) (exact location undecided)
4	Swartklip Refuse Transfer Station (SRTS) (existing facility)
5	Vissershok Integrated Waste Management Facility (VIWMF) (new facility, Currently the Vissershok Landfill Site)
6	Kraaifontein Integrated Waste Management Facility (KIWMF/ ORTS) (new facility, **currently under construction**)
7	Tygerberg Integrated Waste Management Facility (TIWMF) **currently under design**) (new facility alongside Bellville South Landfill Site (BSLS)-
8	Heldeberg Integrated Waste Management Facility (HIWMF) (new facility- **just received license**)
9	Vissershok Waste Management Facility, Private Facility (VWMF)

SOURCE OF INFORMATION:
City of Cape Town,
Spatial Planning, 2010

CITY OF CAPE TOWN : SOLID WASTE MANAGEMENT DEPARTMENT
7km RADIUS AROUND EACH DROP OFF & IWM FACILITY IN THE CMA

Appendix D

Electricity use by the City of Cape Town Solid Waste Department

ELECTRICITY RELATED FINANCIAL INFORMATION ON SWM FACILITIES
2011/2012 FINANCIAL YEAR

	Cost Centers - Facility	Act. Costs (Rands)	Comments
Eskom	20030018 S/W:CO:Impuma:Col	6 259.95	Mawande Mtyi, head of Accounting and Financial Management for Solid Waste Management in the City of Cape Town, said that more accurate numbers were not available. Frustration over the metering of facilities was evident in the communication and it was advised not to rely on the individual split of electricity by facility. The total electricity usage by the solid waste management division was then used to represent full electricity burden of disposal.
	20030044 S/W:Disp.:North:V	522 391.68	
	20030062 Fac & Contr Adm :		
	20030063 S/W:CO:Welgelegen		
	20030064 S/W:CO:Tygerdal:D		
	20030065 S/W:CO:5th Avenue		
	20030066 S/W:CO:Ruyterwach		
	20030067 S/W:CO:Ravensmead		
	20030068 S/W:CO:Uitsig:Dro		
	20030069 S/W:CO:Morningsta		
	20030070 Fac & Contr Adm :		
	20030071 S/W:CO:Adam Tas:D	22 273.68	
	20030072 S/W:CO:Fabriek St	9 363.67	
	20030073 S/W:CO:Gordonsbay		
	20030074 S/W:CO:Macassar:D	5 117.34	
	20030080 S/W:Disp.:South:F	22 690.00	
	20030088 Technical Support	21 116.71	
	20030135 S/W:Impuma:Vaalfo	30 165.46	
	20030136 S/W:Impuma:Khayel	58 563.81	
	20030137 S/W:Two Oceans:Ny	159 132.12	
	20030152 S/W : CO : Potsda	16 290.05	
	* 412050 Electricity	873 364.47	
City of Cape Town	20030020 S/W:CO:Two Oceans	3 138.41	
	20030035 S/W:CO:Wolfgat:Co	2 179.01	
	20030041 S/W:Disp.:North:C	144 701.64	
	20030058 S/W:CO:Atlantis:D	586.81	
	20030094 Contract Manageme	2 077 862.46	
	20030105 Solid Waste Man	10 844.17	
	20030111 S/W:Atlantic:Wood	210 940.30	
	20030112 S/W:Atlantic:Mait	167 399.76	
	20030115 S/W:Atlantic:Mowb	8 084.92	
	20030118 S/W:Atlantic:CBD	182 833.78	
	20030121 S/W:Atlantic:Sea	18 008.91	
	20030124 S/W:Tierberg:Good	129 440.11	
	20030125 S/W:Tierberg:Durb		
	20030128 S/W:Tierberg:Athl	112 004.09	
	20030143 S/W:Two Oceans:We	142 179.86	
	20030144 S/W:Two Oceans:Wy	6 238.28	
	20030154 S/W : CO : Woodst	0.79	
	* 500010 Electricity Consump	3 216 443.30	
	** Total	4 089 807.77	

Total kWh	**4 850 341**
kWh per tonne of disposed waste	**2.84**

Megaflex municipality plan

low off peak	24.17	cents per kwh
low peak	62.19	cents per kwh
high off peak	28.02	cents per kwh
high peak	222.90	cents per kwh
	84.32	cents per kwh
	0.84	**rand/kwh**

