Assessment of the potential contribution of biogas to mitigation of climate change in South Africa

By

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Declaration

I know the meaning of plagiarism and declare that the whole work in this document, save for that which is properly acknowledged, is my own.

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Abbreviations and acronyms

BOD	Biological Oxygen Demand
BCM	Buffalo City Municipality
CDM	Clean Development Mechanism
COCT	City of Cape Town Municipality
COD	Chemical Oxygen Demand
COJ	City of Johannesburg Municipality
COP 15	Conference of the Parties Copenhagen 2009 Accord
DDOC	Decomposable Degradable Organic carbon
DEA	Department of Environmental Affairs of Republic of South Africa
DEAT	Department of Environmental Affairs and Tourism of Republic of South Africa
DOC	Degradable Organic Carbon
$EF_{(T)}$	Annual emission factor
EMM	Ekurhuleni Metropolitan municipality
EPA	Environmental Protection Agency of the United States
ERP	Emissions Reduction Potential
ETM	EThekwini Municipality
FOD	First Order Decay model
GDP	Gross Domestic Product
GHG	Greenhouse gases
HRT	Hydraulic Retention time
IPCC	Intergovernmental Panel on Climate Change
LEAP	Long Range Energy Alternatives Planning
LTMS	Long Term Mitigation Scenarios
MCF	Methane Correction Factor
$MS_{(T,S,k)}$	Fraction of livestock category *T*'s manure handled using manure management system S in climate change region k
MSW	Municipal Solid Waste
Mton $CO_{2\text{-eq}}$	Megatons of carbon dioxide equivalents
N_2O	Nitrous Oxide
NMM	Nelson Mandela Bay Metropolitan Municipality
OFMSW	Organic Fraction of Municipal Solid Waste
OX	Oxidation factor
SWD	Solid Waste Disposal site
TMM	Tshwane Metropolitan Municipality
UNFCC	United Nations Framework Convention on Climate Change
$VS_{(T)}$	Daily volatile solid excreted for livestock category *T*

Abstract

South Africa has its fair share in the global greenhouse gas (GHG) emissions, with recorded 2010 emissions per capita of 10tons/year. This is caused by the energy supply of the country which relies heavily on fossil fuels to drive its energy intensive economy. If this continues under "business as usual", consequences like water and food shortage may be exacerbated. The waste sector has a share of 3% in national GHG emissions. These are caused by methane from biogas produced through anaerobic digestion of organic waste. The objective of this study was to assess the potential contribution that can be achieved in reducing the national GHG emissions by converting waste emissions into useful energy or capturing and destroying them. Three waste resources were investigated because of their abundance in the country: municipal solid waste, municipal wastewater and livestock manure. The national picture of municipal waste was extrapolated from the waste data available in 7 metros in the country (City of Cape Town, Johannesburg, Tshwane, Ekurhuleni, EThekwini, Nelson Mandela Bay, and Buffalo City municipalities). Projected GDP and population growths were used as indicators for extrapolating the national data. The total national organic waste derived from these waste categories was used to estimate their emission share in national GHG emissions and biogas generation in terms of methane production from each waste type. This was forecasted from 2010 to 2025. The methane gas production was optimised by assuming different waste combinations like: municipal solid waste and wastewater, wastewater and livestock manure, and remaining wastewater. In addition, the possible amount of electricity or heat produced from this biogas was estimated. This useful energy was used to evaluate the emission reduction potential (ERP) in the national GHG emissions of the country under "growth without constraints". All these computations were performed by using MS Excel software. It was found that the total organic waste predicted during this period varied from 12 to 17Mton, with the waste emissions share being about 2% of the national GHG emission. Methane generated from this waste was about 644-1075Mm^3 while the total optimal methane generated from these waste combinations was estimated to be 1770-2650Mm^3. In addition, 673-1123GWh of electricity and 1255-2150GWh of heat could be produced (without optimization) from methane over the same period of the forecast. For optimal methane production, the possible useful energy was estimated to be 1362-2037GWh of electricity and 2894-4362GWh of heat. The ERP of methane capture and conversion to useful energy was about 2.1-2.5%. It is concluded that a) capturing and utilisation of methane gas from waste contributes to the reduction of the GHG emissions, b) optimisation of biogas production from waste increase methane yield and therefore useful energy, and c) the best contribution of biogas in climate change mitigation in South Africa would come from the optimal production of methane from waste.

Table of Contents

LIST OF TABLES

LIST OF FIGURES

1 Introduction

1.1 Background

Climate change mitigation in South Africa poses a significant challenge. This is largely due to country's energy-intensive economy which is primarily based on coal, leading to high emissions (Winkler & Marquard 2009). In 2009, the South African greenhouse gas (GHG) emissions were estimated to be about 511 Mtons $CO_{2\text{-eq}}$ (URBAN EARTH 2012). The government acknowledges this and it has shown strong interest to mitigate the emissions in the country and adopt a low carbon growth path in its economy (Tyler 2009).

To address this problem, the South African government through the then Department of Environmental and Tourism (DEAT), published the climate change response strategy where key issues pertaining to the response were identified as follows: adaptation to climate change, developing a sustainable energy programme, meeting international obligation (because the country acceded to the United Nations Framework Convention on Climate Change), integration of climate change response in government, government-industry partnership, domestic legal provisions, climate change related education, climate change related research and development and demonstration, and inventories of GHG emissions and pollutants (DEAT 2004).

Since then, South Africa conducted a study on long term mitigation scenarios (LTMS) in response to the GHG emissions intensity in the country (Winkler 2007, Pegels 2010). The main purpose of the study was to build scenarios of possible futures which are aimed at reducing GHG emissions in the country (Winkler 2007). This included mitigation options for non-energy emission sources like agriculture, forestry, and waste and opportunities to increase emissions reductions in these sectors (Taviv *et al* 2007). In the LTMS study, the "Growth without Constraints" (GWC) scenario reflects the possible growth of the country's emissions without any constraints considered on carbon or any other factor (Winkler *et al* 2011). This was used as a baseline upon which other mitigation options mentioned in the LTMS were measured (Winkler 2007). In 2011, the Department of Environmental Affairs (DEA) published a white paper on the National Climate Change Response of South Africa (DEA 2011a). This policy document confirms the government's commitment to contribute towards the global effort in stabilising GHG emissions in the atmosphere to the levels that avoid catastrophic consequences (DEA 2011a).

Among the mitigation action plans mentioned in the policy, there is a waste management programme which includes, but is not limited to, investigating waste to energy opportunities especially the generation, capture and conversion of methane (DEA 2011a). This information will be used to develop and implement detailed waste related GHG emission mitigation action plans aimed at measurable GHG reductions aligned with the waste sector carbon budgets that maybe set. There is also a cross-cutting potential of not reducing only waste emissions but also of reducing energy related emissions by substituting a fraction of fossil fuels with methane gas from the waste.

1.2 Statement of Research Problem

South Africa is among the highest greenhouse gas emitters globally with emissions of about 9.18 tonnes per capita in 2009 and contributing about 1.49% to global CO_2 emissions (URBAN EARTH 2012). This means that the "business as usual" ways of development in the country (that have environmental impacts) need to change. New policies and strategies (that favour environmental conservation) have to be adopted. The South African government made a pledge under the Fifteenth Conference of Parties (COP 15) in the Copenhagen Accord (2009) to reduce the country's emissions below "business as usual" by 34% and 42% in 2020 and 2025 respectively, provided there would be financial resources, technology transfer, and capacity building support (Eberhard 2011, DEA 2011a).

The waste sector contributes about 3% emissions to the total GHG emissions of the country (URBAN EARTH 2012). This is the main source of biogas that consists of a large fraction of methane (CH_4) gas. Unfortunately, CH_4 is a potent GHG with a global warming potential that is 21 times that of CO_2 (IPCC 2007b). These are significant amounts of emissions that cannot be ignored when considering the mitigation options for the country. In view of this, the National Climate Change Response Policy and the 2007 LTMS have provided guidelines on how the emissions could be reduced and the costs of the mitigation efforts on all the sources of emissions in South Africa including non-energy emission sources like waste, agriculture and land use (DEA 2011a; Winkler 2007). However, the contribution that biogas can make to help the country meet its international mitigation obligations and national policy objectives has not yet been addressed. So, there is need to conduct a quantitative analysis which can provide a broad framework of the potential amount of GHG emissions avoidable through the utilisation of biogas from different waste resources in the country. This could contribute towards achieving the country's national emissions trajectory planned to peak between 2020 and 2025, plateau for the next decade and decline afterwards in absolute terms. The emissions of the country are planned to peak during this period with ranges of lower limit of about 398 Mton $CO_{2\text{-eq}}$ and upper limit of about 583 and 614 Mton $CO_{2\text{-eq}}$ (DEA 2011a). These emission trajectory ranges are the benchmark against which efficacy of mitigation actions will be measured. The framework can also help in the development of the mitigation action plan of the waste sector and determination of the carbon budgets for the sector.

Winkler *et al* (2011) consolidated the emissions trajectory of the country under the GWC scenario of the LTMS. It was assumed the country's emissions would continue to grow as they have in the past without considering any mitigation option to reduce GHG emissions. The GDP of the country was used as a key driver to estimate the emissions trajectory of the country under this scenario. The GWC can also be used as a baseline upon which the impact of capturing and using biogas as an energy source can be measured.

The country's own potential to use biogas as an energy source has already been demonstrated in various projects like: City of EThekwini's landfill gas recovery project, household biogas digesters in Lynedoch Eco-village in Stellenbosch, De Goode Hoop Estate in Noordhoek, Giyani in Limpompo province and others, and industrial biogas digesters like South African Breweries Alrode, PetroSA (CDM) (Bogner & Lee 2005, Boyd 2012). In all these projects, methane was generated, captured and converted to generate electricity and heat. This technical knowledge can be expanded to other waste resources like municipal waste (solid and liquid) and agricultural waste which have currently received very little attention. The climate change mitigation potential of biogas from these waste resources and all other biodegradable waste types in the country is also unknown. This can be assessed through investigating the overall GHG Emission Reduction Potential (ERP) of biogas through capturing, destroying and utilizing it as an energy source.

1.3 Research questions

It was mentioned previously that the waste generated in the country has its fair share of emissions that should be considered when developing the mitigation action plans of the country (DEA 2011a). This would not only reduce waste emission but also energy related emissions. The overall ERP of biogas has been established in other countries (UNFCC 2006, Zhang *et al* 2013). For the South African case, this study addressed it by answering the following question:

- How much biodegradable waste is available in South Africa and its projected growth in future?
- What is the total share of methane in the national GHG emissions "under growth without constraints" and how much biogas can be produced from the available waste resources chosen in terms of only CH_4 generation?
- How much electricity and heat can potentially be generated from this biogas?
- What is the effect of mixing different waste types on biogas production?
- How much GHG emissions can be reduced through destroying or utilising the biogas to generate electricity and heat?

1.4 Objectives

The main objective of this study was to assess the potential contribution of biogas on climate change mitigation in South Africa. Specific objectives of the study were:

a) Map out the national biodegradable waste resource base including its quantity for biogas production up to year 2025.

b) Assess the methane emissions share from these waste resources in the national GHG emissions "under growth without constraints" and then quantify the biogas production from these organic waste resources.

c) Assess the potential amount of electricity and heat that can be generated from the biogas.

d) Evaluate the potential of optimising the biogas production by blending different feedstock of waste types in the biogas digester.

e) Determine the emission reduction potential of biogas through capturing, destroying and utilising it to generate electricity and heat.

1.5 Significance of the study

This study will contribute to our understanding of mitigation options available for South Africa. The government committed itself to reduce the country's emissions by 34% in 2020 and by 42% in 2025. The study will also be helpful in the implementation phase of the National Climate Change Response Strategy flagship programmes, such as the Waste-to-energy (DEA 2011a). In addition, municipalities in the country can benefit from this study in order to meet the vision of creating low carbon, modern, livable and equitable cities. Employment can also be created since the market exists to sell carbon credits to Annex 1 countries under the Kyoto approved CDM projects (Bogner & Lee 2005).

1.6 Structure of the thesis

Chapter 1 describes the background to this work. In Chapter 2, the fundamentals of climate change, biogas and biodegradable waste are presented and discussed. The research methodology used in this study is described in Chapter 3 while findings from the study are reported and discussed in Chapter 4. Finally, conclusions and recommendations drawn from these findings are given in Chapter 5.

2 Literature Review

2.1 Introduction

The aim of this investigation was to assess the potential contribution of biogas on climate change mitigation in South Africa. In this regard, as outlined in Chapter 1, five objectives were set out: map out the biodegradable waste resource, assess the methane share from these waste resources in national greenhouse gas emissions, assess the potential amount of power or direct heat that can be generated by biogas, evaluate the potential to optimise biogas production, and determine the emission reduction potential of biogas through capturing, destroying or utilising it as an energy source.

In this chapter, the fundamentals of climate change, biogas and biodegradable waste are presented and discussed. Previous work on climate change in South Africa is reviewed. In addition biogas as a source of methane (CH_4) is covered. The national picture of biogas resources in South Africa is mapped out in this chapter and the current status of the waste generation from these resources in major metropolitan municipalities in the country is reported. The estimation of CH_4 emissions from these biogas resources is also synthesised. Current available methods of capturing, destroying or utilising biogas as an energy source are also reviewed. Finally the research aspects that informed pursuing this study are highlighted.

2.2 Climate change

Climate change is a term that refers to the major changes in temperature, precipitation (rainfall and snow) patterns, and wind patterns which can last for decades or longer (EPA 2010, Trenberth *et al* 2007). The IPCC (2007a) defines the climate change as any change in the state of the climate that can be identified overtime due to natural variability and human activity. It is attributed to both natural and human causes as follows (EPA 2010):

a) **Natural causes** include changes in the Earth's orbit, the sun's intensity, the circulation of the ocean and the atmosphere, and volcanic activity. These are caused by the earth temperature changes which depend on the balance between the energy entering and leaving its surface (EPA 2012).

b) **Human causes** include burning fossil fuels, cutting down forests, and developing land for farms, cities, and roads. These activities release greenhouse gases (GHG) into the atmosphere or reduce the carbon sink. The GHG affect the amount of heat retained by the earth's atmosphere (IPCC 2007a).

The changes in the temperature of the earth are mainly affected by the GHG concentrations in the atmosphere which trap some of the heat from the surface of earth (EPA 2012). When the sunlight reaches the earth, it can either be reflected back into space or absorbed by earth. Once absorbed, some of the energy is released by earth back to the atmosphere as heat (EPA 2012, LeTreute *et al*

2007). So, the GHG act as a blanket to the planet, making it warmer. This process is depicted in Figure 2-1.

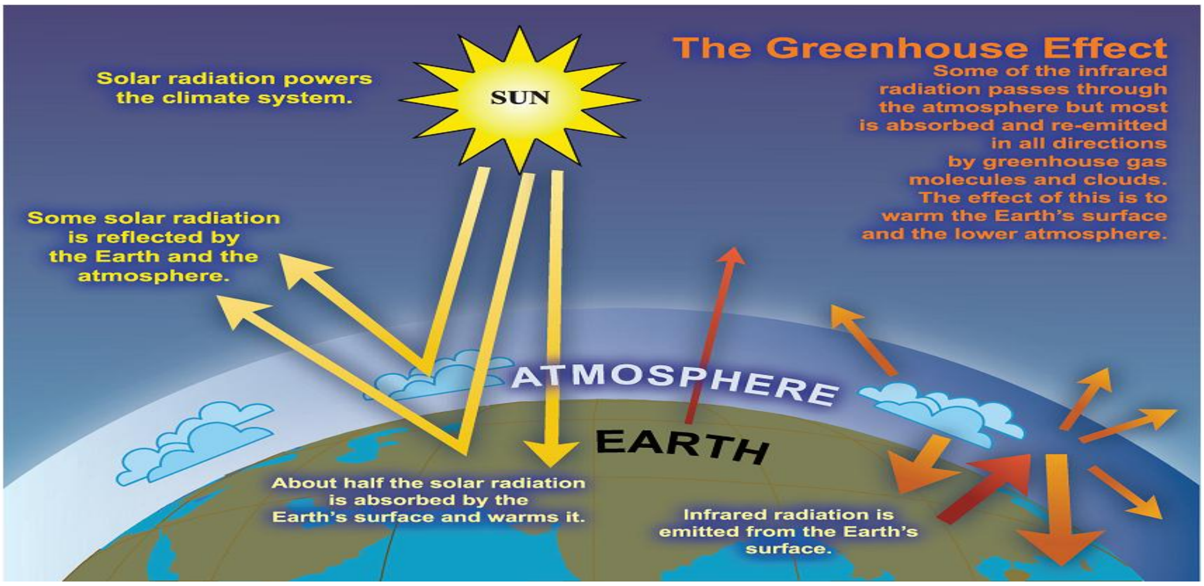


Figure 2-1: Greenhouse gas effect (Source: LeTreut *et al* 2007, EPA 2012)

In the pre-industrial revolution, the GHGs had positive effect to make earth warm so as to be habitable (Nema *et al* 2012). However, in recent times due industrial revolution, the human activities have increased the concentrations of GHGs and have also emitted other potent heat trapping gases like carbon dioxide, methane, nitrous oxide, fluorinated gases, troposphere ozone (IPCC 2007a, Nema *et al* 2012, Senkovska *et al* 2012). This led to a rise in the earth's surface temperature that is detrimental to its species. IPCC (2007a) has shown that the global GHG emissions have grown up significantly since the time of pre-industrial revolution to the extent that this increase was 70% between 1970 and 2004.

2.2.1 Causes of greenhouse gas emissions

The largest growth in GHG emissions post industrial revolution is mainly attributed to energy supply, transport and industry sectors; while residential, commercial, forestry and agricultural sector have been growing at lower but significant rates (IPCC 2007a). This is shown in Figure 2-2 for the greenhouse gas emissions growth between 1970 and 2004.

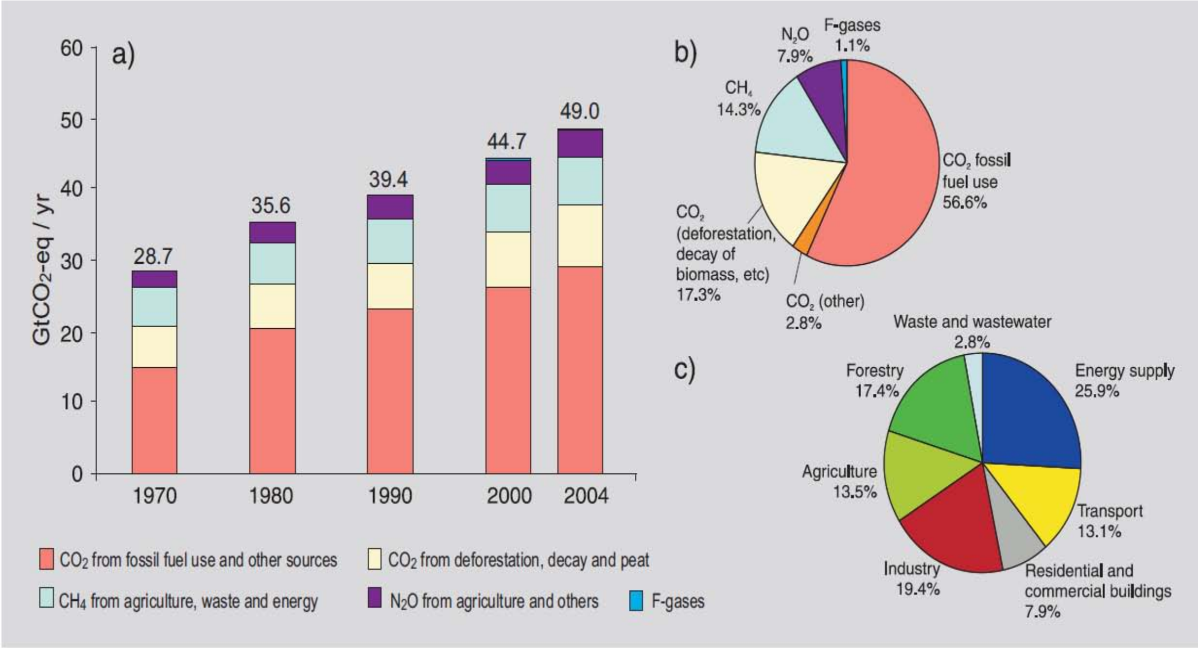


Figure 2-2: Global GHG emissions depicting: (a) The total GHG emissions over the years, (b) The share of each GHG over the same period, and (c) The sources of GHG emissions and the contribution of each source (Source: IPCC 2007a)

Figure 2-2 shows CH_4 emissions from the agriculture, waste and energy contributed about 14.3% of emissions to the total during this period of investigation, of which 2.8% and 13.5% of this comes from the waste and agricultural resources respectively as shown in Figure 2-2 (c). These are significant contributions which should be considered when attempting to mitigate global climate changes. Consequently they form basis for the investigation of this current work.

The evidence of rapid climate change on earth caused by GHG emissions has already been observed (DEA 2011a, EPA 2012, and IPCC 2007a). Among others this includes: increases in the average global temperatures with past decade being the hottest on record, rises in the average global seal level, changes in average rainfall patterns; more intense and longer droughts particularly in the tropics and subtropics.

To avoid the catastrophic consequences of climate change, scientists require the average global temperature increase to be below a maximum of a 2°C above pre-industrial levels (DEA 2011a). Over the past 140 years the mean global temperature has risen by 0.6- 0.9°C and there are suggestions that the future increase might be at a rate of 0.2°C per decade (Nema *et al* 2012, Vegas-Vilarrúbia *et al* 2012).

2.2.2 Climate change in South Africa

South Africa is also a significant contributor to climate change because of its energy intensive economy, with its energy mainly derived from fossil fuel burning (Eberhard 2010, DEA 2011a). The average per capita emissions in South Africa is 7.22 tons CO_2 per annum (Eberhard 2010). Two single most emitters in the country are Eskom’s coal fired power stations which account for about

220 Mt per annum and Sasol's coal to liquid plants (a world's single largest emitter) which account for about 60 Mt per annum of CO_2 emissions (Eberhard 2010, Taylor 2009). Both these emitters contribute almost half of the total emissions of the country (Winkler *et al* 2011).
The two most primary sources of greenhouse gas emissions in South Africa are energy and transport sectors, other sources are (DNT 2010):

a) Deforestation: Wood burning releases CO_2 contained in tree to the atmosphere. When wood decays in the swamp, it produces CH_4 through anaerobic degradation that is emitted to the atmosphere.
b) Organic waste: Landfill waste and waste water disposal; agricultural waste (animal waste and crop residues); organic industrial effluents; coal mines and gas pipelines are all sources of CH_4 production.

c) Fertilisers and other chemicals release nitrous oxide, which causes about 10% as much warming as CO_2.

d) It is predicted that should there be a failure to limit the average global temperature to below levels required by science, the potential impacts on South Africa in the middle to long term would be catastrophic (DEA 2010). This would include: South African coasts warming by 1-2°C, and the interior by 2-3°C and after 2050 warming is projected to be around 3-4°C along the coast and 6-7°C in the interior.

With these kinds of temperature increases, life would change significantly: parts of the country becoming much drier; increased evaporation reducing water availability (affecting human health, agriculture and the environment in general); impacts from the increased occurrence and severity of veld and forest fires and especially extreme weather events like floods and droughts; sea-level rise would negatively affect the coast and coastal infrastructure; mass extinctions of endemic plant and animal species would greatly reduce South Africa's biodiversity (DEA 2010).

2.2.3 South African government response to climate change

Against this climate change threat, the South African government took a responsible obligation as a global citizen by committing the country to make its fair share contribution to global GHG emission mitigation efforts (DEA 2011a). In COP 15 (2009), South Africa pledged to reduce its emissions by 34% in 2020 and 42% in 2025 below its "business as usual" trajectory, conditional on adequate financial support, technological and capacity building support (Eberhard 2010, Winkler 2011 Roelfsema *et al* 2013). During this period, the emissions of the country are aimed to peak between 2020 and 2025 and plateau for a decade and decline in absolute terms thereafter (DEA 2011a).

To effect this commitment, a national policy on climate change was released in 2011 to ensure a coordinated, coherent, efficient, and effective response to the global challenge on climate change (DEA 2011a). One of the objectives of the White Paper is to: "Effectively manage inevitable climate change impacts through interventions that build and sustain South Africa's social, economic, and environmental resilience and emergency response capacity".

To achieve the objectives of the White Paper, South Africa will build the climate resilience of the country, its economy and people and manage the transition to a climate-resilient, equitable and internationally competitive lower carbon economy and society (DEA 2011a). This should be made in a manner that simultaneously addresses South Africa's overriding national priorities for sustainable development, poverty eradication, and social equality (DEA 2011a). Whether a balance can be achieved remains to be seen.

2.2.4 Mitigation potential of South Africa

The first mitigation commitment shown by South Africa was the development of LTMS report which depicted the possible future scenarios that can happen in the country depending on the decision taken in response to the climate change threat (Winkler 2007). This is presented in Figure 2-3.

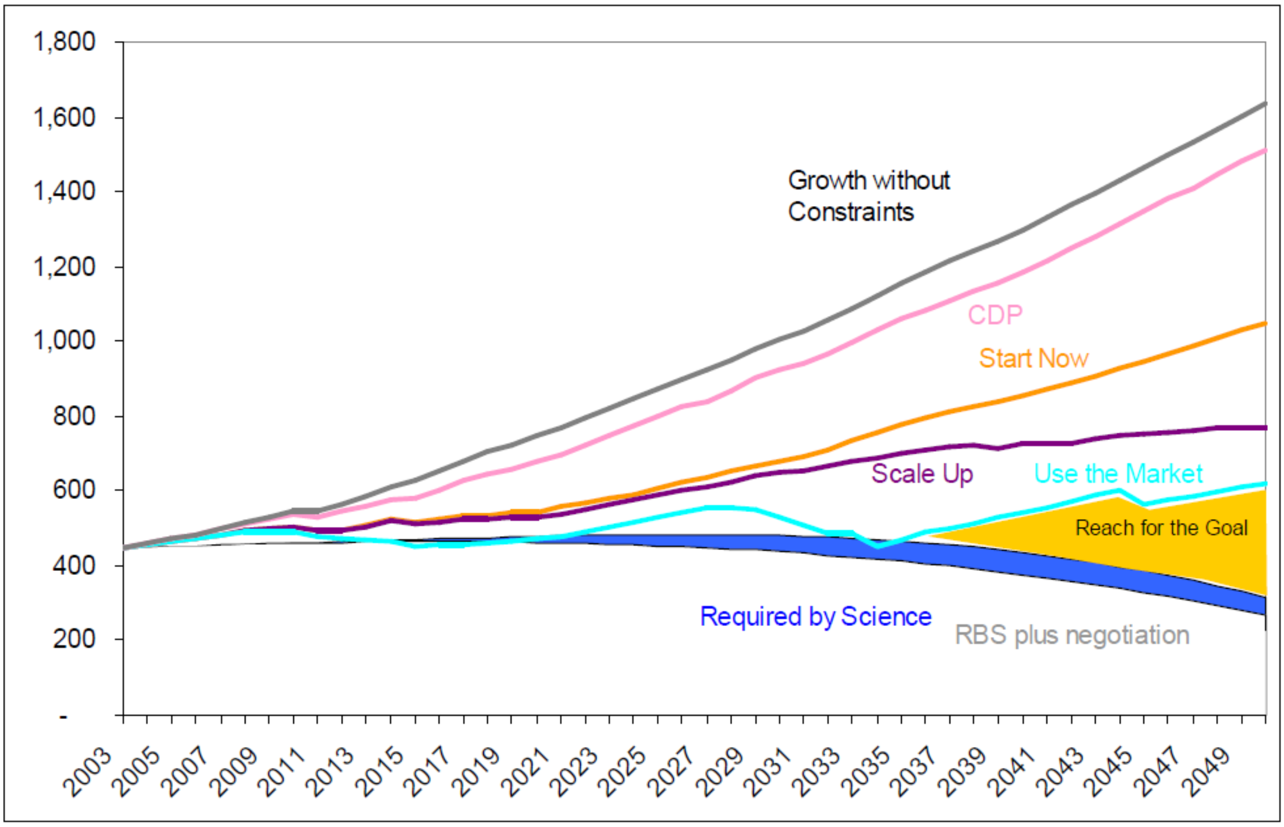


Figure 2-3 South African possible mitigation scenarios (Source: Winkler 2007)

The "growth without constraints" scenario as mentioned in Section 1.1 follows the business as usual without limitations on either economic growth of the country or carbon (Pegels 2010, Winkler *et al* 2011). CDP depicts the "Current Development Plans" scenario which assumed the existing government policies were implemented (Winkler 2007). The "Required by Science" scenario aims at reducing the emissions by 30-40% between 2003 and 2050 (Pegels 2010). For this option, four other options were developed: "Start Now", "Scale Up", "Use the Market" and then "Reach for the Goal" as shown in Figure 2-3.

These options are (Pegels 2010, Winkler 2007): The “Start Now” focuses on positive upfront investments on technologies like energy efficiency, renewables, and nuclear. The “Scale Up” extends on investments in nuclear, renewables, and cleaner coal with carbon capture and storage which have high costs. The “Use the Market” introduces additional economic interests such as carbon tax while “Reach for the Goal” combines the mitigation efforts of these 3 options together with yet unknown technologies and behavioural change. The contribution of this work falls on the first two options.

After the South African cabinet fully considered the country’s mitigation potential under the LTMS study, there was an announcement of the peak, plateau and decline of emissions as described in Section 2.2.3. This strategic policy direction informed the development of National GHG Emissions Trajectory Range projected to 2050. This was to be used as a benchmark against which the efficacy of mitigation action would be measured. The emissions trajectory range specify that the South African GHG emissions will peak between 2020 and 2025 in a range with lower limit of 398 Mtons CO_{2-eq} and upper limit of 583 Mton CO_{2-eq} and 614 Mton CO_{2-eq} from 2020 to 2025. There will be a plateau for a decade with the same lower limit range and upper limit of 614 Mton CO_{2-eq} (DEA 2011a). From 2036 onwards the emissions will decline with lower limit range of 212 Mton CO_{2-eq} and upper limit of 428 Mton CO_{2-eq} by 2050 (DEA 2011a). The decline would be caused by the implementation of the mitigation actions described in the following paragraphs.

