An investigation into the co-benefits of climate change mitigation and adaptation for the waste sector in the eThekwini Municipality

BY

NOMDENI SIMPHIWE NGWENYA

(210546683)

Submitted in fulfilment of the academic requirements for the Master of Science in the School of Environmental Science, Department of Geography, College of Agriculture, Engineering and Science. University of KwaZulu-Natal, Westville Campus.

10 December 2015

As the candidate's supervisor I have approved this thesis for submission.

Signed: Name: Dr Tirusha Thambiran Date: 10 December 2015

As the candidate's co-supervisor I have approved this thesis for submission.

Signed: Name: Dr Michael Gebreslasie Date: 10 December 2015

ABSTRACT

Climate change is regarded as one of the most pressing scientific and political issues currently being faced in this era. The waste sector includes post-consumer waste and wastewater and it is responsible for less than 5% of anthropogenic greenhouse gas (GHG) emissions globally. The aim of this study was to assess whether or not there are climate change mitigation co-benefits that could support climate change adaptation. The eThekwini Municipality has made significant strides in responding to climate change, and as such was chosen as a case study to investigate the opportunities for co-benefits in the waste sector.

The GHG emissions associated with solid waste disposal were quantified using the Intergovernmental Panel on Climate Change guidelines for compiling emission inventories for the sector and emission factors developed for South African municipalities. It was found that CH_4 emissions due to the landfilling of solid were responsible for the highest emissions, followed by CO_2 from the collection and transport of solid waste while CO_2 emissions due to electricity consumption in the landfills were the lowest. The baseline inventory for solid waste was used to generate GHG mitigation scenarios to demonstrate the GHG mitigation potential of the various waste management scenarios considered which had co-benefits for climate change adaptation in general. It was found that landfill gas (LFG) capture with electricity generation had the lowest emissions and resulted in GHG emissions savings. Even though LFG capture and electricity generation is the best option for GHG mitigation it is expensive to implement. Waste management options do not only reduce emissions but have other benefits such as the provision of electricity and compost, extending the lifespan of landfills as well as reducing environmental impacts of solid waste and production of raw materials. Thus even though other options such as composting and recycling have lower GHG mitigation potential, there are substantial co-benefits that could be achieved. The mitigation of GHG emissions from solid waste for example contributes towards climate change adaptation through the use of organic fertilizers.

To quantify emissions from wastewater treatment (WWT) principles of the, International Council for Local Environment Initiatives were used. Due to insufficient data GHG mitigation scenarios

could not be created for WWT. However, GHG mitigation options such as phyto-remedial treatment, thermal treatment of sludge and land application of sludge as compost were highlighted. The major cause of GHG emissions for wastewater is CO_2 emissions due to electricity consumption, followed by N_2O and CH_4 emissions from WWT. Emissions caused by wastewater treatment continue to increase in the municipality, thus the mitigation of these gases will not only reduce emissions but provide other associated benefits. Effective treatment and recycling of wastewater will reduce the environmental burden caused by drought and electricity provision from biogas produced from LFG and wastewater gas will provide more electricity which will ease the burden on Eskom. Climate change mitigation in the waste sector will contribute towards building the resilience of communities against climate change impacts within the EM.

PREFACE

The work described in this MSc dissertation was carried out in the School of Environmental Sciences, University of KwaZulu-Natal, Westville Campus, from February 2014 to December 2015, under the supervision of Dr. Tirusha Thambiran and the co-supervision of Dr. Michael Gebreslasie.

These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any tertiary institution. Where work belonging to others has been used, this has been duly acknowledged.

DECLARATION

I, Nomdeni Simphiwe Ngwenya declare that:

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

2. This dissertation has not been submitted for any degree or examination at any other university.

3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

4. This dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

   a. Their words have been re-written but the general information attributed to them has been referenced.
   b. Where their exact words have been used, then their writing has been placed in italics and inside quotation marks, and referenced.

5. This dissertation does not contain text, graphics or tables copied and pasted from the internet, unless specifically acknowledged, and the source being detailed in the dissertation and in the References sections.

Signed: …  ……..

10 December 2015

Table of Contents

TABLE OF FIGURES

LIST OF TABLES

ACRONYMS and ABBREVIATIONS

AOB - Ammonium-oxidising bacteria
AOA - Ammonium-oxidising archaea
BOD - Biological Oxygen Demand
CBD - Central Business District
CERs - Carbon Emission Reductions
CDM - Clean Development Mechanism
CH_4 - Methane
cm - Centimetres
CO_2 - Carbon dioxide
DCCS - Durban Climate Change Strategy
DSW - Durban Solid Waste
EM - eThekwini Municipality
E - Equivalent
GEF - Grid Emission Factor
Gg - Gigagrams
GHG - Greenhouse gas
GWP - Global warming potential
ICLEI - International Council for Local Environment Initiatives
IPCC - Intergovernmental Panel on Climate Change
ISWM - Integrated Solid Waste Management
IWM - Integrated Waste Management
Kl - kilolitres
Km - kilometres
km^2 - Kilometres squared
LCA - Life Cycle Analysis
LFG - Landfill gas
Ml/d - Megalitres per day
m - Metre
mm - Millimetres
MCCP - Municipal climate change programme
MSW - Municipal Solid Waste
MWh - Megawatt hour
NOB - Nitrite-oxidising bacteria
NO_X - Nitrogen Oxide

N_2O -	Nitrous oxide
O_2 -	Oxygen
PAYT -	Pay as you throw
T -	Tonnes
UNEP -	United Nations Environment Programme
UNFCCC -	United Nations Framework Convention on Climate Change
USEPA -	United States Environmental Protection Agency
WWT -	Wastewater treatment
WWTP -	Wastewater treatment plant

ACKNOWLEDGEMENTS

First and foremost I would like to acknowledge and thank the Almighty God for blessing me with the ability to complete this task.

To my supervisor, Dr. Tirusha Thambiran and my co-supervisor, Dr. Michael Gebreslasie, I am extremely grateful for your expertise, support and utmost patience with me. Thank you for keeping me focused as this thesis would not have been possible.

To my parents Bongani and Thandiwe Ngwenya, thank you for your support and words of encouragement when the going got tough. This one is for you.

To Jabu, Mannie and Sanele thank you for keeping me going throughout this challenging time, I appreciate it.

To my siblings (Pumzile, Mbuso, Jabu), family and friends, I thank you for always being there and making me smile/laugh during the difficult times. I consider myself very fortunate to have you in my life.

Many thanks to the National Research Foundation for the funding that was granted for this study. It was of great assistance.

Thank you to everyone who assisted me with information and data. This includes the eThekwini Energy Office and Durban Solid Waste.

CHAPTER 1

INTRODUCTION

1.1 Background

Climate change is regarded as one of the most pressing scientific and political issues currently being faced in this era due to anthropogenic emissions (Bulkeley and Newell, 2015; Penna and Geels, 2015). Atmospheric changes are caused by the emission of anthropogenic greenhouse gases (GHGs) that have atmospheric lifetimes of decades and centuries. These changes are caused by anthropogenic emissions of GHGs such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) resulting from numerous human activities (Karl and Trenberth, 2003; Alley *et al*. 2007; Stern, 2008; Reddy, 2015). The atmosphere is typically able to respond to various emissions released together with the changes to the surface beneath it (Karl and Trenberth, 2003). Excessive irreversible emission of these gases results in an accumulation of GHGs in the atmosphere, which consequently trap heat and result in global warming, thus increased accumulation of these GHGs results in a warmer planet earth (Stern, 2008; Reddy, 2015; Karl *et al*. 2015). Stern (2008) suggests it is this process of global warming that results in climate change and will affect populations, sectors and species in various complex ways. Global warming is not the only aspect of climate change but is a major component of it and has severe consequences for human and natural systems.

The effects of climate change are predicted to be large where some could be irreversible; with predicted effects including changing precipitation patterns, increased global average temperatures and extreme weather phenomena such as droughts, floods, rising sea levels and the melting of ice caps (IPCC, 2014a). The impacts of anthropogenic emissions on the global climate are a major concern because they are key contributors to the rapidness of this change which has severe impacts associated with it (Taylor *et al*. 2015). This issue of climate change presents a significant problem for global governance because of the scientific uncertainty of its ramifications, the multiple scales of political decision making as well as the processes responsible for the resulting emissions (Bulkeley and Newell, 2015). According to Bulkeley and Newell (2015) the focus for climate change discussions is on nations that are responsible for emissions and whether or not there are measures implemented that are aimed at reducing emissions. Further, Bulkeley and Newell (2015) argue that emissions resulting from several decentralised sources could significantly reduce national and global emissions. A key facet to effectively reducing GHG emissions is to understand causes and impacts of climate change together with the cost of reducing emissions. This will help to determine those areas with the greatest opportunities for mitigation as well as the associated costs for mitigation (Stern and Taylor, 2008).

According to Hoornweg *et al*. (2011) most global GHG emissions are generated as the result of urbanisation which is linked to affluence and rapid population growth in cities. The continuously growing population mainly in developing countries together with their growth in living standards has also contributed to increased quantities of waste generated (Minghua *et al*. 2009; Dedinec *et al*. 2015). The post-consumer waste sector contributes less than 5% of global emissions mainly due to the accumulation and decay of waste in landfills (Bogner *et al.* 2007; Freidrich and Trois, 2011). According to IPCC (2007) and Dedinec *et al*. (2015) the waste sector is the third highest source of anthropogenic CH_4 emissions globally and this matter is of significant concern to environmentalists. However, according to the UNEP (2010) the waste sector can move from being a minor source of GHG emissions to a major saver of such emissions globally, because the prevention and recovery of waste reduces GHG emissions in all the sectors of the economy.

Waste does not only contribute to GHG emissions but it has associated environmental impacts such as the release of airborne pollutants, groundwater pollution due to leachate released by landfills, stratospheric ozone depletion, the emission of heavy metals thus affecting human health (Laurental *et al*. 2014; Di Trapani *et al*. 2015; Lou *et al*. 2015). Further, the waste sector impacts the environment through the contamination of freshwater bodies due to wastewater treatment (WWT), eutrophication of water systems due to the phosphorus content (Lehtoranta *et al*. 2014; Brion *et al*. 2015). Thus, a reduction of GHG emissions in the waste sector could reduce associated environmental impacts. Developing countries are significant generators of emissions from municipal waste due to their high generation of organic waste, yet they are less researched than developed countries (Friedrich and Trois, 2011). In developing countries the generated waste is mainly deposited in sanitary landfill sites without gas recovery and open dumps; this continuously growing deposited waste has negatively affected the health, environment and safety of the population while contributing to global GHG emissions (Bogner *et al*. 2007). Thus effective waste management will result in multiple co-benefits for public health, the environment and public safety. However, municipalities are usually responsible for waste management and they face challenges often due to the lack of financial resources, poor organisation as well as complexity due to system multidimensionality (Guerrero *et al*. 2013).

1.2 Motivation for study

Most emissions from the waste sector can be attributed to CH_4 produced at landfills and N_2O from wastewater treatment plants (WWTPs) and to a lesser extent CO_2 emissions from electricity consumption (Ackerman, 2000; Bogner *et al*. 2007). Of these sources landfills are a major contributor to GHG emissions from the waste sector, with CH_4 emissions accounting for about 90% of waste sector emissions globally and likely to increase unless significantly mitigated (Monnie *et al*. 2006; Bogner *et al*. 2007; Bogner *et al*. 2008). The carbon released as CH_4 has a global warming potential that is 21 times higher than when it is released as CO_2 whereas N_2O has a global warming potential 310 times higher than CO_2 (Ackerman, 2000). Even though these gases occur in smaller concentrations than CO_2 the higher global warming potential results in more effective trapping of energy, the lifetime of CH_4 in the atmosphere is however lower than that of CO_2.

Even though the overall emissions produced by the waste sector are small, the carbon reduction opportunities have not been entirely explored, especially in developing countries (Friedrich and Trois, 2011). This is the basis of this study where GHG mitigation opportunities along the entire life-cycle of post-consumer waste and wastewater will be assessed. Reducing GHG emissions from waste has been the subject of several waste studies particularly in developed countries (Watkins and McKendry, 2015); yet this has only recently begun to occur in developing countries.

In order for developing countries to be able to plan for climate change mitigation it is necessary to develop a baseline emissions inventory that can be used as a basis for future planning. However, according to Freidrich and Trois (2011) developing countries lack a consistent framework for accounting and reporting GHG emissions from waste at municipal level which prevents the comparison of calculated emissions for the same municipality. Therefore, there is a growing urgency to develop robust GHG emissions inventories for the waste sector that will enable realistic reduction targets to be set and effective monitoring of the process made toward reaching the mitigation goals (Freidrich and Trois, 2013a). Developing emissions inventories from the waste sector will enable policy makers to monitor GHG levels within countries.

The waste sector is a contributor towards climate change but it is also at risk of associated impacts because climate related hazards could affect it directly and/or indirectly. There is limited research carried out to date, to determine the extent to which the waste sector is vulnerable to climate change and its adaptive capacity. The risk caused by climate alterations such as extreme temperatures, storms and droughts could pose a threat to the functioning of the waste management sector. An improved understanding of the risk and vulnerability of the waste sector will help determine effective mitigation and adaptation measures which will result in significant benefits not just globally but locally. A thorough knowledge of the risks associated with climate change particularly for the waste sector will further contribute to developing effective mitigation and adaptation measures which will help build the resilience of communities.

Often times the waste sector is targeted for mitigation through the conversion of landfill gas (LFG) to electricity; however activities at various points along the waste stream lifecycle may offer opportunities for adaptation and therefore should be explored as well. It is recommended that the GHG emissions from the waste sector are considered for the entire life-cycle of post-consumer waste and wastewater (Bogner *et al*. 2008), because within each stage there are significant opportunities for reducing GHG emissions and air pollutants whilst providing co-benefits for other sectors and communities. Several opportunities for climate change mitigation exist in the waste sector such as increased recycling and reuse policies which ensure that less waste reaches disposal facilities (Freidrich and Trois, 2011; Xiang *et al*. 2014). Synergies in waste management could include for example, the diversion of organic waste from landfills to a composting plant to produce organic compost, this could also help to reduce short-lived climate pollutants from the avoided landfill waste, and increase moisture retention and fertility of soil treated with organic compost (Illman *et al*. 2013). In order to achieve significant GHG emission reduction in the waste sector as well as socio-economic and environmental benefits integrated solid waste management (ISWM) is recommended (Menikrupa *et al*. 2013). ISWM is an approach that combines applicable treatment methods such as landfilling, recycling, incineration and anaerobic digestion (Hoornweg and Bhada-Tata, 2012; Menikpura *et al*. 2013). Therefore a systematic and holistic approach towards characterising GHG emissions from the waste sector is critical to assess how the waste management process can be optimised to build resilience and adaptive capacity (Turpie *et al*. 2002).

An integrated approach towards waste management for developing countries such as South Africa is necessary in order to achieve effective waste management and simultaneously reduce associated GHG emissions and environmental impacts. South Africa is the 12th largest emitter of GHGs globally (Freidrich and Trois, 2015), thus, integrated and improved management of the waste sector could result in a reduction of the country's overall GHG emissions. Further, the mitigation of GHGs from the waste sector could benefit the country because it will contribute towards the reduction of social, economic and environmental challenges the country faces. As a coastal city the eThekwini Municipality (EM) is at risk of climate change impacts. This has resulted in the EM being a leader in the field of environmental management locally due to the numerous climate change mitigation and adaptation strategies in place (Roberts, 2010), the EM is a suitable as a case study. Further the EM was the first municipality to have an electricity generation project from biogas as well as a wastewater recycling facility in place.

An evaluation of the co-benefits for climate change adaptation in the waste management sector at local level is highly significant because of the contribution local areas have to global changing climates. Successful local risk management and governance supports the notion of thinking globally yet acting locally which according to the NCIRF (2012) makes significant contributions to global efforts for stabilising and minimising the concentrations of GHGs in the atmosphere.

1.3 Statement of purpose

The aim of this study is to investigate opportunities to reduce GHG emissions from waste and wastewater through local interventions and developments within the waste management sector that will simultaneously help to create societies that are resilient to climate change. The specific objectives are:

- To develop a comprehensive GHG emissions inventory related to the waste management sector in the EM;

- To identify interventions that can be implemented in the city that will contribute to the reduction of GHG emissions from the waste sector by using innovative technologies; that will help build climate change resilience and improve waste management;
- To develop an understanding of climate change risk and vulnerability and the adaptation measures that are required to build the resilience of communities.