Source: Eskom 2011b

Tonnes Disposed Waste in 2010

Jan	123 611
Feb	127 834
Mar	142 645
Apr	135 402
May	161 245
Jun	150 110
Jul	136 363
Aug	144 649
Sep	143 204
Oct	123 423
Nov	159 968
Dec	162 412
Total	**1 710 866**

Source: City of Cape Town 2011d

Appendix E

Diesel Consumption at Landfill (based on Coastal Park)

Diesel Purchase / Use by Month	**Amount**	**Unit**
Oct-11 to date	0	litres
Sep-11	6 540	litres
Aug-11	11 238	litres
Jul-11	14 849	litres
Jun-11	8 090	litres
May-11	12 035	litres
Apr-11	10 062	litres
Total 6.5 months	**62 814**	**litres**

Waste Landfilled	**Amount**	**Unit**
Recorded Waste for same period	106 846	tonnes
Free Waste (25% of landfilled waste)	35 615	tonnes
Total Tonnage Landfilled	**142 461**	**tonnes**

Diesel Consumption	**0.44**	**litres/tonne**

Verification Check	**Amount**	**Unit**
Total diesel consumption for 2010	111 186	litres
Estimated annual tonnage by site superint	328 500	tonnes
Diesel Consumption	0.34	litres/tonne