The white paper suggested the mitigation action plans to be implemented in a phased manner i.e. on short, medium, and long terms (DEA 2011a). On short term, the policy suggests among other mitigation options, an increased investment in renewable energy programmes in the electricity sector. Conversion of waste to electricity is part of the renewable energy programmes envisaged, on which this study focuses.

On medium term, some of the mitigation options that are suggested by the policy are: shifting to lower carbon electricity generation options; options for mitigating non-energy emissions in agriculture (this is also of interest to this current study) and land use. On long term planning, information (nationally and internationally) about the outcome of mitigation options, technology development, and any other new information that may suggest additional mitigation actions (DEA 2011a).

Due to the carbon intensive nature of the South African economy and the desire to enable development, the white paper adopted the carbon budget for each sector that would specify the desired emissions reductions, consistent with the benchmark of the national GHG Emissions Trajectory Range (DEA 2011a). This would include identifying an optimal combination of mitigation actions at the least cost to-and with the most sustainable development benefits for the relevant sector and national economy, to enable and support the achievement of the desired emission reduction outcomes consistent with the benchmark National Greenhouse Gas Emissions Trajectory Range (DEA 2011a). So far (at the time of writing this thesis) the carbon budget that will be allocated to each sector of the economy has not been specified.

For implementation of these mitigation actions the policy suggested the near term priority flagship programmes, which include the Waste Management Flagship Programme (DEA 2011a). This programme will establish the GHG mitigation potential of the waste management, including but not limited to, investigating the waste to energy opportunities available within the solid, semi-solid, and liquid waste management especially the generation, capture and conversion and or use of methane emissions. This part forms the focus of this study and explores mitigation potential from all the sectors that are sources of biodegradable waste that generates methane emissions. These waste types include the municipal solid waste, municipal wastewater, and agricultural waste (both crop residues and livestock manure).

This information will be used to develop and implement a detailed waste related GHG emissions mitigation action plan aimed at measuring GHG reductions aligned with any sectorial carbon budgets that may be set (DEA 2011a). This action plan will also detail the development and implementation of any policy, legislation and or regulation required to facilitate the implementation of the plan (DEA 2011a). Any policy development and implementation that will transpire from this action plan would be informed by the establishment of the GHG mitigation potential of waste resources.

2.3 Biogas

Biogas is a mixture of methane (CH_4), carbon dioxide (CO_2) and traces of hydrogen sulphide (H_2S) produced through biodegradation of organic matter in the complete absence of oxygen (House 2007, Navickas 2007, Verma 2002). The organic materials that produce biogas can be food waste, garden waste, crop waste, animal and human faeces (NNFCC 2011). It is produced by micro-organisms in anaerobic conditions from different organic materials and in different environments, e.g. in sludge digesters of wastewater treatment plants (WWTP), bio-waste from industry, manure and energy crop digesters, and in landfills (Arthur *et al* 2011, Rasi *et al* 2011).Typical composition of biogas is showed in Table 2-1 (Letete 2011, Navickas 2007). The biogas production is affected by four factors like: type of organic matter, bacteria, anaerobic conditions, and heat (House 2007).

Table 2-1: Typical composition of biogas (Source: Letete 2011, Navickas 2007)

Name of gas component	Fraction in biogas (%)
CH_4	50-70
CO_2	30-40
H_2S	Traces
NH_3	Traces

2.3.1 Type of organic matter

The biogas producing bacteria feed on organic matter to survive. The type of organic matter affects the time needed for the complete digestion of the organic matter (House 2007).

It is also essential to know the concentration of solids in each type of the organic matter because the production of biogas is influenced by the level of solids in the substrate (Letete 2011, Monnet 2003). A high concentration of solids gives a high yield of biogas (Khalid *et al* 2011).

2.3.2 Bacteria

Bacteria is necessary for the production of biogas in that it converts the organic matter into biogas and this happens through a complex biological process which involves three types of bacteria in three stages (House 2007, Deublein & Steinhauser 2008). This process proceeds in three stages.

In the first stage, there is a fermentative bacterium which hydrolyses the complex organic matter such as fats, carbohydrates, and proteins into soluble molecules (Nayono 2010, Verma 2002). In the second stage, the acid forming bacteria known as acetogenesis bacteria convert these molecules into simple organic acids like propionic acid, butyric acid, and acetic acid as well as carbon dioxide, hydrogen and ethanol (Nayono 2010). In the third stage the methanogenic bacteria produce the biogas by decomposing these acids or reduce carbon dioxide with hydrogen (Nayono 2010, Verma 2002). These stages are described in details in the succeeding sections.

2.3.3 Hydrolysis

The process of hydrolysis involves the degradation of a substance into small particles by addition of water where one fragment of a complex compounds gains the hydrogen ion of a water molecule and the other fragment gains a hydroxyl ion of a water molecule (Verma 2002). This reaction usually needs a catalyst which makes a reaction to occur fast. In this stage the fermentative bacteria which occur naturally act as a catalyst to convert insoluble complex organic matter such as cellulose, proteins, and lipids into soluble molecules such as sugars, amino acids, and fatty acids in the presence of moisture (Deublein & Steinhauser 2008, Verma 2002). This hydrolysis of complex or polymer organic compounds into soluble monomers is aided by the hydrolytic enzymes like cellulases, proteases, lipases, amylases, and others which are present in the naturally occurring bacteria (Deublein & Steinhauser 2008, Verma 2002). The hydrolytic activity is of significant importance in high organic waste and may become rate limiting (Verma 2002). Typical hydrolytic reactions are as follows (Letete 2011, Verma 2002):

Polysaccharides → monosaccharides

Proteins → amino acids

Lipids → fatty acids

In the second stage the products of the first stage reactions are converted by acid forming bacteria called acetogene into simple organic acids, carbon dioxide and hydrogen (Deublein & Steinhauser 2008, Letete 2011, Verma 2002). These simple organic acids are acetic acid, propionic acid, and butyric acids and ethanol (Deublein & Steinhauser 2008, Letete 2011, Verma 2002). The typical acetogenetic reactions are as follows (Ostrem *et al* 2004):

$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2$

$C_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH + 2H_2O$

$C_6H_{12}O_6 \rightarrow 3CH_3COOH$

In the final stage the biogas or methane is produced by methane forming bacteria called methanogene in two ways which are: conversion of acetic acid (CH_3COOH) formed from the acetogenic reaction into methane (CH_4) and carbon dioxide (CO_2), and reduction of CO_2 (also formed from the acetogenetic reaction) by hydrogen (H_2) into CH_4 gas (Verma 2002; Ostrem *et al* 2004; Deublein & Steinhauser 2008). Methanogenes can also be divided into two groups: acetate and H_2/CO_2 consumers (Verma 2002).The methanogenesis reactions can be expressed as follows:

$2CH_3CH_2OH + CO_2 \rightarrow CH_4 + 2CH_3COOH$

$CH_3COOH \rightarrow CH_4 + CO_2$

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

2.3.4 Anaerobic conditions

One of the conditions that are necessary for the production of biogas is the biochemical reaction of organic matter in the complete absence of oxygen called anaerobic digestion. The presence of oxygen oxidises the organic matter into carbon dioxide and water (House 2007).

Therefore to determine a good source of biogas production, factors like these should be known: waste composition; total solids content of the waste; retention time of the whole anaerobic process; and a suitable temperature range (Dublein & Steinhauster 2008, Khalid *et al* 2011, Trzcinsk & Stuckey 2011).

2.4 Sources of biogas

As mentioned in Section 2.3, the sources of biogas are mainly municipal solid waste, municipal wastewater and agricultural waste. These are reviewed in the following sub-sections in details as well as the determination of methane emissions from them.

2.4.1 Municipal Solid Waste

The organic waste which is part of the waste collected by the municipalities consist of household waste, garden or park waste and industrial or commercial waste (Pipatti *et al* 2006).This waste is largely disposed at the municipal disposal sites especially in the developing countries (Themelis & Ulloa 2007). After being disposed and compacted in the municipal landfills, the waste undergoes anaerobic fermentation to produce biogas.

The decomposition of organic matter from the municipality solid waste disposed in the landfills was first generalised in the form of the Buswell equation by Buswell and Hatfield as a representation of organic waste degradation (Lucks 2000; Gerber 2008; Dublein & Steiner 2008; Banks 2009; Matekenya 2009) as follows:

$C_cH_hO_oN_nS_s$ + ¼(4c-h-2o+3n+2s) H_2O → 1/8(4c-h+2o+3n+2s) CO_2+ 1/8(4c+h-2o-3n-2s) CH_4 + nNH_3 + sH_2S

Buswell equation assumes complete degradation of organic fraction of the municipal solid waste, of which in reality this is not the case and also over simplifies the whole process of waste decomposition by overlooking the extent to which the waste decomposes aerobically and anaerobically (Banks 2009, Lucks 2000, Matekenya 2009).

Across the globe, it is estimated that the Municipal Solid Waste (MSW) disposed in the landfills is about 1.5 billion tons with a corresponding methane generation of about 50 million tons (Themelis & Ulloa 2007). From this waste the fraction of the organic waste in US landfills is about 65.8% and it consists of 36.2% paper/cardboard, 5.8% wood, 12.1 yard trimmings, and 11.7% food scraps (Themelis & Ulloa 2007). This quantity of MSW disposed in landfills represents only the reported global municipalities and could be higher than this if all countries municipalities are taken into consideration.

2.4.2 Emissions from Municipal Solid Waste

When the municipal solid waste is disposed in landfills, it undergoes anaerobic digestion which produces biogas (Themelis & Ulloa 2007). A large fraction of this gas constitutes anthropogenic CH_4 gas which has global warming potential that is 21 times that of CO_2 is emitted to the atmosphere (IPCC 2007b).

CH_4 emissions from landfill sites were estimated to contribute about 3-4% of the global greenhouse gases in 2001 (IPCC 2006). They are caused by the decomposition of the fraction of the organic carbon in the waste stream and from which the methane emissions can be estimated as (Aitchison *et al* 1996):

$$\boldsymbol{E_m = \left(MSW_T \times MSW_F \times MCF \times DOC \times DOC_F \times F \times \frac{16}{12} - R\right) \times (1 - OX)} \tag{2-1}$$

Where:
E_m = Methane emissions (Gg/yr)
MSW_T = Total municipal solid waste generated (Gg/yr)
MSW_F = Fraction of municipal waste disposed
MCF = Methane Correction factor
DOC = Degradable organic carbon in disposed waste (Gg C/Gg MSW)
DOC_F = Fraction DOC dissimilated
F = Fraction CH_4 in landfill gas
16/12 = ratio of CH_4 to CO_2
R = Recovered CH_4 (Gg/yr)

OX = Oxidation factor

Degradable organic carbon in disposed waste can be estimated as follows (Pipatti *et al* 2006):

$$\boldsymbol{DOC = DOC_i \cdot W_i} \qquad \textbf{(2-2)}$$

Where:

DOC = Degradable organic carbon in the waste (Gg C/Gg waste)
DOC_i = Fraction of degradable organic carbon in the organic waste type
W_i = Fraction of waste type i by organic waste category, i can be food waste, garden waste, etc.

The first part in equation 1 represent the generation of methane therefore can also be rewritten as (Pipatti *et al* 2006):

$$\boldsymbol{CH_4emissions = \left[\sum_x CH_4generated_{x,T} - R_T\right] \cdot (1 - OX_T)} \qquad \textbf{(2-3)}$$

Where:

CH_4 emissions = Methane emitted in year T (Gg)
T = inventory year
x = waste category
R_T = recovered methane in year T (Gg)
OX_T = oxidation factor in year T

The CH_4 generated throughout the years can be estimated based on the composition and the amount of waste disposed in landfill sites and the waste management practices on the disposal sites (Pipatti *et al* 2006, Zacharof & Butler 2004). This is calculated based on the decomposable degradable organic carbon present in the organic waste disposed (Pipatti *et al* 2006) as follows:

$$\boldsymbol{DDOC_m = W \cdot DOC \cdot DOC_f \cdot MCF} \qquad \textbf{(2-4)}$$

Where:

$DDOC_m$ = Mass of decomposable DOC deposited (Gg)
W = Mass of waste deposited (Gg)
DOC = Degradable organic carbon in the year of deposition (Gg C/Gg waste)
DOC_f = Fraction of DOC that can decompose
MCF = Methane correction factor in the year of deposition

As mentioned before, the organic waste disposed to the municipal landfill does not completely biodegrade over a given period of time, this means the remaining fraction that did not decompose over a given period (say after a year) will accumulate with the fresh waste that will be disposed in the following year (Pipatti *et al* 2006, Thompson *et al* 2008, Zacharof & Butler 2004). The accumulated DDOC at the end of the year T can be estimated using the first order decay model found to be the best representation of landfill conditions by (Pipatti *et al* 2006) as follows:

$$DDOC_{mo} \xrightarrow{k} DDOC_m$$

From the above chemical equation the fresh decomposable degradable organic carbon decomposes over a certain period to yield the remaining DDOC of lesser mass which is best represented mathematically in the following first order differential equation (Levenspiel 1972, Pipatti *et al* 2006):

$$-\frac{d(DDOC_m)}{dt} = kDDOC_m \tag{2-5}$$

Integration of equation 5 gives the following equation

$$DDOC_m = DDOC_{mo}e^{-kt} \tag{2-6}$$

Where:

DDOC$_m$ = mass of decomposable degradable organic carbon remaining after year t
DDOC$_{mo}$ = mass of DDOC at time zero when the reaction starts
k = decay rate constant (1/yr)
t = time in years

This implies that the DDOC$_m$ decomposed after the first year will be as follows:

$$DDOC_m decomposed = DDOC_{mo} - DDOC_{mo}e^{-k}$$

$$DDOC_m decomposed = DDOC_{mo}\left(1 - e^{-k}\right) \tag{2-7}$$

Therefore after the year t (which is between t-1 and t), $DDOC_m decomposed$ will be (Pipatti *et al* 2006):

$$DDOC_m decomposed = DDOC_{mo}\left(e^{-k(t-1)} - e^{-kt}\right) \tag{2-8}$$

Therefore the accumulated DDOC$_m$ after year t is as follows (Firmo *et al* 2011, Pipatti *et al* 2006):

$$DDOC_{ma} = DDOC_{md} + DDOC_{mo}e^{-kt} \tag{2-9}$$

Where DDOC$_{md}$ = disposed fresh waste after year t

The decay rate constant depends on each waste category disposed to the landfill site (Pipatti *et al* 2006, Zacharof & Butler 2004). The k value also determines the life or half-life of each waste category after it was initially disposed to the landfill site (Pipatti *et al* 2006).

The half-life of any decaying material is the time that material will take to decay to half its original value. It can be determined from equation 6 by substituting $DDOC_m$ with half $DDOC_{mo}$ and t with $t_{1/2}$ as follows (EPA 2011, Pipatti *et al* 2006):

$$\begin{aligned} 1/2DDOC_{mo} &= DDOC_{mo}e^{-kt1/2} \\ 1/2 \quad &= e^{-kt1/2} \\ ln1/2 &= -kt_{\frac{1}{2}}\ln{(e)} \end{aligned}$$

This gives half-life of the material as:

$$\boldsymbol{t_{1/2} = \frac{ln2}{k}} \qquad \textbf{(2-10)}$$

The half-life of decomposable waste is affected among other things, by composition of the waste and condition at the waste disposal site, the same goes for the k value (Pipatti *et al* 2006). Larger k values indicate that the waste material has high moisture content and can be rapidly degraded (e.g. food waste). On the other hand low k values are associated with dry conditions and slow degradation of materials such as wood and paper (Pipatti *et al* 2006). Pipatti *et al* (2006) recommended a k value of 0.4 for rapidly degradable materials, k = 0.05-0.07 for slow degradable waste and k = 0.17 for moderately degrading waste.

Therefore the generation of methane can be determined from the decomposed $DDOC_m$ after time t (Firmo *et al* 2011, Pipatti *et al* 2006):

$$\begin{aligned} CH_4generation &= DDOC_mdecomposed \cdot DOC_f \cdot F \cdot \frac{16}{12} \\ &= \boldsymbol{DDOC_{mo}\left(e^{-(t-1)} - e^{-kt}\right) \cdot DOC_f \cdot F \cdot \frac{16}{12}} \end{aligned} \qquad \textbf{(2-11)}$$

The waste deposition in most disposal sites is usually deposited on a daily basis throughout the year, but the CH_4 generation does not begin immediately after the waste has been deposited. There is usually a delay time in the waste decomposition before it start to generate methane (Dudek *et al* 2010 Pipatti *et al* 2006). Dudek *et al* (2010) has shown that the organic waste deposited will start generating methane after 3 months of its deposition and decomposition.

Therefore when the delay time of three months for waste decomposition and methane generation is considered, the decomposed waste during the year of disposal would change equation 7 to (Pipatti *et al* 2006):

$$\boldsymbol{DDOC_mdecomposed = DDOC_{md}\left(1 - e^{-k\left(\frac{9}{12}\right)}\right)} \qquad \textbf{(2-12)}$$

The remaining waste after decomposition in the year of waste disposal would be (Pipatti *et al* 2006):

$$DDOC_m remaining = DDOC_{md} e^{-k\left(\frac{9}{12}\right)} \quad \textbf{(2-13)}$$

So, the accumulated waste after the year of the disposal would be (Pipatti *et al* 2006):

$$DDOC_{ma} = DDOC_m remaining + DDOC_{md} \quad \textbf{(2-14)}$$

The methane correction factor (MCF) accounts for the fact that unmanaged solid waste disposal sites (SWDS) produce less CH_4 from a given amount of waste than managed SWDS. This is caused by a larger fraction of waste that decomposes aerobically in the top layers of unmanaged SWDS (Pipatti *et al* 2006). The methane correction factors for the managed SWDS has the assumed default value of 1, the unmanaged SWDS with waste depth greater than or equal to 5 m has the assumed default value of 0.8, unmanaged SWDS with waste depth less than 5 m has default value of 0.4 and the uncategorised SWDS has the default value of 0.6 (Pipatti *et al* 2006).

Fraction of DOC dissimilated is an estimate of the fraction of the carbon that is ultimately degraded and released from the SWDS (Pipatti *et al* 2006).

The recovered methane gas is estimated to achieve about 85% of the methane gas generated for the full engineered and capped landfill (Timoney 2009). In most developing countries this value is zero as they have yet to have programmes that recover methane gas generated from municipal landfills.

The oxidation factor (OX) reflects the amount of CH_4 from SWDS that is oxidised in the soil or other material covering the waste (Pipatti *et al* 2006). Currently, most industrialised countries with well-managed SWDS use 0.1 for OX (Pipatti *et al* 2006).

In most of the OECD countries the landfill gas or biogas is currently recovered for the generation of electricity and heat, and as from 2001-2006 there were about 955 landfills from where the biogas was recovered (Willumsen 2003 as cited by Themelis & Ulloa 2007). Globally, it is estimated that only about 10% of methane is captured for use as energy source with the rest being emitted into the atmosphere especially in the developing countries (Themelis & Ulloa 2007).

2.4.3 Municipal Solid Waste generation in South Africa

The municipal waste generation in South Africa that ends up in the landfills was estimated in 2011 to be about 20.8 million tons/annum of organic waste (DEA 2012). Six major metropolitan municipalities in the country (like Ekurhuleni, City of Johannesburg, City of Tshwane, City of Cape Town, Nelson Mandela Bay Municipality, and eThekwini Municipality) were alone estimated to dispose about 8.87 million tons of combined solid waste to landfills in 2005 (Von Blottnitz *et al* 2006). In some of these cities, the waste disposal per capita is 3-4 times greater than that in many European cities at more than 2 kg per capita per day.

Municipal waste generation differs across income groups in the country with low, middle and high-income groups disposing about 0.41, 0.74, and 1.29 kg/capita respectively (Fien & Ball 2005 as cited by DEA 2011b). This waste generation across the country was expected to increase at a rate of about 2-3% per annum because of population and economic growth (Fien & Ball 2005 as cited by DEA 2011b).

The country has 226 municipalities with 540 registered landfill sites, of which 61% of them are permitted for waste disposal (Von Blottnitz *et al* 2006). Friedrich & Trois (2013) reported the total number of recorded landfill sites in South Africa to be 1203 with only 44% of these permitted to dispose waste. Of the permitted landfill sites, only 5 have landfill gas collection and flaring system; and only 3 collect and generate electricity from landfill gas (Friedrch & Trois 2013). This information is shown in Table 2-2. Other waste is disposed in unregulated and unplanned dumpsites (Von Blottnitz *et al* 2006). It is estimated there are 15 000 of these dumpsites in the country (Friedrch & Trois 2013).

Waste composition data is fragmented in South African municipalities, with large municipalities recording and publishing this kind of information with irregular frequencies, and many small municipalities have no records at all (Friedrich & Trois 2013). Table 2-2 shows the weighted average waste composition in South Africa calculated from the published waste information for different municipalities (Friedrich & Trois 2013). The waste was weighted according to the mass of waste collected and reaching the landfill sites.

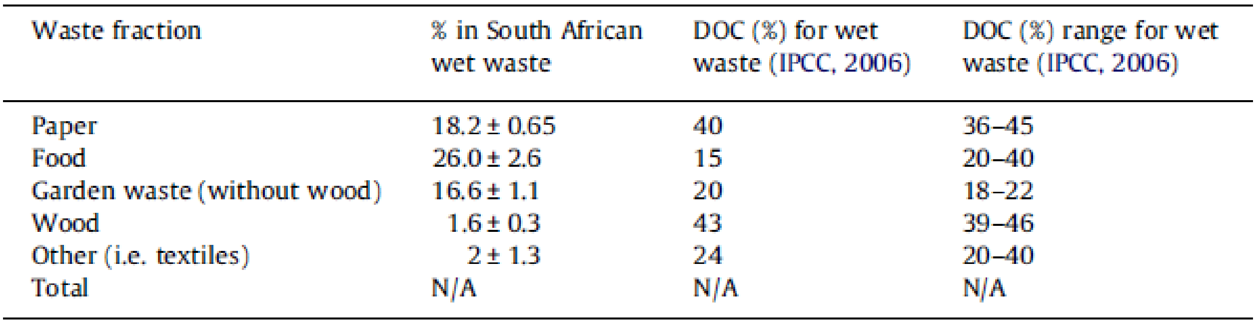
Table 2-2: Municipal waste composition for different municipalities in South Africa with published information (Source: Friedrich & Trois 2013)

Municipality	Waste composition (%) (a) (b) (c) (d) (e) (f) (g)	Amount of waste reaching landfills (tons)	Information on landfill sites
EThekwini, 3.6 million people	(16), (3), (7), (12), (29), (18), (15)	1 654 000 for 2009	4 permitted landfill sites
City of Johannesburg, 3.9 million people	(18.05), (3), (4.15), (10.26), (13.37), (19.40), (31.79)	1 492 000 for 2008	5 permitted landfill sites
City of Cape Town, 3.5 million people	(15), (2), (4), (5), (31), (20), (23)	1 659 400 for 2011	4 permitted landfill sites
Nelson Mandela Bay, 1.1 million people	(18.8), (3), (6.3), (14.9), (46), (4.3), (6.6)	619 099 for 2008	3 permitted landfill sites with medium engineering
Umsunduzi, 616 000 people	(21.1), (4.2), (6), (7.6), (32.1), (0.7), (28.3)	169 000 for 2010	1 permitted landfill site with medium engineering
Umdoni , 62 290 people	(12), (4), (5), (7), 45 together, (8)	31 884 for 2008	1 permitted landfill site with basic engineering
City of Potchefstroom, 128 400 people	(24), (4), (8), (10), (51) together, (3)	647 340 for 2010	1 permitted landfill site with medium engineering
City of Mafikeng, 259 500 people	(4.2), (3.97), (14.39), (7.14), included with “other”, (9.74), (60.51)	52 925-158 775 for 2009	1 permitted landfill site,
Makana, 75 000	(14), (3), (12), (13), (12), (19), (27)	32 986 for 2007	1 permitted landfill site
Weighted average	(18.2 ±0.65), (3.9 ±0.35), (6.9 ±0.54), (12.1 ±0.45), (26.0 ±2.6), (18.2 ±1.14) excl. wood and (1.4 ±0.3) for wood, (15.9 ±3.35)	n/a	n/a

(a) Paper, (b) Metals, (c) Glass, (d) Plastic, (e) Food waste (Organic), (f) Garden waste (Green), (g) Other. The figures under waste composition represent these waste categories chronologically.

The average degradable organic carbon (DOC) of each waste type was calculated for the country using waste data depicted in Table 2-2 and the DOC estimation methodology of IPCC (2006) described in Section 2.4.2, this is shown in Table 2-3 (Friedrich & Trois 2013).

Table 2-3: Average DOC calculation for the different waste types in South Africa (Source: Friedrich & Trois 2013)



Waste fraction	% in South African wet waste	DOC (%) for wet waste (IPCC, 2006)	DOC (%) range for wet waste (IPCC, 2006)
Paper	18.2 ± 0.65	40	36–45
Food	26.0 ± 2.6	15	20–40
Garden waste (without wood)	16.6 ± 1.1	20	18–22
Wood	1.6 ± 0.3	43	39–46
Other (i.e. textiles)	2 ± 1.3	24	20–40
Total	N/A	N/A	N/A

2.4.4 Municipal Solid Waste generation in 6 major Metros in South Africa

This sub-section reviews the status of solid waste generation in 6 major metropolitan municipalities in the country because they represent more than one third of the country's population and have reported data on waste through the integrated waste management plan.

2.4.4.1 City of Cape Town

The City of Cape Town has one of the highest waste footprints in the country with 2.1 million tons of waste being disposed at the City's landfill sites in 2007/8 (COCT 2012). The City's population, which has increased by 3% per annum in recent times has caused this huge amount of waste generation (COCT 2011). The City originally had six landfill sites and three of them are already closed and the remaining three that are currently in operation were filling up at a rate of 7% per annum until the City adopted its Integrated Waste Management Policy in 2006/7 (COCT 2006). After the adoption of the policy, the waste generation growth in the City's landfill sites dropped from 7% to 2.5% per annum (COCT 2011).

The split between residential waste and industrial (combined with commercial) waste in the country is approximately 46 and 54% respectively (COCT 2011). The households generate approximately 46%, the industry excluding hazardous waste approximately 27% and commerce approximately 26% of the waste generation in the city (COCT 2011). From this waste generation in the City, the green and organic waste makes up approximately 40% of it. This kind of waste aggregate is a source of biogas, and when it is disposed and compacted in the city's landfills, it undergoes anaerobic biodegradation process to produce biogas.

In the 2004 status quo report, the city showed that household waste generation in the city depends on the income group (Jeffares & Green 2004). The low-income household generate more organic waste than any income groups at about 57.2% of the total waste with middle and high-income households generating about 38.8 and 38.9% respectively (Jeffares & Green 2004). This is shown in Table 2-4.

Table 2-4: Waste characterisation by income group in the City of Cape Town (Source: Von Blottnittz *et al* 2006)

Waste type	High income (%)	Middle income (%)	Low income (%)
Organic	38.9	38.8	57.2
Paper	17.4	22.7	16.4
Plastic	14	15.5	9.9
Metal	9	4.7	3.5
Glass	12.5	7	6.1
Other	8.2	11.2	6.3

Currently, the City of Cape Town has two composting plants, namely Radnor and Bellville compost plants, which were commissioned in the 1960's (COCT 2012). Both plants were composting up to 126 500 tons/yr of municipal waste and sewage sludge and converting the organic component of it to compost. The Radnor compost plant was closed due to low quality of the compost, which included other household waste like plastic materials and as a result caused low sales of compost (Engledow 2007, and COCT 2012). The Bellville compost plant is currently operating at high costs and is unsustainable (Akhile Consortium 2010 as cited by COCT 2012). This plant takes 90 tons/day of mixed municipal waste from Bellville, Brackenfell, and Durbanville area, sort it by removing plastic waste, glass, metals and other non-degradable waste separately and send it for recycling and landfilling (COCT 2012). The green waste considered to produce compost, includes garden waste and some parts of household food waste.

A large part of other organic waste like paper and cardboard is recycled at large paper companies like Mondi, Sappi, and Nampak, which buy the paper and cardboard at buy-back centres across the city (Engledow 2007).

Part of the green waste especially the food waste still ends up in the City's landfill sites which is then compacted and eventually undergo anaerobic biodegradation to produce biogas. It is estimated that between 45% and 54% of total organic waste could be diverted from the City's remaining landfills (COCT 2012).

2.4.4.2 City of Johannesburg

This City of Johannesburg is the most populated city in the country with an estimated population of the municipal city of 3,607 million people (CIA 2012). It has experienced the biggest population growth within the Gauteng Province from 2001 to 2007 at 20.6% (Stats SA 2001 and 2007 as cited by COJ 2011). This has caused the city to have an increased waste generation due to this population increase, leading the city to be among the highest waste generators in the Country (COJ 2011, Von Blottnitz *et al* 2006). This waste is disposed in the city's 5 disposal sites (GDACE 2008).

The City of Johannesburg is currently curbing about 50 000 tons of garden waste per annum from landfill disposal through composting it, and this is done at the Pikitup site in Panorama on the West

Rand (GDACE 2008). The plant receives shredded garden waste from various garden depots in Johannesburg and composts it for domestic, agricultural and municipal markets (GDACE 2008).

The other organic waste like paper and cardboard are recycled by major paper companies in the country like Sappi, Mondi, Nampak, etc, of which there is a success recovery rate of about 57% in 2006 (GDACE 2008).

This shows that other household organic waste such as food waste end up in the city's landfills. After they are compacted they eventually undergo an anaerobic biodegradation process that produces biogas.