The key question to be answered in this study is:

What are the co-benefits for climate change mitigation and adaptation in the waste management sector in South Africa?

1.4 Thesis organisation

This thesis consists of Six Chapters. Chapter One provided a brief background to the study which includes the motivation, aims, objectives and key questions to be addressed in this dissertation.

Chapter Two provides a comprehensive literature review on climate change mitigation in the waste sector, its sources and GHG mitigation mechanisms for the management of solid waste and wastewater. Further, a review on climate change risk, vulnerability and adaptation of the waste sector and coastal cities is also provided.

Chapter Three provides knowledge on the EM together with the landfill sites and WWTPs which were used as study areas. Moreover this chapter contains information on the management of wastewater and solid waste together with the climate change risk faced by the EM and the adaptation measures in place.

Chapter Four discusses the methodological approach used for the study; it includes the process followed for data acquisition and analysis.

Chapter Five presents the results and discussion of the study. It entails the description of GHG emissions from solid waste disposal and wastewater treatment as well as the GHG mitigation scenarios for solid waste.

Chapter Six outlines the conclusions of the study, the limitations encountered and recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

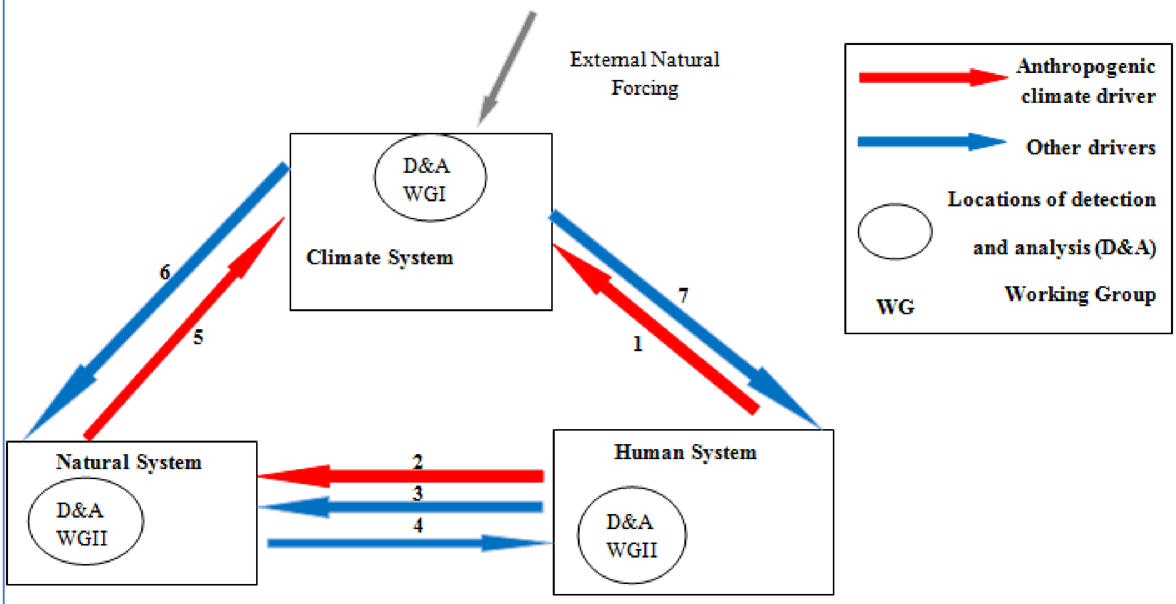
Climate change signifies a multi-faceted global change problem that is characterised by numerous stressors, various actors as well as multiple time scales (Adger, 2006; van der Linden, 2015). It is therefore necessary to develop and implement strategies that could reduce emissions while simultaneously contributing towards climate change adaptation strategies. This is because climate change results in impacts that could turn healthy populations into vulnerable populations (Ferreira *et al*. 2015). Anthropogenic GHGs from the waste sector are a contributor of climate change and are recognised as an environmental concern (Liamsanguan and Gheewala, 2008). Thus, an evaluation of emissions in the waste sector need not only focus on the reduction of these emissions but also how local communities and industries can benefit from these reductions which will encourage their participation. The first section of this chapter reviews climate change mitigation for solid waste management and wastewater treatment. The sources of GHG emissions, GHG reduction mechanisms and the various approaches for quantifying these emissions will be discussed individually. The second section of this chapter focuses on climate change risk, vulnerability and adaptation. Further climate change impacts on coastal cities, the EM and the waste sector are discussed together with climate change adaptation strategies in the EM.

2.2 A review of climate change mitigation in the waste sector

2.2.1 An overview of the climate change challenge

One of the factors making planet earth habitable is its natural greenhouse effect which has the ability to trap heat from the sun as well as prevent certain solar rays from being emitted back into the atmosphere. Globally, changes in atmospheric composition are caused by anthropogenic emissions of GHGs such as CO_2 produced by the burning of fossil fuels as well as CH_4 and N_2O caused by numerous human activities (Barton *et al*. 2007; Menikrupa *et al*. 2013; Reddy, 2015; Van Den Berg *et al*. 2015). The reflectivity, absorption properties, geometry, size distribution and interactions with moisture and clouds of emitted GHGs can lead to net cooling or net heating respectively (Karl and Trenberth, 2003). GHGs trap outgoing radiation from the earth back to space and create warming of earth, thus resulting in the term for human induced climate change called global warming (Koulaidis and Christidou, 1999; Karl and Trenberth, 2003).

Evidence of climate change exists from a number of natural systems that are impacted by increasing temperatures since 1970 (Stone *et al*. 2013). Climates have varied naturally in the past, but current circumstances differ because they are human induced and are occurring at rapid rates (Karl and Trenberth, 2003). The impacts of recent changes in climate on both natural and human systems are occurring across all continents and oceans with current impacts being caused by warming and or changes in rainfall patterns (Cramer *et al*. 2014). Figure 1 shows the interactions between climate change and natural and human systems together with the associated direct and indirect impacts on both systems. Anthropogenic drivers (red arrows) and natural drivers (blue arrow) interact through various interfaces. Impacts of anthropogenic drivers influence other systems. Grey arrow shows how alterations in external drivers influence the behaviour of the system. The table shows drivers and their associated impacts. Climate change is impacting coastal systems, water resources and ecosystems on land and the sea. With rising sea levels, coastal areas are being inundated, as the oceans absorb more CO_2 they are becoming acidified and water resources are declining because of decreasing rainfall which affects animal and plant species that cannot migrate hastily (Cramer *et al*. 2014). Further, climate change affects human systems by changing social and economic factors. Socially humans are being affected through the limited ability to practice agriculture as there is limited rainfall; this affects their livelihood and food security. In certain areas climate change is known to have led to conflict because of limited availability of food resources (Pachauri *et al*. 2014).



	Example of drivers	Example of Impacts	
		Direct Impacts	Indirect Impacts
1	Emission of CO_2	Warming	Altered crop yield Shift in species phenology
2	Emission of CO_2	Carbon fertilisation of plants	Increase in forestry yield Change in humidity
3	Pollution of river catchment	Decrease in fisheries	
4	Plague of crop pests	Decrease in crop yield	
5	Forest fire	Increased windiness	
6	EL Nino event	More wild fires	
7	El Nino event	Fisheries	

Figure 1: Illustrates the interaction of the three systems within the earth. (Source: Stone *et al*. 2013).

2.3 Climate change mitigation

Climate change mitigation is defined as the anthropogenic intervention to minimise GHG emission sources and increase the extent of carbon sinks (Illman *et al*. 2013; IPCC, 2014b; Reddy, 2015). Mitigation actions have been described by Garibaldi *et al*. (2014) as those actions aiming to reduce GHG emissions independent of whether they may or may not have a climate objective. According to Mergenthaler, (2015) the mitigation of climate change could possibly be one of the most significant challenges for public policy in the 21st century. Developed countries have more awareness and responsibility towards climate change mitigation because they are responsible for a lion's share of emissions and have the financial means for implementing mitigation technologies (Illman *et al*. 2013). Delaying mitigation actions in developing countries can constrain the achievement of low temperature targets thus implying higher overall mitigation costs (IPCC, 2014b). The significance of mitigation studies is that the conservation or sequestration of carbon buys time to enable other GHG mitigation strategies to be developed and implemented (Metz, 2001). Reddy (2015) states that most mitigation strategies utilise present technologies, thus technological development is a significant driver which will ensure the adequacy of mitigation in the future. This technological development could serve as a hindrance for developing countries as some of them are not technologically advanced.

Mitigation mechanisms do not only have to be technical but mitigation can occur through the terrestrial ecosystem where forests provide carbon sequestration particularly because biological mitigation is less costly than technological mitigation. Biological mitigation options may have economic, social and environmental benefits beyond reducing CO_2 in the atmosphere if appropriately implemented. These options have the potential to increase biodiversity, provide employment in rural and urban areas and sustainable land management. However, according to Metz (2001) if incorrectly implemented these measures could result in loss of biodiversity, ground water pollution and even community disruption. There are however co-benefits as biological mitigation would enable the diversion of energy use from fossil fuel sources and therefore conserve the already threatened carbon pools. In mitigation policies, coal, possibly oil and gas, as well as some energy intensive sectors could suffer an economic disadvantage (Metz, 2001). On the other hand those industries such as renewable energy industries are most likely to benefit from climate change mitigation because of the availability of financial resources that would have been directed to the carbon-intensive sectors.

The successful implementation of GHG mitigation strategies has many economic, technical, political, social, and institutional constraints which hinder the use of the economic, technical and social opportunities that come with mitigation. The modification and removal of these barriers as well as improving the distribution of technology has much potential for GHG mitigation. Social learning, innovation and changes in the structures of institutions could significantly contribute to mitigation techniques (Metz, 2001). Climate change mitigation measures will have an impact on other societal issues because a reduction of carbon emissions mostly results in a simultaneous improvement of local and regional air quality. Mitigation strategies will affect agriculture, land-use and waste management, food security, human health, biodiversity and local environmental quality; however in some cases these impacts may not be positive (Metz, 2001; IPCC, 2014b).

Further research is required for understanding the scientific, economic, environmental and social aspects of climate change mitigation (Metz, 2001). Appropriate methodologies and improved data sources for climate change mitigation are needed as these will strengthen future research particularly for mitigation in developing countries (Metz, 2001). The reduction of atmospheric concentrations of GHGs globally requires all countries to work together because it cannot be achieved by the actions of individual countries or national governments alone (Mergenthaler, 2015). Effective mitigation will increase adaptive capacity and reduce vulnerability while encouraging socio-economic development paths that will also mitigate emissions (Ayers and Huq, 2008). Climate change mitigation should not be viewed in isolation of adaptation because successful linking of the two ideas will simultaneously address the mitigation priority of developed countries and the mitigation and adaption requirements of developing countries (Venema and Rehman, 2007).

Climate change mitigation in developing countries is often overlooked because alleviating poverty is still a high priority (Zotos *et al*. 2009; Garibaldi *et al*. 2014). Another major challenge for climate change mitigation in developing countries is moving from policy and planning towards implementation due to the resource, capacity and institutional constraints (Zotos *et al*. 2009; Garibaldi *et al*. 2014). Ehrhardt-Martinez *et al*. (2015) states that in order to achieve better mitigation there has to be a change in the present structure of economic and social systems. Hence developing countries such as Brazil and South Africa are using mitigation actions to address and reduce levels of inequality (Zotos *et al*. 2009). Linking mitigation actions to the countries policy objectives and planning capacity would result in successful implementation of mitigation strategies. Thus the integration of waste management into local and national policy objectives could result in more effective GHG mitigation strategies for the waste sector.

2.2.2 Climate change mitigation in the waste sector

The waste sector is responsible for about 5-6% of anthropogenic GHG emissions globally (Bogner *et al*. 2008; Zuberi *et al*. 2015). CH_4 is a principle gas emitted from landfills, it accounts for 75% of total waste sector GHG emissions and it is considered to be the largest source of climatic impact in the waste sector (Angelini *et al*. 2009; UNEP, 2010). The waste sector could have a significant role for climate change mitigation in developing countries

(Dedinec *et al*. 2015). This is because the mitigation of climate change in the waste sector encourages climate friendly waste management and results in positive outcomes such as reducing health risk, employment for a number of people, avoids local pollution and provides environmental protection (Menikrupa *et al*. 2013). Appropriate mitigation measures employed in the waste sector should be environmentally and socio-economically sustainable and effective. Further, developing countries continue to lag behind their developed counterparts with regards to environmentally friendly waste management (Zotos *et al*. 2009). Factors that hinder GHG mitigation in the waste sector for developing countries are rapid urbanisation, non-implementation of the polluter pays principle, lack of awareness and education for the public regarding sustainable consumption and the lack of social responsibility (Zotos *et al*. 2009; Hoornweg and Bhada-Tata, 2012).

In order to reduce GHG emissions from the waste sector it is encouraged that all stakeholders work together. In the study by Guerrero *et al*. (2013) the main stakeholders identified are local authorities, central government, private contractors, households and the commercial and industrial sectors. Research institutions, health care facilities, media and recycling companies were not regarded as significant stakeholders, yet the integration of all these stake holders could yield significant results for solid waste management and wastewater treatment. Consequently, improved management could result in reduced GHG emissions together with indirect climate change adaptation strategies. Thus, for the waste sector there should be emphasis on GHG reduction mechanisms that provide co-benefits for the environment, society and the economy. These co-benefits are based on controlling emissions in the atmosphere and simultaneously resulting in benefits for climate change mitigation and adaptation (Thambiran and Diab, 2011).

2.2.3 Sources of emissions from the waste sector

The major sources of GHG emissions from the waste sector arise from the landfilling of solid waste and the treatment of wastewater (Karakurt *et al*. 2012). There are also emissions due to the use of electricity by both solid waste and wastewater management. The CH_4 emitted from the waste sector accounts for 15-19% of all anthropogenic non CO_2 GHG emissions globally (Karakurt *et al*. 2012; Yusuf *et al*. 2012). Therefore, the identification of the major sources of emissions in the waste sector will help with the development of specific mitigation strategies that will improve waste management and reduce associated emissions.

2.2.3.1 Emissions from solid waste

GHGs are not only emitted during waste treatment but are also emitted during the transportation and handling of waste as well as the operation of machinery due to the use of fossil fuel based energy. The life-cycle assessment of waste assists in showing all sources of emissions and it could help highlight indirect paths that could significantly reduce GHG emissions and other impacts caused by solid waste (Menikrupa *et al*. 2013). The cycle for post-consumer waste begins when a product has been identified as waste in households until its final disposal in the landfill (“cradle to the grave”) (Mohareb *et al*. 2008; Carapina *et al*. 2014). Thus according to Lalet *et al*. (2010) the waste cycle involves: collection and transportation; waste transfer; mechanical pre-treatment; sorting; recycling and recovery; waste treatment and landfilling. Carbon emissions are released from the collection and transport of waste, electricity consumption and landfilling. However, a majority of the emissions are caused by decaying material in landfills and with minor emissions associated with leachate production and electricity consumption.

2.2.3.1.1 Collection and Transport

The collection and transport of waste is a foundation of the waste management system globally (Eisted *et al*. 2009). Transport causes long-term damage to the climate due to the consumption of fossil fuels by vehicles (Chapman, 2007). The transport sector is dependent on fossil fuels which according to Pegels (2010) result in atmospheric emissions as well as other environmental and health impacts. Furthermore, fossil fuels are non-renewable and their availability is limited (Dincer, 2000; Ashfaq *et al*. 2015). This dependency on fossil fuels makes the transport sector a major contributor to global GHG emissions (Chapman, 2007). Gases emitted by vehicles are CO_2, nitrogen oxides (NO_X) and carbon monoxide (Kinnaer and Rolfe, 2015); but CO_2 is the main GHG emitted (Morgadinho *et al*. 2015). Therefore, the main GHG emitted during the collection and transport of waste due to the combustion of fuel is CO_2 with small amounts of other GHGs such as CH_4 and N_2O also emitted (Chen and Lin, 2007; Freidrich and Trois, 2011). The actual emissions vary with load size, fuel type (diesel and petrol) and the vehicles engine model (Chen and Lin, 2007). Thus the use of non-renewable fossil fuel derived fuel consumption needs to be limited due to environmental impacts (Perlaviciute and Steg, 2015).