Uncertainty	**95 percentile range**	
Normally distributed	0.54-.034	+/- 2SD

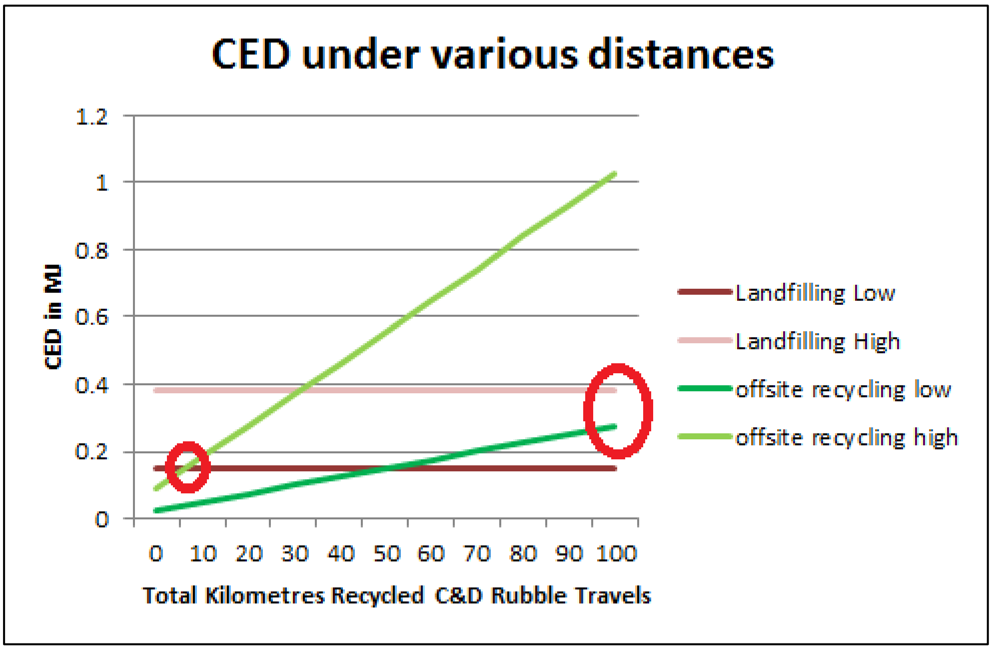
Appendix F

Materials Recovery Facility Performance

Month	Received Comingled Waste (tonnes)	Processed Recyclables (tonnes)	Waste (tonnes)	Unexplained (tonnes)	Recovered Glass (tonnes)	Unexplained (% of Received Comingled Waste)
Jan-10	446	276	135	35		8%
Feb-10	560	314	199	47		8%
Mar-10	590	355	200	35		6%
Apr-10	538	299	147	92		17%
May-10	631	256	189	185		29%
Jun-10	717	283	254	180		25%
Jul-10	691	321	193	176		26%
Aug-10	632	269	198	164		26%
Sep-10	613	308	226	79		13%
Oct-10	563	311	205	48		8%
Nov-10	626	318	192	117		19%
Dec-10	584	304	176	104	26	18%
Jan-11	545	276	167	102	16	19%
Feb-11	694	417	193	84	31	12%
Mar-11	830	465	326	39	27	5%
Apr-11	716	408	250	58	26	8%
May-11	672	338	243	91	24	14%
Jun-11	818	496	266	56	26	7%
Jul-11	829	501	266	62	15	7%
Aug-11	788	471	274	43	27	6%
Sep-11	868	485	256	127	15	15%
Oct-11	961	547	334	80	36	8%
Nov-11	924	556	337	31	31	3%
Total	15 834	8 573	5 226	2 036	301	**13%**

Appendix G

C&D Waste, Sensitivity Analysis 3



For the bottom of the offsite recycling range (based on the formula y=0.0025x -0.0242)

Intersection with:	Landfilling	Landfilling Low	Landfilling High
Transportation Distance	117.3	69.7	161.7

For the top of the offsite recycling range (based on the formula y=0.0093x + 0.0897)

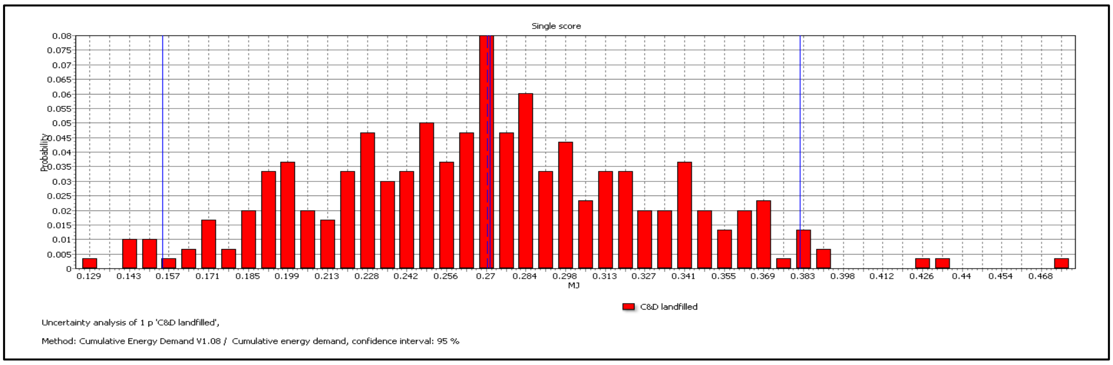
Intersection with:	Landfilling	Landfilling Low	Landfilling High
Transportation Distance	19.3	6.5	31.2

Appendix H

Monte Carlo Simulation Outputs

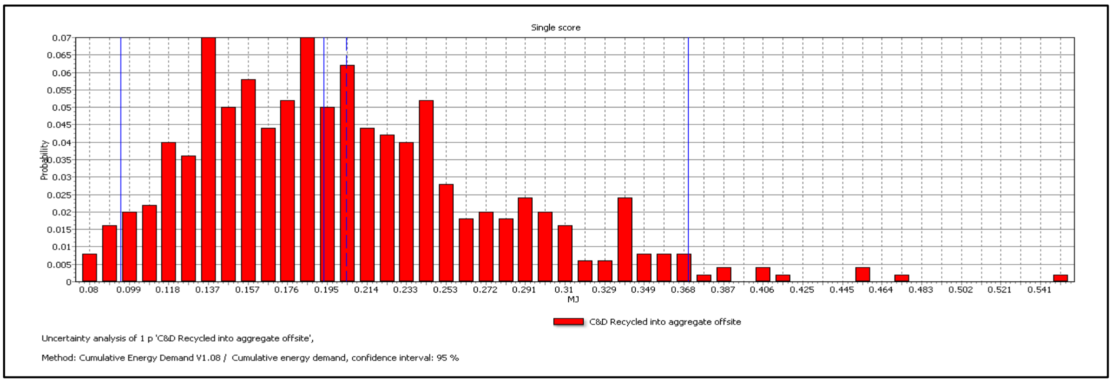
C&D Landfilling Scenario - CED

Impact category	Unit	Mean	Median	SD	CV (Coefficient of Variation)	2.5%	97.5%	Std.err.of mean
Single score	MJ	0.271	0.271	0.0587	21.7%	0.154	0.382	0.0125