2.4.4.3 City of Tshwane Municipality

The City of Tshwane generates more waste than any other municipality in the country, which is disposed in nine landfill sites of the municipality (GDACE 2008). It developed a waste minimisation programme, which included recycling of the waste that is received in the municipality's landfill sites (GDACE 2008). There were two drop-off centres that were built and training was provided on the environment need to recycle waste for the reclaimers (GDACE 2008).

This initiative resulted in about 595,901 tons of the total waste received in 2006/7 being reclaimed from the landfill sites (GDACE 2008). The biggest contribution to this reclaim was the recovery of the used bricks (GDACE 2008). The organic waste like paper and cardboard are diverted from the municipality's landfills and recycled by large paper companies in the country (GDACE 2008). The rest of the organic waste is left in landfills of the city.

2.4.4.4 Ekurhuleni Metropolitan Municipality

The Ekurhuleni Metropolitan Municipality established a policy of diverting all the garden green waste from the landfill sites as well as paper and cardboard waste (GDACE 2008). This type of waste constituted about 500,000 tons per annum of the total waste generated in 2004/5 (Von Blottnitz *et al* 2006). The rest of the organic waste is disposed in city's five landfill sites.

This municipality started Clean Development Mechanism (CDM) projects in 4 of their operational landfill sites. The CDM allows developing countries to earn certified emission reduction credits through emission reduction projects at one ton CO_2 equivalent for each credit (EMM 2011). These credits can be traded to developed countries for use as part of their emission reduction targets stipulated under the Kyoto Protocol. The municipality signed a purchasing agreement with the Spanish energy utility company called ENDESA where they were required to reduce a minimum of CO_2 emissions equivalent of 800 000 tons during the five year contract period (2007-2012) (EMM 2012).

These emission reduction credits were earned through capturing of CH_4 gas generated in those four landfill sites and combusted it for electricity generation (EMM 2011). In this way, there are two types of emissions that are reduced: CH_4 emissions which would have been flared to atmosphere and avoided CO_2 emissions through reduction in fossil fuels burning in power generation plants.

Since the time of commissioning of these projects, the landfill gas capturing and combustion systems have earned a total of 175 031 tons CO_2 equivalent reductions in June 2008 (EMM 2011). From July 2010 – June 2011, the emission reductions credits earned were 46 934 (EMM 2012).

The municipality currently recovers the landfill gas using vertical wells and horizontal collection systems (EMM 2011). Wellheads connect individual gas wells to the gas collection pipework laid to upgrade biogas extracted to facilitate condensate management (EMM 2012). Wellhead controls include gas monitoring points for quality, pressure and gas flow (EMM 2012). Landfill gas is extracted from the landfill under a vacuum (EMM 2012). Flow control valves control vacuum pressure at each well and pneumatic pumps installed in the vertical wells and the knockout pods extract leachate and condensate from the system (EMM 2012).

2.4.4.5 Nelson Mandela Metropolitan Municipality

Waste generated in the Nelson Mandela Metropolitan Municipality is disposed in three licensed landfill sites in the municipality (NMBM 2013).The municipality started the composting of green garden waste as well as diversion of paper and cardboard from the municipality's landfill sites (NMBM 2005). The rest of the organic waste remains being disposed in the landfill sites.

There is also a landfill gas to energy project proposed for two of the municipality's main landfill sites. The description of the project is as follows (UNFCCC 2011):

The project will collect the LFG (containing approx. 50% CH_4 by volume) by means of a number of horizontal and vertical extraction wells installed into the sites. The LFG is extracted via interlinking pipe network to a blower which creates lower pressure inside the wells than inside of the landfill site. The LFG is pumped from landfill site and delivered to LFG engines with excess gas being delivered to a high-temperature enclosed flare system. The destruction of CH_4 and generation of electricity occurs in the system at the same time. The amount of methane destroyed and electricity generated are accurately monitored with specialised equipment.

2.4.4.6 EThekwini Municipality

The EThekwini Municipality has approximate population of 3.16 million people (Trois & Jagath 2011). Solid waste in the municipality is disposed at three landfill sites of the city (EMA 2011). Paper and cardboards are diverted from the landfill sites for recycling.

This Municipality started a CDM project in two of the landfill sites in the municipality, which were Mariannhill and Bisasar landfills. The Mariannhill landfill, which takes about 450 tons/day of waste and peak at around 700 tons/day consist of a single 1 MW engine that has been installed (EMA 2011). The gas from this landfill sites is extracted through 13 vertical and six horizontal wells (EMA 2011).

The Bisasar landfill, which is the busiest landfill site in South Africa (Von Blottnitz *et al* 2006), takes about 3500 tons/day of waste and peak around 5000 tons/day (EMA 2011). It consist of six one MW and one 0.5 MW engines that has been installed (EMA 2011). The gas is collected through 77 vertical and 77 horizontal wells (EMA 2011). The schematic layout of the project from gas extraction to electricity generation and distribution is shown in Figure 2-4. The extraction of landfill gas through the installed gas wells is schematically represented in the methane balance Figure 2-5 (Bogner *et al* 2007, Moodley *et al* 2010):

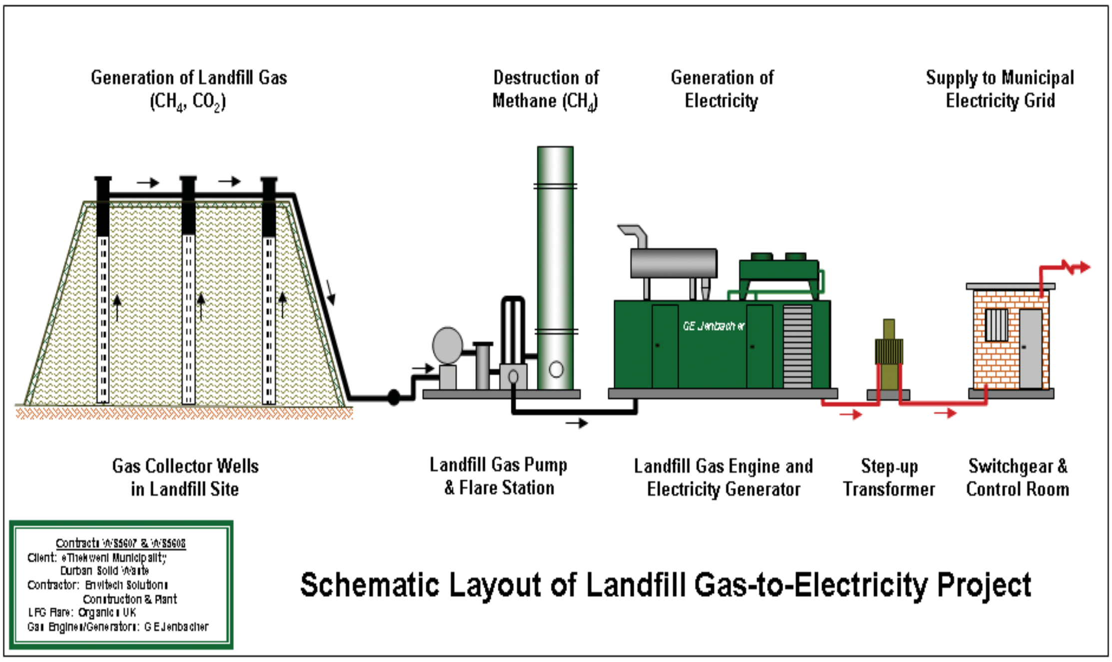


Figure 2-4: Layout of Landfill Gas to Electricity Project at eThekwini Municipality (Source: Strachan *et al* 2007)

Figure 2-4 shows how biogas generated from the disposed municipal solid waste can be captured and utilised as an energy source for both heat and electricity generation.

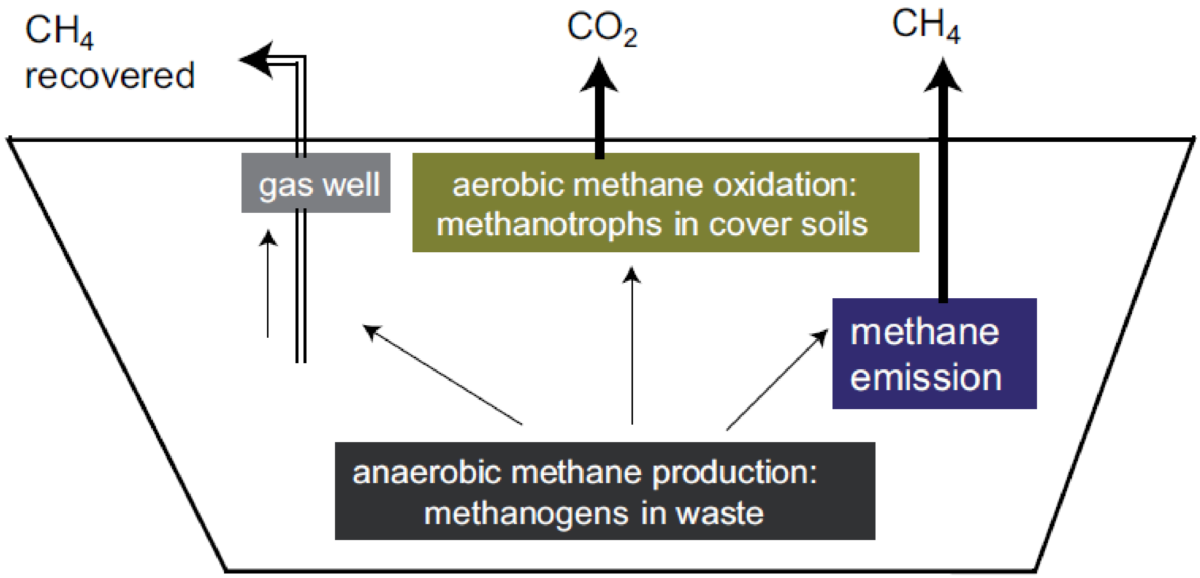


Figure 2-5: Methane recovery from the typical landfill site (Source: Bogner *et al* 2007)

From Figure 2-5 the CH_4 recovered can be determined using mass balance of CH_4 method as follows:

$$\boldsymbol{CH_4 recovered = CH_4 produced - (CH_4 oxidised + CH_4 emitted)} \qquad \textbf{(2-15)}$$

CH_4 is produced through anaerobic digestion of the organic waste and it is recovered through the gas wells. Some of the CH_4 produced is emitted to the atmosphere, some of it is oxidised aerobically to become CO_2 as showed in the following chemical equation:

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

The lessons from the projects like these can be extended to other municipalities in the country to reduce GHG emissions from the waste disposed in South African landfills. The best thing about this technology is that it has the potential to reduce the burning of coal in the South African power stations, thus reducing associated CO_2 emissions. It should also be mentioned that landfill sites are anticipated to generate landfill gas for the next 20-25 years after their closures (UNFCCC 2011). Therefore this period can also be considered for the landfill sites in the country that are already closed.

2.4.4.7 GHG emissions in South African landfills without gas collection

The majority of landfills in South Africa do not have landfill gas collection system (Friedrich & Trois 2013). The direct emissions from these types of landfills are estimated as follows (Friedrich & Trois 2013):

$$\boldsymbol{Emitted\ CH_4 = generated\ CH_4 \cdot MCF \cdot (1 - OX)} \qquad \textbf{(2-16)}$$

The direct GHG emissions from the dumps are estimated as follows (Friedrich & Trois 2013):

$$CH_4 emitted = DOC \cdot D_{LFG} \cdot \frac{55}{100} \cdot \frac{16}{12} \qquad \textbf{(2-17)}$$

D_{LFG} is the fraction of DOC dissimilated as landfill gas of which 55% becomes CH_4.

2.4.5 Municipal Wastewater

Globally, Municipal Wastewater in countries with extensive wastewater collection infrastructure is treated in their centralised wastewater treatment plants (ERG & PA 2009). During the treatment process, the solids and organic content of the wastewater are reduced using physical processes to settle or filter out solids and biological processes in which microorganisms such as bacteria consume the organic constituents (Fine & Hadas 2012). The biological processes include the anaerobic biodegradation of the organic matter to produce CH_4 and CO_2.

Wastewater originates from a variety of domestic, commercial and industrial sources and may be treated on site (uncollected), sewed to a centralised plant (collected) or disposed untreated nearby or via an outfall (Doorn *et al* 2006).

The extent of CH_4 production depends primarily on the quantity of degradable organic material in the wastewater, the temperature of the wastewater, and the type of treatment system (Ozgun *et al* 2013). An increased temperature of the wastewater causes an increase in the rate of CH_4 production (ERG & PA 2009, Ozgun *et al* 2013). The commonest parameters that can be used to measure the level of CH_4 generation in wastewater are the biological oxygen demand (BOD), which represents the amount of oxygen required to completely consume the organic matter in a wastewater through aerobic decomposition process or chemical oxygen demand (COD), which represents total material available for chemical oxidation (Listowski *et al* 2011). Higher BOD/COD concentrations in wastewater show that the wastewater will yield higher amounts of methane (Doorn *et al* 2006, ERG & PA 2009). Since the BOD is an aerobic parameter, it may be less appropriate for determining the organic components in anaerobic environments; also both the type of wastewater and the type of bacteria present in the wastewater influence the BOD concentration of the wastewater (Doorn *et al* 2006). Usually BOD is more frequently reported for domestic wastewater, while COD is predominantly used for industrial wastewater.

The retention time of the wastewater in a given type of treatment system also influences the quantity of CH_4 generated by that waste type particularly if the wastewater treated contains high concentration of suspended solids which are insoluble organics (RPI 2013). In such cases the recommended retention time should be 10-20 days (RPI 2013).

CH_4 production from the wastewater is directly resulting from anaerobic digestion of organic matter present in wastewater (Doorn *et al* 2006, Listowski *et al* 2011). The main environmental factors which influence the production of CH_4 include retention time, pH, temperature, presence of sulphate reducing bacteria and methanogens (Guisasola *et al*. 2008 as cited by Listowski *et al* 2011).

2.4.5.1 Emissions from the wastewater

Wastewater is also considered a global warming factor because in the absence of proper treatment that involves anaerobic removal of the organic fraction of the wastewater, the carbon that is present in the discharged wastewater stream will eventually enter the ecosystem as CH_4 (Doorn *et al* 2006, Listowski *et al* 2011). CO_2 generated from the anaerobic decomposition of wastewater is not considered to be greenhouse gas and is excluded from the total emissions because it is of biogenic origin (Doorn *et al* 2006).

The IPCC estimates CH_4 emissions from wastewater as follows (PDG 2004):

$$\boldsymbol{E_{CH4} = Total\ COD \times B_o \times MCF} \qquad \textbf{(2-18)}$$

Where:

COD = Chemical Oxygen Demand of the wastewater to be treated

B_o = Maximum methane producing capacity (0.25 kg CH_4/ kg COD

MCF = Methane correction factor

In most of the developed countries the wastewater treatment process is also used as an energy source, where the CH_4 generated under anaerobic conditions in the wastewater treatment tank is captured for electricity and heat generation (Listowski *et al* 2011). The same cannot be said about the developing countries like South Africa where very little effort has been made to capture methane from the wastewater treatment sludge that is disposed to the environment (Snyman 2007).

2.4.5.2 Status quo of municipal wastewater treatment in South Africa

Wastewater treatment in South Africa occurs in about 986 plants nationally (Adewumi *et al* 2010). Most of these plants are relatively small in capacities with: 7% of them having a capacity about 25 ML/day or more; 10% of them having a capacity of 10-25 ML/day; 21% of them having a capacity of 2-10 ML/day; 11% of them having a capacity of 0.5-2 ML/day; and 50% of them with a capacity less than 0.5 ML/day (Snyman 2007).

From the national survey made by Snyman (2007), it was found that about 81% of the plants have inadequate disposal and use of the sludge and none of them complied with sludge disposal guidelines that were developed earlier in 2007. As a result, this caused a negative environmental and health impacts. This survey was made in 51 plants in 9 provinces across the country as depicted in Figure 2-6.

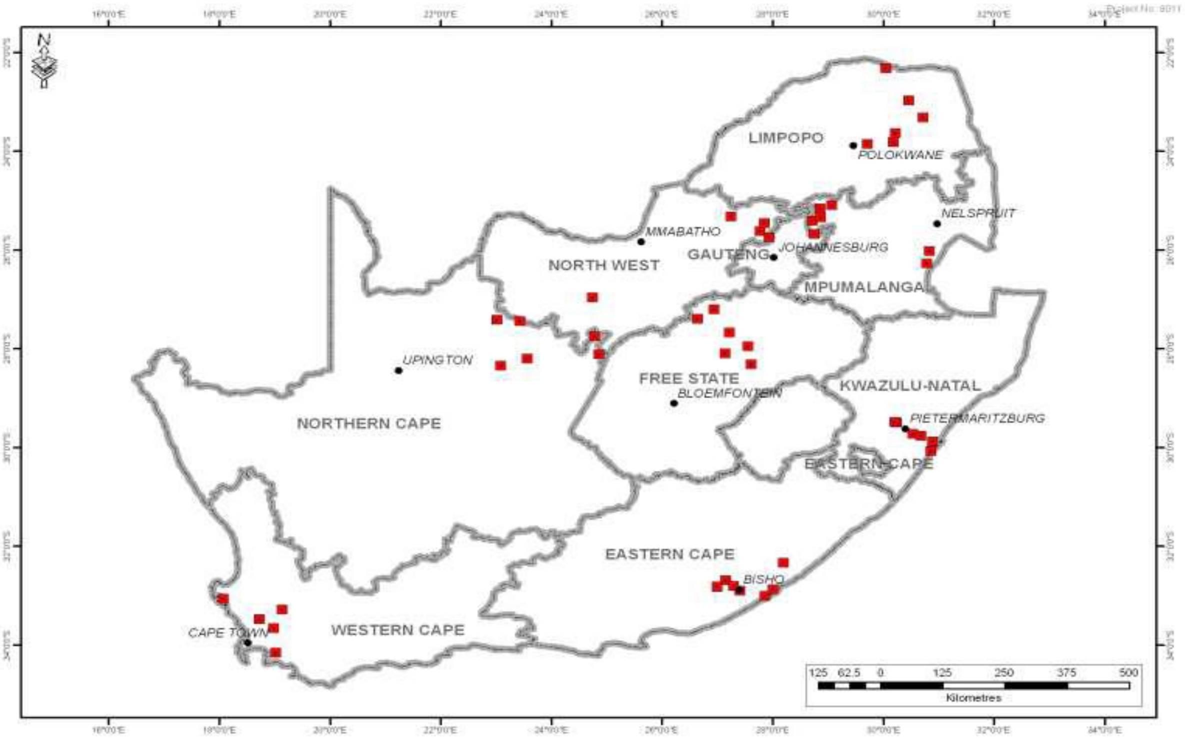


Figure 2-6: Locations (red squares) of the wastewater treatment plants that were surveyed (Source: Snyman 2007)

Von Blottnitz *et al* (2009) evaluated the potential of using wastewater as an energy source in South Africa, which included both the industrial and domestic wastewater. They have found that from the total municipal wastewater of the country, about 18.91 kg/s of methane gas can be removed for electricity generation.

For the City of Cape Town municipality it was discovered that the municipal wastewater has about 22% of the daily loads from the industrial wastewater with the rest coming from commercial and domestic wastewater (Von Blottnitz *et al* 2009). Other industries carry their pre-treatment on site before discharging it to the wastewater treatment plants, while others discharge them directly to land, rivers or sea (Von Blottnitz *et al* 2009).

For the eThekwini municipality, most of the industries do not discharge their wastewater into the municipal wastewater treatment plants, but some have their own on-site treatment and others discharge it directly to sea at very high loads containing high COD (Von Blottnitz *et al* 2009).

This shows the anaerobic treatment of municipal wastewater which would include biogas capture has received very little attention in the country today. The consequence of this is massive emissions of anthropogenic methane into atmosphere.

2.4.5.3 Industrial wastewater

Biogas production from industrial wastewater is based on the concentration of degradable organic matter in the wastewater, volume of the wastewater, and the propensity of the industrial sector to treat their wastewater in the anaerobic systems (Doorn *et al* 2006). The sources of industrial wastewater that have a high biogas production are (Hernandes *et al* 2013, Rodriques *et al* 2013): brewing, paper and pulp, fruit processing, meat and poultry processing, food and beverages, and petrochemical industries.

The wastewater from these industries is either discharged to the municipal wastewater system treated on site, or directly discharged to the ecosystem at high volume of loads (Doorn *et al* 2006, DEA 2012). The emissions are estimated using Eq. (2-18).

2.4.6 Agricultural waste

The biogas production is only reviewed for the livestock manure, because in South Africa, all the crops that are cultivated are not grown in wetlands like rice cultivation. Therefore the decomposition of their residues is not anaerobic but aerobic and they emit CO_2 instead of CH_4 gas.

When the livestock manure (dung and urine) decompose under anaerobic conditions, during storage and treatment, they produce CH_4 (Dong *et al* 2006). These conditions occur most readily when large numbers of animals are managed in a confined area (e.g. dairy farms, beef feedlots, and swine and poultry farms), and where manure is disposed of in liquid-based systems i.e. lagoons (Dong *et al* 2006).

2.4.6.1 Emissions from the livestock manure

The main factors influencing CH_4 emissions from the animal manure are (Chadwick *et al* 2011): the amount of manure produced and the portion of it that decomposes under anaerobic conditions. The amount of manure depends on the rate of waste production per animal and the number of animals kept confined, the portion that decomposes depends on how the manure is managed. When manure is stored or treated as a liquid (e.g. in lagoons, ponds, tanks, or pits), it decomposes anaerobically and can produce a significant quantity of CH_4 (Massé *et al* 2011). The temperature and the retention time of the storage unit greatly affect the amount of CH_4 produced (El-Mashad *et al* 2004). When manure is handled as a solid (e.g. in stacks or piles) or when it is deposited on pastures and rangelands, it tends to decompose under more aerobic conditions and less CH_4 is produced (Dong *et al* 2006).

The emissions from managed livestock manure can be estimated as follows (Dong *et al* 2006):

$$\boldsymbol{CH_{4manure} = \sum_{(T)} \frac{(EF_T \cdot N_T)}{10^6}} \qquad \textbf{(2-19)}$$

Where:

CH_4 manure = CH_4 emissions from manure management, for a defined population, Gg CH_4 yr^{-1}

EF_T = emission factor for the defined livestock population, kg CH_4 $head^{-1}$ yr^{-1}

N_T = the number of head of livestock species/category *T* in the country

T = species/category of livestock

The emission factor can be determined as follows (Dong *et al* 2006):

$$\boldsymbol{EF_T = (VS_T \cdot 365) \cdot \left[B_{o(T)} \cdot \frac{0.67kg}{m^3} \cdot \sum_{S,k} \frac{MCF_{S,k}}{100} \cdot MS_{(T,S,k)}\right]} \tag{2-20}$$

Where:

$EF_{(T)}$ = annual CH_4 emission factor for livestock category *T*, kg CH_4 $animal^{-1}$ yr^{-1}

$VS_{(T)}$ = daily volatile solid excreted for livestock category *T*, kg dry matter $animal^{-1}$ day^{-1}

365 = basis for calculating annual VS production, days yr^{-1}

$B_{o(T)}$ = maximum methane producing capacity for manure produced by livestock category *T*, m^3 CH_4 kg^{-1} of VS excreted

0.67 = conversion factor of m^3 CH_4 to kilograms CH_4

$MCF_{(S,k)}$ = methane conversion factors for each manure management system *S* by climate region *k*, %

$MS_{(T,S,k)}$ = fraction of livestock category *T*'s manure handled using manure management system *S* in climate region *k*, dimensionless

2.4.6.2 Status of South African livestock manure production and management

As mentioned before, biogas from livestock manure is only produced when a large number of the animals are kept in confined areas e.g. in dairy farms, beef feedlots, swine and poultry farms and where manure is disposed in liquid based systems like lagoons (Doug *et al* 2006). In South Africa, this is also the case where out of the 2005 cattle population of 13.8 million, 8.2% and 15% is made of dairy cows and beef feedlots respectively with a population growth of about 0.2% (Taviv *et al* 2007). The swine population in 2005 was about 1.656 million pigs with a population growth of 0.61%. The poultry population around the same year was about 20.5 million chickens with average life cycle of 60 days in a year and they had the population growth of 2.4% (Taviv *et al* 2007).

Taviv *et al* (2007) also found that the manure excreted by the livestock in South Africa is managed by storing some of it in the lagoons and spreading the rest in the agricultural soil. This is shown in Table 2-5:

Table 2-5: %manure stored and handled by different manure management systems for different animal types (Source: Taviv *et al* 2007)

Management System	Free range	Dairy	Feedlot	Pigs	Poultry
% lagoons	0	50	20	50	20
% spread	100	50	80	50	80

The percentage of manure stored in lagoons as shown in Table 2-5 undergoes anaerobic digestion that produces biogas. From this biogas CH_4 gas will be emitted into atmosphere of which this is estimated to constitute about 30% of all agricultural CH_4 emissions (Taviv *et al* 2007).

There are currently potentially few biogas initiatives in South Africa like the Lesedi Biogas Project in Gauteng province which was expected to generate about 5.3 MW of electricity with manure from 130 000 cattle by mid-2011 (DA 2010). There is also a project under investigation in the Limpopo province that will supply about 180 rural households with biogas from 60 digesters with a capacity of 15 m^3 each (DA 2010).

2.4.7 Typical biogas technologies used for biogas production

Under the Section 2.4, the biogas resources have been highlighted as well as the emissions that from the biogas production. It has also been shown that biogas, due to its heat capacity, can also be used as an energy source. Therefore, instead of disposing organic waste to the ecosystem, it can be converted to useful energy. One way of achieving this is through the use of biogas digesters which produce biogas as an energy source for heat and electricity generation. In the following sub-sections, different types of this technology are reviewed.

2.4.7.1 Chinese Fixed Dome Digester

This type of digester is installed under the ground where the gas and the slurry are in the same storage tank (Helanya 2010, Letete 2011). Both the pit and dome are constructed by bricks and cement (Helanya 2010). As the gas is collected above the decomposing feedstock it displaces the sludge towards the displacement tank where it is collected as the fertiliser. Biogas is collected through the gas pipe and transferred to the point of use where it is used as an energy source either for heat or electricity generation. This is shown in Figure 2-7

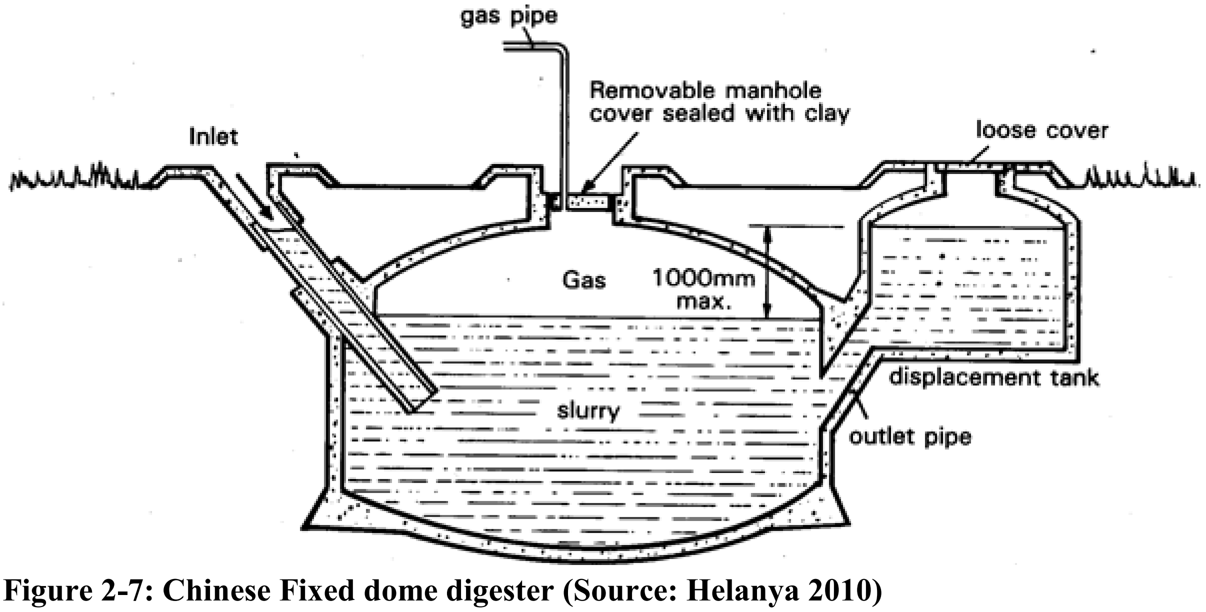


Figure 2-7: Chinese Fixed dome digester (Source: Helanya 2010)

2.4.7.2 Indian floating drum digester

This biogas digester has a floating gas cover that expands and contracts according to the volume of gas produced (Helanya 2010, Letete 2011). The mixing tank is used to mix the feedstock which is then transferred through the inlet pipe to the storage tank where the anaerobic process happens (Helanya 2010, Sibisi & Green 2005). The slurry is collected in the pit below the ground. The gas drum made of steel is placed on top with its opening facing downward. The gas collects in the drum and floats higher as more gas is produced and lower as gas is removed (Helanya 2010). This is shown in Figure 2-8.