Barton *et al*. (2007) states that in most developed countries the collection of waste involves waste collection from households or mutual collection points to the site of disposal. However, in most developing countries particularly in African cities, this service is limited because of the low financial base and human resources (Barton *et al*. 2007; Friedrich and Trois, 2013). Diesel fuelled trucks are used for the collection and transport of waste (Freidrich and Trois, 2013). According to Clark *et al*. (2002) information on emissions from heavy-duty diesel vehicles is limited; this could be why there is limited information on emissions caused by the collection and transport of waste. Another factor contributing to the limited information could be the variability of these emissions, the complexity associated with calculating these emissions and details required. Trucking emissions are variable because of the below listed factors (Kiennar *et al*. 2015):

- Nature and properties of fuels and oils
- Engine and vehicle characteristics
- The condition and age of the vehicle
- The extent of stops and idling and average speeds
- Driving situations such as climatic conditions, terrain and traffic
- Driver behaviour

Freidrich and Trois (2013a) listed factors that are necessary for more accurate calculation of emissions caused by the transport and collection of waste: the average trip length and average loads per vehicle, taking into account that waste vehicles operate differently during the collection process and normal transport, the topographical conditions and road conditions which all influence emissions. However, the IPCC (2006) guidelines provide country specific guidelines and equations for calculating emissions caused by transport using mileage or fuel use; therefore these guidelines could be used for calculating waste sector transport emissions also. According to Chen and Lin (2007) using fuel used instead of mileage covered is the more accurate option because of the uncertainty with mileage covered.

In order to reduce GHG emissions associated with the transport and collection of waste, Ravindra *et al*. (2015) recommended that the optimisation of transportation routes could reduce fuel consumption and energy use from the collection point to the site of disposal. Most waste collection trucks are dependent on the consumption of diesel as a fuel source, thus in order to minimise emissions caused by the consumption of diesel and petrol alternative renewable energy sources could be used. Alternate fuels that can be used which would reduce emissions are biofuels and liquid petroleum gas which provide a clean burning alternative when compared to gasoline and diesel (Chapman, 2007). Zotos *et al*. (2013) states that biofuel programmes have been successfully organised by several municipalities in European Union member states. The disadvantage with biofuels is that energy input is required for processing the fuel and the cost of biofuels is higher than conventional fuels (Chapman, 2007; Morgadinho *et al*. 2015). However, this initiative could promote the greening of waste collection trucks which are responsible for most transport emissions in the waste sector.

2.2.3.1.2 Electricity consumption

In the waste sector GHG emissions are not only caused by landfilling, emissions are also caused by electricity consumption for operation and maintenance activities. Energy emissions during the treatment and disposal of waste are those emissions resulting from the combustion of CH_4 to produce electricity and emissions from electricity consumption due to basic lighting in the municipal buildings (Trois and Jagarth, 2011). Electricity generation is a major contributor of CO_2 emissions globally (Zuberi *et al*. 2015). Fossil fuel derived electricity is the predominant source of energy (Sebri and Ben-Salha, 2014) that is linked to several environmental problems ranging from GHG emissions to acid rain (Dincer, 2000).

The use of and dependency on fossil fuel derived electricity needs to be limited because of the depletion of natural resources and the environmental problems caused (Perlaviciute and Steg, 2015). Several options exist for abating GHGs from electricity production such as: energy conservation, carbon capture and storage, fossil fuel switching and the use of renewable energy (IPCC, 2011). In response, some governments have implemented the use of renewable energy to ensure energy security, reduce environmental pollution and create employment (Ashfaq *et al*. 2015). Hence renewable energy sources are gradually becoming a significant part in the power supply sector (Li *et al*. 2015b). The recovery of energy from waste using the applicable treatment methodology contributes to reduce GHG emissions from waste and fossil fuel derived electricity (Menikrupa *et al*. 2013). Therefore the waste sector is capable of reducing its electricity emissions by using renewable energy produced from LFG capture systems that convert this gas to electricity. However in existing literature (Chen and Lin 2007; Zhao *et al*. 2009; Freidrich and Trois, 2013a; Zhou *et al*. 2014) quantifying indirect emissions caused by electricity consumption in the waste sector are not considered and there is limited information available.

2.2.3.1.3 Disposal

Landfilling is often regarded as the ultimate disposal method even when there other options such as recycling and incineration. In developing countries landfilling is the main disposal method while developed countries are reliant on landfilling as an important part of waste management (Agamuthu, 2013). In developed countries emissions from landfills were stabilised due to stringent regulations, however CH_4 emissions are expected to continue rising in developing countries because of their dependency on landfills and insufficient control systems (Agamuthu, 2013). Further, in developing countries the waste legislation focuses on concentrating and containing the waste with a majority of this waste being untreated and unsorted (Trois *et al*. 2007). This results in the landfilling of large quantities of untreated waste thus resulting in significant emissions. The major gases emitted by the decay of waste in landfills are CH_4, CO_2 and to a lesser extent N_2O (Barton *et al*. 2007). There is a debate on whether or not these CO_2 emissions contribute to global warming however; IPCC (2006) confirmed that this CO_2 does not contribute to overall GHG emissions and global warming because it is of biogenic origin. The quantity of GHGs emitted is dependent on the fraction of degradable organic carbon and the volume of waste (Barton *et al*. 2007). The waste degradation process is largely dependent on the waste composition, the rate of disposal and climatic conditions which determine the quantity of emissions produced over time (Trois and Simelane, 2010).

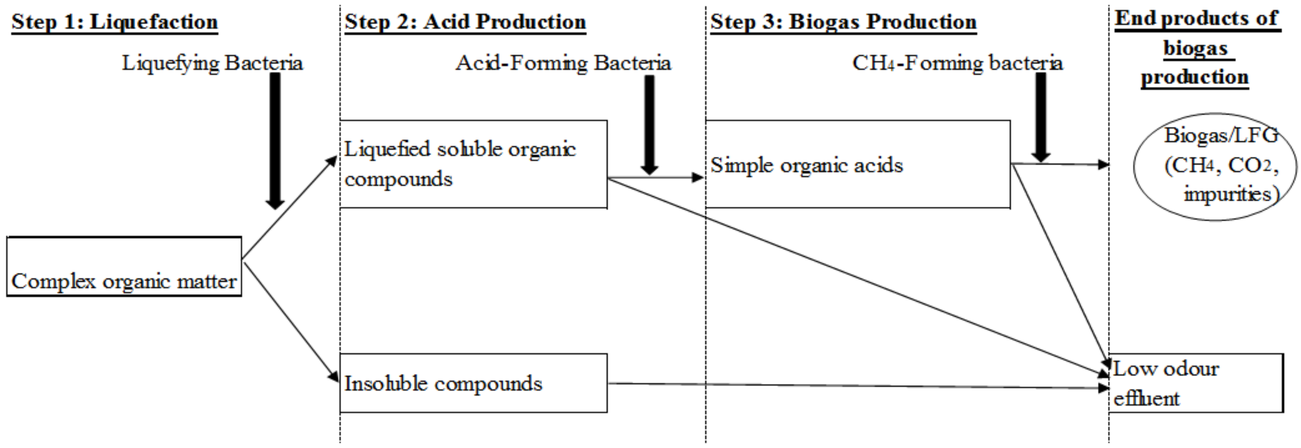


Figure 2: Three steps for the conversion of complex organic matter to biogas during anaerobic digestion in landfills (Source: Zuberi *et al*. 2015).

In cities or large towns in developing countries dump sites are common and their emissions are less than those of controlled dump sites (Freidrich and Trois, 2013). Since dumpsites are relatively shallow, this reduces the potential for the generation of CH_4. Furthermore due to space limitations in dumps, the waste is often burnt thus emitting CO_2, dioxins a well as furans (Barton *et al*. 2007). This does however increase the opportunity for CH_4 to be oxidised by the aerobic layer thus producing a lower CH_4 to CO_2 ratio (Barton *et al*. 2007). Even though dumpsites produce lower emissions than landfills, they do however have negative environmental impacts such as pollution and creating an environment for vermin.

The degradation of biogenic material in landfills occurs in two ways: firstly, the aerobic process occurs in the open air of the landfill and produces CO_2 or the second being an anaerobic process occurring within the internal layers of the landfill that produces CH_4 (Finnveden *et al*. 1995; Angelini *et al*. 2009). The overall carbon content of municipal solid waste can be distinguished as fossil carbon which is a non-degradable and biogenic carbon content. Biogenic carbon is commonly found in biodegradable fractions such as organic kitchen waste as well as garden and paper waste. Barton *et al*. (2007) stated that the highest impact of carbon emissions are from landfills without electricity production or gas flaring and these emissions are higher than those at open dump sites. Thus, according to Zuberi *et al*. (2015) landfilling should be prioritised last in waste management because of its high GHG emissions when compared to other waste management options.

Table 1: Advantages and disadvantages of landfills (Source: Cheng and Hu, 2010).

Advantages	Disadvantages
Universal solution that provides the ultimate disposal of waste	Cost increases with liner, stricter regulations and leachate collection
Easy to implement and relatively low cist	Requires extensive area of land
Complements with other technology options for handling residual waste	Could result in secondary pollution problems: air pollution, groundwater contamination and soil contamination
Is able to derive LFG as a by-product for industrial and household uses	Could become a breeding ground for pests and diseases
As the landfill expands, cots are incurred incrementally	Site location is limited by the geology and natural stability of the underlying soil
	Results in long distance transportation of waste to the site.
	Emissions continue post-closure of the landfill site

2.2.3.2 GHG emissions from wastewater

GHGs from wastewater are emitted throughout the entire cycle of wastewater as shown in Figure 3. These key sources of emissions are discussed in more detail in the following sub-sections.

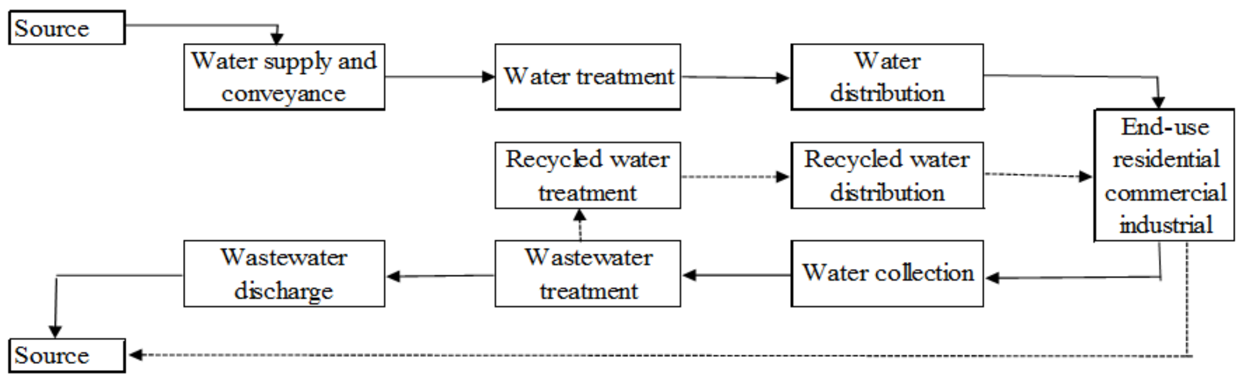


Figure 3: Typical water-use cycle for cities. The dashed arrows show that the paths can infrequently occur (Source: Major *et al*. 2011).

2.2.3.2.1 WWT treatment and processes

All wastewater must be treated prior to its disposal or recycling for reuse. WWT is generally divided into primary, secondary and to a lesser extent a tertiary component. Primary treatment involves the screening, sedimentation, and filtration of coarse materials (Saharan *et* *al*. 2014). For secondary treatment the water settled during primary treatment is pumped into the secondary treatment plant which consists of aeration basins and clarifiers (Friedrich *et al*. 2008; Saharan *et al*. 2014). The diffused air system or mechanical clarifiers may be used for aeration (Freidrich *et al*. 2009). Secondary treatment produces effluent which is treated with chemicals during tertiary treatment also referred to as the water recycling step. The secondary treatment stage is responsible for most electricity use and N_2O production (Freidrich *et al*. 2009). The recycling of wastewater and reuse of treated water is not fully explored in developing countries (Ashton *et al*. 2012). Further, Ashton *et al*. (2012) states that the driving force behind WWT is water provision and the need to protect the environment because wastewater can have negative impacts associated with it. Thus effective WWT could result in reduced environmental impacts and water provision through recycling.

Post treatment, wastewater sludge is often landfilled however this is not encouraged as it could result in the emission of harmful gases such as hydrogen sulphide in LFG. According to Bogner *et al*. (2008) wastewater and sludge anaerobic digestion can produce useful biogas for process heating and onsite electricity generation which will substitute the fossil fuel used for generating electricity and heating. The reuse of wastewater for irrigation and industrial purposes results in climate change adaptation techniques. Bogner *et al*. (2008) stated when efficiently applied WWT can directly reduce the atmospheric emissions of GHGs. The treatment of wastewater has several environmental benefits because it can replenish groundwater aquifers and it can prevent the eutrophication of water systems which the wastewater is being emptied into.

Both aerobic and anaerobic WWT are associated with significant GHG emissions because of the processes involved as well as wastewater composition. Anaerobic processes are the most favourable for both developed and developing countries even though they contribute to increased GHG emissions while the flaring of wastewater sludge is recommended to reduce its associated CH_4 emissions (El-Fadel and Massound, 2001; Cakir and Stenstrom, 2005).
The CH_4 from wastewater is produced microbially under strict anaerobic conditions where anaerobic WWTPs can produce and emit between 50-80% of CH_4 (Law *et al*. 2012). The N_2O emitted from wastewater accounts for 3% of N_2O emissions from all sources and is ranked as the 6th largest contributor to global N_2O emissions (Law *et al*. 2012). Therefore a further discussion on N_2O is provided below.

Processes responsible for N_2O production

N_2O emissions from wastewater are an intermediate product of microbial nitrogen cycling due to reduced aeration, high moisture contents and abundant nitrogen (Bogner *et al*. 2008). N_2O is predicted to be the most dominant ozone depleting agent in the 21st century where 40-50% of its annual increase in the atmosphere is attributed to human activity (Ravishankara *et al*. 2009). N_2O is a necessary intermediate in the heterotrophic denitrification pathway and is produced by autotrophic nitrifying bacteria with ammonia-oxidising bacteria as a by-product (Kampschreur *et al*. 2008). WWTPs are designed to achieve high nitrogen conversion rates; this because according to Law *et al*. (2012) domestic water generally contains high concentrations of nitrogen with about 20-70mg/L total nitrogen. Therefore in order to ensure nearly complete nitrogen removal within 3-8 hours, treatment plants apply high nitrogen loading which results in high nitrification and denitrification rates that are expected to have an impact on the N_2O production rate (Law *et al*. 2012). WWT plants are engineered systems therefore there is great potential for mitigating these N_2O emission rates by redesigning the process design of WWTPs or their operational conditions (USEPA, 2013). The nitrification and denitrification stages are responsible for N_2O production; Figure 4 highlights the main parameters that produce N_2O.

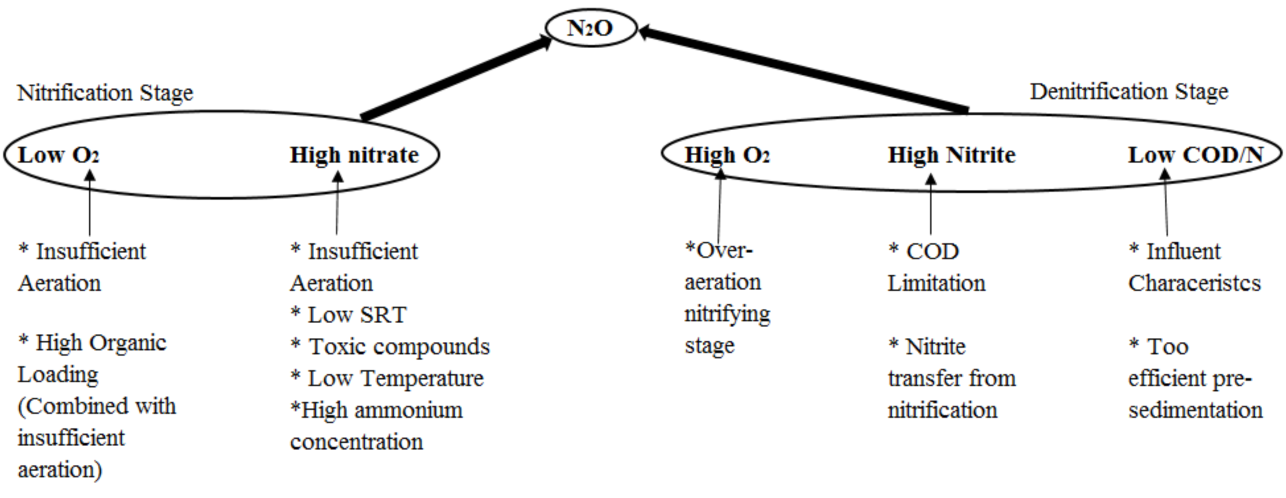


Figure 4: Main parameters responsible resulting in N_2O emissions (Source: Kampschreur *et al*. 2008).