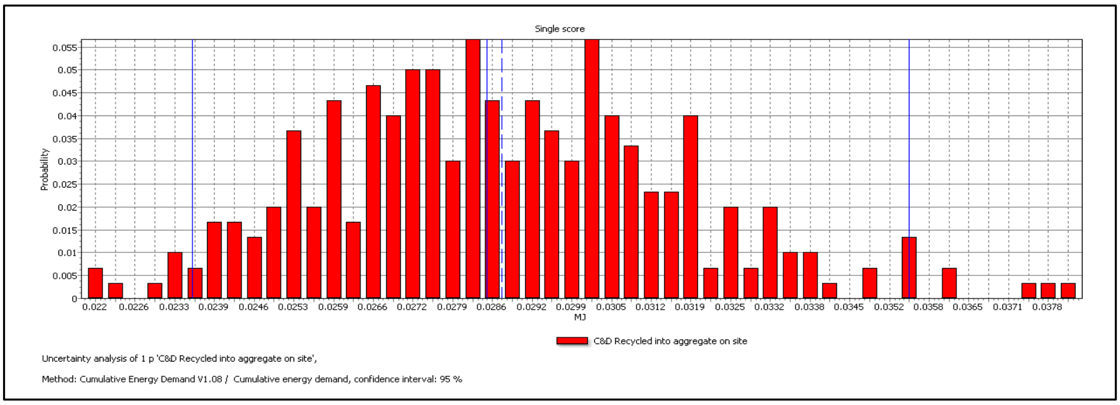
C&D Recycling Offsite - CED

Impact category	Unit	Mean	Median	SD	CV (Coefficient of Variation)	2.5%	97.5%	Std.err.of mean
Single score	MJ	0.204	0.193	0.0728	35.6%	0.0951	0.37	0.0159



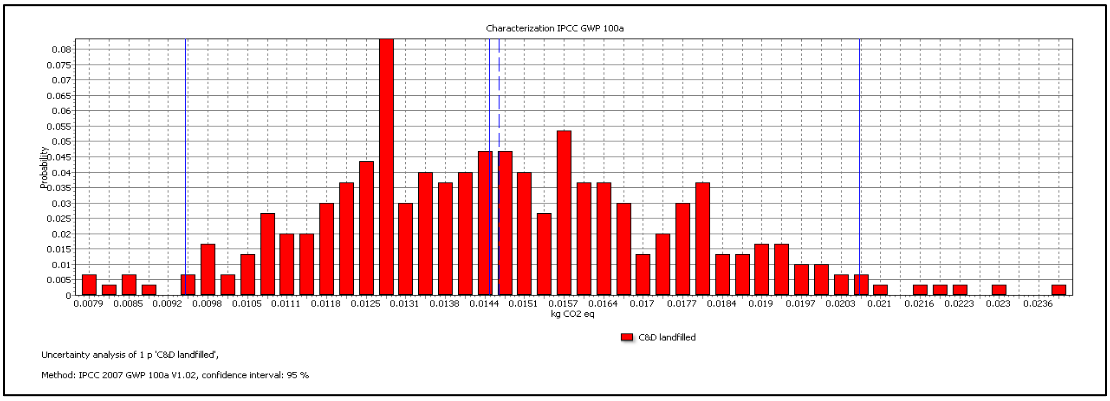
C&D Recycling Onsite - CED

Impact category	Unit	Mean	Median	SD	CV (Coefficient of Variation)	2.5%	97.5%	Std.err.of mean
Single score	MJ	0.0287	0.0285	0.00293	10.2%	0.0236	0.0355	0.0059