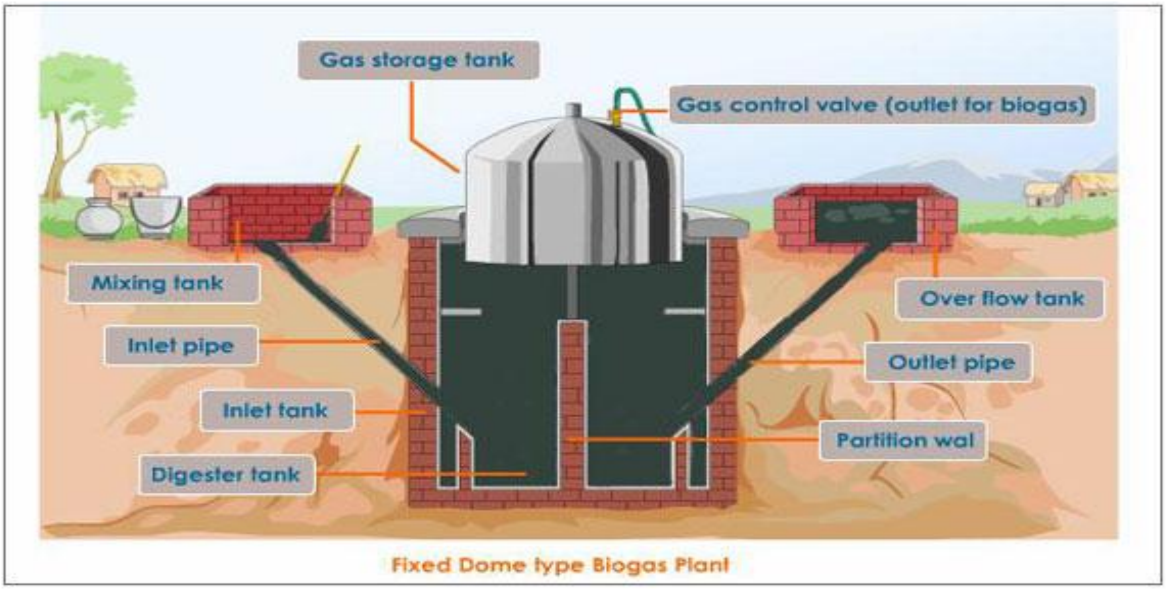


Figure 2-8: Indian floating drum digester showing the digester built under ground with immersed floating drum to collect biogas (Source: Letete 2011)

2.4.7.3 Bag Digester

This biogas digester consists of a plastic cylindrical bag placed in a trench with an inlet and outlet pipe (Helanya 2010). When the gas is produced it inflates the bag which can be weighed down at the top to maintain the gas pressure. The lower two-thirds of the bag are filled with the slurry (Helanya 2010).

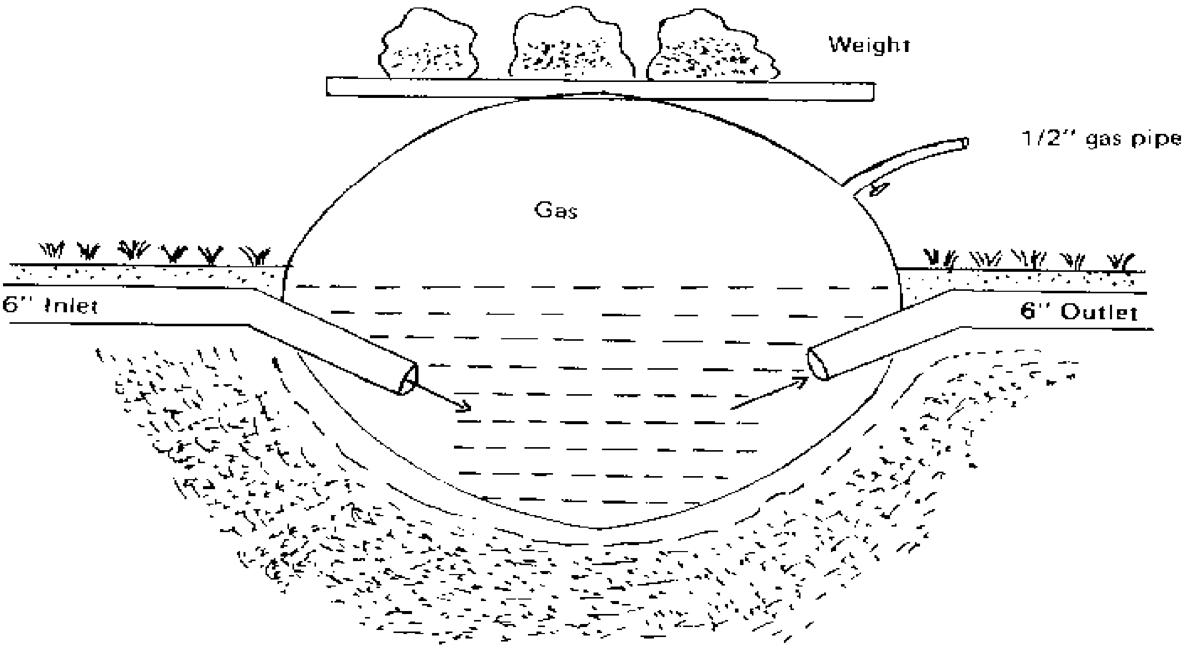


Figure 2-9: Bag digester placed in a trench with inlet and outlet pipe to feed the waste and discharge effluent respectively (Source: Helanya 2010)

All these three types of biogas digesters are suitable for small scale biogas production that can be used for off-grid heat and electricity generation (Helanya 2010 Sibisi & Green 2005). They are even more efficient and less costly if they can be used directly for heating (Cheng 2013).

2.4.8 Optimisation of biogas production

It is also possible to design biogas digesters for the large scale biogas production that can be used to generate grid electricity and heat (Bates 2007, Juwi 2013, and Krieg & Fischer 2008). One such example is the case study made on Holsworthy Biogas Plant in UK by Pace (2013). This biogas plant mixes different types of waste like livestock manure collected by lorries from 17 farms and food waste from local food factories. These waste types are mixed together in the pit and passed through the pasteurisation process to kill disease carrying bacteria and viruses by heating the mixture up to 70°C after which it is transferred to the 4000 m^2 biogas digester at 37°C. The CH_4 gas produced from this plant is piped to large gas engines to generate electricity for the area which is enough to power 3500 homes with electricity of 14 million kWh every year. The digestate is given back to the farmers as fertiliser for farm fields. This plant is shown in Figure 2-10 and Figure 2-11.

Figure 2-10: Holsworthy Biogas Plant in UK (Source: Pace 2013)

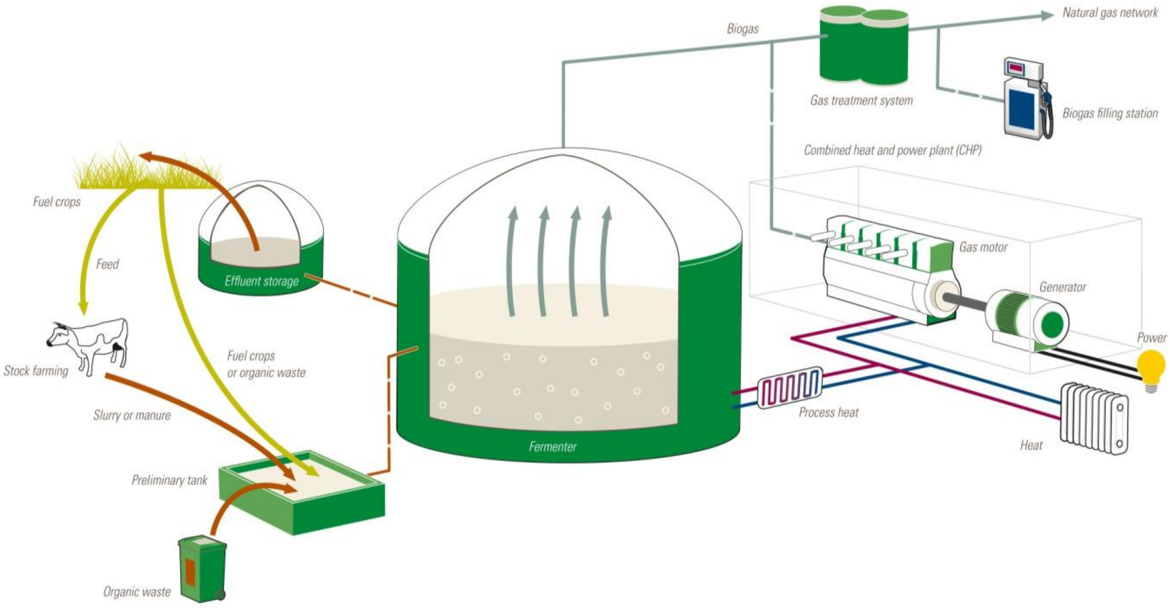


Figure 2-11: Biogas production and utilisation as an energy source for large scale operation (Source: Juwi 2013)

When the waste types are blended in the preliminary tank (Figure 2-11), it is recommended that one or more impeller blades should be used to make a homogenous mixture before it is fed to the fermenter (Krieg & Fischer 2008). To kill the disease carrying bacteria, it is recommended that the mixture should be heated using the internal heating coils and heat exchangers or external heating jacket (Sims 2002). After the mixture is fed to the fermenter, Munganga *et al* (2010) and Sims (2002) recommend that it should be diluted with water to meet favourable conditions of anaerobic digestion of 5-8% solids in effluent stream. The best operating temperature inside the digester was found to be in the mesophillic temperature range of 35-37°C (Pace 2013, Sims 2002). The retention time of the waste mixture in the fermenter is estimated to be 25 days (Sims 2002).

Elangoa *et al* (2007) also investigated the production of biogas from the mixture of municipal solid waste and domestic sewage. This was made on the batch type of a reactor operated on mesophillic temperature range of 26-36°C and at fixed retention time of 25 days. This resulted in the reductions of 88% total solids (TS) and 89.3% COD in the effluent stream of the homogenous mixture.

2.5 Research aspects identified

In this chapter, evidence has been provided on how biogas is produced from different waste resources and its effect on global climate change. The estimation of CH_4 emissions from different organic waste resources has also been presented.

The status of the waste generation in South Africa has also been highlighted especially in three waste categories like municipal solid waste, municipal wastewater and agricultural waste (livestock manure) and also how biogas is generated from these waste resources. It has also been shown that in most cases in the country these waste resources are disposed to the waste disposal sites and waste storage (in case of manure). After undergoing anaerobic digestion they produce biogas which consist a high percentage of CH_4 which is emitted to the atmosphere. As one of the greenhouse gases, it has been shown in Section 1.1 that CH_4 from waste contributes about 3% of the total GHG emissions in the country (Urban Life 2012). The GHG emission trajectory plan for the country has also been reviewed.

It has also been shown that CH_4 gas is a good energy carrier. This means that an opportunity exists in South Africa to reverse CH_4 emissions to energy generation. This can be achieved by capturing the biogas generated from these waste resources and turning it into useful energy source that can generate electricity, heat. This has the potential to reduce burning of fossil fuels in the South African power plants which are the major sources of GHG emissions in the country. It would be interesting to learn how much this effort would contribute to the reduction of these emissions.

Different technologies currently used to convert organic waste into energy have been reviewed in this chapter. These include extraction of biogas from the landfill sites, and digestion of different organic waste types in the biogas digesters. In the following chapter, the methodology that was used to address the research objectives proposed in Chapter 1 is presented.

3 Research Methodology

3.1 Introduction

Literature survey shows that the sources of biogas in the country are in abundance with about 20.8 million tons/annum of organic waste recorded to be disposed in South African landfills in 2011 (DEA 2012). The disposed waste releases CH_4 emissions which contribute about 3% in the total GHG emissions in South Africa (Urban Life 2012). The aim of this investigation was to assess the potential contribution of biogas on climate change mitigation in South Africa.

In this regard, five objectives were set out as outlined in Chapter 1. Chapter 2 provides a review of literature. In this chapter, the methodology that was used to achieve these objectives is reported. The approaches and data that were used to achieve specific objectives are presented.

3.2 Approach

The research objective was to quantify the biodegradable waste that is currently available in South Africa. This was aggregated into three different waste resources: a) municipal solid waste which includes general waste from residential, commercial sectors, and industrial waste; b) municipal wastewater which includes domestic, commercial and industrial wastewater; and c) agricultural waste particularly livestock manure. These waste resources are the main sources of biogas and are also in abundance in the country, hence they were chosen. Each waste resource was quantified separately to determine how much organic waste is produced in the country using 2010 as a baseline. Then, the quantity of each waste type was forecasted up to 2025. These time frames were chosen because 2010 is the first year after which the COP 15 pledge was made, and 2025 is the last year of emissions peaking in South Africa as announced by the 2008 cabinet (DEA 2011a). The organic waste from these resources was quantified so as to estimate the total emissions from them and use this as efficacy upon which mitigation potential can be used through biogas capture, destroy or utilisation.

The second research objective was to assess the $CO_{2\text{-eq}}$ emissions share from these waste resources in the national GHG emissions forecast under "growth without constraints" scenario. The amount of biogas that causes those emissions should also be quantified. This was only assessed in terms CH_4 generated because the GHG emissions from waste are caused by this gas. The share of $CO_{2\text{-eq}}$ emissions was estimated between 2020 and 2025 because this is the period over which the emissions are planned to peak before they stabilise for the decade (DEA 2011a).The quantity of CH_4 from these waste types was determined so as to estimate the amount of useful energy that can be generated from the biogas produced.

The third research objective was to assess the potential electricity and heat that can be generated from biogas from these waste resources. This objective was proposed to estimate the CO_2 emissions from coal that can be avoided through substituting coal with CH_4 gas in generating heat and electricity.

The fourth research objective to optimise the biogas production and estimate amount of electricity and heat that can be generated from the biogas. This is evaluated by determining the potential of mixing these waste resources selected in this study using the case study reviewed in Section 2.4.8 in Chapter 2. It is also shown that biogas can be optimised by combining municipal wastewater and municipal solid waste in the biogas digester. This approach is adopted in this study by combining these waste resources and extending to the blending of livestock manure plus equivalent parts of the remaining wastewater. The remaining wastewater was assumed to be digested alone to assess the amount of biogas that can be produced.

The fifth research objective was to estimate the emissions reduction potential of biogas using the national GHG emissions trajectory ranges of upper and lower limit targets as efficacy upon which the reduction potentials can be measured. This was also evaluated on the pledge made in the "COP15 under Copenhagen 2009 Accord".

3.3 Collection and processing of waste data

The waste data that has been collected and used in this study is the organic part of the waste in the following three waste categories: Municipal solid waste, municipal wastewater and agricultural waste. The industrial wastewater data is incorporated in the municipal wastewater as most industries divert their wastewater effluents to the municipal wastewater system.

3.3.1 Municipal solid waste data

The waste data was sourced from the published waste management strategies of the seven major metros in South Africa which are: City of Cape Town (COCT), City of Johannesburg (COJ), Tshwane Metropolitan Municipality (TMM), EThekwini Municipality (ETM), Ekurhuleni Municipality (EMM), Nelson Mandela Metro (NMM), and Buffalo City (BM). The fraction of organic waste and the waste growth from these metropolitan municipalities are also presented. These municipalities were chosen because of the availability of their waste data in their waste management strategies. The data for COCT and EMM was readily available for the baseline year (2010). However for the other municipalities this was extrapolated to 2010 using the waste growth and the waste generated in the following expression (Parker 2002):

$$\boldsymbol{W_{2010} = W_b(1 + r^n)} \qquad \textbf{(3-1)}$$

Where:

W_{2010} = waste generated in 2010
W_b = the waste generated in the base year
r = the average waste growth in that municipality
n = the number of years from base year to 2010.

This is presented in Table 3-1 and further details of the waste generation data can be found in Appendix 7.1.1.

Table 3-1: Municipal waste data of seven metropolitans in South Africa

Municipality	Waste type	Waste amount (Mtons)	Waste growth (%)	Organic waste (%)
COCT	General waste	1.268	2.5	30-35
COJ	General waste	1.499	6	13
TMM	General waste	2.402	3.48	20
EMM	General waste	1.743	0.88	12
ETM	General waste	1.4	1.69	45.67
NMM	General waste	0.405	2.45	50.3
BCM	General waste	0.316	3	25

3.3.2 Estimation of national organic waste data

The national picture of the solid waste generation is quantified by looking at the ratio of the national population to the total population of these metros. This is by considering the fact that the waste generation in general, is measured per capita in most cases (DEA 2011b, DEAT 2005). Therefore, the national waste generation is estimated as follows:

$$\boldsymbol{National\ organic\ waste} = \frac{\boldsymbol{N_P}}{\boldsymbol{M_P}}.\boldsymbol{Total\ organic\ waste\ from\ seven\ major\ metros} \qquad \textbf{(3-2)}$$

Where: $\frac{N_P}{M_P} > 1$ and is the ratio of national population to the total population of these metros.

It can also be estimated using the GDP growth of the country which is the second key driver of the waste generation in the municipality as follows (Parker 2002):

$$\boldsymbol{National\ organic\ waste} = \boldsymbol{W_B(1 + e_B)^n} \qquad \textbf{(3-3)}$$

Where:

e_B = the GDP growth rate of the country

n = the year number of the forecast

The GDP growth in South Africa is targeted to be between 3 and 6%, but in reality it has ranged between 2-4% below political desired range (Winkler *et al* 2011). Therefore, the average GDP growth used in this study was 3%, taking the average reality of it. Both equations were used in this study to estimate the national organic waste.

3.3.3 Municipal wastewater

The municipal wastewater data was sourced from the study made by Burton *et al* (2009) and also published documents of these major metros in the country. The data collected by Burton *et al* (2009) was in the form of surveys, workshops, and case studies across the country for the energy from wastewater project they were evaluating. This was made only for COCT and ETM. Therefore this wastewater data is not the true reflection of the actual wastewater generated in the country due to poor waste data collection in the country. This is presented in Table 3-2 and the full details of wastewater generation in the municipalities are given in Appendix 7.1.3. The data for the national wastewater generation was estimated using the ratio of national population and economic growth as shown in Section 3.3.2.

Table 3-2: Municipal wastewater data

Municipality	Daily load (Ml/day)	COD influent (mg/l)
COCT	544	837
COJ	980	433
TMM	547	500
EMM	257	416
ETM	504	823
NMM	187	600

3.3.4 Agricultural waste

The agricultural waste data include the different feedstock excretes. It was sourced from the statistics of the different types of livestock in the country like cattle, pigs, and poultry. The manure from other livestock like sheep and goats is not included because these animals are not kept in confinement, which makes their manure not to biodegrade anaerobically (Taviv *et al* 2007). The crop waste is not included because the types of crops cultivated in the country are not water borne and are used for livestock feeding (DA 2006).

The data used to determine the variables in equations (2-19) and (2-20) is taken from the IPCC 2006 default values for estimating the gross energy of the average feed intake and from the data compiled by Taviv *et al* (2007) for estimating the number of animals in each livestock category. The livestock selected are cattle, pigs, and poultry because they are kept in solitary confinement as mentioned in Section 2.4.6.2. This data is presented in Table 3-3. This is the national data of the livestock from which the forecast of the animals was made. The life expectancy of the animals reviewed in Section 2.4.6.2 was used.

Table 3-3: Livestock population of different categories kept in confinement

Livestock type	Population (million)	Population growth	Manure VST (kg-dm/day/animal	Bo (m^3/kg)	MCF (%)	MS (%)
Dairy cow	1.1316	0.2	5.152	0.13	76	0.5
Beef feedlot	2.07	0.2	1.881	0.12	76	0.2
Pig	1.6	0.61	0.49	0.29	76	50
Layer flock	23.1	2.4	0.02	0.24	1.5	20
Broil	18.73	2.4	0.02	0.24	1.5	20
Breeder	5	2.4	0.02	0.24	1.5	20

3.4 Quantification of total organic waste

The total organic waste generated in the country is determined through a simplified waste material balance from all the waste resources in the country as follows (Whitwell & Toner 1973):

$$\boldsymbol{OFMSW.M_{sw} + COD.M_{ww} + V_{ST}.M_{lm} = M_{tw}} \qquad \textbf{(3-4)}$$

Where:

MSW = municipal solid waste

WW = wastewater

AW = agricultural waste (animal manure waste)

OFMSW = organic fraction of municipal solid waste

M_{sw} = total municipal solid waste disposed in landfills (This includes general waste from domestic, commercial and industrial waste as well as hazardous waste containing organic material).

M_{ww} = total wastewater diverted to municipal sewerage system (This include domestic, commercial and industrial wastewater

M_{lm} = total livestock manure produced in the country

V_{ST} = the volatile solids in the livestock manure containing organic material, and

M_{tw} = total waste generated in the country

The total organic waste generation in the country was forecasted in the future using the population and economic growth of the country as indicators.

3.5 Quantifying the biogas production

The biogas production is expressed in the form of CH_4 produced because it constitutes the greater part of biogas, and it is emitted to the atmosphere thereby causing global warming. The total quantity of CH_4 from these waste resources was then used to estimate the share of waste emissions in the national GHG emission under "growth without constraints" between 2020 and 2025 as elaborated in Section 3.2. This was also used to estimate the amount of energy carried by CH_4 generated from the waste categories examined in the present study. Banks (2009) reports that biogas-derived CH_4 carries about 18.3MJ/m^3. Therefore, the estimated amount of energy carried by CH_4 can be expressed mathematically as follows:

$$\boldsymbol{E_{carried} = E_{content} \cdot v_{CH4}} \qquad \textbf{(3-5)}$$

Where:

$E_{content}$ = the energy content of CH_4 estimated to be 18.3MJ/m^3 above, and,

v_{CH4} = the volume (in m^3) of CH_4 generated.

The estimation of total quantity of CH_4 generated from the waste categories is presented in the following sub-sections.

3.5.1 *Methane generation from Municipal Solid Waste*

The estimation of CH_4 production from municipal solid waste depends on knowledge of the chemical formula of the waste. Therefore to be able to determine the chemical formula of the waste, one needs to know the element composition of it.

Munganga *et al* (2010) did an elemental analysis of the OFMSW for COCT where the bio-methane potential of municipal solid waste of the city for different organic waste types was determined. Malla (2011) also used the analysis by Munganga *et al* (2010) to determine the chemical formula of the OFMSW of the City of Cape Town. The elementary analysis data used by Malla (2011) was also used in this work. However it should be mentioned that the samples upon which the analysis was made were food waste samples.

Typical food waste elementary composition is given by Reinhart (2004) and when compared to the food composition investigated by Munganga *et al* (2010), the deviation is less than 10%. Therefore this is assumed acceptable for this study and is used as elementary composition for other food waste for all major metros chosen. In the reference, the composition is expressed in percentage. To show the typical chemical structure of the waste, 100g of waste was assumed and from it the number of moles for each element was calculated using the following equation (Reinhart 2004):

$$\boldsymbol{n_o = \frac{m}{M_{mo}}} \qquad \textbf{(3-6)}$$

Where:

n_o = the number of moles of each element,

m = the mass of the element in waste and,

M_{mo} = the molar mass of each element.

The molar composition of food waste is as follows (Reinhart 2004): Carbon (C) is 4 moles, Hydrogen (H) is 6.4 moles, Oxygen (O) is 2.35 moles, Nitrogen (N) is 0.19 moles, Sulphur (S) is 0.0125 moles.

Sulphur has a very small number of moles, therefore it is neglected. To get the chemical formula of the waste, all the elements are divided by element with least number of moles, which gives the following chemical formula: $C_{21}H_{34}O_{13}N$

The above mentioned chemical structure undergoes anaerobic decomposition to produce CH_4, CO_2, traces of ammonia and hydrogen sulphide. Its decomposition as reported in literature is known as Buswell equation (Lucks 2000):

$C_{21}H_{34}O_{13}N + \frac{1}{4}(4c-h-2o+3n+2s)\ H_2O \rightarrow 1/8(4c-h+2o+3n+2s)\ CO_2 + 1/8(4c+h-2o-3n-2s)\ CH_4 + nNH_3$

The coefficients in the equation are subscripts of C, H, O, and N. Therefore the coefficient of CH_4 in Buswell equation is: $1/8(4*21+34-2*13-3*1) = 11$

The coefficient of CO_2 is: 1/8(4*21-34+2*13+3*1) = 10
This means the percentage of CH_4 from the decomposition of this waste will be:
$\%CH_4 = 11/(11+10) = 53\%$

The CH_4 gas is produced through the biodegradation of the carbon chain of the waste. To estimate its generation from the disposed waste, the decomposable degradable organic carbon (DDOC) present in waste should be determined first as shown in equation (2-11). This would need the determination of degradable organic carbon (DOC) in the waste which is estimated using equation (2-2).
From the waste chemical formula mentioned above which is $C_{21}H_{34}O_{13}N$, the fraction of degradable organic carbon (DOC_i) can be calculated as follows (Banks 2009):

$$\boldsymbol{DOC_i = \frac{element\ mass\ of\ carbon}{total\ element\ mass\ of\ waste}} \qquad \textbf{(3-7)}$$

$$\therefore DOC_i = \frac{21\times12}{21\times12+34\times1+13\times16+14} = 0.496$$

This is for the chemical formula without moisture, but in reality there is moisture in the waste disposed. The calculation for the chemical formula with moisture is presented in Appendix 7.2.1. The DOC was estimated using this parameter and the data presented in Table 3-1 to determine the value of W_i in equation (2-2).

DDOC in waste was determined using equation (2-4), which was then substituted in equation (2-11) to estimate CH_4 generation as explained in sub-section 2.4.2. This was converted to volume amount using Standard Conditions of Temperature and Pressure (STP), which says 1mol of gas at STP equals 22.4litres (Banks 2009).

3.5.2 Methane production from the municipal wastewater

The CH_4 that can be produced from wastewater is determined using the chemical oxygen demand of the wastewater (COD). This is the amount of oxygen needed to oxidise methane. The high values of COD indicate high volumes of CH_4 that will be produced by the wastewater (ERG & PA 2009).
This is determined as follows (UNFCCC 2008):
$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
1 kmole of CH_4 requires 2 kmoles of O_2
Therefore 16kg of CH_4 requires 64kg of O_2

Therefore 1kg of COD (O_2) is equivalent to 16/64 = 0.25 kg of CH_4

The COD of the influent wastewater stream is given by each municipality. The CH_4 generation can be estimated by modifying equation (2-18) as follows:

$$\boldsymbol{E_{CH4} = W_i \times (COD_{in} - COD_{ef}) \times B_o \times MCF} \qquad \textbf{(3-8)}$$

For cases where there is no methane recovery system in anaerobic digesters, MCF is taken to be 0.8 and for digesters with methane recovery system, MCF is taken to be 1 (UNFCCC 2008). The digestion of the wastewater would take 10-20 days before it generates the biogas (RPI 2013).

3.5.3 *Methane production from the livestock waste*

CH_4 production from the livestock manure was estimated using equation (2-19) and (2-20). The data that was used is presented in Table 3-3.

3.6 Assessing the potential of generating electricity and heat using biogas

The biogas that can be harvested from the waste resources chosen in this study carry potential energy that can be converted to useful energy in the form of electricity, heat, etc. as shown in Section 2.4.8. The total energy input that can be generated using biogas can be expressed using equation (3-5) as follows (Malla 2011):

$$\boldsymbol{E_t = \frac{E_{content} \cdot v_{CH4} \cdot availability}{24}} \qquad \textbf{(3-9)}$$

Where:

v_{CH4} = the volume of biogas produced (m^3)

$E_{content}$ = the energy content of CH_4 gas (6kWh/m^3, Banks 2009)

$availability$ = the availability of energy source (%)

This is divided by 24 to convert the units kWh into kW

The biogas generated from municipal solid waste can be harvested after the first 3 months of waste disposal in first year (Pipatti *et al* 2006). This means that the availability of energy from this waste type after the first year of waste disposal would be:

$$availability = \left(\frac{365\ days - 25\ days}{365\ days}\right) \cdot 100 = 75\%$$

For the municipal wastewater, biogas would be generated after 20 days to get the maximum digestion of the wastewater (RPI 2013). Therefore the availability of this energy source would be: (365-20)/365 = 94.5%.

The electrical power that can be generated from biogas can be estimated as follows:

$$\boldsymbol{E_p = E_t \cdot efficiency} \qquad \textbf{(3-10)}$$

The typical electricity efficiency of biogas is 35% (Banks 2009)

The thermal power that can be generated from biogas and used directly can be estimated as follows:

$$\boldsymbol{E_{th} = E_t \cdot thermal\ efficiency} \qquad \textbf{(3-11)}$$

The biogas has a typical thermal efficiency of 50%

Some of the electricity generated from the biogas fuel is used in the plant to drive electrical equipment such as agitators, compressors, and pumps as well as to provide light in the plant.
Therefore the electricity consumed in the plant is:

$$E_{consumed} = E_p \cdot F_{consumed} \tag{3-12}$$

Where: $F_{consumed}$ is the fraction of the electricity consumed internally before supplied to the grid. Typical fraction of electricity consumed by Eskom internally in South Africa is 2% of what the plant has generated (Eskom 2012).

As shown earlier in Section 3.5.1 that the percentage of CH_4 in the biogas is about 53% from the waste composition used. It is suggested that the minimum allowable CH_4 % that can be used in the biogas boiler should be 60% (Dublein & Stainhauser 2008). Also for any biogas that has CH_4 composition less than 60% should be scrubbed with a scrubbing unit to upgrade the CH_4 composition (Malla 2011). The scrubbing unit is assumed to be 0.75 $kWh_{el}/\ m^3$ of CH_4 enriched biogas stream (Murphy *et al* 2004 as cited by Malla 2011).

The electricity required of a scrubber is:

$$E_{scrubber} = \frac{0.75 \cdot v_{CH4\ enriched\ biogas}}{24} \tag{3-13}$$

Therefore the electricity that can be supplied to the grid is:

$$E_{grid} = E_p - E_{consumed} - E_{scrubber} \tag{3-14}$$

Therefore the heat that can be used directly is:

$$E_H = E_{th} - E_{scrubber} \tag{3-15}$$

3.7 Optimisation of biogas generation from the mixture of waste resources

As mentioned in Section 3.2, the case study reviewed in Section 2.4.8 was used to evaluate the optimisation of biogas through the scenarios of combining the waste resources selected for this study. The first combination assessed was between the municipal solid waste and the municipal wastewater adopting the work done by Elangoa *et al* (2007). Here the organic fraction of the municipal waste is assumed to be mixed with the municipal wastewater in the stirred tank reactor to make a homogenous slurry which is then loaded to the biogas digester as depicted in Figure 3-1.