The production of N_2O mostly occurs in the activated sludge units of WWTPs (Kampschreur *et al*. 2008). Complete nitrification is step 1-2 in Figure 5 below while step 3-6 is the complete denitrification process. 1. Aerobic ammonia oxidation through autotrophic and heterotrophic ammonium-oxidizing bacteria and ammonium-oxidizing archaea; 2. Aerobic nitrite oxidation; 3. The reduction of nitrate to nitrite; 4. Reduction of nitrite to nitric acid; 5. Reduction of nitric oxide to nitrous oxide; 6. Reduction of nitrous oxide to dinitrogen gas; 7. Nitrogen fixation; 8. The oxidation of ammonium oxidation with nitrite to dinitrogen gas. Nitrogen monoxide (NO) and N_2O are intermediates of the catabolic respiratory pathway which reduces nitrate or nitrite to nitrogen.

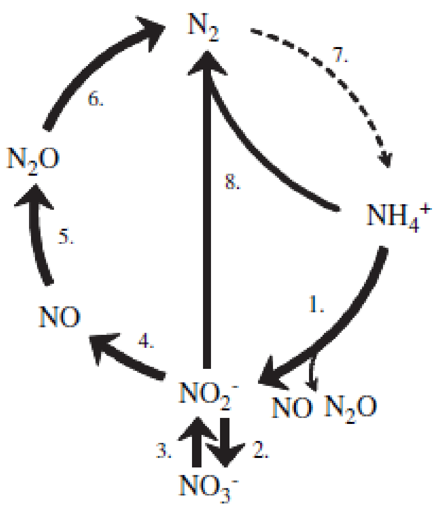


Figure 5: Image showing biological nitrogen conversions. (Source: Kampschreur *et al*. 2008).

Nitrification

Nitrification is performed by groups of microbes called ammonium-oxidizing bacteria (AOB) and ammonium-oxidizing archaea (AOA) which convert ammonia in to nitrite as well as nitrite-oxidizing bacteria (NOB) which are responsible for converting nitrite to nitrate. Kampschreur *et al*. (2008) stated that nitrification is mostly executed by autotrophic AOB and NOB that utilise ammonia or nitrite as their source of energy and CO_2 as a source of carbon. As per Park *et al*. (2006) AOA have been found to occur in WWTPs that are operated at low dissolved oxygen levels with long solid retention times. According to Kampschreur *et al*. (2008) there are no indications that heterotrophic ammonia oxidisers or ammonia oxidising archaea have a key role in sludge activated plants however they could be important in the production of N_2O. The concentration of dissolved oxygen is controls the amount of N_2O emitted during nitrification.

Denitrification

Denitrification is performed by micro-organisms, bacteria and archaea which combine the oxidation of inorganic or organic substrates for the reduction of nitrate, nitrite, nitrogen monoxide and N_2O. N_2O is an intermediate during the denitrification process, therefore incomplete denitrification results in the emission of N_2O (Kampschreur *et al*. 2009). Most denitrifying agents use oxygen as an electron acceptor attributed to the high energy yield while according to Robertson *et al*. (1995) some microorganisms are able to denitrify under both aerobic and anoxic conditions. Furthermore AOB is able to denitrify from nitrite to N_2O using hydrogen or ammonium as the electron donor through a process known as nitrifier denitrification (Bock *et al*. 1995).

In many developing countries the lack of developed wastewater infrastructure and technology results in higher wastewater CH_4 and N_2O emissions than in developed countries (Bogner *et al*. 2008). A major challenge in the developing world regarding WWT is the available technology for specific applications. Treating wastewater is an attractive option because the overall impact of climate change on water resources could decrease the quantity and quality of water available. Treated wastewater can be re-used or discharged, but re-use is the most desirable option for agricultural and horticultural irrigation, artificial recharge of aquifers, or industrial applications (Bogner *et al*. 2008). The treatment of wastewater could be a solution for water provision in many countries because it may protect drinking water supplies but for developing countries the major challenge for treatment is the cost and maintenance of appropriate technologies.

2.2.3.2.2 Electricity Consumption

According to Friedrich *et al*. (2009) most of the carbon emissions from wastewater are associated with electricity consumption during treatment and recycling. This use of fossil fuels to produce electricity results in fossil fuel depletion and acidification (Wang *et al*. 2015). Niero *et al*. (2014) performed a life cycle assessment on WWT and for all the plants studied it was found that the main contributor towards GHG emissions was fossil fuel based electricity consumption. Furthermore the study by Wang *et al*. (2015) assessed the environmental implications of stringent GHG emissions of WWTPs in China, it was found that 35% of emissions were CO_2 emissions generated by the production of electricity. From this it is clear that electricity is a significant contributor of GHGs from the treatment of wastewater. Efforts to achieve energy recovery and savings from WWTPs are often very problematic, highlighting the need to improve energy efficiency (Wang *et al*. 2015). Energy use can be reduced by employing high efficiency air-diffusers or controlling the air supply scheme in WWTPs (USEPA, 2013; Wang *et al*. 2015). Further, decreased aeration for the plants results in lower electricity consumption (Schaubroeck *et al*. 2015). The use of digester gas derived from wastewater sludge for electricity provision could minimise dependence on fossil fuel derived electricity for WWTPs (Niero *et al*. 2014; Wang *et al*. 2015).

2.2.4 GHG reduction mechanisms for solid waste

2.2.4.1 Recycling

A major aim of waste management is to reduce the quantity of waste sent for disposal while increasing the rate of recycling (Nzeadibe, 2015). The recycling of waste reduces the amount of waste disposed in landfills and therefore saves the municipality costs in the operation of landfills thus contributing towards sustainable landfilling (Couth and Trois, 2010). The recovery, recycling and re-use of waste has significant influences on the quantity of GHG emissions from the waste sector (Zuberi *et al*. 2015). The extent of emissions avoided when recycling is depended on the type of material and the specific fossil fuel avoided. Recycling provides an option to divert end of life materials such as steel or electronics from landfills and it highlights the resource value of waste. Further, recycling has socio-economic spin-offs which include profits for the community and recovery businesses (Menikpura *et al*. 2013; Mesjasz-Lech, 2014).

Separate waste collection is a significant part of waste recycling because it results in the formation of labour intensive jobs and contributes towards effective recycling (Trois and Simelane, 2010; Nzeadibe, 2015). Separate waste collection and sorting of waste is key because it separates and protects those items to be reused or recycled from those that could damage them such as wet waste. The development of waste separation programme's is often hindered by the limited knowledge regarding technologies and good practices for effective waste management, the lack of decision makers that are interested in environmental issues and the lack of equipment for the collection of sorted materials (Guerrero *et al*. 2013). The three most important components of waste separation are whether awareness has been created to communities and the availability of machinery and equipment to manage and recycle the waste (Guerero *et al*. 2013). Figure 6 depicts a wet and dry separate collection model which is suitable for both developing and developed nations. This model is suited to all waste reduction mechanisms and contributes towards a practical waste management strategy.

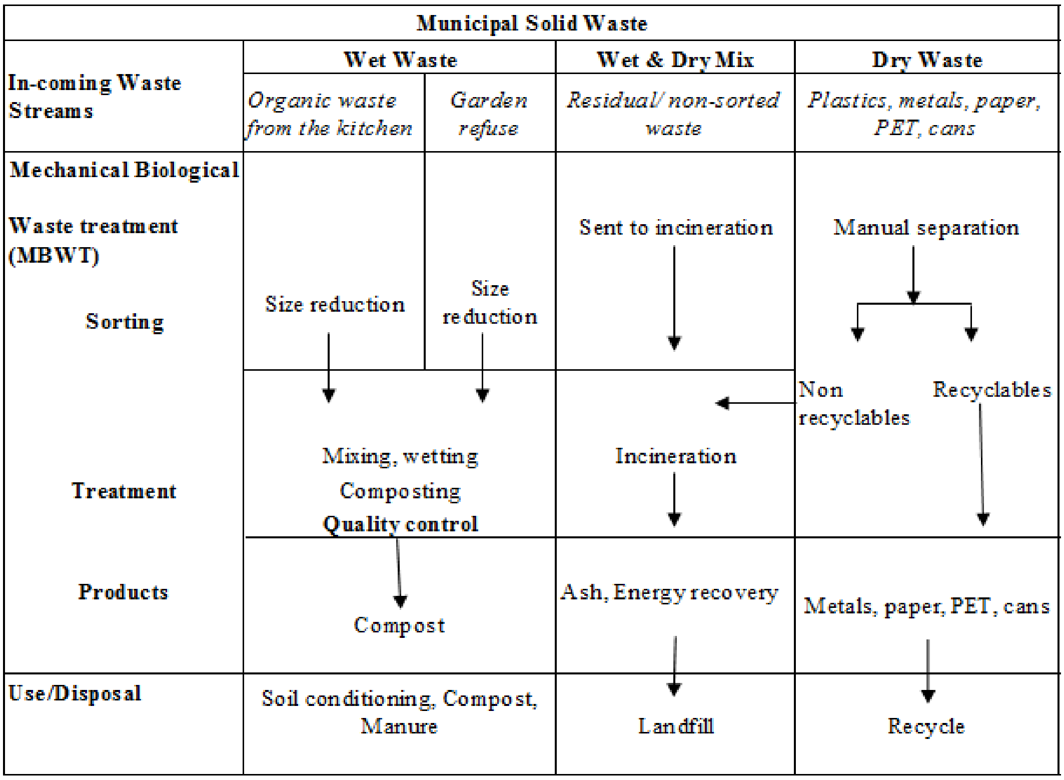


Figure 6: Proposed separate wet and dry model to promote recycling and composting (Source: Trois and Simelane, 2010).

Several cities in developing countries lack effective the waste recovery programmes, and this gap has been filled by the informal sector (Nzeadibe, 2015). In developing countries the livelihoods of the poor are dependent on collecting recyclable material on the streets and at disposal sites (Guerrero *et al*. 2013; Nzeadibe, 2015). Therefore, this informal sector contributes to poverty eradication. Wilson *et al*. (2006) states that a major challenge for waste management in developing countries is how to work together with this informal sector while improving their livelihoods and efficiency of recycling. Waste scavenging and picking is an adaptive response to poverty by poor communities. The informal sector is skilled at identifying recyclable materials and consequently use innovative measures to collect and process these materials (Nzeadibe, 2015; Ravindra *et al*. 2015). Informal waste collectors recover materials from waste thrown on the streets prior to collection or recover secondary raw materials from vehicles transporting municipal solid waste and also sort through wastes from dumps (Benarche, 2003; Ravindra *et al*. 2015). An example of the informal recycling system is shown in Figure 7. The informal sector has important contributions for income generation, working conditions and social status but the less organised it is, then the people involved do not realise the value of the raw materials being collected (Wilson *et al*. 2006). However, informal recycling could have negative impacts for the health of scavengers because no protective equipment is used to handle the waste.

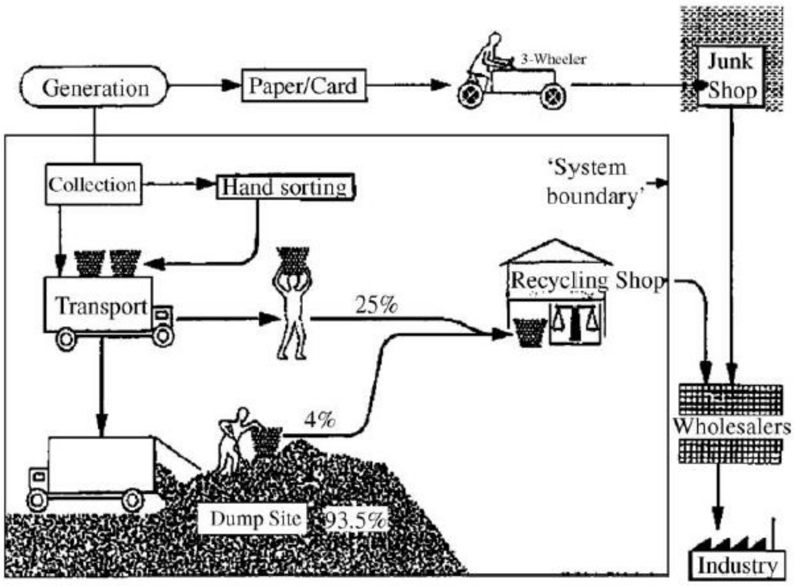


Figure 7: Flow chart showing the informal recycling system (Source: Wilson *et al*. 2006).

There are limited studies in developing countries that quantify GHG emission savings from recycling and re-use of waste due to the limited available data. The recycling process consumes a significant amount of fossil fuel derived electricity and could result in the emission of GHG emissions mostly in the form of CO_2 (Bovea *et al*. 2010). Thus, improving the energy use efficiency of recycling technologies could reduce GHG emissions from this process (Gentil *et al*. 2009). However, the recovered materials replace an equivalent amount of energy and materials that would be required for the production of virgin sources (Menikrupa *et al*. 2013). Therefore, indirect GHG savings from materials recovery from waste must be acknowledged (Gentil *et al*. 2009). The recycling of materials is associated with high financial costs especially those of purchasing and maintaining machinery, but new products are associated with extreme environmental costs (Couth and Trois, 2010). It could be seen as less costly to dispose waste than recycling it; however manufacturing virgin goods has higher costs for the environment that recycling.

In order to divert waste from landfills in the United Kingdom organisations and charities are able to claim recycling credits to the value of the cost of the disposal inclusive of landfill tax (Couth and Trois, 2010); this highlights an opportunity for clean development mechanism (CDM) to assist with these incentives in the poorer countries.

Recycling enables pollution to be avoided for all impact categories such as fuel consumption due to transport and electricity use for the waste and production of virgin materials (Bovea *et al*. 2010). However, some recycling initiatives in developing countries have failed due to the lack of finances. This failure occurs because in many developing countries recycling and municipal solid waste are not treated as integrated systems (Zeng *et al*. 2010). Matete and Trois (2008) specified that in Durban, South Africa the income generated by the zero waste project could not cover the monthly running expenses of the project which highlights the dire need for financial assistance, less costly machinery and incentives for recycling. This shows that recycling projects are not failing because of the lack of available material but due to underlying management and financial issues.

In order to improve waste management and promote recycling the local authorities in Hellenic Republic have implemented a pay as you throw (PAYT) scheme, thus charging households depending on the quantity of waste (Zotos *et al*. 2009). Each PAYT is adjusted according to the waste collection method used as well as the local socio-economic conditions. Although this is a good initiative it would not be applicable in the context of developing countries where a majority of the population is living under poverty. Municipalities may thus not make extensive profits from recycling but it will extend the lifetime of the existing landfill sites, create jobs and result in cleaner communities (Blight and Musane, 2007). Recycling within a community is influenced by social influences, regulatory and philanthropic factors (González-Torre and Adenso-Diaz, 2005). Therefore, communities in developing countries need to be educated and made aware of the opportunities that lie with waste recovery, recycling and re-use. Furthermore, Guerrero *et al*. (2013) stated that making recycle bins available to the public would increase the fractions within communities that separate and recycle.

2.2.4.2 Composting of waste

Composting is a natural process with numerous benefits for GHG emissions reduction in the waste sector because it reduces the organic fraction of waste which is a significant contributor towards emissions (Di Maria and Micale, 2015). It is a cornerstone towards sustainable development yet it is often not included in waste management programmes (Hoornweg *et al*. 1999). Composting is considered a cornerstone because it has the ability to contribute towards climate change mitigation and adaptation. Further, composting reduces the volume of landfilled waste, specifically the organic content thus extending the lifespan of the landfill (Menikrupa *et al*. 2013; Li *et al*. 2015a). According to Freidrich and Trois, (2013b) waste in developing countries has an organic carbon content ranging between 50-78%. Thus, composting should be encouraged particularly in developing countries because of their waste contents and it is the degradation of this organic matter that results in GHG emissions. Composting can take place within households as well as at waste management sites. However, it should be encouraged from household level because it will minimise the amount of organic waste collected and promote waste separation at this level.