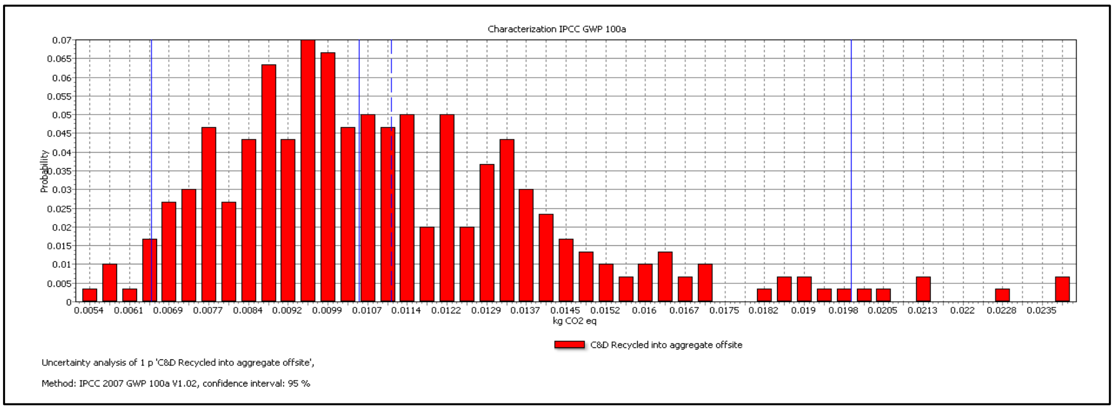
C&D Landfilling - GWP

Impact category	Unit	Mean	Median	SD	CV (Coefficient of Variation)	2.5%	97.5%	Std.err.of mean
IPCC GWP 100a	kg CO2 eq	0.0147	0.0145	0.00289	19.7%	0.00946	0.0206	0.0114



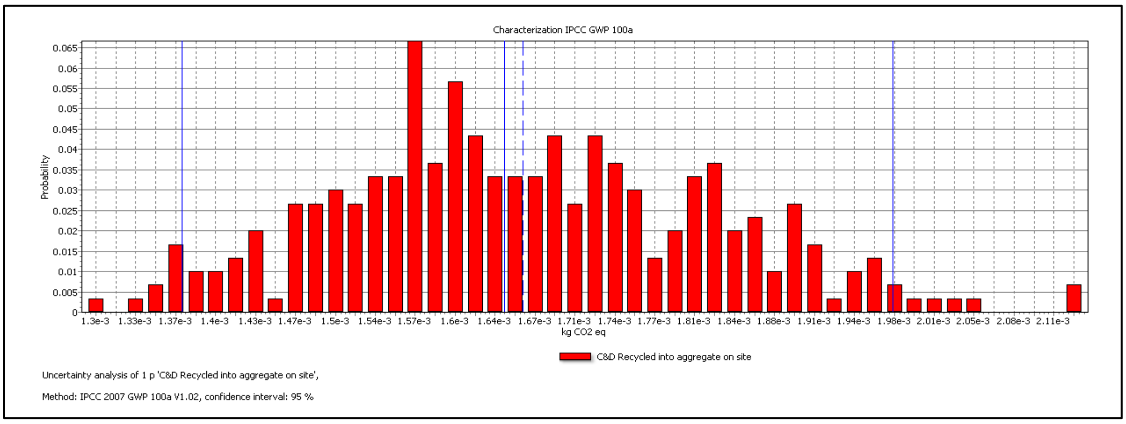
C&D Recycling Offsite - GWP

Impact category	Unit	Mean	Median	SD	CV (Coefficient of Variation)	2.5%	97.5%	Std.err.of mean
IPCC GWP 100a	kg CO2 eq	0.0111	0.0105	0.00325	29.2%	0.00657	0.0199	0.0169



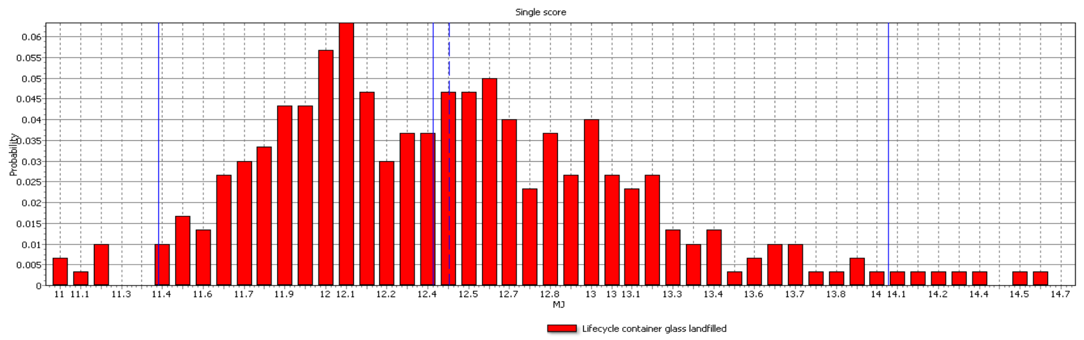
C&D Recycling Onsite - GWP

Impact category	Unit	Mean	Median	SD	CV (Coefficient of Variation)	2.5%	97.5%	Std.err.of mean
IPCC GWP 100a	kg CO2 eq	0.00166	0.00165	0.000158	9.53%	0.00137	0.00198	0.0055