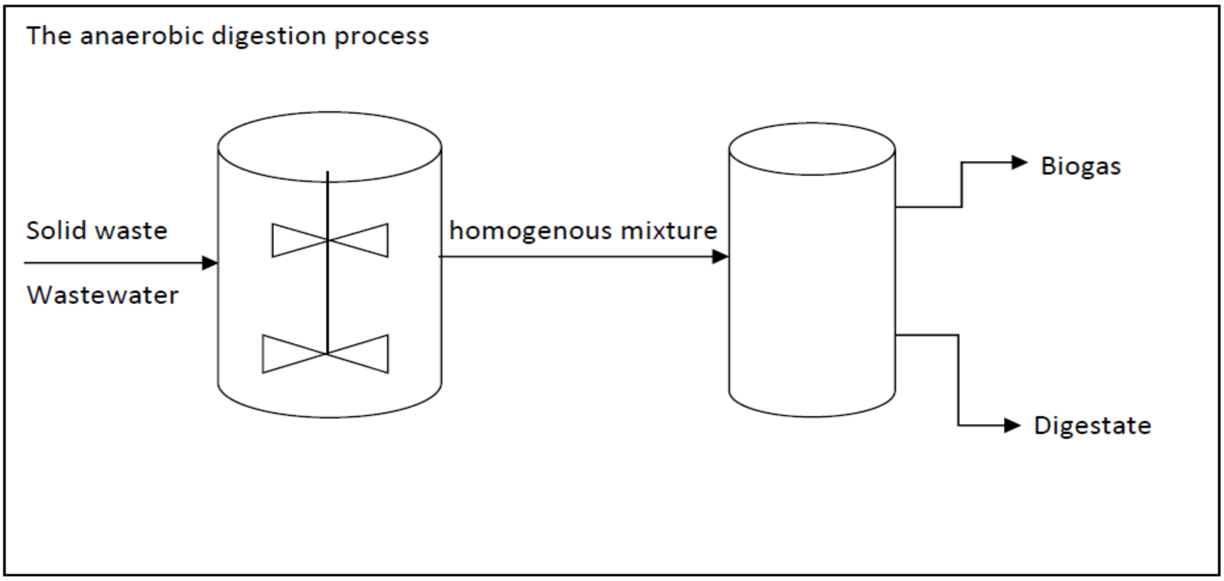


Figure 3-1: The anaerobic digestion process of optimising the generation of methane from different waste categories

After the municipal solid waste is sorted to have the organic fraction only, it would need to be blended and mixed with dosages of wastewater continuously until it becomes a homogenous slurry. The mixer recommended for large scale operation consists of two impeller blades, which continually mix the slurry before it is fed to the biogas digester to undergo anaerobic digestion (Krieg & Fischer 2008). It is further diluted with wastewater before being fed to the digester to meet favourable conditions of anaerobic digestion of 5-8% solids in the effluent stream (Munganga *et al* 2010, Sims 2002). The slurry is then pasteurised to kill the disease carrying bacteria at temperature of about 70°C (Krieg & Fischer 2008; Pace 2013). To start the process, the feedstock in the digester is heated using internal heating coils and heat exchangers or external heating jacket (Sims 2002). After pasteurisation the slurry is fed to the biogas digester at the recommended mesophillic temperature of 35-37°C (Pace 2013; Sims 2002).

Since the disposition of solid waste to the landfill and loading of municipal wastewater to the wastewater treatment works occurs every day, the mixing of these waste types need to happen on a daily basis throughout the year. The mixture of this type of slurry is estimated to biodegrade over the period of 25 days (Elangoa *et al* 2007). This means that the effluent of the slurry has to be removed every 25 days, but the slurry has to be loaded every day of operation.

The material balance around the mixing tank is as follows (Levenspiel 1972):

$$Input = Output + disappearance\ of\ reactants\ by\ reaction\ + accumulation$$

$$\boldsymbol{x_{sw}M_{sw} + x_{ww}M_{ww} = x_{sl}M_{sl} + (-r_{sw})V} \quad \textbf{(3-16)}$$

Where:
x_{sw} = the solids concentration of the municipal solid waste
M_{sw} = loading rate of the municipal solid waste (ton/time)
x_{ww} = solids concentration in the municipal wastewater
M_{ww} = amount of wastewater mixed solid waste to produce anaerobic favourable slurry (ton/time)
x_{sl} = solids concentration favourable for anaerobic reaction in a slurry
M_{sl} = mass flow rate of the slurry loaded to the biogas digester

The disappearance of the reactants (solid waste and wastewater) is transformed to the slurry as an output. Since the required mixture is homogenous one, there is no accumulation of reactants.

The wastewater is used as an inoculum; therefore this reduces equation (3-6) to the following equation:

$$\boldsymbol{x_{sw}M_{sw} = x_{sl}M_{sl}} \qquad \textbf{(3-17)}$$

To make the slurry that will undergo anaerobic digestion, the amount of wastewater added would be:

$$\boldsymbol{M_{ww} = M_{sl} - M_{sw}} \qquad \textbf{(3-18)}$$

This wastewater contains some small percentage of solids concentration, therefore this makes the actual wastewater added to make the desired slurry to be:

$$\boldsymbol{M_{ww} = M_{sl} - M_{sw} + x_{ww}M_{ww}} \qquad \textbf{(3-19)}$$

Therefore the DOC of the slurry would be estimated as follows:

$$\boldsymbol{DOC_{sl} = DOC_{sw} \cdot M_{sl}} \qquad \textbf{(3-20)}$$

Where:
DOC_{sl} = Degradable organic carbon of the slurry (tons C)
DOC_{sw} = Degradable organic carbon of the solid waste loaded (tonC/ton Waste)

Since the desired solids concentration in the effluent stream is between 5 and 8%, the slurry density inside the digester is closed to that of water. Therefore, as mass value of water equals to the value of volume of water, the volume of slurry would be equal the value of its mass minus the desired fraction of solids in it as follows:

$$\boldsymbol{V_{sl} = M_{sl} - x_{sl}M_{sl}} \qquad \textbf{(3-21)}$$

The total working volume of the digesters across the country would be (Sims 2002):

$$\boldsymbol{V_{w} = V_{sl} \cdot HRT} \qquad \textbf{(3-22)}$$

Where: HRT is the hydraulic retention time of the slurry before complete degradation
Therefore the COD of the slurry can be estimated as follows:

$$\boldsymbol{COD_{sl} = COD_{ww} \cdot V_{sl}} \qquad \textbf{(3-23)}$$

COD_{sl} = Chemical oxygen demand of the slurry (tons)
COD_{ww} = Chemical oxygen demand of the wastewater (mg/l)

Therefore the DDOC of the slurry would be:

$$\boldsymbol{DDOC_{sl} = DOC_{sl} + COD_{sl}} \qquad \textbf{(3-24)}$$

The methane generation can be estimated using equation (2-11). The difference is the k-value which would be higher for the biogas digesters than in landfill sites. The k-value of the slurry can be estimated using equation (2-6).

As mentioned in Section 2.4.2, the organic waste does not completely biodegrade, only the fraction of it degrades. Therefore, the fraction of the DDOC of slurry that biodegrades is:

$$\boldsymbol{x_{sl} = \frac{DDOC_{slo} - DDOC_{sl}}{DDOC_{slo}}} \qquad \textbf{(3-25)}$$

This means $DDOC_{sl}$ can be expressed in terms of the fractional conversion as follows:

$$\boldsymbol{DDOC_{sl} = DDOC_{slo} \cdot (1 - x_{sl})} \qquad \textbf{(3-26)}$$

Substituting equation (3-26) in equation (2-6) and take natural logarithms on both sides will give the k-value of:

$$\boldsymbol{k = -\frac{ln(1 - x_{sl})}{t}} \qquad \textbf{(3-27)}$$

Where: x_{sl} is the fractional biodegradation of the slurry over the retention time of the anaerobic digestion of the slurry in the biogas digester.

This methodology of optimising CH_4 generation from the scenario of combining these waste resources was also used for the scenario of combining livestock manure and the portion of remaining municipal wastewater from the first combination. The only difference would be in the calculation of the CH_4 generation. For the estimation of CH_4 generation from these two waste types, the CH_4 generation potentials (B_o) of these waste types are used using equation (3-8). The B_o is 0.25 for wastewater and 0.22 for the livestock slurry.

The remaining wastewater should be digested on its own in the biogas digester. The CH_4 generation is estimated using equation (3-8).

3.7.1 Electricity and heat generation from the optimised biogas generated

Electricity and heat generation from the optimised biogas generation was estimated using the same methodology described in Section 3.6. The difference was only the percentage availability of the energy source which is higher for the biogas optimisation scenarios because of the shorter retention times. The percentage availabilities for these scenarios are described as follows (Elangoa *et al* 2007, Sims 2002):

For the waste combinations of municipal solid waste and wastewater, municipal wastewater and livestock manure, the retention time of 25 days was assumed based on the case study reviewed in Section 2.4.8. Therefore this availability would be for this scenario: (365-25)/365 = 93%.

The digestion of wastewater alone has retention of between 10 and 20 days (RPI 2013). The average for this gives a retention time of 15 days and gives the energy source availability of: (365-15)/365 = 96%.

As mentioned previously in Section 3.7, the blended feedstock needs to be heated first before digestion. The heat that is required to heat the slurry feedstock is expressed as follows (Coulson & Richardson 1999):

$$\boldsymbol{Q_{sl} = m_{sl} \cdot cp_{sl} \cdot (T_2 - T_1)} \qquad \textbf{(3-28)}$$

Where:

cp_{sl} = specific heat capacity of the slurry feedstock fed to the digester (kJ/kg.k)
T_2 = mesophillic temperature range inside the digester (°C), this is between 35 and 37°C (Pace 2013, Sims 2002)
T_1 = ambient temperature of the feedstock (here it is taken as the mean temperature in South Africa), °C.

Therefore the heat that can be used directly from these waste combination scenarios is:

$$\boldsymbol{E_H = E_{th} - (Q_{sl} + E_{scrubber})} \qquad \textbf{(3-29)}$$

The heat required to heat the slurry feedstock can be sourced from the heat wasted during conversion of biogas energy to heat and electrical energy as the biogas has electrical and thermal efficiency of 30 and 50% respectively. This would only be possible after the process has started to save the heat that would otherwise be wasted. This energy efficiency or energy management intervention would help improve the process efficiency and conserve energy.

Inefficiencies occur during the combustion process and the electricity generation process (ERI 2005, Zeitz 1997). During the combustion process the low thermal efficiency is caused among other factors by the improper mixing of gas and the surrounding air as well as the insufficient insulation of the furnace (ERI 2005, Zeitz 1997). Too much excess air that is mixed with the gas would waste heat because the gas leaving the furnace is hot and therefore leaves with considerate amount of energy (ERI 2005, Zeitz 1997). Excess air is necessary for the combustion process to ensure complete combustion of fuel (which is biogas in this case) (ERI 2005, Zeitz 1997). Therefore the improvement of thermal efficiency lies with recovering the heat that is lost with hot flue gas that is leaving the furnace and using it to heat the slurry feedstock which would then eliminate the need to heat the slurry feedstock with heat sourced from the burning of fossil fuels. This would improve the thermal efficiency of the combustion chamber and ultimately increase the amount of heat that is used directly from biogas.

The electrical efficiency can be improved through recovering the heat that is lost when the steam is transferred from the boiler to the steam turbine in the form of returning the condensate to heat the boiler feed water, thus reducing the amount of fuel that would be combusted (biogas in this case).

3.8 Emission reduction potential of biogas

The emission reduction potential (ERP) of biogas was determined through two phases: the first phase looked at the CH_4 emissions avoided through capturing and destroying, the second phase assessed the total avoided emissions through utilisation of biogas to generate electricity and heat. These emission quantities avoided were then used to evaluate on how much they contribute on National GHG Emissions Trajectory ranges stated for between 2020 and 2025 in National Climate Change Response Policy. Their contributions were also assessed on the COP 15 pledge.

Generally the emission reduction potential of biogas can be expressed as follows (UNFCC 2006):

$$\boldsymbol{ERP = Baseline\ emissions - total\ avoided\ emissions} \qquad \textbf{(3-30)}$$

Where:

Baseline emissions = the country's emissions under "growth without constraints" scenario

total avoided emissions = the emissions avoided through CH_4 capture, destroy or utilisation.

The emissions avoided through carbon capture and destroying is estimated by considering CH_4 gas destroyed through flaring process as follows (UNFCC 2006):

$$\boldsymbol{MD_{flared} = \left(CH_4 flared - PE_{flare}\right) \cdot GWP_{CH_4}} \qquad \textbf{(3-31)}$$

Where:

MD_{flared} = the avoided CH_4 emissions through capturing and destroyed using the flaring process (ton $CO_{2\text{-eq}}$)

$CH_4 flared$ = the actual CH_4 gas captured and destroyed through flaring (ton $CO_{2\text{-eq}}$)

PE_{flare} = the project emissions from flaring (ton CO_2)

GWP_{CH_4} = the global warming potential of CH_4

Equation (3-31) is substituted in equation (3-30) to assess the ERP of biogas through CH_4 capture and destroy.

The avoided emissions through CH_4 capture and utilisation for generating both electricity and heat is estimated as follows (UNFCCC 2006):

$$\boldsymbol{ER_{CH4}} = (\boldsymbol{E_{mD}} - \boldsymbol{P_e} - \boldsymbol{leakages} + \boldsymbol{avoided\ fossil\ fuel\ emission}) \cdot \boldsymbol{GWP_{CH_4}} \quad \textbf{(3-32)}$$

Where:
$\boldsymbol{ER_{CH4}}$ = the CH_4 emissions avoided through capture and utilisation of CH_4 (ton $CO_{2\text{-eq}}$)
E_{mD} = the actual CH_4 captured and utilised (ton $CO_{2\text{-eq}}$)
P_e = project emissions (ton CO_2)

Leakages are the amount of CH_4 leaked to atmosphere when CH_4 was captured or recovered. The value of leakages is expressed as follows (UNFCCC 2006):

$$\boldsymbol{leakages = 1 - (e + f)} \quad \textbf{(3-33)}$$

Where:
e = the typical CH_4 recovery efficiency, which 0.85 (Timoney 2009)
f = the oxidation factor as stated in Section 2.4.2.

Again equation (3-32) was substituted in equation (3-30) to assess ERP of biogas through CH_4 capture and utilisation for electricity and heat generation. The emission factor of CO_2 from CH_4 combustion is estimated as 1.021 ton/MWh (UNFCC 2006).

The contribution of biogas to mitigate climate change in South Africa was assessed by determining the percentage contribution of biogas capture and utilisation as an energy source on achieving the National GHG Emissions Trajectory ranges between 2020 and 2025. This contribution was only made for biogas capture and utilisation because the national waste flagship on waste is going to be established for conversion of waste into energy. This was also assessed in achieving the reductions made in COP 15 pledge.

3.9 Computational procedure

The quantity of waste was forecasted between the period of 2010 and 2025 as explained in Section 3.2. The collected raw was used to determine the organic waste from all the waste categories chosen in this study. From the organic waste data, the biogas generated from each waste type was estimated using the relevant equations. This step enabled the estimation of biogas-derived CH_4 emissions using emissions equations for each waste category. In the case of municipal solid waste and wastewater, this was made for each metro and then extrapolated to get a national picture using the methodology described in Section 3.3.2. The national quantities of each biogas-derived CH_4 were then added together to get the total national CH_4 from organic waste in South Africa. This was also done for CH_4 emissions from these waste resources. The potential energy carried by CH_4 was then determined, which was followed by estimating the power and heat that can be generated from the total CH_4 quantity as presented in Section 3.6. Finally the Emission Reduction Potential (ERP) of CH_4 capture, destroy, or utilisation was evaluated. The contribution of biogas ERP in achieving the National GHG Emissions Trajectory ranges was evaluated between 2020 and 2025 as explained in

Section 3.2.The effect of optimising CH_4 generation through different waste combinations suggested was also evaluated. This was done for both the estimation of power and heat generation as well as evaluating the ERP from optimised CH_4 generation. This is depicted in figure 3-2. All computations were performed in Excel software.

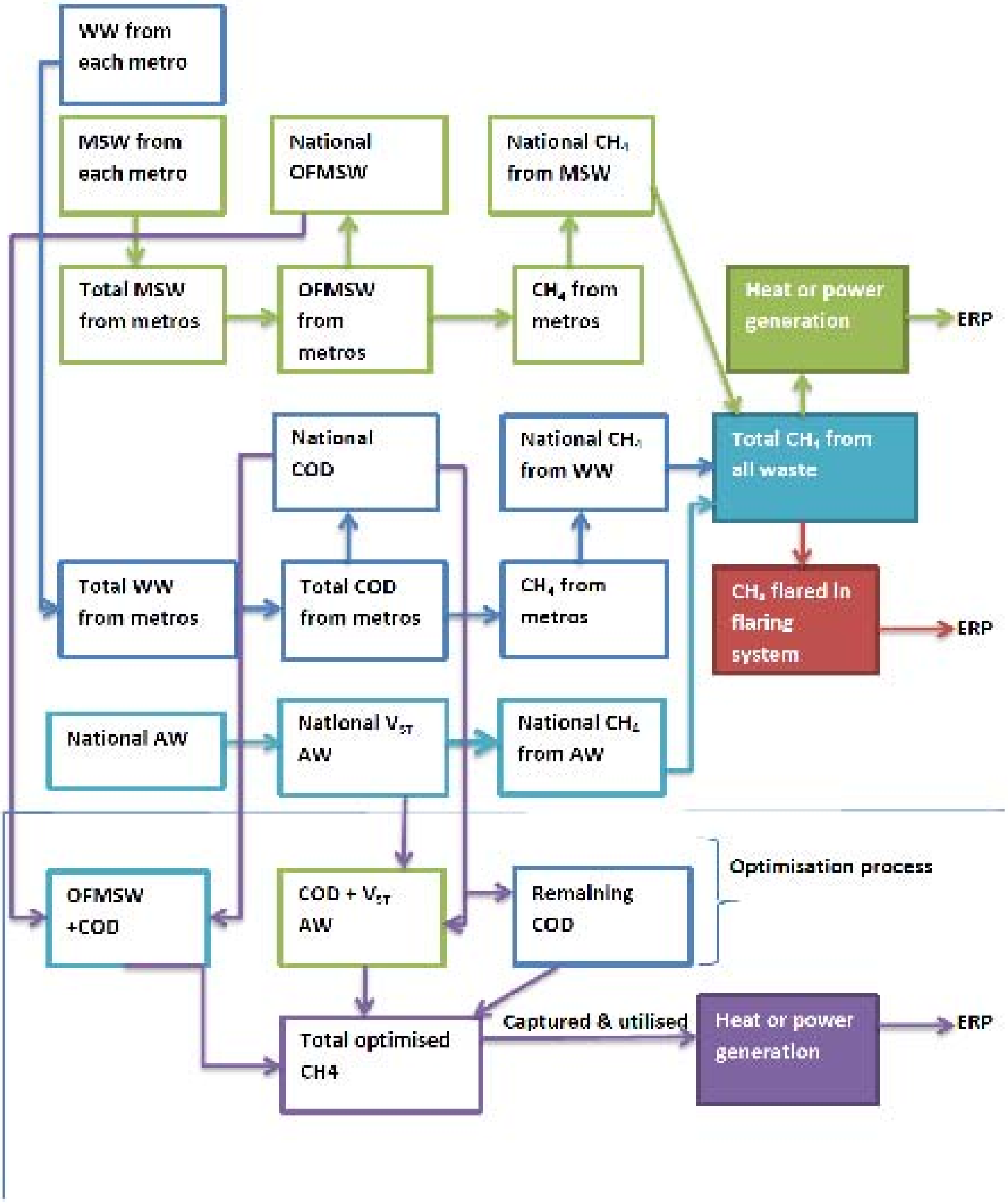


Figure 3-2: Flow chart of the methodology followed to address the objectives and research questions of this study. OFMSW denotes organic fraction of municipal solid waste.

The top part of Figure 3-2 shows the steps that were followed to address the main purpose of this study, where the CH_4 emissions from these waste resources can be captured and destroyed or converted to useful energy. The bottom part shows the alternative to the capturing of CH_4 emissions, which is optimisation of CH_4 production so as to get more quantity of it that will be converted to useful energy. This approach evaluated the impact that will be made by this on increasing the contribution of biogas in reducing the GHG emissions in South Africa. This is possible through increasing the amount of coal that can be substituted in heat and power plants. All the results are presented and discussed in Chapter 4.

4 Results and discussion

4.1 Introduction

Knowledge about the theory of climate change, biogas and biodegradable waste is vital for the development of suitable interventions to mitigate climate change. The theoretical interaction amongst climate change, biogas and biodegradable waste was examined in Chapter 2. It was shown that biogas from waste contributes to climate change. Current methods of capturing, destroying or utilising biogas were also reviewed. Chapter 3 focused on the methodology used to address the objectives of this investigation. In this chapter, findings from this investigation are presented. The chapter focuses on organic waste and its associated emissions, production of methane, CO_2 equivalent emissions from organic waste, optimisation of methane generation and utilisation for electricity and heat generation, and emission reduction potential of the biogas. The results are presented and discussed in details in this chapter.

4.2 Organic waste and associated emissions

4.2.1 Quantity of organic waste

The national picture of the organic waste is quantified from three organic waste categories selected for this study: municipal solid waste (MSW), municipal wastewater (WW) and livestock manure (AW). The organic waste from municipal solid waste and wastewater was forecasted for the 7 municipalities chosen for this study. This was based on the fraction of organic waste disposed in their landfills. These results were used to estimate the national picture. Figure 4-1 shows quantities of municipal solid waste for the 7 municipalities. The organic solid waste forecast data for each municipality is presented in Appendix 7.1.1.

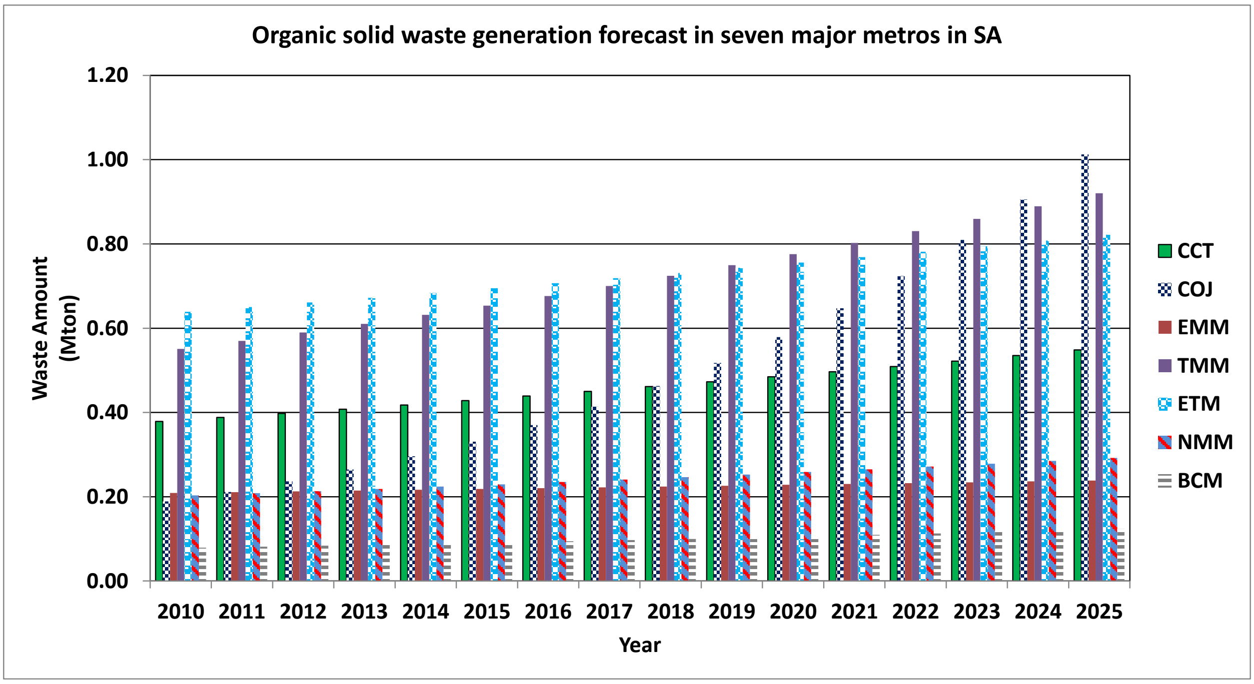


Figure 4-1: Organic fraction of municipal solid waste generation forecast in 7 metros in South Africa

The organic waste generation depends on the organic fraction of the municipal solid waste disposed and the waste management practice in that municipality in the form of waste disposed and waste growth in that municipality as shown in Table 3-1 in Section 3.3.1. The City of Johannesburg (COJ) at the beginning of the forecast has low organic waste disposed in landfills, but started to increase over years until it had the highest waste disposed in its landfills than other metros. This is caused by the high waste growth in that municipality as shown in Table 3-1. The high waste growth in that municipality is caused by the high population growth in it which is biggest in Gauteng Province (COJ 2011). The EThekwini (ETM) and Tshwane (TMM) municipalities have also higher organic waste disposed in their landfills because of high volumes of waste disposed. For the case of ETM this is also caused by high fraction of organic material in the waste stream generated in the municipality. The Buffalo City (BCM) has lowest organic waste generated and disposed which is caused by the low organic waste disposed in their landfills as shown in Table 3-1.

The quantities of municipal wastewater in six metros with variations in time are presented in Figure 4-2. The organic wastewater forecast for each municipality is presented in Appendix 7.1.3.

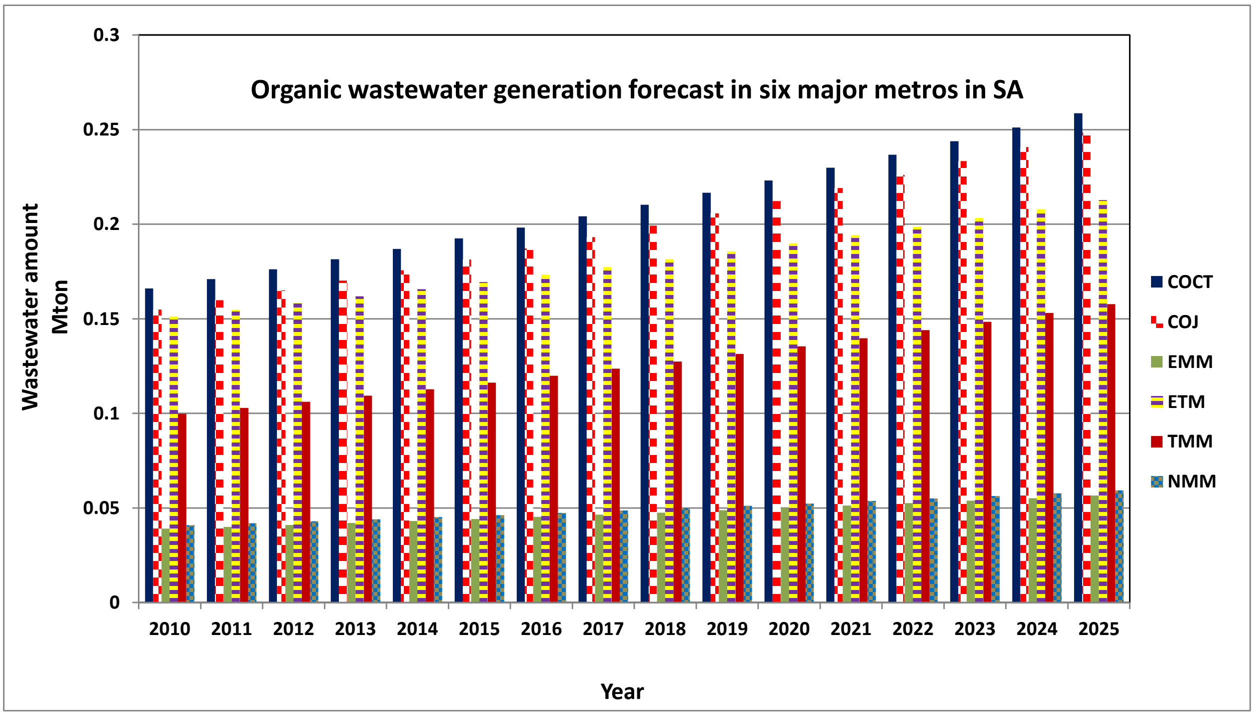


Figure 4-2: Organic fraction of municipal wastewater generation forecast in 6 Metros in South Africa

The organic wastewater generation depicted in Figure 4-2 depends on the COD of the daily wastewater load to the large extent and to the volume of wastewater to small extent. As shown in Table 3-2 that the City of Cape Town (COCT) and ETM have the higher organic wastewater generation because of high COD in their wastewater streams. The COJ has also the high organic wastewater generation because of huge daily loads than other municipalities as shown also in Table 3-2. The Ekurhuleni (EMM) and Nelson Mandela (NMM) metros have lowest organic wastewater compared to other metros because of low daily wastewater loads in their treatment works as shown in Table 3-2. In municipalities like COCT, ETM and COJ the wastewater generation increases over time. This is caused by the higher population growth in those metros than in others.

To estimate the national organic forecast from these two waste categories, the total waste generation forecast from the municipalities chosen was used by considering population and economic growth as indicators as explained in Section 3.3.2. These estimations were compared against each other for MSW and WW. This was done to check the difference each waste indicator has from each other in estimating the national organic waste for each waste type. The estimation of national livestock manure waste depends only on the population reported for each animal type kept in confined area; therefore no comparison of it was made. The population of each livestock category was reported on a national scale. This is presented in figures 4-3 and 4-4.