Composting can either occur in open wind rows or closed buildings with gas collection treatment (aerobic and anaerobic processes respectively). Composting involves two stages, firstly the collected waste should be sorted and the bio-waste should be removed of any plastics plus metals and then shredded. In the second stage the bio-degradable waste is then composted in closed vessels or open windrows for a certain period with the piles being turned a minimum of three times a week (Couth and Trois, 2010). During the composting process only small amounts of CH_4 and N_2O may be generated. The reduction of water during composting reduces the costs of treatment as well as emissions from the machinery and improves the quality of waste reaching the landfill. A significant disadvantage of aerobic composting is the release of dust which contains bio-aerosols which have possible odours (Gutiérrez *et al*. 2015; O’Connor *et al*. 2015). Anaerobic composting has more benefits because of the potential to produce energy from the captured gas, however the conversion of gas to energy process and technology are very costly and would require CDM funding.

According to Ayers and Huq (2008); Blengini (2008); Boldrin *et al*. (2009); Cheng and Hu (2010); and Di Maria and Micale, (2015) when converting waste to fertiliser, GHG savings occur during the application of waste derived compost instead of organic fertiliser and when carbon is bound to the soil after the compost is applied. Composting successively integrates with materials recovery, recycling and incineration operations (Cheng and Hu, 2010). This is because it reduces moisture from the waste stream since during the composting stage the moisture content of waste can drop from 55% to 35%, it promotes the reduction of CH_4 generation rates, it enhances fertiliser application and it improves the cities overall waste management (Hoornweg *et al*. 1999; Di Maria and Micale, 2015). Since the reduction of GHG is of global concern, composting is one of the preferred GHG reduction mechanisms.

According to Cheng and Hu, (2010) composting can be costly to implement. Furthermore, the compost produced could result in soil pollution and there are issues of odour and bio-aerosol emissions as well as the control of disease producing organisms that have to be considered. Thus, generating good quality organic fertilisers requires efficient source segregation of organic matter which increases cost as well as the impact associated with collection and transfer activities (Di Maria and Micale, 2015). The lack of proper sorting and separation of materials produces composts with low nutrients and high heavy metals contents (Cheng and Hu, 2010; Li *et al*. 2015a); this results in composting being an unpopular choice in waste management where there is little or no sorting occurring at source. One of the major limiting factors with regards to composting is that there are difficulties in securing finances because according to Hoornweg *et al*. (1999) the revenue generated from the sale of compost will seldom cover processing, transportation and application costs. During the composting process GHGs are released because the machinery used in the composting facility requires fuel and energy on the other hand the degradation process produces small quantities of CH_4 and N_2O (Blengini, 2008; Bovea *et al*. 2010; Friedrich and Trois, 2013b; Di Maria and Micale, 2015). Figure 8 below illustrates pathways of exposure to pollutants derived from the composting of municipal solid waste.

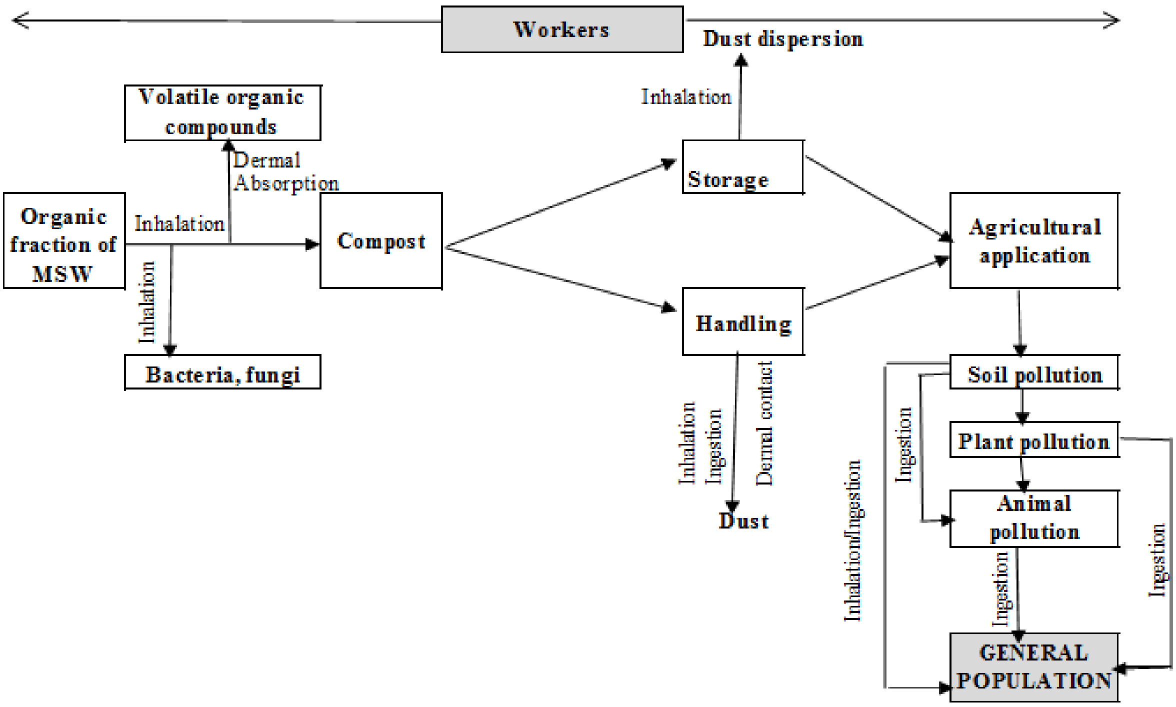


Figure 8: Pathways of exposure to pollutants derived from the production and utilization of compost derived from the organic fraction of MSW (Source: Domingo and Nadal, 2009).

2.2.4.3 Thermal Waste Treatment

Thermal waste treatment involves high temperatures when processing waste but is not only restricted to combustion where during thermal treatment energy can be recovered in the form of heat, fuel or electricity. Thermal processes have minor carbon emissions when compared to landfilling (Bogner *et al*. 2007). Further, according to Consonni *et al*. (2005) thermal treatment reduces the mass of waste, offsets the use of fossil fuel derived energy and contributes to an avoidance of GHG emissions even though there are small emissions from CO_2 sources. The UNEP (2010) stated that thermal treatment with energy recovery could be eligible for CDM funding; this will encourage the participation of developing countries but the waste would have to undergo pre-treatment. The thermal treatment of waste with energy recovery results in large GHG savings because of the production of amounts of energy which could then substitute the use of fossil fuels. The CH_4 emissions from landfills can either be combusted into CO_2 and water vapour or used as an energy source for heating or converting into electricity via an engine or turbine (Sabbasa *et al*. 2003). Thermal waste processes include incineration with and without energy recovery, production of refuse-derived fuel as well as gasification and pyrolysis (Zuberi *et al*. 2015).

2.2.4.3.1 LFG Capture

LFG is a GHG produced from the anaerobic digestion of solid waste in landfills and is mainly composed of CH_4 and CO_2 (Ahmed *et al*. 2015). This biogas produced by landfills is 50-55% in CH_4 by composition which is the main GHG emitted by the waste sector (Zuberi *et al*. 2015). LFG recovery is a common waste treatment technology and has been implemented in a minimum of 1150 solid waste treatment plants worldwide (Agamuthu, 2013). At solid waste disposal sites the LFG is combusted and electricity is then generated either in a turbine or a nearby industry. Menikrupa *et al*. (2013) stated that landfills with gas recovery systems in place provide an opportunity for generating renewable energy and receive financial revenue through CDM (Menikrupa *et al*. 2013). CDM enables developing countries to implement LFG capture schemes which reduce waste emissions while improving waste management, address climate change and generate an income through the sale of CERs and the energy generated. Furthermore, the use of biogas produced form landfills could reduce the gap between energy supply and demand (Zuberi *et al*. 2015).

LFG capture does not only provide electricity but reduces GHG emissions by utilising or converting the CH_4 that would have been emitted directly into the atmosphere (Inglezakis *et al*. 2015). The UNFCCC prefers that LFG collected is used for generating electricity and not for sole flaring (Couth and Trois, 2010). The success of the LFG capture project is relative to the country, the type of landfill and even the technology used for extraction but in some instances LFG projects have been able to extract 50-75% of the gas generated in landfills (Santaalla *et al*. 2013). The quality of the waste combusted fuel is dependent on the energy content of the waste which is measure of its lower heating value or higher heating value (Inglezakis *et al*. 2015). The use of LFG for electricity production requires extensive gas cleaning to remove the corrosive trace particles and requires capital cost for purchasing power generation movers such as dual fuel engines, gas turbines and spark ignition engines (Zuberi *et al*. 2015). In addition, the recovery of LFG encounters certain problems due to inappropriate application of LFG technologies, inadequate extraction systems that allow air intrusion, site conditions which limit LFG recovery; dry waste, aerobic conditions and even fires (Rettenberger, 2009; Ahmed *et al*. 2015). According to Ahmed *et al*. (2015) the problem is how to systematically evaluate these factors while simultaneously reducing environmental footprint and maximising profit. The potential for electricity production contributes to the reduction of GHG emissions however it is recommended that flaring and gas collection be prioritised as the last option during waste management.

Since most LFG most recovery systems began after the landfill was in operation for a significant amount of time, this results in the landfills still emitting CH_4 into the atmosphere even with LFG in place (Menikrupa *et al*. 2013). There is also a debate on whether or not to introduce LFG CDM for old and completed landfills which are a significant source of carbon and CH_4 emissions. However, it should also be considered that the emission of CH_4 from landfills decreases with time and LFG recovery form these landfills may not be necessary. Thus, Couth and Trois (2010) have argued that the practicability of LFG capture in older landfills is questionable especially for developing countries. The challenge then is to investigate how the GHG released by closed landfills can be mitigated.

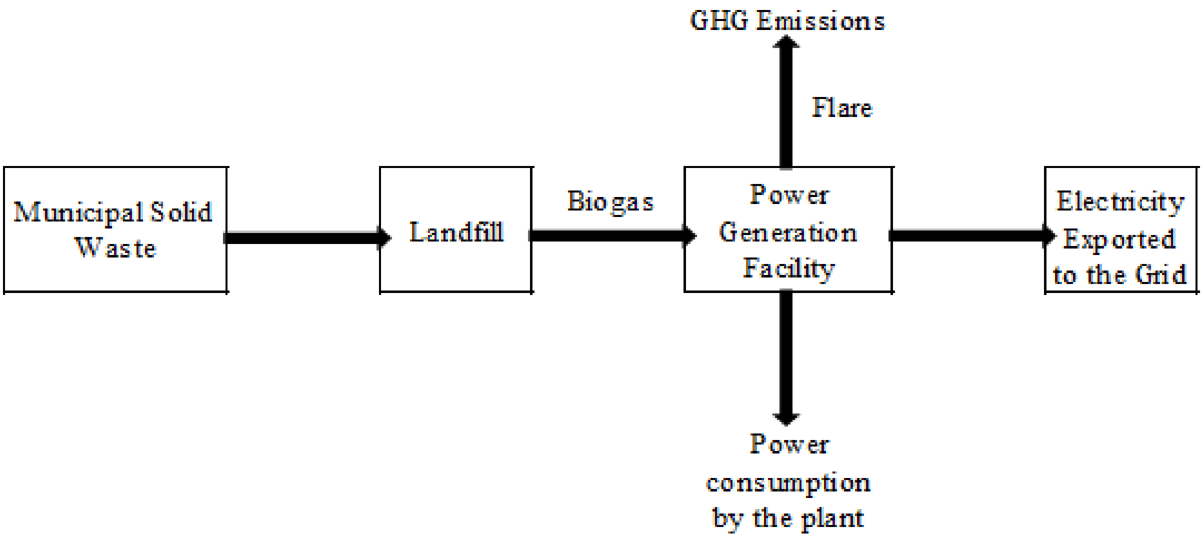


Figure 9: Schematic diagram of a power generation facility utilising LFG (Source: Zuberi *et al*. 2015).

2.2.4.3.2 Incineration

Incineration is a commonly applied thermal treatment in developed countries (UNEP, 2010). Incineration has been implemented successfully around the world, particularly by developed countries and developing countries such as China (Cheng and Hu, 2010). Developed countries have high rates of waste incineration because of the limited space available for landfilling (Consonni *et al*. 2005). The incineration of waste prevents possible gaseous and aqueous pollution that could be caused by landfills and it could provide renewable energy (Du *et al*. 2006; Cheng and Hu, 2010). However incineration is not a viable option for developing countries because of the high capital costs, the history of unsustainable projects as well the composition of the waste which is high in moisture (Bogner *et al*. 2008). Further, Menikrupa *et al*. (2013) stated that there is a possibility of failure if incineration technologies are applied to developing countries without any changes to suit their local conditions since they are designed for developed countries. The incineration process is ideal and highly recommended for those countries with limited landfilling space and sufficient capital. Incineration releases a significant amount of fossil based CO_2 into the atmosphere due to the combustion of plastics and textiles (Menikrupa *et al*. 2013). With the availability of sufficient funding, incineration with gas recovery for electricity production would be suited for developing countries. Table 2 below is a summary of the advantages and disadvantages associated with the incineration of municipal solid waste.

Table 2: Advantages and disadvantages of incinerating solid waste (Source: Cheng and Hu, 2010; Zhang *et al*. 2010).

Advantages	**Disadvantages**
Can reduce the volume of waste disposed in the landfill by 90%;	Compared to other options it has high capital, operational and maintenance costs;
Minimum pre-processing of waste is required;	Requires operator expertise;
Better resource integration than landfilling;	Could discourage the recycling and reduction of waste;
Air emissions can be controlled ;	The fly ash must be disposed in hazardous landfills;
The bottom ash from incineration is biologically clean and stable, and it can be used in the construction industry as well as the building of roads;	In order to treat the gas, air pollution control equipment is essential;
The heat produced from combustion can be used as a source of electricity.	It does not save energy in the long-term because resources are not recycled;

2.2.4.3.3 Gasification and Pyrolisis

Pyrolysis and gasification involve heating the waste in an oxygen free environment instead of burning it or even producing gas (Bebb and Kersey, 2003). During pyrolysis the waste is heated to high temperatures which results in a gas or fuel that is burnt to produce heat or electricity. The heating of waste instead of burning is what makes pyrolysis and gasification different from incineration. Most of the technologies for pyrolysis or gasification require pre-treatment of the waste to be utilised and thus the glass, metals and inert materials must be separated before processing. Pyrolysis produces solid residue which is a combination of the non-combustible materials and carbon as well as and a synthesis gas termed syngas (DEFRA, 2013).

Gasification is considered to be a process between pyrolisis and combustion because it involves the partial oxidation of a substance (DEFRA, 2013). Therefore during this process oxygen is added in amounts that are insufficient to allow the fuel to be completely oxidised thus preventing combustion. The gasification process is mostly exothermic although some heat is required to initialise and sustain the process (DEFRA, 2013). Similarly to pyrolisis the main product produced is syngas which is composed of carbon monoxide, CH_4 and hydrogen. Figure 10 below shows the pyrolysis and gasification systems together with their by-products. The advanced thermal treatment of waste is a highly mechanised process requiring advanced technologies; therefore this option is not practical for developing countries because of the associated costs of implementation and maintenance.

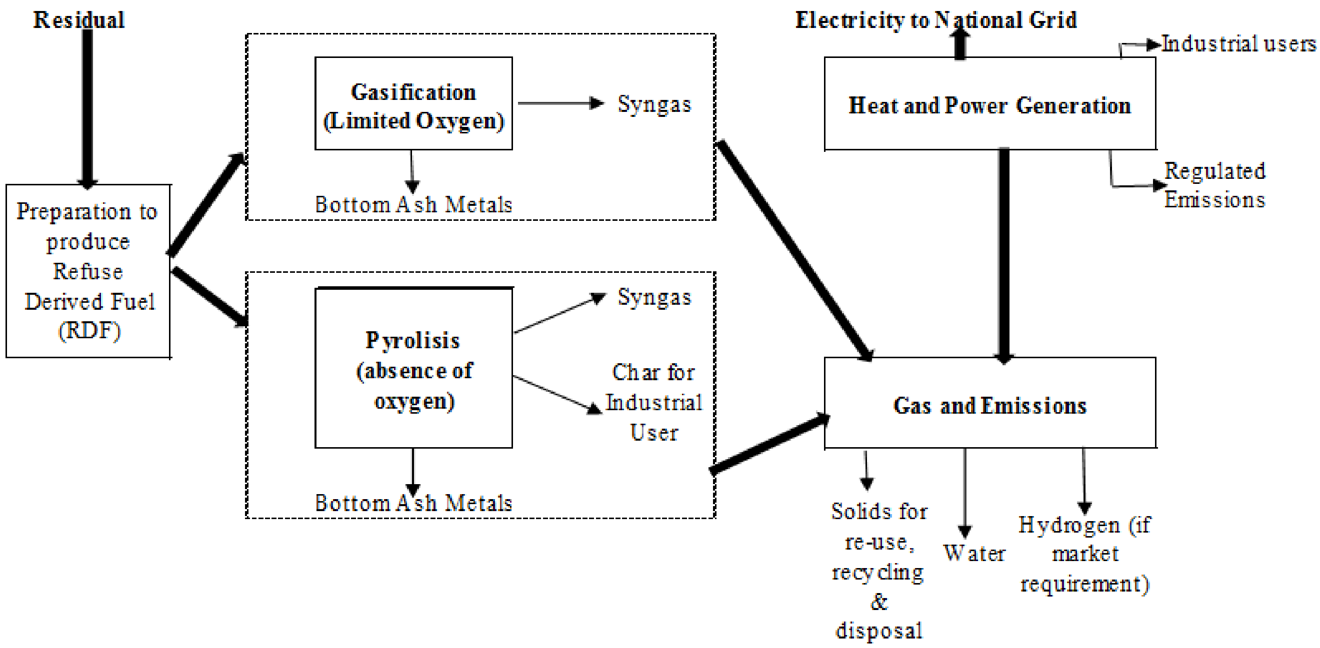


Figure 10: An overview of the thermal treatment generic process flow (Source: DEFRA, 2013).