Glass Landfilling – CED

Impact category	Unit	Mean	Median	SD	CV (Coefficient of Variation)	2.5%	97.5%	Std.err.of mean
Single score	MJ	12.4	12.4	0.65	5.22%	11.4	14	0.00302

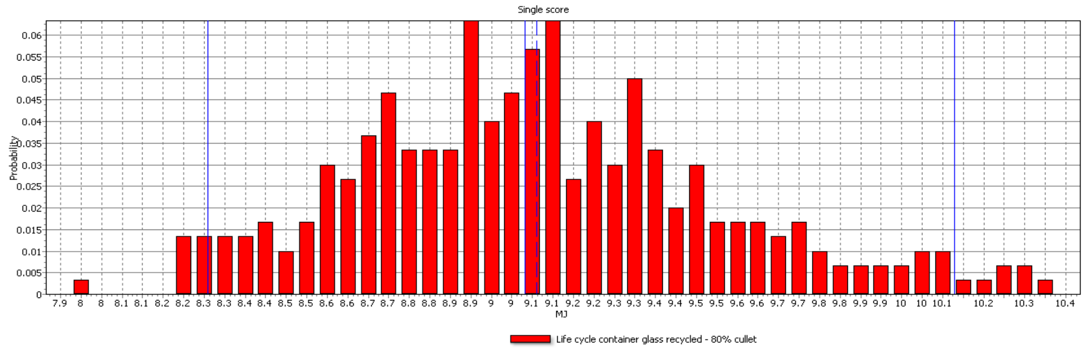


Uncertainty analysis of 1 p 'Lifecycle container glass landfilled',

Method: Cumulative Energy Demand V1.08 / Cumulative energy demand, confidence interval: 95 %

Glass Recycling 80% – CED

Impact category	Unit	Mean	Median	SD	CV (Coefficient of Variation)	2.5%	97.5%	Std.err.of mean
Single score	MJ	9.08	9.06	0.446	4.91%	8.28	10.1	0.00283

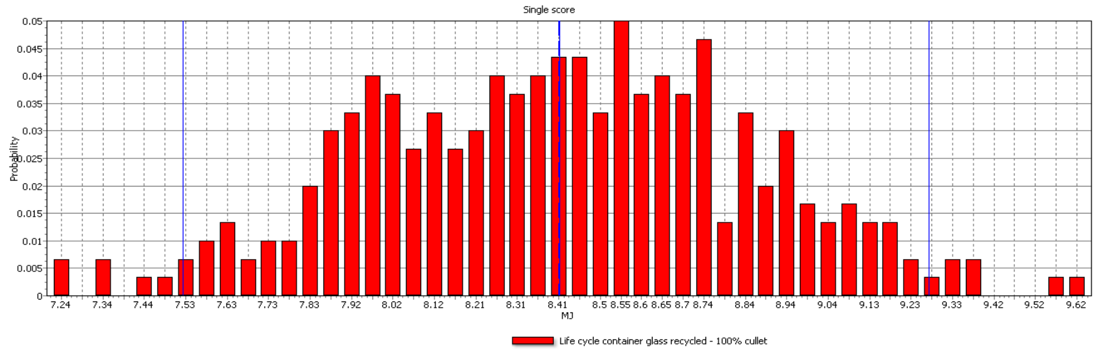


Uncertainty analysis of 1 p 'Life cycle container glass recycled - 80% cullet',

Method: Cumulative Energy Demand V1.08 / Cumulative energy demand, confidence interval: 95 %

Glass Recycling 100% – CED

Impact category	Unit	Mean	Median	SD	CV (Coefficient of Variation)	2.5%	97.5%	Std.err.of mean
Single score	MJ	8.41	8.41	0.446	5.31%	7.53	9.27	0.00307