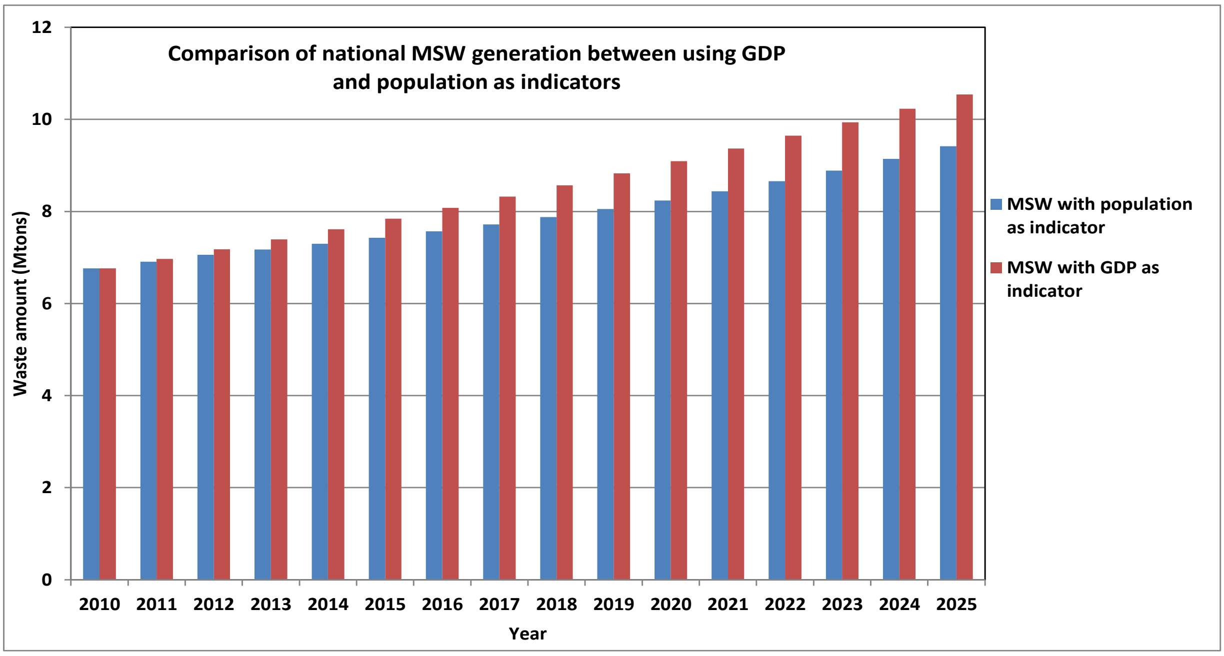


Figure 4-3: Comparison of national MSW generation forecast using population and GDP growth as indicators

Figure 4-3 shows there is slight difference in the forecast made for municipal solid waste between these two indicators. The deviation is between 0 and 3% over the whole period. This means both methods are valid and can be used in estimating the future organic waste growths. In both cases the organic waste in South Africa is assumed to continue growing in line with “growth without constraints scenario” stated in the LTMS study.

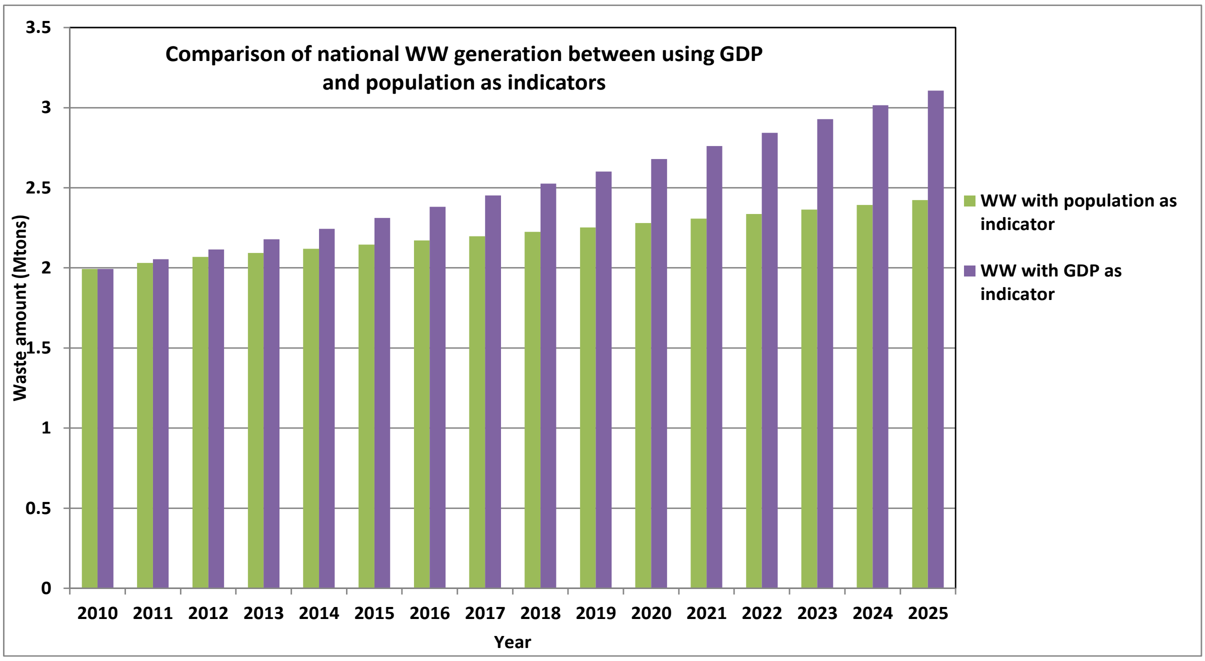


Figure 4-4: Comparison of national WW generation forecast using population and GDP growth as indicators

Figure 4-4 also did not show big difference between these indicators in estimating the WW generation with deviations that are between 0 and 13% over the period of forecast. The GDP growth indicator gave slightly higher estimation of wastewater between 2021 and 2025 of about 10-13%. The difference is caused by the GDP growth used in the country taken as 3% based on previous GDP growth used by Winkler *et al* (2011). The national population ratio to the total population in the metros was estimated to be between 3 and 2.35 as shown in Appendix 7.1.2. Therefore, when there is a big difference between GDP and this ratio, there will also big difference in the national waste estimation using these indicators.

In most publications the national wastewater data is published in per capita generation (Burton *et al* 2009, Ellis 2013), this also applies in estimation of MSW (DEA 2011b). Therefore for further analysis, population was used to estimate and forecast organic waste from MSW and WW in South Africa.

The total national organic waste in South Africa was found by adding all these organic waste quantities. The total organic waste quantity was then compared to the organic waste estimated under the national waste information baseline report by DEA (2012). The national waste information report also based the estimation on economic and population data, similar to the method used in this thesis. For the reasons mentioned previously, the national waste information data was also forecasted using the population as an indicator. This is presented in Figure 4-5. As reported in Section 2.4.4, the green waste in metros is diverted from landfill sites. So, it was also left out from the present analysis. Many municipalities that have waste strategy in South Africa are planning to divert green waste from landfills. However the national waste information report included all organic waste generated without stating the fraction that is disposed in landfills (DEA 2012).

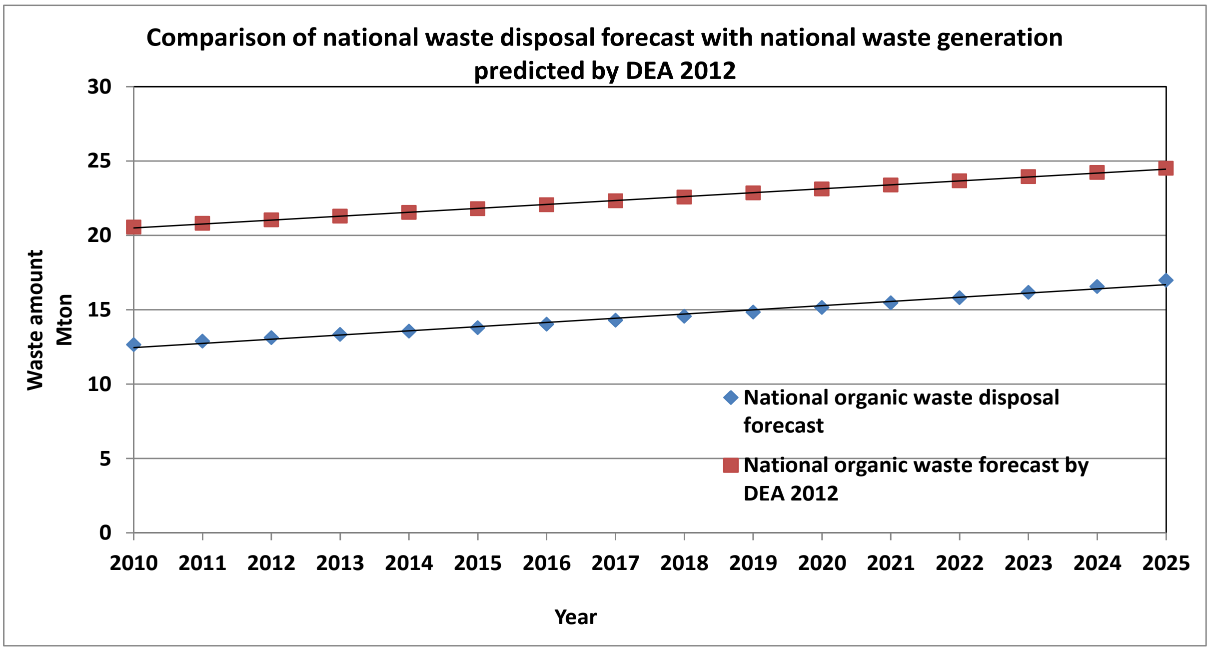


Figure 4-5: Comparison of national organic waste forecast estimated by DEA (2012) and present study

It can be seen that the national organic waste estimated by DEA (2012) is significantly higher than the organic waste from the waste categories chosen for this thesis. This is expected because the national waste information baseline reported all organic waste generated in 2011, whereas in this study only the disposed waste was considered. It can be seen that the difference between the two predictions varied from 30 and 39%. This indicates that the accuracy of estimating the disposable national organic waste using the present technique would improve if the actual data of the disposed organic waste can be established. The deviation is attributed to the green waste and the amount of waste that is not disposed. The disposable organic waste modelled in this study qualifies to be used until the actual data of the waste generated and disposed from all the sectors that are organic waste resources is compiled in South Africa.

Under the current status in South Africa, the organic waste is largely disposed to landfills or to lagoons in reference to livestock manure, as shown in Sections 2.4.4 and 2.4.6.2. After undergoing anaerobic degradation, they produce biogas which consists of a large percentage of CH_4 gas that is emitted to the atmosphere without being recovered with exceptions of Ekurhuleni and eThekwini municipalities (EMA 2011, EMM 2012).

4.2.2 Degradation of organic solid waste

When the organic waste is disposed, it is only the fraction of the organic carbon that biodegrades to produce the biogas (Pipatti *et al* 2006). Therefore it is important to estimate the decomposable degradable organic carbon (DDOC) from the organic waste disposed in the landfills. The estimated accumulated quantity of DDOC that can be achieved under the current waste "growth without constraints" from 2010 to 2025 is shown in Figure 4-6. Equation (2-9) was used for this estimation. It is observed that there is a large amount of DDOC accumulated from the organic waste disposed in South African landfills. Currently, with the exceptions of some major landfills from the City of eThekwini and Ekurhuleni municipalities, this DDOC ends up decomposing and eventually generating anthropogenic methane gas which is emitted to the atmosphere (COCT 2012, EMA 2011 GEDACE 2008).

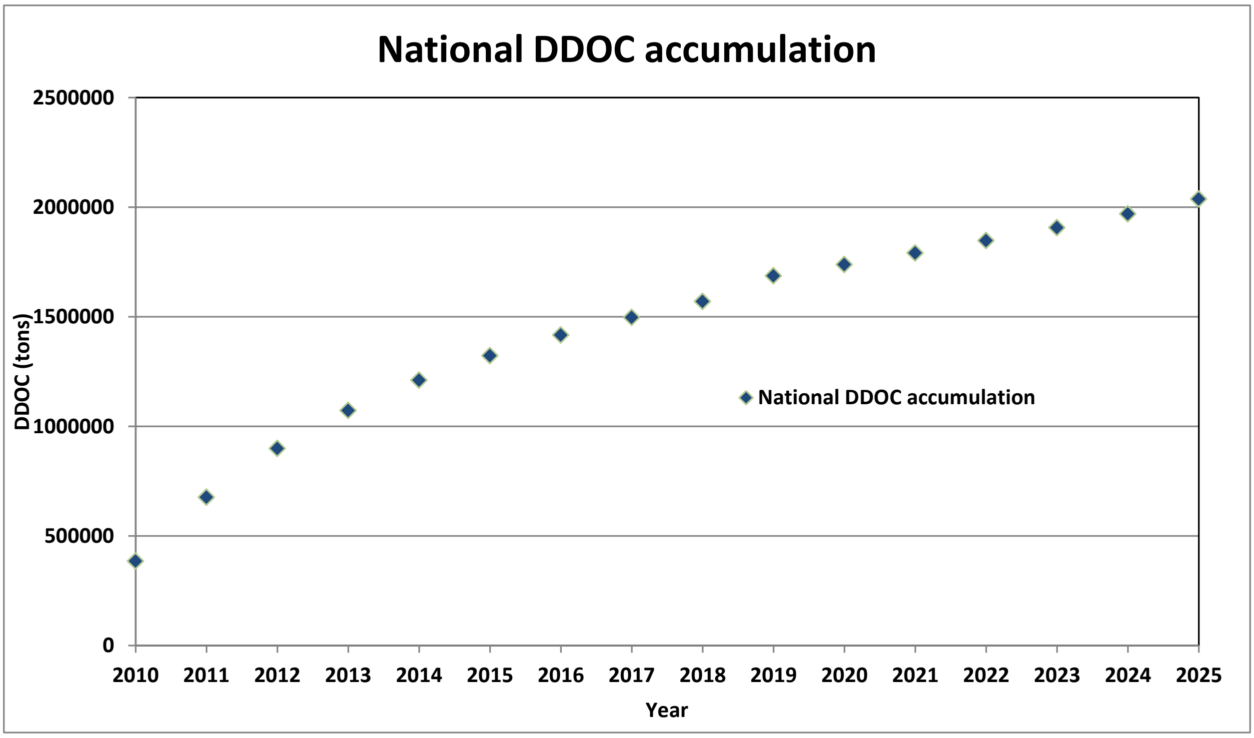


Figure 4-6: National DDOC accumulation forecast from South African landfills

The DDOC does not biodegrade completely within a space of one a year to produce biogas. It biodegrades gradually over the years until it is depleted from the municipal solid waste disposed in the landfills (Pipatti *et al* 2006, Thompson *et al* 2008). Figure 4-7 shows an example of life of the DDOC from the original waste disposed as it gradually decomposes until it is completely digested. Equation (2-6) was used for this estimation. It is seen that the DDOC of the organic waste disposed in landfill decays exponentially over the years from the disposal year (2010) until it gets depleted around 2060. As this organic fraction of the waste continually decays in South African landfills, the methane gas will also be generated over this period of time which would be emitted to the atmosphere, thus causing an increase to the GHG emissions of the country.

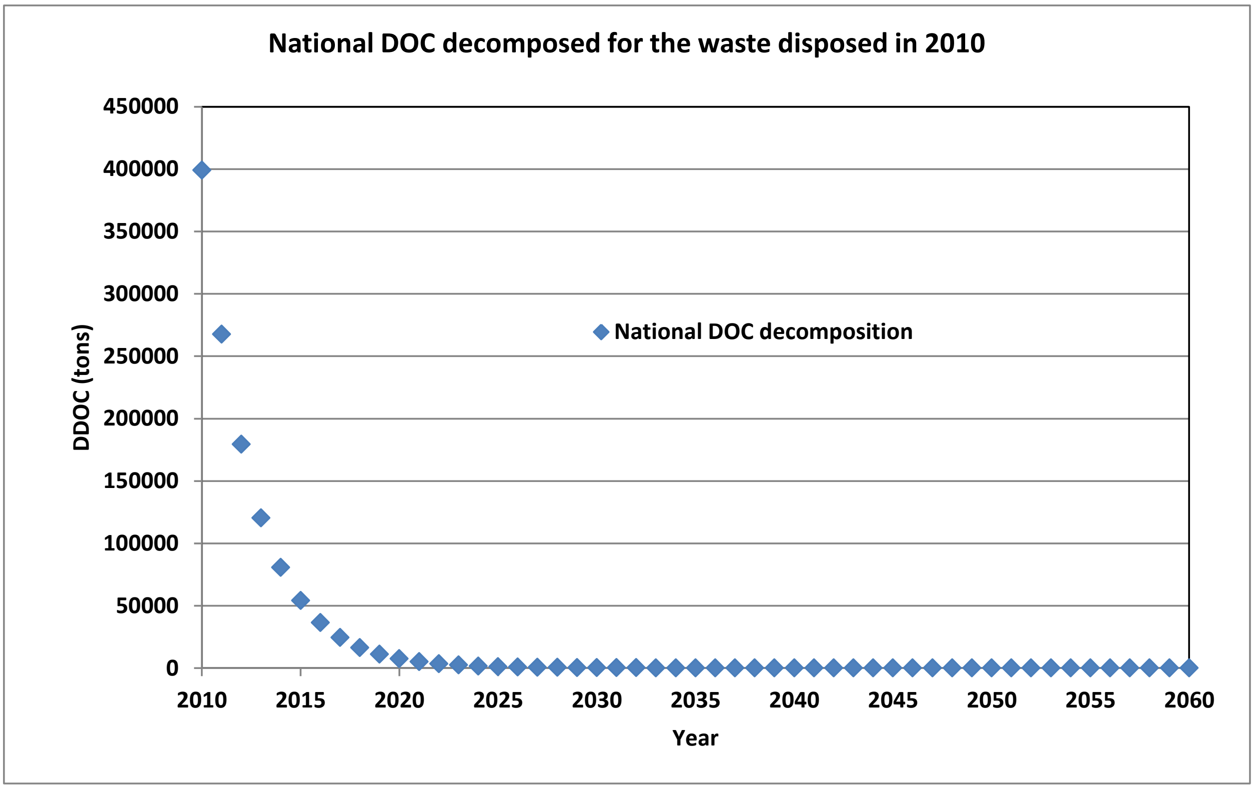


Figure 4-7: Duration of the national DDOC decomposition for the waste originally disposed to the landfills in 2010

4.2.3 Half-life of the DDOC in landfills

The half-life of organic waste DDOC disposed in South African landfill was calculated using the k-value of 0.4 yr^{-1} as shown in Section 2.4.2. This value is for rapidly degradable organic waste (Pipatti *et al* 2006), and is taken for the organic waste disposed in South African landfills. As reported in Section 2.4.4, in almost all major landfills in the country, the other organic waste such as paper and garden waste is diverted from the landfills for recycling and composting (COCT 2011, COJ 2011, EMA 2010, and GDACE 2008). Equation (2-10) was used to estimate the half-life of DDOC and it was found to be about 1.733 years.

Table 4-1 shows the half-life of DDOC using different values of k. The higher values of k indicate quick degradable organic waste which causes shorter half-lives of DDOC. The lower values indicate the slow degradable organic waste which causes longer half-lives of DDOC.

Table 4-1: Half-life of DOC disposed in South African landfills

k-value (yr^{-1})	Half-life of DDOC (yr)
0.1	6.931
0.4	1.733
1.2	0.578

Figure 4-8 shows the effect of k-value on DDOC initially disposed in 2010. It is seen that the k-value has a significant effect on the decomposition rate of the organic waste disposed in the landfill sites.

The life of the DDOC in landfills decreases exponentially with increasing k-value. Equation (2-5) and (2-6) were used.

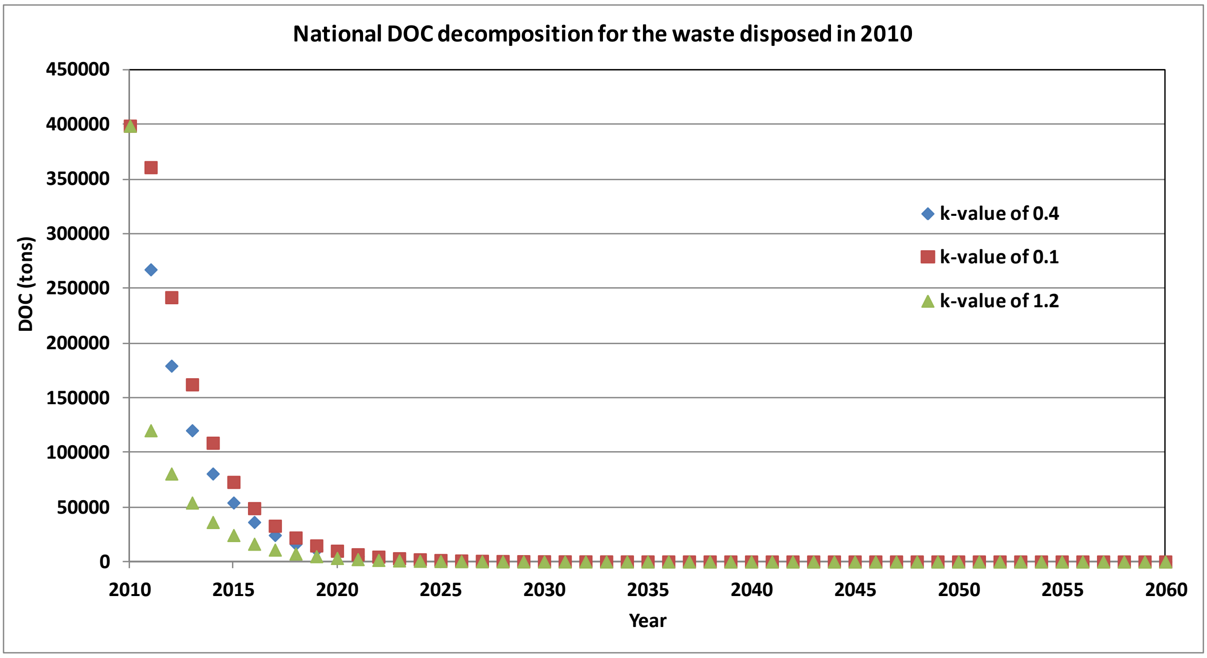


Figure 4-8: The effect of k-value on the life DDOC initially disposed in 2010

As mentioned in Section 2.4.2, the k-value is greatly influenced by the waste composition disposed and the conditions in the landfill sites (Pipatti *et al* 2006). Therefore, great care should be taken in disposing different types of organic waste in the landfill sites, and in the management of the landfills.

4.2.4 CO_2 equivalent emissions from organic waste

As stated in Section 2.4.2, in most developing countries the CH_4 gas produced from organic waste disposed in landfill sites is emitted to the atmosphere without being recovered. It was also mentioned in the same section that some of the livestock manure are handled in lagoons without any CH_4 gas recovery systems in South Africa. This sub-section quantified the CH_4 emissions from these waste types and expressed in CO_2 equivalents.

Figure 4-9 shows that these organic waste categories particularly wastewater and solid waste make significant contribution to the GHG emissions in the country, as can be seen they are in the order of million tons per annum. These emissions were forecasted under “growth without constraints” scenario where each organic waste type is disposed to the ecosystem without treating it to remove the biodegradable matter of the waste.

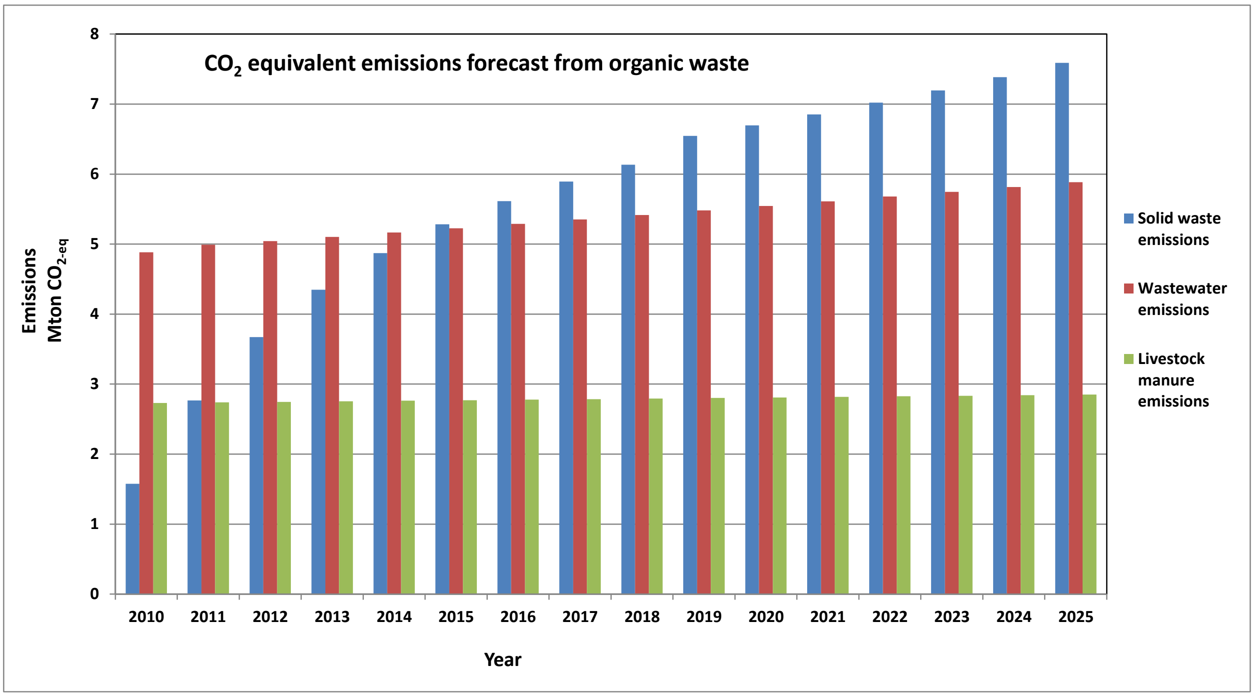


Figure 4-9: CO$_2$ equivalent emissions forecast from different organic waste categories

The emissions from various types of organic waste are then added together to determine the share of emissions from the organic waste in the total GHG emissions predicted under "growth without constraints" scenario. This is shown in Figure 4-10.

It is observed that the share of emissions in the total GHG emissions from the organic waste types considered in this study (2%) is comparable to share (3%) reported by Urban Life (2012). Although this share is relatively low, it cannot be ignored in an attempt to reduce emissions of the country to the targets specified in Climate Change Response Policy. This is important because the destruction of CH$_4$ emissions through capturing them for use as an energy source has a cross-cutting effect in reducing the energy emissions.

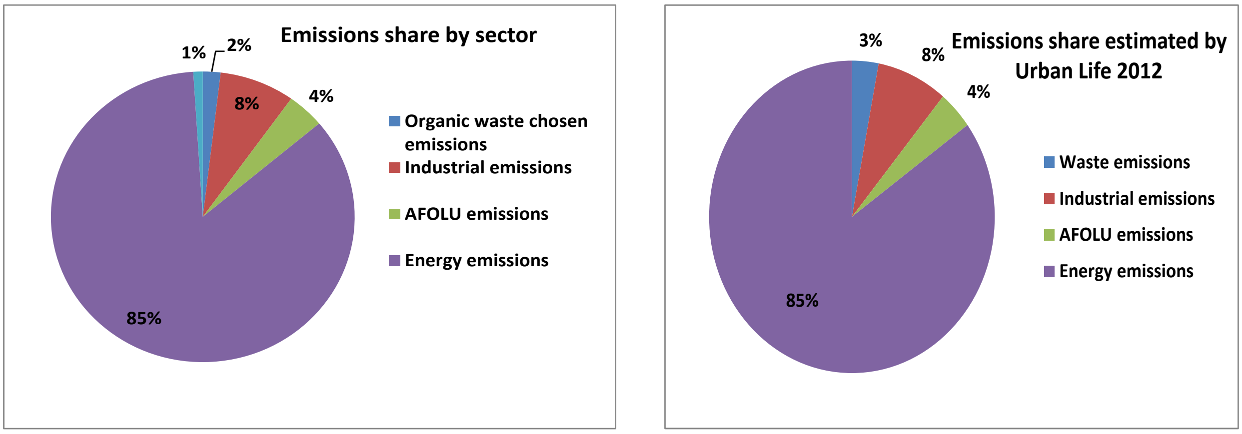


Figure 4-10: Share of emissions from the organic waste types chosen in national GHG emissions under "growth without constraints." AFOLU denotes agricultural, forest, and other land use

4.2.4.1 Effect of k-value, B_o for wastewater and animal manure on methane emissions

As reported in Section 4.2.3, the k-value is directly proportional to the decomposition rate of DOC. This would also mean that it is directly proportional to the CH_4 emitted to the atmosphere from the landfill sites because methane emissions are the product of DDOC. This also needs to be proven for CH_4 emissions from wastewater and livestock manure whether their CH_4 generation capacity (B_o) has also the same effect on the fraction of CO_2 equivalent CH_4 emission in the years the pledge was made. This is presented in Table 4-2.

Table 4-2: Effect of k and B_o-values on CO_2 equivalent methane emission from waste water and livestock manure

Year	National CO_2 baseline emissions ($MtonCO_{2-eq}$)	B_o wastewater ($kgCH_4/kgCOD$)	B_o livestock manure (m^3/kg)	k-value (yr^{-1})	CO_{2-eq} CH_4 fraction from organic waste (%)
2020	800	0.2	0.15	0.2	1.67
2025	950	0.2	0.15	0.2	1.56
2020	800	0.25	0.22	0.4	2.29
2025	950	0.25	0.22	0.4	2.41
2020	800	0.3	0.3	0.8	2.55
2025	950	0.3	0.3	0.8	2.66

It is observed that the k and B_o-values have noticeable effect on the overall GHG emissions because an increase in these parameters causes an increase in the fraction of CH_4 emission in overall predicted emissions of the country. This shows that the composition of the organic waste type, the type of disposal and the conditions at the disposal sites are very crucial in determining the GHG emissions from the organic waste.

Therefore, for the effective climate change mitigation through reducing CH_4 emissions from the waste resources, great consideration should be given to all the factors that affect these parameters. Digestion of these waste types using anaerobic digesters as reported in Section 2.4.8 can be helpful in reducing GHG emissions.