2.2.5 Mechanisms to finance climate change mitigation

CDM is said to be one of the most innovative tools of the Kyoto Protocol which resulted from the Earth Summit in Rio de Janiero in 1992 (Dechezlepretre *et al*. 2008). The aim of

CDM is to achieve sustainable development and contribute towards the reduction of GHG emissions, particularly those in developed countries but Brown *et al*. (2004) have criticised CDM benefits for being more hypothesised than real because of the quantity of projects implemented successfully. It is considered a significant vehicle for initiating projects to control GHG emissions in Africa because of the financial incentive (Lam *et al*. 2015). CDM is an arrangement that allows industrialised countries with GHG reduction commitments to invest in projects that reduce emissions in developing countries as an alternative to more costly emission reductions in their own countries (Michaelowa and Jotzo, 2005; Dechezlepretre *et al*. 2008; Gentil *et al*. 2009; Lam *et al* 2015). Schneirder *et al*. (2008) states that CDM is the only market based technique for changing the emissions of activities in developing countries. The goals of the CDM are to provide support to developing countries that host CDM to offset emissions in developed countries that are aligned with sustainable development (Taiyab, 2006; Couth and Trois, 2010).

The main goal of CDM is to reduce costs associated with GHG reduction; however it is also a means for boosting technology transfer between developed and developing countries (Dechezlepretre *et al*. 2008). However, Dechezlepretre *et al*. (2008) has stated that even though technology transfer is expected it is questionable whether it is occurring in true practice and is this occurrence frequent. In studies completed by Haites *et al*. (2006) and Dechezlepretre *et al*. (2008) it was found that only one third of CDM projects in their database involved technology transfers and these accounted for two thirds of annual emissions reductions. These studies further found that 80% of LFG recovery projects involved technology transfers. The implementation of CDM projects in developing countries has associated co-benefits because it could reduce emissions as well as increase their course of development through increased technology transfers (Schneider *et al*. 2008).

CDM offers an important route to attracting investment in areas such as the waste sector to reduce GHG emissions particularly in developing countries (Barton *et al*. 2007). In doing this developed countries have the potential to provide emissions reductions strategies and equipment that is more suited to the needs of developing countries. CDM projects have to calculate certified emission reductions (CERs) or voluntary emission reductions for each year which requires specific project information (Barton *et al*. 2007). These CERs help developing countries to gain emissions reduction credits where the financing country can use these units to offset its own emissions. The process and rules required for a country to obtain CERs is complex and each party has a cap for their emission reductions.

It is recommended that simpler and quicker means for obtaining the CER are implemented as it will encourage participation from all sectors and countries. CDM and CERs together provide a controlled manner in which GHG can be accounted and reported for project specific waste emissions in developing countries (Jewaskiewitz *et al*. 2008). According Halsnael and Shukla (2009) CDM projects are the only mechanisms that enable developing countries to participate in the Kyoto Protocol and join the global mitigation of climate change.

The success of CDM projects in developing countries will be dependent on the institutional capacity and policy of that country (Halsnael and Shukla, 2009). CDM projects have a significant role to play in the waste sector which is often not regarded as a priority because of its minor contributions to global GHG anthropogenic emissions. This is because it will assist with the provision of the required strategies, appropriate technologies required for the different waste management stages as well as the desired funding to encourage industries to participate.

2.2.6 Innovative Technologies for WWT

2.2.6.1 Phyto-remediation for WWT

According to Hartman (1975) the use of plants for water treatment and sludge disposal is centuries old. This is because some plant systems are able of concentrating some toxic inorganics (Cunningham and Ow, 1996). The inorganics are concentrated as plants acquire elements through their shoots during their growth process with only a few elements that can be harmful to them (Cunningham and Ow, 1996). This is where the success of phyto-remedy lies because plants can absorb these inorganics in wastewater thus substituting the chemicals and technology use (Lishenga *et al*. 2015). Furthermore, the use of phyto-remedy for WWT is appropriate because it is environmentally friendly, low cost and treats the wastewater before it is released to water bodies (Lishenga *et al*. 2015). The limits of phyto-remediation are that the contaminant must be within the root zones of actively growing plants which implies depth, water, physical, nutrient, atmospheric and chemical limitations (Cunningham and Ow, 1996). Research in this field is motivated by the currently costly and environmentally unfriendly WWT techniques. Consequently the use of phyto-remediation results in the use of a technology that is environmentally sound, low cost, low impact and visually appealing (Cunningham and Ow, 1996; Roongtanakiat *et al*. 2007; Rezania *et al*. 2015).

Vetiver Grass for WWT

The use of vetiver grass for WWT is a relatively recent and innovative phyto-remedial technology with absorbent characteristics that are suitable for treating wastewater and the leachate produced from landfills (Truong *et al*. 2001). Vetiver grass is a fast growing perennial grass of family grimineae characterised by a deep root system with a very high biomass production, it has a high water usage and nutrient uptake rates, is tolerant to adverse environmental conditions (Kumar and Prasad, 2015). Vetiver grass is not a hydrophyte but it prefers wet and water logged habitats that will enable it to grow and develop (Lishenga *et al*. 2015). Vetiver can be used for environmental protection because it currently used for mine rehabilitation, erosion control projects as well as WWT (Troung, 2000; Kumar and Prasad, 2015; Rezania *et al*. 2015). Vetiver grass has a great ability to remove heavy metals such as nitrogen, potassium; phosphorus, cadmium and manganese from contaminated water and it can uptake significant quantities of, lead and mercury (Hengchaovanich *et al*. 2000 and Le *et al*. 2015). According to Lishenga *et al*. (2015) the nitrogen and phosphorus removing ability of vetiver grass makes it effective for use as a WWT system.

Wastewater is commonly treated using traditional systems that are highly dependent on electricity and require skilled personnel (Boonsong and Chansiri, 2008). These traditional WWTPs require very expensive continuous costs of operation and the use of fossil fuel derived electricity which is the opposite when using the vetiver system (Lishenga *et al*. 2015). Vetiver grass can be used to improve the water quality of effluent before it is discharged or prior to treatment using mechanisation. It can be used on locations where there is plenty of land available and where the local government would rather not pay for the installation and operation of high cost solutions. Vetiver grass is a green and environmentally friendly WWT technology method because it does not require clean water for growth and it can grow in any type of soil because of its wide pH range (Lishenga *et al*. 2015). This solution is therefore appropriate for developing countries with limited funds available for technology and sufficient land space.

Vetiver needs a platform on which to grow and when it is not planted directly on the ground it is recommended that it be placed on floating pantoons in sewage effluent ponds as it cannot float by itself. This factor makes it easy for maintenance because when water has been purified and the grass has grown, the floating vetiver can easily be removed. The vetiver system has many uses for instance the vetiver shoot can be used for handcraft products or biofuels while the root part can be used as a source of essential oils (Roongtanakiat *et al*. 2007). Vetiver can also be planted on the edges of rivers or lakes where sewage effluent is commonly discharged to minimise eutrophication and algal blooms in wastewater storage dams thus protecting the life in aquatic systems. It will not only result in less GHG emissions but it will also reduce and control offsite pollution from wastewater. According to Lishenga *et al*. (2015) vetiver constructed wetlands are a good alternative for WWT when compared to conventional WWT.

2.2.6.2 Thermal treatment of sewage sludge

The main alternatives for sludge disposal are landfilling, land application as well as incineration; incineration is quite costly and land application for agricultural use is dependent on reservations from consumers and farmers (Salsabil *et al*. 2010; Pilli *et al*. 2015). Sludge incineration is a vital step for the reduction of wastewater sludge where efficient thermal treatment requires knowledge of the heavy metal and salt content because it assists with choosing the correct flue gas cleansing system (Zorpas *et al*. 2001). Incineration decreases the volume of sludge by approximately 30% and it provides environmental benefits of energy production (Schauebroeck *et al*. 2015; Wang *et al*. 2015). According to Schaubroeck *et al*. (2015) the emission of toxic substances into the atmosphere is a significant drawback for incineration. Thus, Bogner *et al*. (2007) stated that in order to maximise the benefits of CH_4 sludge incineration, electricity generation from it is vital as it will provide energy while reducing emissions of CH_4 and other toxic substances into the atmosphere. Furthermore, Bogner *et al*. (2007) acknowledged that the global impact of incineration with gas recovery is small compared to that of landfilling but the operation cost of the former is higher. The incineration of sludge can contribute to energy provision in the WWTP thus reducing the costs and use of fossil fuel derived energy. The benefits associated with thermal treatment are the reduction of wet sludge volumes to be landfilled thus expanding the lifetime of landfills as well as the destruction of heavy metals (Zorpas *et al*. 2001; Schauebroeck *et al*. 2015). The major disadvantage of incineration of sludge is the exorbitant cost of construction and running the technology particularly in developing countries, but with effective CDM implementation, significant technology transfer can occur and funding for the plant will be provided.

2.2.6.3 Land application of sewage sludge

According to Wang *et al.* (2008) and Giusti (2009) sewage sludge has been applied on agricultural soils in several countries globally and it has been shown to increase plant productivity due to an improvement in the soil properties. Sewage sludge is the result of sewage treatment processes. Metcalf and Eddy (2003) have stated that the landfilling and land application of sludge are the most economical methods for its disposal. The application of sewage sludge has an incentive because of its use as fertiliser as well as soil conditioning properties (Singh and Agrawal, 2008; Giusti, 2009). However it is necessary to know the chemical composition of the sewage from various treatment plants prior to land application. The macronutrients in the sludge are a good source of plant nutrients while the organic constituents provide the necessary soil conditioning properties (Singh and Agrawal, 2008). Since urban sewage systems seldom transport only domestic wastewater to the treatment plants it may contain toxics also. The pH in wastewater ranges from acid to alkaline and it contains variations of heavy metals zinc, manganese and copper (Giusti, 2009). It is the heavy metal content and pH levels that determine whether or not wastewater sludge can be applied to land.

Sludge application enables the recycling of soil nutrients and it could reduce the use of chemical fertilisers. During the land application of sewage sludge, there are air emissions of nitrogen and carbon compounds, the combustion of diesel by the tractor, nitrate leaching as well as heavy metal deposition on the soil (Schaubroeck *et al*. 2015). If sludge application is not correctly administered it could result in soils that contain significant concentrations of toxic constituents as well as metals (Singh and Agrwal, 2008). Generally, the application of sludge to agricultural land increases growth and production plants but the sewage effluent has to be treated prior to application. This is because the amendment of sludge improves soil properties such as bulk density, porosity, and water holding capacity as well as aggregate stability (Singh and Agrawal, 2008; Wang *et al*. 2008).

2.3 Vulnerability and adaptation in the face of risk in a changing climate

In order to identify appropriate mitigation options that could have co-benefits for climate change adaptation, it is necessary to understand how climate change is likely to affect communities and the types of responses that are required. The following sub-sections provide an overview of climate change risk, vulnerability and adaptation with a view to developing a context of how adaptation can be achieved while simultaneously reducing emissions. A knowledge of the risks and vulnerabilities faced by countries will result in better mitigation strategies that will significantly contribute towards effective climate change adaptation for the various sectors and local communities.

2.3.1 Climate change risk and vulnerability assessment in the waste sector

2.3.1.1 Climate change risk

Risk is the probability of impacts of anticipated losses or damages that result from exposure of a given hazard over a specified time period (Schneiderbauer and Ehlrich, 2006; Kraemer *et al*. 2014; Schwartz *et al*. 2014). The recognition of risk depends on the following components: hazard, exposure and vulnerability (Crichton, 1999; Brooks, 2003), the relationship of these three is depicted in Figure 11 below. The probability of the outcome is largely dependent on the probability of occurrence of the hazard together with the social vulnerability of the affected system. Risk can further be divided into two concepts: event risk and outcome risk (Sarewitz *et al*. 2003). Event risk is the risk of occurrence of a hazard while outcome risk is the risk of a specific outcome. Furthermore, the level of risk is connected to the vulnerability of populations through their normal existence where the most vulnerable populations are at highest risk (Blaikie *et al*. 2014).

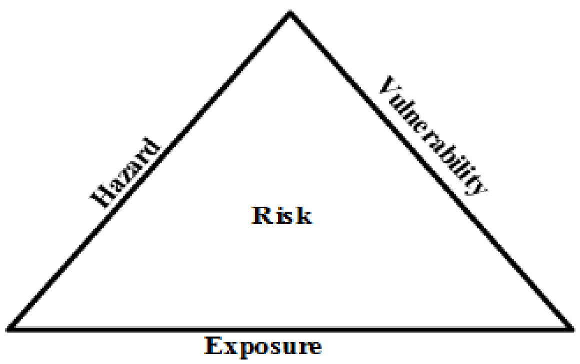


Figure 11: The risk triangle (Source: Crichton, 1999).

With increasing climate change, the potential for climate induced risk is greater. Therefore, the reduction and management of risk should be incorporated at all levels of adaptation planning (UNFCCC, 2006). Risk reduction and adaptation are supported by different policy frameworks and methodologies in addition to having different cultural and theoretical backgrounds (Schipper, 2009). However the integration of risk, adaptation and mitigation could have significant consequences for the reduction of climate change impacts. Specifically, it requires combining research from different backgrounds thus making the approach more comprehensive. Incorporating disaster risk will ultimately result in the development of more applicable adaptation strategies. Furthermore, Serrao-Neumann *et al*. (2015) advise that there is limited guidance on how to incorporate climate adaptation and disaster risk reduction because the relationship between the two fields remains unclear. Integrating climate change risk and climate change adaptation necessitates better collaboration between researchers, practitioners and policy makers.

Planning for climate change involves the consideration of climate associated risks including those with a slow onset such as temperature and precipitation (UNFCCC, 2006). Planning policies have attempted to lesson risks through restricting development in high risk areas and applying the necessary development controls (Serrao-Neumann *et al*. 2015). In order to minimise these forth coming risks caused by the increasing pressures of complex problems caused by climate change, holistic measures need to be implemented (Serrao-Neumann *et al*. 2015). All geographical areas are at risk of experiencing climate change impacts, whether negative or positive. Households, centres of economy, natural zones such as wetlands and forests are at risk of climate change impacts (Sarewitz *et al.* 2003; Boughedir, 2015). Oppenheimer *et al*. (2014) have identified key risks associated with climate change:

- Risk of injury, death, ill-health, destruction of livelihood in low-lying coastal zones and sea level rise for coastal areas
- Risks caused by weather extremes resulting in a destruction of infrastructure networks and services such as health, water supply, electricity as well as emergency services.
- Risk of mortality and morbidity during times of extreme heat and especially for vulnerable populations and outdoor workers.
- Food insecurity caused by precipitation, flooding, drought, and warming changes and extremes.

- Risk of loss of coastal, marine, inland and terrestrial biodiversity as well as ecosystem goods and services which are a source of provision for livelihoods.

Developing countries lack formal commercial and public instruments for managing risk, consequently resulting in households and communities bearing the local risk and relying on informal means to manage environmental variability (Eakin *et al*. 2014). The provision of information about the support available from government as well as creating awareness about the possible effects of climate change could reduce the risk to be suffered by communities. Furthermore, targeting vulnerable communities could prove beneficial to disaster risk management.