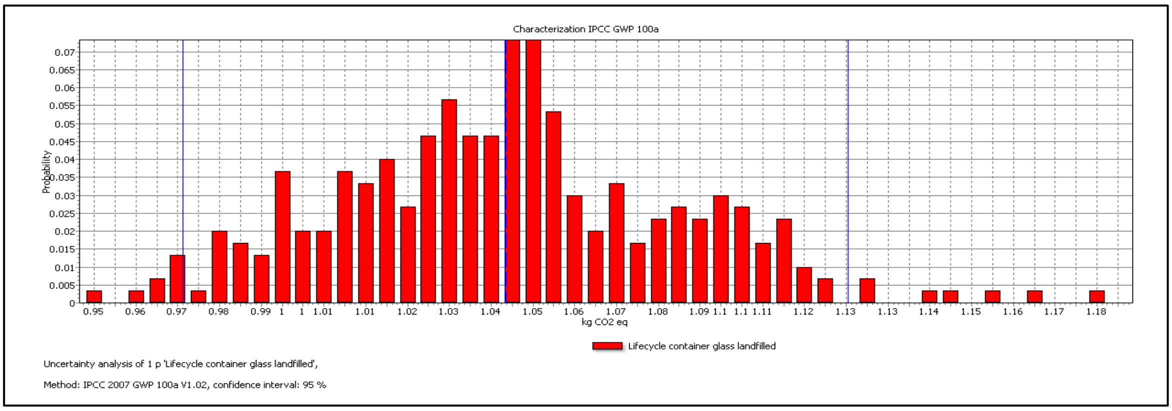


Uncertainty analysis of 1 p 'Life cycle container glass recycled - 100% cullet',

Method: Cumulative Energy Demand V1.08 / Cumulative energy demand, confidence interval: 95 %

Glass Landfilling – GWP

Impact category	Unit	Mean	Median	SD	CV (Coefficient of Variation)	2.5%	97.5%	Std.err.of mean
IPCC GWP 100a	kg CO2 eq	1.05	1.05	0.0395	3.77%	0.973	1.13	0.00218

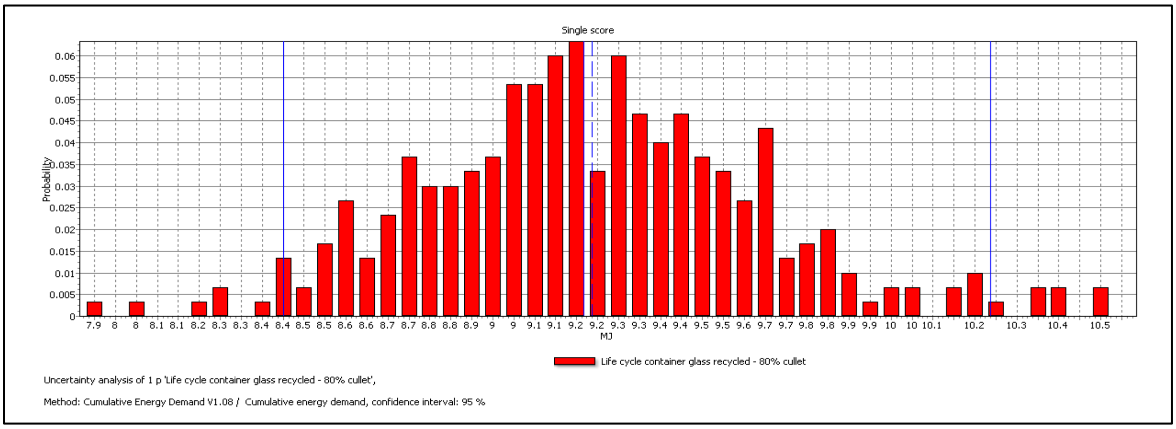


Uncertainty analysis of 1 p 'Lifecycle container glass landfilled',

Method: IPCC 2007 GWP 100a V1.02, confidence interval: 95 %

Glass Recycling 80% – GWP

Impact category	Unit	Mean	Median	SD	CV (Coefficient of Variation)	2.5%	97.5%	Std.err.of mean
IPCC GWP 100a	kg CO2 eq	0.664	0.664	0.0295	4.44%	0.603	0.723	0.00257