4.3 Quantifying biogas production

4.3.1 Methane generation from municipal organic solid waste

The national generation of CH_4 from municipal organic solid waste in South Africa than can be recovered from the landfills was estimated using equation (2-15). The recovery rate is estimated to be 85% for the fully engineered, and a capped landfill was used to estimate the CH_4 that can be recovered (Timoney 2009). Table 4-3 shows levels of methane generation and recovery forecast from municipal organic solid waste. The quantity of CH_4 quantity for each municipality chosen in this study is presented in Appendix 7.3.1.

Table 4-3: Methane generation and recovery forecast from municipal organic solid waste

Year	CH_4 generation Mm^3	Recovery rate %	Recoverable CH_4 Mm^3
2010	102.90	85	87.47
2011	181.74	85	154.48
2012	242.92	85	206.48
2013	289.82	85	246.34
2014	327.01	85	277.96
2015	357.24	85	303.65
2016	382.53	85	325.15
2017	404.38	85	343.72
2018	423.91	85	360.33
2019	455.17	85	386.89
2020	468.90	85	398.56
2021	483.24	85	410.75
2022	498.33	85	423.58
2023	514.30	85	437.16
2024	531.31	85	451.61
2025	549.47	85	467.05

The recoverable CH_4 gas shown in Table 4-3 is the potential source of energy with a net calorific value of about 18.3MJ/kg (Banks 2009). The net calorific value of coal used by Eskom power stations is 19MJ/kg (Eberhard 2011). Therefore this means the quantity of CH_4 that can be recovered from landfill carries enough energy content to replace coal as a fuel source. When CH_4 gas is not recovered from the landfill it can also cause hazardous consequences like landfill fire explosion because CH_4 gas creates an explosive combustion reaction when it reacts with oxygen (Matekenya 2009).

4.3.2 Methane generation from the municipal wastewater

The CH_4 generation from the current municipal wastewater treatment works in South Africa was estimated using equation (3-8). This is generated from the sludge that is disposed in the sludge disposal sites. The forecast from 2010 to 2025 is shown in Table 4-4. A methane correction factor (MCF) was used because in many municipal wastewater treatment plants in South Africa, the sludge does not have the methane recovery system (Snyman 2007). The quantity of CH_4 quantity for each municipality chosen in this study is presented in Appendix 7.3.2.

Table 4-4: Methane generation and recovery forecast from municipal wastewater

Year	CH_4 generation Mm^3	MCF %	CH_4 recovery Mm^3
2010	457.62	80	366.09
2011	467.89	80	374.31
2012	472.78	80	378.22
2013	478.42	80	382.73
2014	484.12	80	387.30
2015	489.90	80	391.92
2016	495.74	80	396.59
2017	501.65	80	401.32
2018	507.64	80	406.11
2019	513.69	80	410.95
2020	519.82	80	415.86
2021	526.02	80	420.82
2022	532.30	80	425.84
2023	538.65	80	430.92
2024	545.08	80	436.07
2025	551.59	80	441.27

The CH_4 gas estimated in Table 4-4 is emitted to the atmosphere in many municipalities after it has been generated from anaerobic digestion of the disposed wastewater sludge. In municipalities like the six major metros in the country which have the anaerobic bioreactors in their wastewater treatment plants, the CH_4 gas generated is flared to the atmosphere thus making significant contribution to global warming. As the CH_4 generated from wastewater is bigger than the CH_4 generated from the solid waste, this means wastewater sludge in South Africa carry more energy content than municipal solid waste.

4.3.3 Methane generation from the livestock waste

CH_4 generation from livestock manure was estimated using equations (2-19) and (2020). Table 4-5 shows a forecast of CH_4 generation from livestock from 2010 to 2025. CH_4 generated is from the manure that is managed under liquid base manure management systems which are lagoons for most South African cases (Taviv *et al* 2007). The quantity generated is higher than that from the municipal solid waste but lower than that from the municipal wastewater. This indicates that manure can also not be ignored when recovering energy from waste.

Table 4-5: Methane generation and recovery forecast from livestock manure

Year	CH_4 generation Mm^3	MCF %	CH_4 recovery Mm^3
2010	123.81	80	99.05
2011	124.16	80	99.33
2012	124.51	80	99.61
2013	124.86	80	99.89
2014	125.22	80	100.17
2015	125.57	80	100.46
2016	125.92	80	100.74
2017	126.28	80	101.02
2018	126.64	80	101.31
2019	127.00	80	101.60
2020	127.36	80	101.89
2021	127.72	80	102.18
2022	128.08	80	102.47
2023	128.45	80	102.76
2024	128.81	80	103.05
2025	129.18	80	103.35

4.3.4 Effect of k- and B_o-values on the recovered methane generated from the organic waste types chosen

The recoverable CH_4 from these waste types are added together, and then a sensitivity analysis was performed by changing k and B_o parameters to verify their effect on the generated methane that can be recovered for utilisation as an energy source. However, it should be noted that the parameters that are reviewed in literature are: 0.4 for the k-value, 0.25 and 0.22 for the wastewater B_o and livestock manure B_o respectively (Pipatti *et al* 2006, Doorn *et al* 2006, Dong *et al* 2006). Figure 4-11 shows the effect of k- and B_o-values on the total recoverable CH_4 generated from organic waste.

It should be noted that the total CH_4 generation from these waste types is for the systems without CH_4 recovery systems. Figure 4-11 confirms that parameters such as k-value for municipal solid waste, B_o-values for municipal wastewater and livestock waste have a significant effect on the recovery rate of CH_4 generated from these waste types. It is observed that methane recovery increases with k. An increase in the recoverable CH_4 would lead to an increase in the useful heat and electricity that can be generated from the waste. This would also mean more reduction on the GHG emissions of the country.

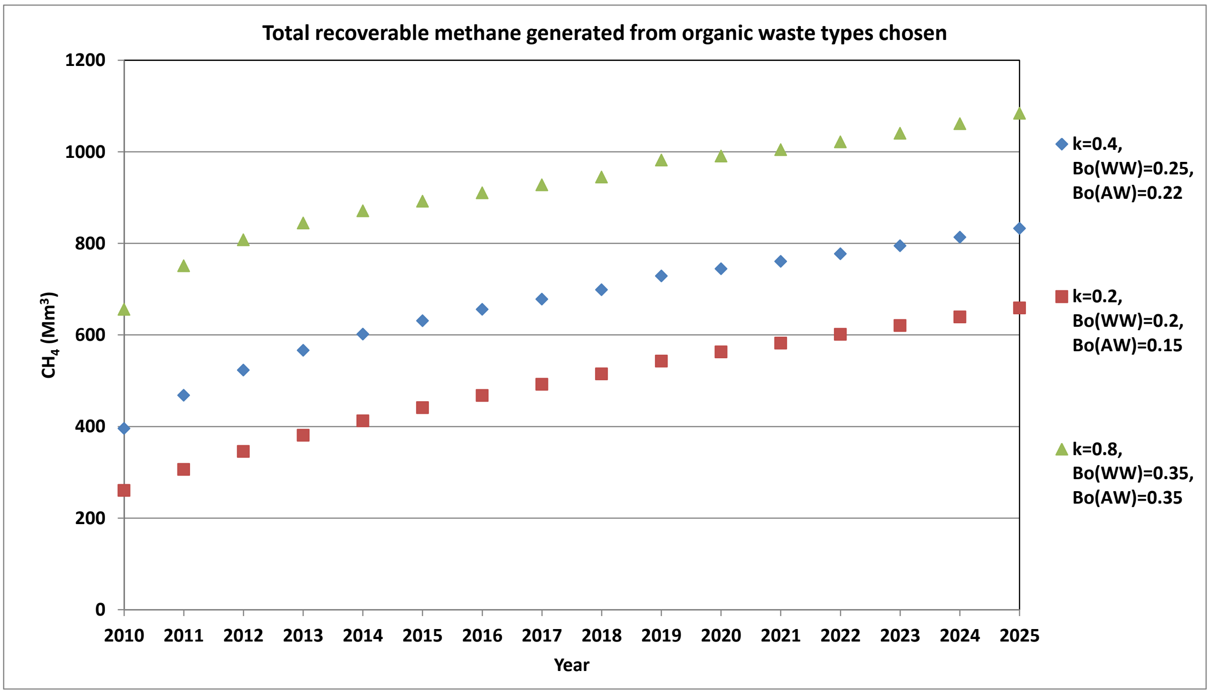


Figure 4-11: effect of parameters such as k- and B$_0$-values on total recoverable methane generated from organic waste.

If the CH$_4$ generated from these waste types is intended to be harvested for utilisation as an energy source; great care should be taken about factors like: conditions at the landfill sites, composition of municipal solid waste, physical and chemical properties of the municipal wastewater, and storage type and volatile solids concentration for the livestock manure. To improve or optimise the CH$_4$ generation from these waste types, the naturally occurring anaerobic digestion process can be simulated in a biogas digester.

Under anaerobic process in the biogas digester, parameters like temperature range suitable for anaerobic conditions, waste composition, and the desired digestion fraction of the organic waste can be controlled (Sims 2002). The retention time of the anaerobic process can also be reduced if these factors are controlled to meet the desired ranges stated in Section 3.7. As shown in Section 4.2.3 that the k-value is proportional to time of digestion (shorter retention time would increase the k-value). Higher k-values caused by shorter retention time would increase the CH$_4$ yield from the organic waste fermented. The quantity of biogas captured would also increase as there would less leakage in the biogas digester. The leakages from the biogas digester are estimated to be 5% (UNFCC 2006).

4.4 Evaluation of the amount of energy carried by methane gas and utilisation as an energy source

The total recoverable CH$_4$ generated from these waste types were then added together to evaluate the potential energy carried by organic waste and the amount of electricity and heat that can be generated from these waste types. The total potential electricity and heat generated from energy carried by national organic waste methane is presented in Table 4-6. The electricity can be fed to the grid and the total heat generated can be used directly for cooking, space heating or for any industrial heating application. It is observed that there is a significant amount of energy (in biogas), which currently is going to waste and eventually contributing to climate change.

Table 4-6: Total potential electricity and heat generation from energy carried by national organic waste methane

Year	Total CH_4 Mm^3	Potential Energy from CH_4 GWh	Potential electricity feed to grid GWh	Potential heat generated GWh
2010	644.13	2301	673	1255
2011	720.70	2722	753	1418
2012	776.21	3041	811	1536
2013	819.62	3293	857	1628
2014	854.53	3498	893	1702
2015	883.37	3668	923	1762
2016	907.93	3814	949	1813
2017	929.51	3943	971	1858
2018	949.09	4061	992	1898
2019	977.89	4238	1022	1958
2020	992.59	4328	1037	1987
2021	1007.74	4421	1053	2017
2022	1023.43	4518	1070	2049
2023	1039.77	4621	1087	2081
2024	1056.85	4728	1104	2115
2025	1074.75	4842	1123	2150

As the organic waste generation in South Africa is forecasted to continue increasing due to increase in population and economic growth in the country, there will also be a high demand for heat and electricity in the country. This would mean more reliance on fossil fuels like coal if the energy supply continues “under business as usual” scenario which would be unsustainable. Therefore, Table 4-6 provides evidence that there is an alternative energy source going to the waste in the country that cannot continue to be ignored. As shown here this can reduce reliance on coal in South Africa’s energy supply, thus reducing the associated GHG gas emissions.

4.5 Optimisation of methane production and utilisation for electricity and heat generation

In this sub-section the anaerobic process that occurs naturally was simulated to happen in the biogas digester to assess the CH_4 generation under controlled conditions. This was investigated through making different combinations of waste that are presumed to increase the generation of methane in the biogas digesters. These combinations that are thought to be reasonable and possible to be combined across the country are: municipal solid waste plus portion of wastewater that will be required in the slurry formation, livestock manure plus portion of remaining wastewater from the first combination, and the digestion of remaining wastewater alone. Equations (3-17)-(3-27) were used to estimate the DDOC, COD and k-value of the slurry; and equation (2-11) was used to estimate the CH_4 quantity. Optimisation of methane generation from different organic waste combinations is presented in Figure 4-12.

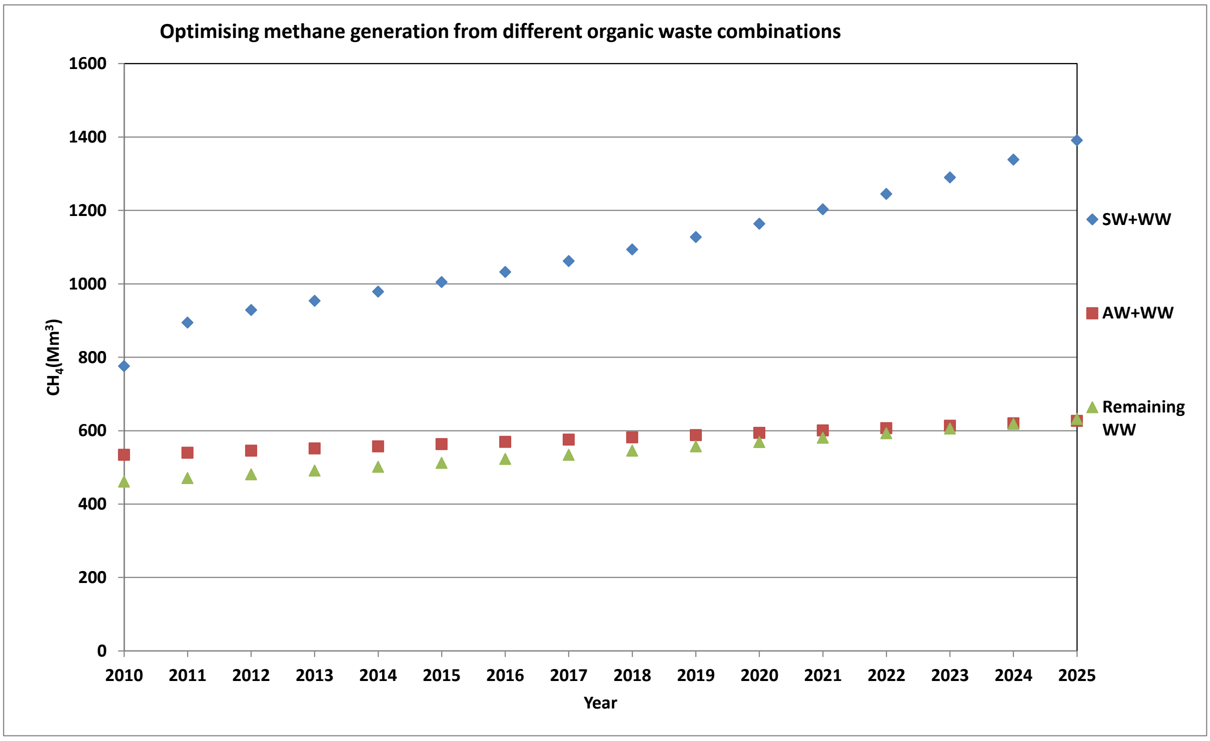


Figure 4-12: Optimisation of methane generation from different organic waste combinations

Methane generated from the different waste combinations shown in Figure 4-12 was higher than the total CH_4 generated from all the waste types shown in Figure 4-11. This is evident when comparing the quantity of CH_4 generated from each waste combination to the total CH_4 generated from all the waste types shown in Figure 4-11 when the k and B_o values reported in literature were used.

Methane generated from the combination of MSW and WW gave the highest yield of CH_4 than other combinations. This is probably caused by the reaction mechanism between these two organic waste types which gave rise to both DOC and COD of the slurry as shown in Section 3.7. This was also confirmed by Elangoa *et al* (2013) where shorter retention time for this mixture resulted in COD and DOC reduction of 88-90% in effluent stream. The combination of AW and WW and the remaining WW also gave higher CH_4 yields than the total CH_4 generation from all the waste types. The advantage of digesting these feedstock combinations in a biogas digester is that there is less gas leakage (about 5%) when biogas is collected (UNFCC 2006).

The CH_4 gas collected from these different waste combinations can be used to generate electricity and heat. This would also mean an increase in the quantity of fossil fuels that can be replaced.

4.5.1 Heat and electricity generation from the total optimal methane generation

The potential total energy, electricity and heat that can be generated from the total CH_4 generated from the waste combinations are presented in Table 4-7.

Table 4-7 suggests the amount of energy that would be available if the waste types are combined. From this amount of energy, there is also a possibility of generating larger amounts of electricity and heat than what can be generated from the total CH_4 generated from each waste in Table 4-6.

Table 4-7: Total potential electricity and heat generation from energy carried by the total methane generation from the waste combinations suggested

Year	Potential Energy from CH_4 GWh	Electricity feed to grid GWh	Total heat generated GWh
2010	10625	1952	3850
2011	11430	2100	4150
2012	11732	2156	4260
2013	11977	2201	4350
2014	12224	2246	4440
2015	12480	2293	4534
2016	12748	2343	4632
2017	13029	2394	4734
2018	13324	2448	4842
2019	13634	2505	4955
2020	13960	2565	5074
2021	14304	2628	5200
2022	14668	2695	5333
2023	15053	2766	5473
2024	15461	2841	5622
2025	15896	2921	5781

The effect of optimising biogas generation through waste combinations is shown in Figure 4-13. It is seen that the potential electricity that can be generated from the total CH_4 produced by the proposed waste combinations would increase by 51%. The direct heat produced would increase by 57%. This indicates the attractiveness of utilising the organic waste in South Africa as an energy source. This could help the country to increase its energy security which is under threat with the electricity sector being under supply (Pegels 2010). This could also contribute to climate change mitigation plans of the country where CH_4 emissions from organic waste are destroyed, and also utilised instead of fossil fuels.

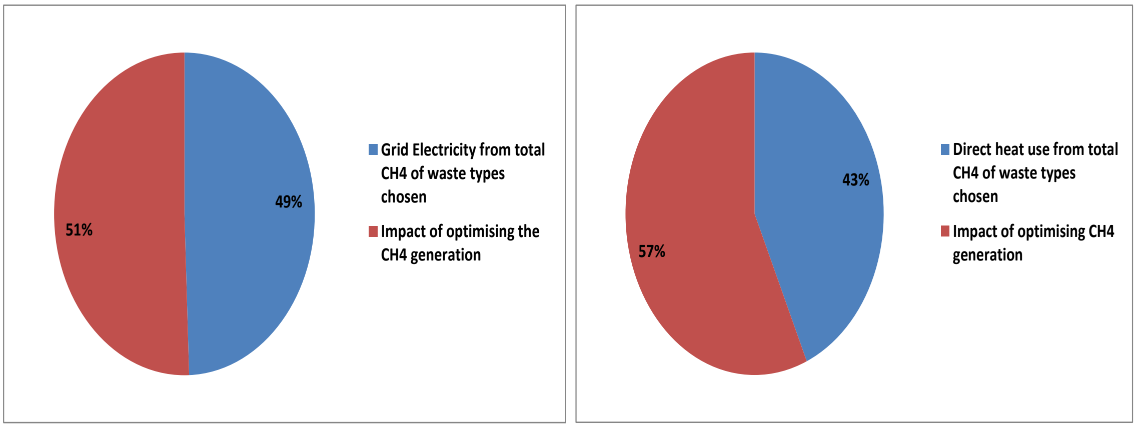


Figure 4-13: Effect of optimising the biogas generation through waste combination suggested on electricity and heat generation from waste

4.6 Emission reduction potential of the biogas

Methane captured and destroyed is presented in Table 4-8 where the reduction was assessed against the total GHG emissions under "growth without constraints" scenario. It is observed that this can contribute between 1.49 and 1.73% in reducing the total GHG emissions in South Africa. The share of CH_4 emissions from the organic waste was shown (in Figure 4-10) to be 2% in national GHG emissions under "growth without constraints scenario". Therefore the ERP of biogas through CH_4 capturing and destroying contributed about 77-80% in reducing the organic waste emissions.

Table 4-8: Emission reduction potential (ERP) of capturing and destroying methane emissions

Year	GHG emissions $MtonCO_{2-eq}$	CH_4 emission generated $MtonCO_{2-eq}$	CH_4 emissions destroyed $MtonCO_{2-eq}$	ERP from total GHG %
2010	567	10.92	8.44	1.49%
2011	587	12.10	9.46	1.61%
2012	607	12.96	10.20	1.68%
2013	628	13.63	10.77	1.71%
2014	650	14.17	11.24	1.73%
2015	673	14.62	11.62	1.73%
2016	697	15.00	11.95	1.71%
2017	721	15.34	12.23	1.70%
2018	746	15.64	12.49	1.67%
2019	772	16.10	12.87	1.67%
2020	800	16.33	13.06	1.63%
2021	827	16.57	13.26	1.60%
2022	856	16.82	13.47	1.57%
2023	886	17.07	13.68	1.54%
2024	917	17.34	13.91	1.52%
2025	950	17.63	14.14	1.49%

Table 4-9 shows the emission reduction potential (ERP) of capturing and utilising CH_4 as an energy source. The ERP estimated from this assessment shows that capturing and utilisation of biogas not only eradicates the organic waste emissions (estimated to be 2%) but also can reduce coal emissions. This is evident from a comparison of the ERP (1.49-1.73%) in Table 4-8 for capturing and destroying with ERP (2.1-2.5%) in Table 4-9 for biogas capturing and utilisation.

Table 4-9: Emission reduction potential (ERP) of capturing and utilising CH_4 as an energy source

Year	GHG emissions $MtonCO_{2\text{-eq}}$	CH_4 emission generated $MtonCO_{2\text{-eq}}$	Total avoidable CH_4 emissions $MtonCO_{2\text{-eq}}$	ERP from total GHG %
2010	567	10.92	11.97	2.11%
2011	587	12.10	13.41	2.29%
2012	607	12.96	14.45	2.38%
2013	628	13.63	15.27	2.43%
2014	650	14.17	15.92	2.45%
2015	673	14.62	16.46	2.45%
2016	697	15.00	16.92	2.43%
2017	721	15.34	17.32	2.40%
2018	746	15.64	17.69	2.37%
2019	772	16.10	18.23	2.36%
2020	800	16.33	18.50	2.31%
2021	827	16.57	18.79	2.27%
2022	856	16.82	19.08	2.23%
2023	886	17.07	19.38	2.19%
2024	917	17.34	19.70	2.15%
2025	950	17.63	20.03	2.11%

The ERP of biogas estimated in Table 4-9 was used to assess the contribution biogas capture and utilisation can make in achieving the trajectory ranges between 2020 and 2025. The results of this analysis are presented in Table 4-10. This contribution was also assessed on the pledge made under COP 15 Accord and findings are given in Table 4-11.

Table 4-10: Contribution of biogas on the national GHG emissions trajectory ranges

Year	(a) (Mtons $CO_{2\text{-eq}}$)	(b) (Mtons $CO_{2\text{-eq}}$)	(c) (Mtons $CO_{2\text{-eq}}$)	(d) (%)	(e) (Mtons $CO_{2\text{-eq}}$)	(f) (%)
2020	800	18.50	583	8.55	398	4.61
2025	950	20.03	614	5.97	398	3.63

(a) National GHG emissions, (b) Total avoided CH_4 emissions, (c) GHG trajectory upper limit range, (d) Biogas contribution to achieve upper limit range, (e) GHG trajectory lower limit range, (f) Biogas contribution to achieve lower limit range.

The assessment in Table 4-10 was made by first determining the emissions that would need to be reduced from national GHG emissions to achieve the emissions trajectory ranges of upper and lower limits. Then from this reduction, the contribution that biogas capture and utilisation can make in achieving the reduction was assessed. This was found to be between 8.55 and 5.97% in achieving the upper limit range in 2020 and 2025 respectively. To achieve the lower limit range this was found to contribute between 4.61 and 3.63% over the same period. This contribution is significant, especially when considering the fact that the waste emissions have a share of 3% in the national GHG emissions (Urban Earth 2012). Moreover this contribution has a cross-sectorial contribution to electricity emissions reductions. So far, the Climate Change Policy of South Africa has not set the desired emissions reduction from each sector that is consistent with National GHG Emissions Trajectory Ranges (DEA 2011a). Therefore this assessment can be used in developing a carbon emissions budget for the waste sector.

Table 4-11 shows the contribution of biogas capture and utilisation evaluated based on the pledge made in COP 15 Accord. This table shows that the biogas capture and utilisation can make a meaningful contribution to achieve the emission reductions stated in the COP 15 pledge. The contributions that can be achieved are between 6.81 and 5.02% between 2020 and 2025 from organic waste that only has a share of 2% in national GHG emissions. This indicates that biogas can make an important contribution in mitigating climate change in South Africa. The utilisation of biogas as a renewable energy source would not only help South Africa achieve its climate change mitigation ambitions but also low carbon energy development with potential GHG emissions reductions of 2.1-2.45% coming from organic waste conversion to energy. This would also oversee an increase in energy security of the country through an increase in renewable energy uptake.

Table 4-11: Contribution of biogas on the pledge made in COP 15 Copenhagen 2009 accord

Year	(a) (Mtons $CO_{2\text{-eq}}$)	(b) (Mtons $CO_{2\text{-eq}}$)	(c) (Mtons $CO_{2\text{-eq}}$)	(d) (%)
2020	800	271.78	18.50	6.81
2025	950	398.75	20.03	5.02

(a) National GHG emissions, (b) Pledge committed emissions reduction, (c) Avoided CH_4 emissions, (d) Biogas contribution to achieve the commitment made in a pledge.

4.6.1 Impact of optimal biogas generation on emission reduction potential of biogas (ERP)

The capturing and utilisation of the total optimal CH_4 generated from the waste combinations suggested in this study gives a better ERP of biogas than when CH_4 was not optimised. This is evident from Table 4 12, where the ERP for optimal CH_4 generation is between 5 and 6%. These are significant GHG emission reductions considering that they are also coming from the same organic waste that has the share of 2% emissions in the national GHG emissions. This proves that the significant GHG emissions reduction from biogas can be achieved through optimising its production by combining different organic waste feedstock available, at least those that were used in this study.

The impact of optimising the CH_4 generation was also assessed against the National Emissions Trajectory Ranges to determine the contribution it can make to achieve these trajectory ranges. Same methodology was used as the one used in Section 4.6. Findings from this analysis are presented in Table 4-13.

Table 4-12: Emission reduction potential of capturing and utilising the optimal CH_4 generation

Year	GHG emissions $MtonCO_{2\text{-eq}}$	CH_4 emission generated $MtonCO_{2\text{-eq}}$	Total avoidable CH_4 emissions $MtonCO_{2\text{-eq}}$	ERP from total GHG %
2010	567	26.56	32.19	5.68%
2011	587	28.57	34.64	5.91%
2012	607	29.33	35.56	5.86%
2013	628	29.94	36.30	5.78%
2014	650	30.56	37.05	5.70%
2015	673	31.20	37.83	5.62%
2016	697	31.87	38.64	5.55%
2017	721	32.57	39.49	5.48%
2018	746	33.31	40.39	5.41%
2019	772	34.08	41.33	5.35%
2020	800	34.90	42.32	5.29%
2021	827	35.76	43.36	5.24%
2022	856	36.67	44.47	5.19%
2023	886	37.63	45.64	5.15%
2024	917	38.65	46.88	5.11%
2025	950	39.74	48.19	5.08%

Table 4-13: Contribution of biogas to the national GHG emissions trajectory ranges when methane generation was optimised

Year	(a) (Mtons $CO_{2\text{-eq}}$)	(b) (Mtons $CO_{2\text{-eq}}$)	(c) (Mtons $CO_{2\text{-eq}}$)	(d) (%)	(e) (Mtons $CO_{2\text{-eq}}$)	(f) (%)
2020	800	42.32	583	19.56	398	10.54
2025	950	48.19	614	13.15	398	8.74

(a) National GHG emissions, (b) Total avoided CH_4 emissions, (c) GHG trajectory upper limit range, (d) Biogas contribution to achieve upper limit range, (e) GHG trajectory lower limit range, (f) Biogas contribution to achieve lower limit range.

As expected, the CH_4 capture and utilisation as an energy source under total optimal generation of CH_4 can make better contribution in achieving the National GHG Trajectory Ranges. It is seen that this can contribute between 19.6 and 13% to achieve the upper limit range, and between 10.6 and 8.7% to achieve the lower limit range between 2020 and 2025 respectively. These observations indicate that the best contribution of biogas in mitigating climate change in South Africa can be achieved through capturing and utilising optimally generated CH_4 as an energy source. However the economic benefits of these types of projects are not yet known. As mentioned in Section 4.6, CH_4 capture and utilisation has the cross-sectorial contribution as it can also decrease the emissions from electricity generated by coal fired plants. This contribution could be further improved if the correct data of the waste can be collected as well as information on the reaction kinetics of the micro-organism that produces the bacteria that affect the decomposition rate of the biodegradable material of organic waste.

This assessment can provide useful information in developing the GHG mitigation potential of the waste management sector which would include opportunities to convert waste into energy as elaborated in DEA (2011a). This would also be useful in developing a detailed waste related GHG emission mitigation action plan envisaged in the National Climate Change Response White paper.

5 Conclusions and recommendations

5.1 Introduction

Climate change poses a significant challenge in South Africa as reported in Chapter 1. Consequently, there is need to find sustainable solutions. In this regard, the present investigation sought to make a contribution toward the global effort in mitigating this environmental problem.

The main purpose of this work was to assess the potential contribution that biogas recovered from the organic waste resources can make to mitigate climate change in the country. The waste resources considered were chosen based on their abundance (mostly dumped at disposal sites or waste handling sites). These include municipal solid waste, municipal wastewater and agricultural waste, particularly livestock manure. The objectives of the investigation were geared towards the national emission trajectories of the country which are set to peak between 2020 and 2025 by upper limit ranges of 583 Mton $CO_{2\text{-eq}}$ and 614 $CO_{2\text{-eq}}$ in 2020 and 2025 respectively; and by a lower limit range of 398 Mton $CO_{2\text{-eq}}$ during the same period. Five specific objectives were set out.