2.3.1.2 Climate change vulnerability

Ongoing climate change will exacerbate those burdens currently being experienced by the poor and vulnerable societies (Morgan, 2011). The injustice of climate change is that those who are most likely to suffer the effects are vulnerable societies and communities that have contributed the least to its formation; commonly the poor and developing countries. Thus, vulnerable societies are those that need to be equipped on how to adapt to changing climates. Ellison (2015) and Ferreira *et al*. (2015) describe vulnerability as a term used for describing factors that could negatively affect a population's ability to deal with a certain disaster. In addition, Brooks (2003) describes two types of vulnerability: biophysical and social vulnerability. Biophysical vulnerability suggests a physical component is connected with the type of hazard as well as its impacts on the social component being related by the properties of a system that acts to intensify or decrease the damage caused by the impact. Social vulnerability refers to the factors that could result in disasters and the ability to react to those disasters when communities are exposed to them (Hou *et al*. 2015).

Further, Fankhauser and McDermott (2014) state that vulnerability is a function of exposure, sensitivity and adaptive capacity. Where adaptive capacity is the ability of the system to respond to challenges by managing risks and impacts caused by climate change together with the potential to develop new strategies while implementing effective approaches (Gallopin, 2006; Marshall *et al*. 2010; Daze *et al*. 2011).

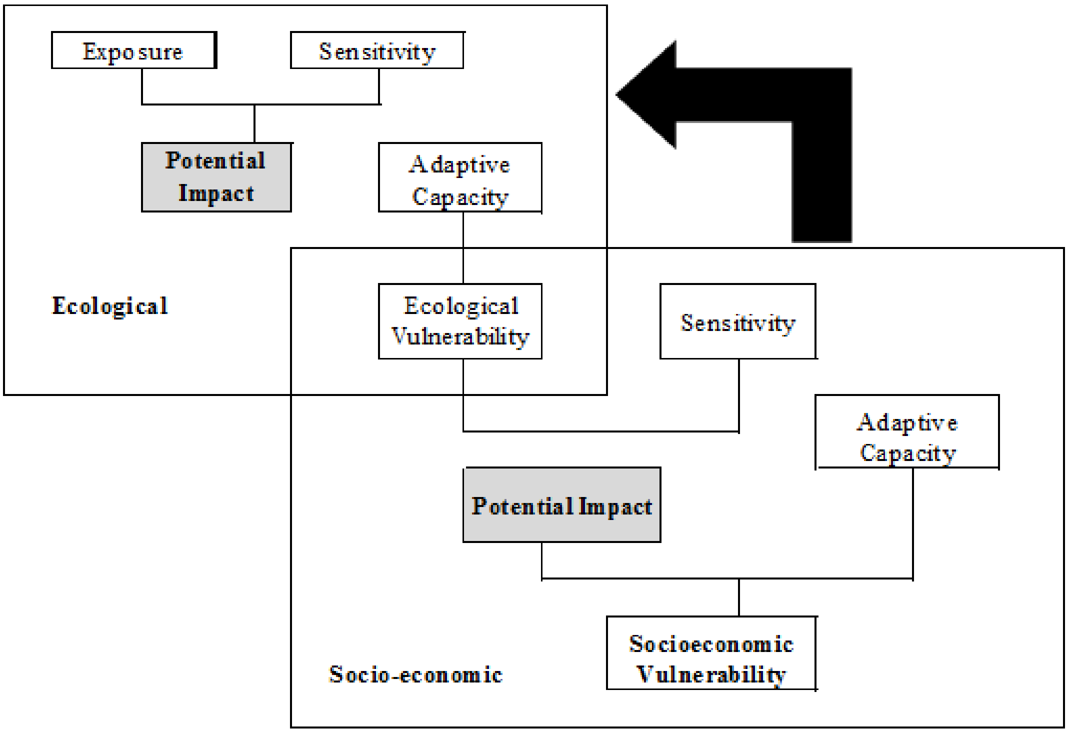


Figure 12: Framework for conceptualising vulnerability across ecological and social (socio-economic) areas. (Source: Marshall *et al.* 2013).

Climate change vulnerability differs amongst countries and even households; in order to have effective adaptation, strategies and activities suited to meet the needs of the various groups are recommended (CARE Vietnam, 2013). Even though vulnerabilities may differ all countries and sectors are predicted to experience vulnerability due to exposure, social vulnerability, institutional vulnerability, economic vulnerability and environmental vulnerability (Oppenheimer *et al.* 2014). Vulnerability to climate change tends to be high when communities are dependent on natural resources (Fankhauser and McDermott, 2014; GIZ and MoEF&CC, 2014). Further, developing countries are most vulnerable to climate change impacts due to the lack of resources for adapting financially, technologically and socially (Daze *et al.* 2011; Fankhauser and McDermott, 2014; van der Linden, 2015). Factors such as age, gender, health status and disability affect the vulnerability of communities and determine whether or not they have the ability to cope and adapt to a certain disaster (GIZ and MoEF&CC, 2014; Ferreira *et al.* 2015). Further, it is not only humans that are vulnerable but ecosystems and geographic areas can experience vulnerability while ecosystem services such as water availability can enhance vulnerability (Oppenheimer *et al.* 2014). The complexity of climate change vulnerability lies in the many factors contributing to it and that it is not stationary where current vulnerability will differ from future vulnerability in the same area.

Since vulnerability is a theoretical concept that is difficult to quantify and directly measure, thus creating a challenge on the development of a standardised methodology for measuring vulnerability. Several data are required for quantifying vulnerability, it is not just climate data that is required for effective vulnerability assessment but there is also a need for accurate and consistent socio-economic data particularly because poverty is regarded as a key factor for vulnerability (UNFCCC, 2007). Understanding the needs, priorities and capacities of vulnerable groups will contribute to effective adaptation processes as these groups will be the main targets for adaptation strategy, support and funding. A majority of developing countries lack the institutional resources to perform vulnerability analysis as well as assessing corrective measures to initiate mitigation alternatives (Al-Amin and Leal Filho, 2014). This is because the former countries do not have the instruments to plan, visualise and apply alternative methods suitable to them.

In order to reduce the vulnerability of communities a thorough understanding of their ability to adapt and cope with the predicted climate change impacts is required (Marshall *et al*. 2010; Lieske *et al*. 2015). The risks which societies are exposed to as well as the quality of the options available have to be assessed for effective vulnerability reduction. Vulnerable communities will require support and assistance in order to cope with the associated climate change impacts while implementing adaptation strategies that will sustain their livelihood for the future (Marshall *et al*. 2010). A reduction in vulnerability will reduce the risk caused by climate related hazards (Cavan *et al*. 2015).

2.3.1.3 Climate change adaptation

Climate change adaption is described by Biesbroek *et al*. (2014) and Bowyer *et al*. (2014) as the efforts which plan and select the best options to solve the impacts of the changing climate efficiently and effectively. Climate change adaptation is concerned with minimising the vulnerability of communities and the environment concerned (Ayers, 2010; Martin *et al*. 2015), and it is a reactive approach towards the potential effects of extreme weather phenomena to be caused by future climatic changes (Adger *et al*. 2005; Bowyer *et al*. 2014).

Furthermore, it is concerned with adjustments in human or natural systems in response to climate change effects thus minimising harm but exploiting the associated benefits (IPCC, 2014a). Several definitions for adaptation are found in the literature thus highlighting the limited consensus when it comes to the definition within the climate change community. However a commonality is that adaptation is a risk management process (Bowyer *et al*. 2014) and it is local and contextual (Eaken *et al*. 2014). Adaptation is only recently having a major role in the IPCC agenda, where in the 5th IPCC assessment report it has been allocated ten new chapters dealing with climate change impacts, adaptation and vulnerability (Martin *et al*. 2015). Adaptation research lies at the intersection of many disciplines in both natural and social sciences, which explains why there tends to be different approaches towards adaptation, where some approaches use resilience and others use vulnerability or hazards approach (Funfgeld and McEvy, 2011). The integration of these approaches is recommended because it would significantly contribute towards effective climate change adaptation because climate change may result in hazards which will adversely affect vulnerable communities and it may decrease the resilience of the environment and community at large. Figure 13 below shows the general approach towards climate change adaptation.

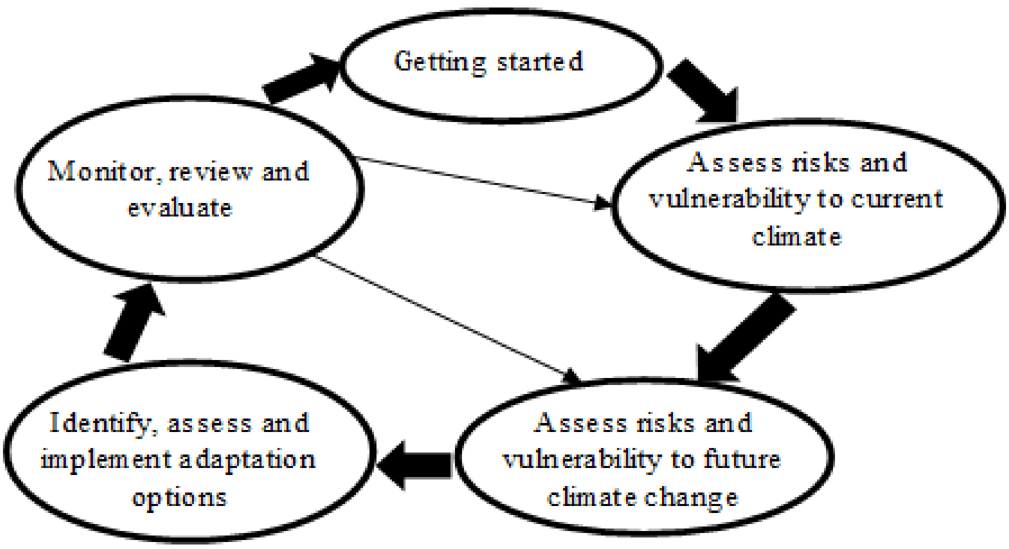


Figure 13: A general climate change adaptation process (Source: Turner *et al*. 2014).

There is limited focused research on adaptation which is caused by the long-term neglect of adaptation science, partially due to the novelty of the topic in practice (Moser and Boykoff, 2013). Planned adaptation will help address structural vulnerabilities within communities and highlight the interconnection between climate change and vulnerable communities and aspects such as poverty, inequity, livelihoods and access to services (Broto *et al*. 2015). Thus with efficient planning, adaptation strategies could decrease vulnerability by reducing exposure and increasing the resilience of those elements at risk to climate change impacts (Cavan *et al*. 2015). Bowyer *et al*. (2014) recommend that adaptation planning be included in all climate sensitive areas that countries and sectors may have and that adaptation activities need to consider non-climatic factors that are key towards understanding the impacts of climate change in the exact context. When dealing with climate change adaptation, climatic-impacts should not be considered in isolation from the entire system. Literature on adaptation monitoring and evaluation focuses on processes monitoring and evaluating progress towards the outcomes of adaptation and minimum attention to how these outcomes could be better defined to ensure success (Moser and Boykoff, 2013).

Developing countries face critical challenges regarding climate change adaptation due to the lack of financial, technological and institutional capacity (Brooks *et al*. 2005; Barr *et al*. 2010). However, Biesbroek *et al*. (2014) state that optimising the governance process could avoid barriers that hinder effective climate change adaptation (Biesbroek *et al*. 2014). According to Eakin *et al*. (2014) adaptation is a more significant concern for developing countries than it is for devolved ones. But Moss *et al*. (2013) states that vulnerability is not restricted to developing countries, citing events such as hurricanes Katrina and Sandy that occurred in the United States which demonstrate that even if infrastructure meets strict building standards and early reliable warning systems are reliable and available, the losses experienced can still be extreme and devastating. Thus for both developed and developing countries, adaptation is about forward planning and effective adaptation strategies need to consider the implications of uncertainties associated with climate change (Bowyer *et al*. 2014). Figure 14 below highlights the challenges associated with defining and achieving adaptation success and shows the range associated with identifying future targets of impacts. The figure shows us that it is the space between present and future valuation, the various adaptation pathways and the coping range that results in complexities and challenges for achieving adaptation success (Moser and Boykoff, 2013).

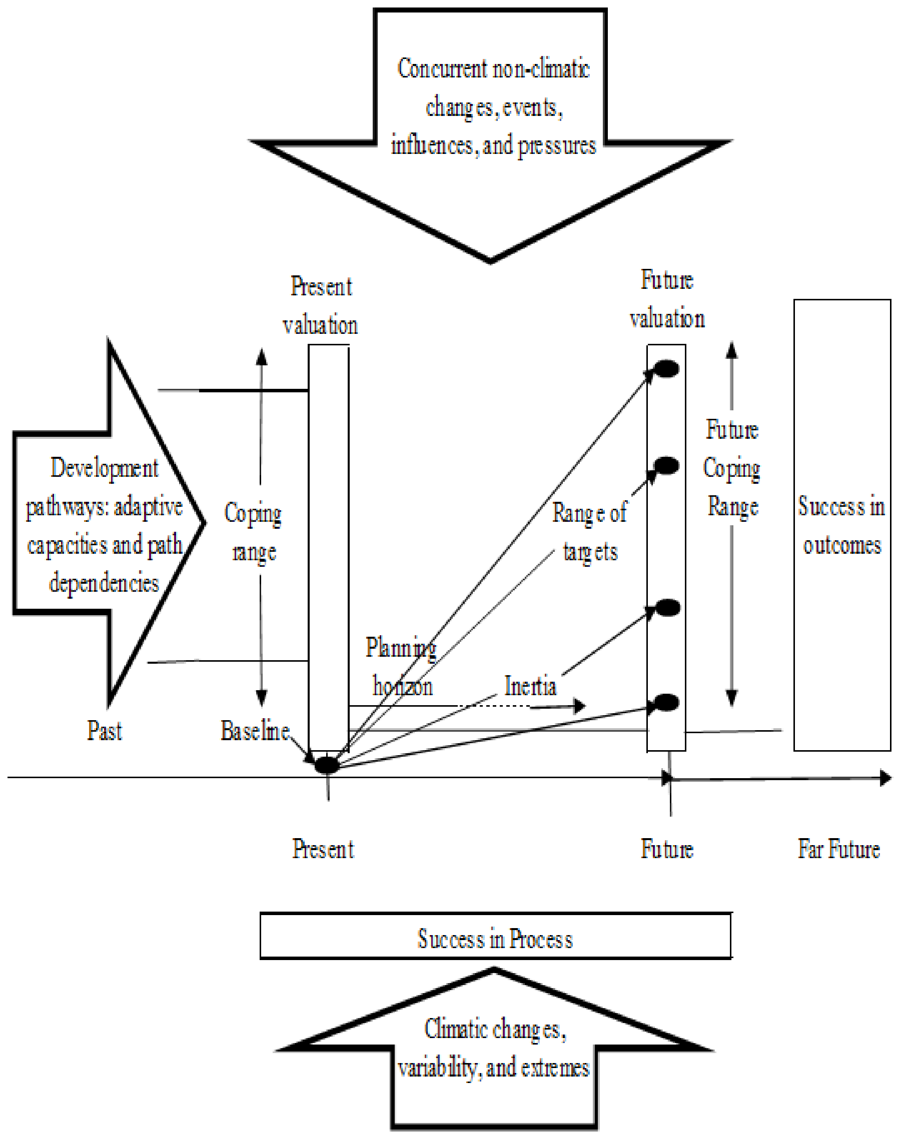


Figure 14: Challenges in defining and achieving adaptation success (Source: Moser and Boykoff, 2013).

Human and natural systems have the capacity to cope with adverse circumstances but, with continuing climate change, adaptation will be needed to maintain this capacity (Noble *et al.* 2014). Merging adaptation and development agendas has been challenging because of the trade-offs between traditional development concerns and the required actions for adaptation (Martin *et al*. 2015). Where for instance challenges such as unemployment necessitate solutions conflicting with ecological priorities such as resource maintenance. Adaptation is crucial and complementary towards mitigation efforts and the two concepts are not to be viewed as isolated. However, critics have argued that emphasis has been placed on mitigation in the funding policy (Damodaran, 2015) and even if mitigation is successful adaptation would still be required. Dow *et al*. (2013) stated that the larger the climatic change and its associated impacts the less likely it is that adaptation will be successful because of the technical, physical and social limits to adaptation. This highlights the importance of mitigation and how these two concepts should be viewed as integrated systems. Adaptation is important because climate change will occur even with mitigation in place (Fungveld and McEvoy, 2011) and according to Martin *et al*. (2015) it is easier to implement than mitigation because it is more local and it has more immediate outcomes.