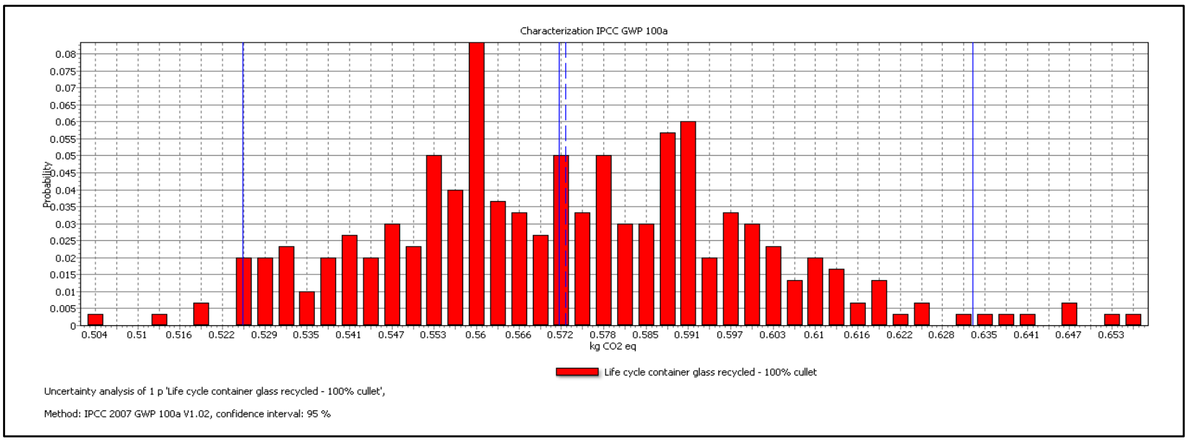


Uncertainty analysis of 1 p 'Life cycle container glass recycled - 80% cullet',

Method: Cumulative Energy Demand V1.08 / Cumulative energy demand, confidence interval: 95 %

Glass Recycling 100% – GWP

Impact category	Unit	Mean	Median	SD	CV (Coefficient of Variation)	2.5%	97.5%	Std.err.of mean
IPCC GWP 100a	kg CO2 eq	0.573	0.572	0.0268	4.69%	0.525	0.633	0.00271



Uncertainty analysis of 1 p 'Life cycle container glass recycled - 100% cullet',

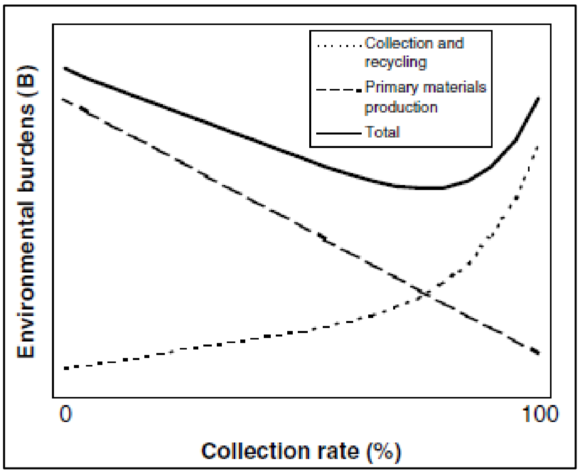
Method: IPCC 2007 GWP 100a V1.02, confidence interval: 95 %

Appendix I

Non-linearity in LCA

Ekvall et al (2007)express this concept with the following simplistic graph. Note that while reduction in primary materials for increased recycled content is linear, the collection function is not. When the collection system becomes more cumbersome in its attempt to collect as much of the material as possible, it also loses its efficiencies of scale. This could be the case for glass collection in less-educated neighbourhoods that don't properly separate the recyclables; the additional energy spent to conduct collections and separate the glass from the rest of the recyclables is likely much higher for the same amount of glass from other neighbourhoods simply because the process is not as efficient.

Figure 32: The Non-linear Relationship between Burden and Collection Rate



(Ekvall, et al., 2007)

This attribute of LCA may impose on the validity of the values assigned to the extreme cases in the sensitivity analysis for glass collection methods. When collecting 80% of the recycled glass via kerbside programmes, for example, the same burdens per functional unit may not apply in the top quartile of the collection rate. This inhibits the ability of the model to find a true optimum level of activity (Ekvall, et al., 2007).