Fundamentals of climate change have been presented in Chapter 2. This theory was used in formulating a suitable method (Chapter 3) for achieving the objectives of this investigation. Quantities of waste were estimated for 7 municipalities. These quantities were used to estimate the national levels of waste materials. Then, the amount of biogas (which contains methane) produced was calculated from the wastes. Finally, electric and heat energy that can be obtained from the biogas was computed. Findings from this investigation are reported in Chapter 4. Conclusions and recommendations drawn from these results are presented in this chapter.

5.2 Conclusions

5.2.1 Quantity of organic waste available in South Africa and its associated emissions share in national GHG emissions

It was crucial to establish the quantity of organic waste because the decomposition of these waste types, in the absence of oxygen, produces biogas. Biogas consists of large fraction of CH_4 which is emitted to the atmosphere when these organic waste types are disposed. In most cases, the waste is disposed without recovering the anthropogenic CH_4 gas which has the global warming potential that is 21 times that of CO_2.

The municipal organic solid waste quantity was estimated based on the municipal organic solid waste that can be disposed from all the municipalities in South Africa provided all the municipalities in the country can collect waste, sort it according to the waste that can be reused, recycled, diverted from landfill sites as well as the one disposed on the landfills. The organic solid waste falls under the waste category disposed to the landfills. The basis for this estimation was the total waste disposed in 7 major municipalities in the country and ratio of national population to the total population of these metros. This was compared to the quantity estimated in the national waste information baseline report (DEA 2012). It was found that the estimation made in this study is not far off from the estimation made in the national waste information baseline report. The wastewater quantity was estimated in the same way. The livestock manure quantity was estimated using the reported population of the livestock in the country and the average daily excretes from each animal. The total organic waste quantity from these waste resources was estimated to be about 12-17Mton over the period of forecast.

The organic waste emissions share in the national GHG emissions under "growth without constraints scenario" was found to be 2%. This is 1% less than the waste emission share estimated by Urban Earth (2012). The CO_2 emissions from the biogas is not included because it is of biogenic origin meaning its net carbon emissions are accounted from the original process they were derived from (Pipatti *et al* 2006).

It is concluded that there is abundant organic waste in South Africa that is still being disposed in landfill sites of the municipalities in the country. This has its fair share in national GHG emissions in the country as stated above.

5.2.2 Quantity of biogas produced from organic waste

The quantification of biogas was made in the form of CH_4 because it is the part of biogas that is anthropogenic GHG and it also carries energy that can be used. This was estimated for each waste type considered in this investigation.

Results show that the estimated total quantity of CH_4 from organic waste sources (from 2010 to 2025) varied between 644 and 1075 Mm^3. It is inferred that there is significant potential for recovering this gas in South Africa. The k-and B_o values affect the CH_4 generation with high values of these parameters result in high levels of CH_4.

5.2.3 Potential electricity and heat that can be generated from biogas methane

It was necessary to determine the potential electricity and heat that can be produced from biogas methane. This enabled the computation of the emissions reduction potential of biogas through capturing and usage of the CH_4 gas. In addition, this would assist in the avoidance of burning fossil fuel such as coal, to produce the same amount of electricity and heat.

It was found that the methane gas from the biogas produced from the waste resources can generate the direct heat usage of about 1255-2150 GWh and electricity of about 673-1123 GWh between 2010 and 2025. Therefore, there is significant potential to generate electricity and heat from waste resources.

5.2.4 Optimisation of biogas production from these waste resources and utilisation for electricity and heat generation

In Chapter 4, it was established that the methane gas generated from organic waste is influenced by factors that affect the decomposition of the waste materials. These factors are outlined in Chapter 2 under literature review. It is argued that since the anaerobic digestion is a natural process, and the process parameters that affect the generation of methane cannot be controlled, the biogas digester should be designed to mimic the natural process. This was achieved by combining different types of organic wastes such as municipal solid waste and municipal wastewater, livestock manure and municipal wastewater and the remaining wastewater was digested on its own in the digester.

It was found that the controlled anaerobic digestion inside the digester would increase the yield of methane gas from these organic waste types because crucial process parameters like k-value, would increase and the retention time would be shortened. The reaction kinetics that would shift the reaction in the direction that increases the CH_4 yield was not established due to lack of information on the reaction of micro-organisms that cause decomposition of degradable material of organic waste.

It was found that the optimisation of methane generation from these waste combinations could result in between 1770 Mm^3 and 2650 Mm^3 of CH_4 gas between 2010 and 2025 respectively. This would increase the amount of electricity generation by about 1362-2037 GWh, and heat generation by about 2894- 4362 GWh during the same period. This is about 3 times (or more) the quantity of methane generated without optimisation. So, optimisation of biogas production could results in significant reduction in coal that is burnt in coal fired power and steam plants in the country.

5.2.5 Emission reduction potential of the biogas (ERP) and its contribution in the reduction of national GHG emission to achieve the national emissions trajectory ranges

As indicated in Section 5.2.3, the utilisation of biogas as an energy source would not only curb the methane emissions to the atmosphere but would also avoid CO_2 emissions caused by coal burning to obtain the same amount of energy carried by methane. The ERP of biogas was evaluated to investigate the amount of methane that can be destroyed when captured and utilised from these waste resources.

It was observed that the total the amount of methane that can be captured and destroyed from the waste resources has an ERP of 1.49-1.73% contribution to national GHG emissions reduction between 2010 and 2025. When the assessment of CH_4 capture and utilisation was made, it was found that this has an ERP that can contribute about 2.1-2.5% to reduce national GHG emissions. To achieve the National Emissions Trajectory ranges, biogas capture and utilisation can contribute between 4.61 and 3.63% to achieve the lower limit range between 2020 and 2025. To achieve the upper limit ranges this could contribute between 8.55 and 5.97% over the same period.

When the biogas capture and utilisation were assessed under optimal biogas generation conditions using the suggested waste combinations, biogas had an ERP of 5-6% contribution to national GHG emissions between 2010 and 2025. This also contributed between 10.6 and 8.7% in achieving the lower limit of National Emissions Trajectory ranges between 2020 and 2025. In achieving the upper limits, this contributed between 19.6 and 13%. Therefore this shows that the optimal generation of CH_4 as an energy source would give the best contribution of biogas in mitigating climate change in South Africa.

Therefore, the fact that the capturing and utilisation of methane from biogas produced in anaerobic digestion of organic wastes in the country to generate electricity and heat gives significant emission reduction potential (ERP), indicates that biogas can significantly contribute to the mitigation of climate change in South Africa. Besides reducing the GHG emissions of the country, the utilisation of organic waste as an energy source would also reduce the amount of waste that goes to landfill sites, and therefore alleviate the burden (on the municipalities of the country) of waste disposal.

5.3 Recommendations

a) It was demonstrated that the biogas capture and use can make a good contribution to the reduction of the national GHG emissions under “growth without constraints” scenario. However, the cost benefit of this project is unknown. Therefore, there is need to evaluate the economic viability of capturing and utilising biogas as an energy source in the future research work.

b) It was mentioned that the contribution of biogas to the mitigation of climate change could be further improved by applying the by-product of anaerobic digestion in agricultural soils to replace the inorganic fertilisers. Therefore the emission reduction potential associated with such an intervention should be investigated.

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7 Appendix

7.1 Waste Data

7.1.1 Municipal solid waste data

7.1.1.1 City of Cape Town

The city of Cape Town was found from the personal communication with the then Municipal Solid Waste Manager (Mr Peter Novella) and from the Integrated Waste Management Strategy of the City.

Table 7-1: (Source: Novella 2012) Waste disposed in 2010

Waste type	Waste amount (Mton)	% organics	Waste growth (%)
General waste	1.229	30	2.5
Garden waste	0.1135	N/A	2.5
Rubble	0.2605	none	2.5
Special waste	0.01975	50	2.5

Garden waste is diverted from landfill to compost production

The typical waste composition from the municipal landfills was determined by *Munganga et al* (2010) for the City of Cape Town as follows:

Table 7-2: Source: (Munganga *et al* 2010) Chemical composition of the Solid waste disposed in Cape Town landfills

Sample no	C (%)	H (%)	N (%)	S (%)	O (%)
1	43.94	6.27	2.20	0.40	42.19
2	46.15	6.07	2.15	0.40	40.23
3	47.47	6.12	2.24	0.40	38.77
4	39.08	5.63	2.24	0.40	47.65
Average	**44.16**	**6.02**	**2.20**	**0.40**	**42.21**

The organic waste generation forecast was estimated using the following waste growth expression described in Section 3.3.2 and forecasted from 2010 to 2025 as follows:

$$\boldsymbol{W_{2010} = W_b(1 + r^n)}$$

Table 7-3: Organic waste generation disposal forecast in City of Cape Town Municipality

Year	Organic waste (Mton)
2010	0.38
2011	0.39
2012	0.40
2013	0.41
2014	0.42
2015	0.43
2016	0.44
2017	0.45
2018	0.46
2019	0.47
2020	0.48
2021	0.50
2022	0.51
2023	0.52
2024	0.53
2025	0.55

7.1.1.2 Waste data in City of Johannesburg

The waste data from City of Johannesburg was sourced from the Integrated Waste Management strategy of the municipality.

Table 7-4: Source: (Naidoo 2007 and GDACE 2008) Waste disposed in 2010

Waste type	Waste amount (Mton)	% organic waste growth	Waste growth (%)
Total waste	1.4992	13	6

The organic waste generation forecast was modelled from 2010 to 2025 using equation (3-1)

Table 7-5: Organic waste generation disposal forecast in the City of Johannesburg Municipality

Year	Organic waste (Mton)
2010	0.19
2011	0.21
2012	0.24
2013	0.26
2014	0.30
2015	0.33
2016	0.37
2017	0.41
2018	0.46
2019	0.52
2020	0.58
2021	0.65
2022	0.72
2023	0.81
2024	0.91
2025	1.01

7.1.1.3 Waste data in Ekurhuleni Municipality

The waste data from Ekurhuleni municipality was sourced from the Integrated Waste Management strategy of the municipality.

Table 7-6: Source: (GDACE 2008, Snyman 2009) Waste disposed in 2010

Waste type	Waste amount (Mton)	Waste growth (%)	Organic waste (%)
General waste	1.743	0.88	12

The organic waste generation forecast was modelled from 2010 to 2025 using equation (3-1)

Table 7-7: Organic waste generation disposal forecast in Ekurhuleni Municipality

Year	Organic waste (Mton)
2010	0.209
2011	0.211
2012	0.213
2013	0.215
2014	0.217
2015	0.218
2016	0.220
2017	0.222
2018	0.224
2019	0.226
2020	0.228
2021	0.230
2022	0.232
2023	0.234
2024	0.236
2025	0.238

7.1.1.4 Waste data in Tshwane Metropolitan Municipality

The waste data from Tshwane municipality was sourced from the Integrated Waste Management strategy of the municipality.

Table 7-8: Source: (GDACE 2008, Snyman 2009) **Waste disposed in 2010**

Waste Type	Waste amount (Mton)	Waste growth (%)	Organic waste (%)
General waste	2.754	3.48	20

The organic waste generation forecast was modelled from 2010 to 2025 using equation (3-1)

Table 7-9: Organic waste generation disposal forecast in Tshwane Metropolitan Municipality

Year	Organic waste (Mton)
2010	0.551
2011	0.570
2012	0.590
2013	0.610
2014	0.632
2015	0.654
2016	0.676
2017	0.700
2018	0.724
2019	0.749
2020	0.776
2021	0.803
2022	0.830
2023	0.859
2024	0.889
2025	0.920

7.1.1.5 Waste data of EThekwini Municipality

The waste data from EThekwini municipality was sourced from the Integrated Waste Management strategy of the municipality.

Table 7-10: Waste disposed in 2010 Source: EThekwini Municipality 2004

Waste type	Waste amount (Mton)	Waste growth (%)	Organic waste (%)
General waste	1.4	1.69	45.67

The organic waste generation forecast was modelled from 2010 to 2025 using equation (3-1).

Table 7-11: Organic waste generation disposal forecast in EThekwini Municipality

Year	Organic waste (Mton)
2010	0.639
2011	0.650
2012	0.661
2013	0.672
2014	0.684
2015	0.695
2016	0.707
2017	0.719
2018	0.731
2019	0.743
2020	0.756
2021	0.769
2022	0.782
2023	0.795
2024	0.808
2025	0.822

7.1.1.6 Nelson Mandela Metropolitan

The waste data from Nelson Mandela Bay municipality was sourced from the Integrated Waste Management strategy of the municipality.

Table 7-12: Source: (NMM 2005) Waste disposed in 2010

Waste type	Waste amount (Mton)	Waste growth (%)	Organic waste (%)
General waste	0.405	2.45	50.3

The organic waste generation forecast was modelled from 2010 to 2025 using equation (3-1).

Table 7-13: Organic waste generation disposal forecast in Nelson Mandela Metropolitan

Year	Organic waste (Mton)
2010	0.204
2011	0.208
2012	0.214
2013	0.219
2014	0.224
2015	0.230
2016	0.235
2017	0.241
2018	0.247
2019	0.253
2020	0.259
2021	0.265
2022	0.272
2023	0.279
2024	0.285
2025	0.292

7.1.1.7 Buffalo City Municipality

The waste data from Nelson Mandela Bay municipality was sourced from the Integrated Waste Management strategy of the municipality.

Table 7-14: Source: (BCM 2002) **Waste disposed in 2010**

Waste type	Waste amount (Mton)	Waste growth (%)	Organic waste (%)
General waste	0.317	3	25

The organic waste generation forecast was modelled from 2010 to 2025 using equation (3-1).

Table 7-15: Organic waste generation disposal forecast in Buffalo City Municipality

Year	Organic waste (Mton)
2010	0.079
2011	0.082
2012	0.084
2013	0.087
2014	0.089
2015	0.092
2016	0.095
2017	0.097
2018	0.100
2019	0.103
2020	0.106
2021	0.110
2022	0.113
2023	0.116
2024	0.120
2025	0.123

7.1.2 National Waste generation forecast

To get the national municipal solid waste data, the ratio of national population to the total population of the metros was used. This was done by estimating the national population using the national population growth, and the population in each metro was also estimated using each population growth. This was all modelled up to 2025. Growth equation shown in Section 7.1.1.1 was used in estimating the population over the forecast period. The ratio of national population to the population of the metros was done by dividing the national population on each year of the forecast by the corresponding total population in the metros. This is presented as follows:

Table 7-16: Estimation of ratio of national population to the total population in metros

Year	Total population in metros (million)	National population (million)	Ratio (N_p/M_p)
2010	17.013	51.160	3.0070
2011	17.390	51.771	2.9770
2012	17.778	52.381	2.9465
2013	18.284	53.000	2.8986
2014	18.806	53.625	2.8515
2015	19.342	54.258	2.8051
2016	19.895	54.898	2.7594
2017	20.463	55.546	2.7145
2018	21.047	56.201	2.6703
2019	21.648	56.864	2.6267
2020	22.267	57.535	2.5839
2021	22.904	58.214	2.5417
2022	23.559	58.901	2.5001
2023	24.233	59.596	2.4593
2024	24.927	60.299	2.4190
2025	25.641	61.011	2.3794

7.1.3 Municipal wastewater data

The municipal wastewater from the six municipalities which have the available data is presented using the daily wastewater load to the municipal wastewater system and the influent chemical oxygen demand (COD). The organic wastewater is estimated by multiplying the COD with daily wastewater load.

7.1.3.1 City of Cape Town

7.1.3.1.1 Daily wastewater data

Influent COD: 837 mg/l

Table 7-17: Municipal wastewater daily load to treatment works

Daily wastewater(Mℓ/day)	COD (ton/day)
120	100.44
32	26.78
14	11.72
2.5	2.09
0.5	0.4185
0.1	0.0837
0.03	0.025
200	167.4
55	46.035
37.5	31.388
34	28.458
14	11.718
5	4.185
0.03	0.025
46	38.502
30	25.11
7	5.859
4.5	3.767
3.5	2.93
1.2	1.004

7.1.3.2 City of Johannesburg

Daily wastewater: 980 Mℓ/day
Industrial effluent on it: 7.4055 Mℓ/day
COD of industrial effluent: 8194 mg/l, therefore COD of industrial influent = 60.681 tons/day
COD of domestic wastewater: 430 mg/l, therefore COD = 418.22 tons/day

7.1.3.3 Ekurhuleni wastewater data

COD: 416 mg/l

Daily wastewater (Mℓ/day)	COD (ton/day)
45	18.72
45	18.72
70	29.12
11	4.576
10	4.16
18	7.488
30	12.48
28	11.648

7.1.3.4 EThekwini Municipality

Table 7-18: Municipal wastewater daily load to treatment works

Daily wastewater (Mℓ/day)	COD (mg/l)	COD (ton/day)
192.05	768.53	147.595
10.94	769.19	8.414
63.21	623.36	39.400
15.10	822.08	12.411
4.45	618.51	2.749
24.57	660.4	16.226
11.87	528.12	6.271
52.30	561.95	29.392
1.46	951.04	1.386
66.10	648.98	42.901
1.63	829.83	1.353
1.32	410.92	0.544
0.84	671.80	0.567
0.57	683.18	0.389
7.72	926.44	7.148
14.44	837.42	12.094
19.13	782.58	14.969
8.84	2806.67	24.799
1.04	827.06	0.857
6.22	731.72	4.552

7.1.3.5 Tshwane Municipality

Daily Wastewater: 547 Mℓ/day
COD: 500 mg/l, therefore COD = 273.5 ton/day

7.1.3.6 Nelson Mandela Bay Metropolitan

Daily wastewater: 187 Mℓ/day
COD: 600 mg/l, therefore COD = 112.2 ton/day

7.2 Estimation of waste composition and waste structure

Chemical formula for the municipal solid waste moisture using the waste data of Munganga *et al* (2010)

$$n(mols) = \frac{m(g)}{MM(g.mol^{-1})}$$

By taking 100g from each sample of Munganga *et al* (2010) we will have the volatile solids amount from each sample:

Table 7-19: Determination of volatile solids from the data of Munganga *et al* (2010)

Sample no	**C (%)**	**H (%)**	**N (%)**	**O (%)**	**Moisture (%)**	**VS (%)**	**VS (g)**
1	43.94	6.27	2.20	42.19	17	82	13.94
2	46.15	6.07	2.15	40.23	16	90	14.4
3	47.47	6.12	2.24	38.77	17	88	14.96
4	39.08	5.63	2.24	47.65	22	68	14.96
Average	**44.16**	**6.02**	**2.20**	**42.21**	**18**	**82**	**14.57**

7.2.1 Amount of moisture

The amount of moisture in the samples would be determined through subtracting VS from each 100g sample. The masses of hydrogen and oxygen in the moisture would be found using molecular mass of water (H_2O = 18g/mol) as follows:
Mass (oxygen) = (molar mass O/molar mass H_2O)*mass of moisture
Mass (Hydrogen) = (molar mass H_2/molar mass H_2O)*mass of moisture

Table 7-20: Moisture composition in the data of Munganga *et al* (2010)

Sample number	**Moisture (g)**	**O (g)**	**H_2 (g)**
1	86.06	76.498	9.56
2	85.6	76.09	9.42
3	85.04	76.54	9.35
4	85.04	76.54	9.35
Average	85.44	76.42	9.42

Therefore the mass of each element in each 100g sample is: $m_{element}$ (g) = VS (g)*% element

Table 7-21: Element mass from each waste sample from data of Munganga *et al* (2010)

Sample no	C (g)	H (g)	N (g)	O (g)
1	6.125	10.43	0.307	82.379
2	6.646	10.39	0.31	81.882
3	7.102	10.37	0.335	81.391
4	5.846	10.29	0.335	82.719
Average	6.43	10.37	0.322	82.093

This gives the molar composition of:

Sample no	C (mol)	H (mol)	N (mol)	O (mol)
1	0.5104	10.43	0.0219	5.1487
2	0.5538	10.39	0.022	5.1176
3	0.5918	10.37	0.0239	5.0869
4	0.5358	10.29	0.0239	5.1699
Average	**0.548**	**10.37**	**0.023**	**5.131**

To get the chemical formula of the waste, all other elements should be divided by the small number of moles, which is number of moles of nitrogen in this case (Reinhart 2004). Therefore the chemical formula of the waste is: $C_{24}H_{451}O_{223}N$

The coefficients of Buswell equations are:

$C_{24}H_{451}O_{223}N$ + ¼(4c-h-2o+3n+2s) H_2O → 1/8(4c-h+2o+3n+2s) CO_2+ 1/8(4c+h-2o-3n-2s) CH_4 + nNH_3

CO_2 coefficients = 11.75

CH_4 coefficients = 12.25

This gives the average methane concentration on the waste samples of approximately 51.04%

7.3 Methane production from the organic waste

7.3.1 Methane generation from the municipal solid waste

The recoverable methane produced from the seven major municipalities in the country is projected from 2010 up to 2025 using the waste growth of each municipality and the recovery efficiency of 85% (Timoney 2009):

Table 7-22: Recoverable methane generated from solid waste disposed in seven major municipalities in South Africa

Year	COCT (Mm^3)	COJ (Mm^3)	EMM (Mm^3)	TMM (Mm^3)	ETM (Mm^3)	NMM (Mm^3)	BCM (Mm^3)
2010	4.60	2.48	2.74	7.21	8.37	2.66	1.04
2011	8.12	4.60	4.79	12.80	14.71	4.70	1.83
2012	10.85	6.51	6.33	17.20	19.55	6.28	2.46
2013	12.99	8.29	7.50	20.73	23.28	7.51	2.95
2014	14.71	10.01	8.39	23.62	26.19	8.50	3.35
2015	16.10	11.75	9.07	26.05	28.50	9.30	3.69
2016	17.26	13.55	9.61	28.15	30.36	9.97	3.97
2017	18.26	15.45	10.03	30.01	31.90	10.54	4.21
2018	19.13	17.51	10.36	31.71	33.20	11.04	4.43
2019	19.92	19.74	10.64	37.30	34.32	11.49	4.64
2020	20.65	22.20	10.87	37.78	35.32	11.90	4.83
2021	21.33	24.92	11.06	38.49	36.22	12.29	5.01
2022	21.99	27.94	11.24	39.38	37.06	12.66	5.19
2023	22.63	31.29	11.39	40.42	37.86	13.03	5.37
2024	23.27	35.03	11.53	41.58	38.62	13.38	5.54
2025	23.90	39.20	11.66	42.84	39.37	13.74	5.72

The graphical representation of this forecast is:

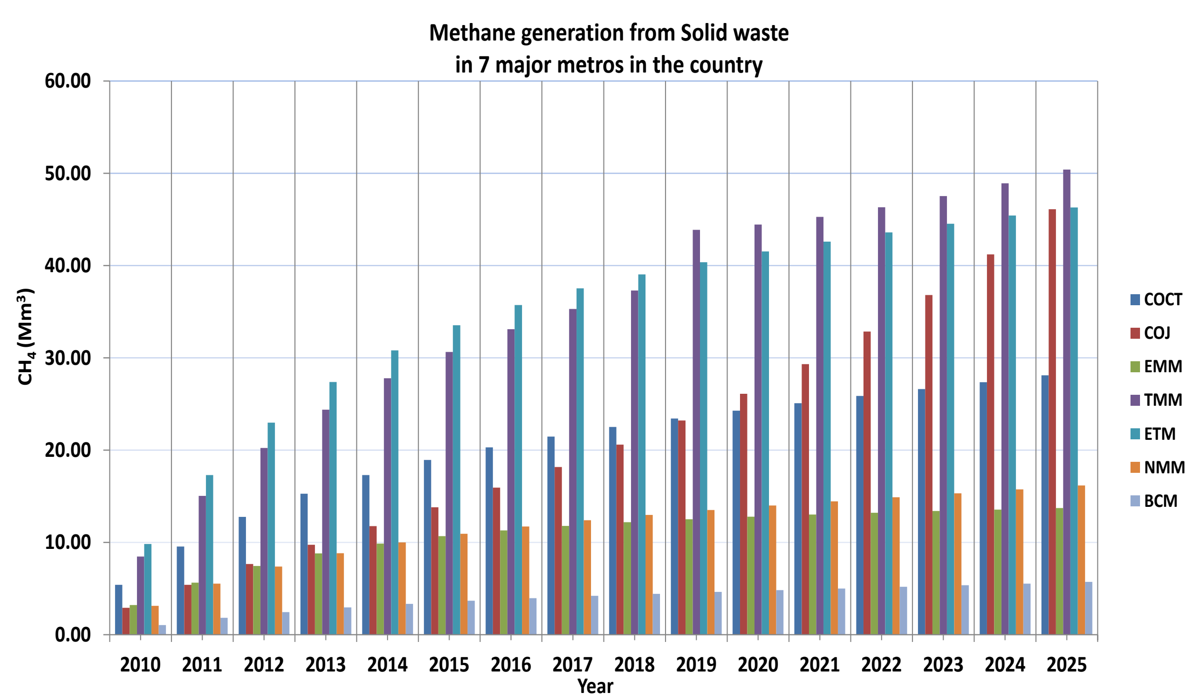

Figure 7-1: Recoverable methane generated from the solid waste disposed in seven major municipalities in South Africa

7.3.2 The methane production from the municipal wastewater

As mentioned the IPCC (2006) predicts 70-75% digestion of the volatile matter in the wastewater to methane and carbon dioxide. The digestion period of influent COD to generate methane and carbon dioxide is 20 days. This means the delay period before the biogas can be generated is 20 days.

Over the period of a year the recoverable methane generated will be:

$$CH_4(generation) = \left(COD_{influent} - COD_{effluent}\right) \cdot Q_l.B_o \cdot (365 - 20) \cdot recoveryrate$$

Where: Q_l is the daily load of municipal wastewater

Bo is the methane production capacity equal to 0.25kg CH4/kg COD

Therefore the methane generation from these major municipalities from 2010 up to 2025 is:

Table 7-23: Recoverable methane generated from municipal wastewater in six major municipalities in South Africa

Year	COCT (Mm^3)	COJ (Mm^3)	EMM (Mm^3)	TMM (Mm^3)	ETM (Mm^3)	NMM (Mm^3)
2010	17.58	18.50	4.13	10.57	14.45	4.34
2011	18.11	19.39	4.21	10.60	14.78	4.44
2012	18.65	19.45	4.29	10.63	15.12	4.55
2013	19.21	20.03	4.37	10.66	15.47	4.67
2014	19.78	20.63	4.46	10.70	15.83	4.79
2015	20.38	21.25	4.55	10.73	16.19	4.91
2016	20.99	21.89	4.63	10.76	16.56	5.03
2017	21.62	22.55	4.72	10.79	16.95	5.15
2018	22.27	23.22	4.81	10.82	17.34	5.28
2019	22.93	23.92	4.91	10.86	17.73	5.41
2020	23.62	24.64	5.00	10.89	18.14	5.55
2021	24.33	25.38	5.10	10.92	18.56	5.69
2022	25.06	26.14	5.20	10.95	18.99	5.83
2023	25.81	26.92	5.30	10.99	19.42	5.98
2024	26.59	27.73	5.40	11.02	19.87	6.13
2025	27.39	28.56	5.50	11.05	20.33	6.28

The graphical presentation of the forecast is:

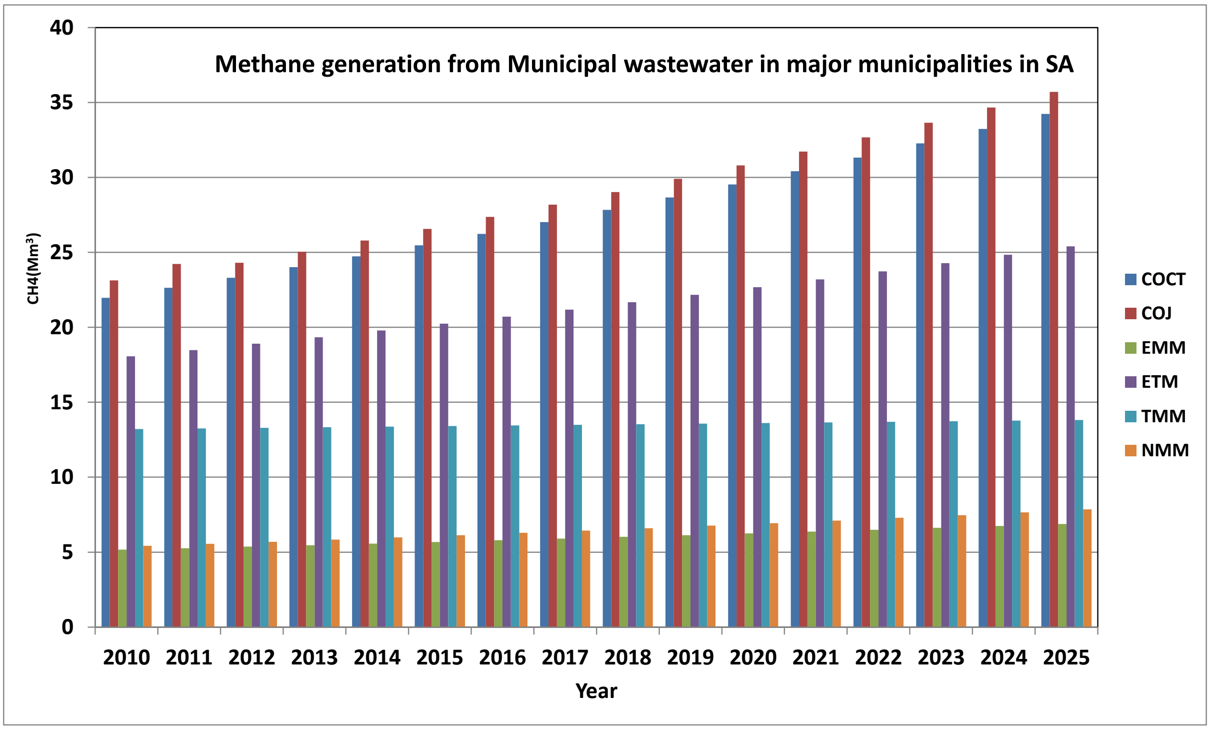

Figure 7-2: Recoverable methane generated from municipal wastewater in six major municipalities in South Africa