2.3.1.4 Defining the relationship between risk, vulnerability and adaptation

According to Sarewitz *et al*. (2003) the relationship between risk and vulnerability is not cumulative where a reduction of vulnerability means reduced impacts of risk however a reduction in risk outcomes will not always reduce the vulnerability. Thus a reduction in vulnerability could result in better coping and adapting to the risk. The relationship between risk and vulnerability is that the identification of key vulnerabilities enables the identification of risks about developing hazards caused by the changing climate (Oppenheimer *et al*. 2014). Risk and vulnerability are context specific because different societies might rank the risk and vulnerability factors differently because the damage experienced could vary. A focus on either of the two could result in negative outcomes where the risk could have dire consequences for vulnerable communities. Vulnerability reduction is a necessity for human rights while risk is not considered a human rights issue, consequently risk management approaches are subject to rigorous quantification than vulnerability approaches (Sarewitz *et al*. 2003). For effective planning, coping and adaptation to extreme weather events, the vulnerability associated with social processes should be understood together with the probability of occurrence of the risk.

2.3.1.5 Risk and vulnerability assessment

2.3.1.5.1 Identifying key risks

Risks are considered key because of the high vulnerability of systems of communities exposed to them. Risk identification criteria consider the frequency, magnitude and intensity of a hazardous event that systems are exposed to. Criteria considered when determining key risk are: magnitude, the probability that risks will occur together with their associated timing, the persistence and irreversibility of the risk determining conditions (Oppenheimer *et al*. 2014).

- *Magnitude*. Risks with a large magnitude of consequences are important because of the potential impacts. Consequences are determined by economic loss, mortality and morbidity of humans and cultural importance.
- *The probability that risks will occur together with their associated timing*. Key risks are those in which there is significant probability that the climate induced hazard will occur under conditions where communities are highly susceptible and have little or no ability to cope.
- *The persistence and irreversibility of the risk determining conditions.* This is where the primary causes of the risks cannot be minimised.

2.3.1.5.2 Identifying key vulnerabilities

Key vulnerabilities are those vulnerabilities that make it difficult for communities to adapt to climatic hazards. When assessing vulnerability five criteria are used to determine whether the key vulnerabilities of communities namely: the exposure of a socio-ecological system or society to climatic stressors, significance of the vulnerable systems, the limited ability of societies and socio-ecological system to cope and adapt to the change while reducing the associated impacts, the persistence of vulnerable settings and extent of irreversibility of the consequences (Oppenheimer *et al*. 2014):

- *The exposure of a socio-ecological system or society to climatic stressors*. If a system will not be exposed to hazardous climatic events in the future then its vulnerability is not key.
- *Significance of the vulnerable systems*. Views on importance will vary amongst societies, ecosystems or regions. Defining key vulnerabilities considers these groups, sectors or ecosystems as vulnerable.
- *The limited ability of societies, and socio-ecological systems to cope and adapt to the change while reducing the impacts of climate change related hazards.* Currently the waste sector has minimum resilience for coping with climatic change especially in the

context of developing countries. For instance extreme floods could affect landfill sites which could potentially be filled with water and thus increasing their leachate generation ability and ground water seepage.

- *The persistence of vulnerable settings and extent of irreversibility of the consequences.* Factors which cannot be altered and are persistent are considered key. This could include the irreversible damage to landfills and wastewater storage tanks as well as consistent marginalisation of the waste sector which restricts funding in this sector.
- *The presence of conditions that increase the susceptibility of societies to cumulative stressors in complex yet interacting systems.* Conditions that make it difficult populations or socio-ecological systems to adapt and cope with the change.

2.3.2 Climate change impacts

2.3.2.1 Climate change impacts on coastal cities

Climate change impacts are largely dependent on the climate, its geographical location, cultural, social, political and economic conditions (UNFCCC, 2007). The impact of temperature increases and global warming caused by climate change directly affect and exacerbate vulnerability by: destructing the environment and infrastructure, degrading natural resources as negative health impacts to be suffered by humans (CARE Vietnam, 2013; Al-Amin *et al*. 2015). According to Howden *et al*. (2007) and Lieske *et al*. (2015) coastal populations and industries are going to face extreme challenges because of the multi-faceted influences exerted by climate change. Climate change impacts present challenges for coastal cities and populations because of the processes occurring in the coastal zone and its associated environmental value (Romieu *et al*. 2010; Broto *et al*. 2015; Lieske *et al*. 2015).

Marshall *et al*. (2010) and Hunt and Watkiss (2011) have stated that monitored observations support projections of rising temperatures, increasing sea levels, intensifying storms alterations in ocean currents and rainfall patterns. It is these changes that pose a dire threat to coastal communities and industries. Coastal cities are vulnerable to tidal inundation, rising water tables, accelerated erosion and ecological changes (Lieske *et al*. 2015; Schwartz *et al*. 2014). Johnson and Marshall (2007) stated that the ecological effects of the changing climate on tropical marine systems will be diverse and long lasting. This is because of the effects on biodiversity and marine species that will have difficulty in adapting to the rapidly changing climate. Thus without any effective assistance, coastal areas will struggle to cope with these changes.

The infrastructure and vegetation in coastal cities will be affected because an increase of the high tide could result in extreme weather phenomena such as flooding and increased coastal erosion, thus placing a significant portion of the population and vegetation at risk, particularly those in the low lying coastal areas (Awor *et al*. 2008; Lieske *et al*. 2015). The biodiversity of coastal cities is at risk where increased temperatures could affect water temperatures, water resources and river flows thus resulting in an increase in evaporation from rivers and habitat loss for species (Awuor *et al*. 2008). Coastal flora and fauna are at significant risk, with the flora being at higher risk because of its inability to easily migrate. With increasing temperatures, coastal cities could realise a shift in energy demand from winter warming to summer cooling (Hunt and Watkiss, 2011). The increasing demand in electricity could result in increased atmospheric emissions due to the use of fossil fuel derived energy thus exacerbating the climate change problem. The potential impacts of extreme events in coastal cities could possibly result in food insecurity, the deterioration of the precarious infrastructure and an increase of vector-borne diseases (Broto *et al*. 2015).

2.3.2.2 Impacts on the waste sector

Climate change impacts are most likely to be caused by known extreme weather phenomena that are worsened by the unpreparedness of vulnerable human communities and sectors. Waste management has minimum of five types of impacts on climate change namely: landfill CH_4 emissions; the recovery of energy from waste; reduction in industrial energy use and emissions caused by recycling and waste reduction; carbon sequestration in forests due to increased demand for virgin paper as well as the energy used for long distance transport of waste (Ackerman, 2000). The time scales associated with some of the consequences caused by the manner in which waste is managed and climate changes are comparable (Bebb and Kersey, 2003). This is because both of the long-term ability of their impacts. Understanding the potential impacts of climate change on the waste sector at an early stage would assist policy makers, regulators as well as site operators. Indoor and outdoor waste management facilities give rise to several health and safety issues. Outdoor waste management activities are directly affected by weather conditions as well as potential hazards which are most likely to affect the movement of vehicles and the nature of the waste. Table 3 shows the potential impacts of climate change on all waste management processes. The extent to which climate change could affect waste management depends on the location and characteristics of each site.

2.3.2.2.1 Impacts on solid waste transport

An understanding of the extent of climate change impacts on the road transport sector is required to reduce the consequences thereof (Strauch *et al*. 2015). Transportation infrastructure will be affected by interconnected climate change impacts (Koetse and Rietveld, 2009; Rattanachot *et al*. 2015 and Schwartz *et al*. 2014). Weather events will influence the operation of the transport system, including the collection, transport and disposal of solid waste. Climate change impacts caused by intense storms could hinder access to public lands and roads (Strauch *et al*. 2015). Delays caused by storms affect all forms of transport (Schwartz *et al.* 2014). Alternate routes during such times could be explored and utilised, however waste collection trucks travel on specified routes which could make it difficult to find alternate routes. Further, Schwartz *et al*. (2014) stated that there is less resilience to be gained by alternative routing and the impacts thereof could be more intense. Alternate routes could possibly result in longer routes which would require more fuel for trucks and thus increase associated GHG emissions from the transport of solid waste.

The impacts associated with climate change are not new since floods and storms have long been challenges for the transport sector what is new is the frequency and intensity of these occurrences (Schwartz *et al*. 2014). Schwartz *et al*. (2014) stated that roads, bridges, trucks, cars and the people that convert infrastructure and vehicles into working transportation networks are the most vulnerable components in the transportation system. According to Rattanachot *et al*. (2015), disruptions in the transportation system can be partly offset by adaptation. Adaptation actions include infrastructure designed for future climatic conditions, abandoning infrastructure designs that would be too costly to protect and operational changes (Rattanachot *et al*. 2015). However, adaptation strategies are required specifically for the waste sector which would be easily and efficiently applied when experiencing extreme weather conditions that would minimise the accumulation of waste upon failure to collect and transport it.

2.3.2.2.2 Impacts on electricity consumption

Extreme weather has an adverse effect on the reliability of the power system (Blake *et al*. 2015). Following flooding electricity supply may not be restored immediately thus resulting in customer dissatisfaction (Blake *et al*. 2015). Electricity use is a significant portion of the WWT process as well as the recycling, electricity generation and incineration of solid waste. Thus a power shortage could hinder the daily workings on landfill sites and WWTPs. Climate change is predicted to result in higher temperatures that are expected to increase the electricity demand for cooling (Mideksa and Kallbeken, 2010). Consequently, Davis and Clemmer (2014) stated that extreme heat reduces the efficiency of power plants and place stress on electricity systems because it is when it is needed the most for cooling purposes. This strain on electricity supply particularly in warm conditions could result in power shortage, which would affect particularly WWT. The electricity sector is vulnerable to climate change impacts because electricity supply is dependent on water for cooling, with increasing drought the electricity sector is most likely to be at risk (Davis and Clemmer, 2014). It is clear that there is a risk of electricity supply shortage that could affect the daily workings particularly in WWTPs.

2.3.2.2.3 Impacts on solid waste disposal

Climate stressors affect solid waste directly and indirectly. According to Enete (2010) increased temperatures are likely to increase water demand for workers and site operations, reduce air quality and impact biological processes such as composting. The waste decomposition rate is related to the temperature where higher temperatures could alter the decomposition rates and result in increased emissions. Furthermore increased temperatures could affect the skin conditions of workers due to increased exposure to sunlight. Flooding poses a threat to wastewater infrastructure where heavy rains could degrade the landfill and cause breaks in the infrastructure and enable leachate to flow to surrounding areas (USAID, 2012). Landfills located in close proximity to the coast are vulnerable to sea level rise where water infiltration could lead to an overflow of waste from the landfill (USAID, 2012).

2.3.2.2.4 Impact on WWT

According to Zouboulis and Tolkou (2015) climate change has significant impacts on WWTPs. The processes occurring in WWTPs are affected by climate change where extreme weather events could result in untreated sewer flows and increased flooding (Danas *et al*. 2012; Zouboulis and Tolkou, 2015). This means that more sewage will be dumped into the receiving bodies of water, which could potentially affect water supply and the ecosystems in those areas. Increased storms could be harmful to wastewater infrastructure such as effluent pipes. Temperature increases could have effects on biological processes occurring during WWT because wastewater contains a certain amount of decomposable organic matter (Kampshreur *et al*. 2009) which at higher temperatures could experience quicker decomposition rates thus resulting in increased emissions of CH_4. Further, warmer temperatures could increase the bacteria reaction rates thus reducing the density of the settled sludge (Danas *et al*. 2012). Climate change is also predicted to intensify drought in certain areas, as this occurs the reuse of wastewater will become a necessity where the effluent produced will have to be a higher quality and could strain existing treatment processes (Danas *et al*. 2012). A decline in water availability could imply an increase in eutrophication, a decline in water quality in rivers and lack of oxygen for aquatic and oceanic species. This decline in quality of rivers could ultimately result in an increase of the costs associated with WWT.

Table 3: The potential climate change impacts on the various waste management processes (Source: Beb and Kersey, 2003; USAID, 2012).

Waste management option	Collection	Transfer	Biological Processes	Thermal Processes	Mechanical Processes	Landfills
Rising temperatures	• Increased frequency of collection due to decomposition and resulting odour as well as increasing exposure to vermin • Reduce productivity of outdoor workers, due to heat stress • Result in high risk of putrescible disease waste is handled	• Reduce productivity of indoor and outdoor workers due to heat stress • Increased risk of transmitting diseases due to handling of putrescible waste • Increased dour due to increased rate of decomposition	• Affect the decomposition rate of the waste during windrow processing. Increased temperature in addition to sufficient moisture could increase the decomposition rate. • Decrease productivity of outdoor and indoor workers productivity • Increased vermin such as flies during windrow composting • Increased nuisance of odour, dust and bioaerosols	• Affect workers productivity due to unbearable working conditions indoors and outdoors • Increased waste decomposition rates thus resulting in increased odours and dust as well as insect infestation	• Reduce productivity of indoor and outdoor workers due to heat stress • Increased risk of transmitting diseases due to handling of putrescible waste • Require changes to equipment because of increased potential of dust, odour and bioaerosol release as well as combustion risk in waste receptors and processing areas	• Change waste decomposition rate which would later affect LFG generation rates • Decreased water availability which could alter site hydrology therefore affecting leachate production. Increased leachate strength due to reduced dilution • Affect the workers productivity • Increased vermin such as flies as well as risk of bad odour exposure
Reduced summer precipitation		• Reduced water availability for management of the site	• Affect the waste decomposition rate • A decline in water available for site management activities such as suppressing dust • Increased dust potential and combustion risk	• Reduced water availability for management of the site	• Reduced water availability for management of the site	• Change decomposition rate and site hydrology • Increased leachate strength • Reduce water availability for management activities of the site such as dust suppression

Increased precipitation	• Destruction of transport infrastructure from increased flooding thus affecting the collection and delivery of the waste • Containers to keep the waste dry will be required	• Increased flooding on site which results in inundation of site facilities such as roads, offices and even weigh bridges. • Disruption and destruction of transport infrastructure due to floods	• Increased flooding on site which results in inundation of site facilities • Affect the waste decomposition rate	• Increased occurrences of flooding and inundation of site facilities • Affect the combustion process of waste due to higher moisture content than expected	• Increased occurrences of flooding and inundation of site facilities such as roads and offices as well as weigh bridges	• Increased occurrences of flooding on site due to groundwater saturation • Change the waste decomposition rate • Increased leachate production in winter months which result in increasing treatment and disposal costs • Increased slope instability and increased erosion risk of capping layers
Reduced cloud cover		• Reduced shaded areas over waste reception vessels	• Increased risk of sunburn and skin cancer susceptibility to outdoor workers due to over exposure			• Increased risk of sunburn and skin cancer susceptibility to outdoor workers due to over exposure • Negative impact on exposed materials lifespan. Materials include plastic pipework, Polyethelyne Liner
Increased storm occurrences	• Frequent incidences of windblown debris and litter • In sever instances, collection workers	• More frequent incidences of windblown debris and litter • In severe instances, collection workers	• More frequent incidences of windblown debris and litter • Damage to buildings	• More frequent incidences of windblown debris and litter • Damage to buildings	• Damage to buildings • Alter the availability and cost of insurance cover	• Increased occurrences of windblown litter and debris and in some cases increased risk of

	are exposed to higher risk of injury from flying objects	are exposed to higher risk of injury from flying objects • Alter the availability and cost of insurance cover	• Alter the availability and cost of insurance cover	• Alter the availability and cost of insurance cover		injury from flying objects. • Damage to buildings • Alter the availability and cost of insurance cover
Rising sea level	• Hinder collection cycles on the coast	• Increased occurrences of flooding and inundation of site facilities near the coast	• Increased occurrences of flooding and inundation of site facilities near the coast	• Increased occurrences of flooding and inundation of site facilities near the coast	• Increased occurrences of flooding and inundation of site facilities near the coast	• Increased occurrences of flooding and inundation of site facilities near the coast

2.4 Summary

This chapter provided a review on climate change mitigation for solid waste management and wastewater treatment together with climate change risk, vulnerability and adaptation for coastal cities and the waste sector. The major sources of emissions for solid waste were identified as landfilling, vehicle emissions from the collection and transport of solid waste as well as electricity consumption while for wastewater the major sources were identified as electricity consumption and the entire WWT process. GHG mitigation mechanisms explored for solid waste are recycling, composting of organic waste, thermal treatment of waste and LFG capture with electricity generation. Thus, for effective mitigation of solid waste emissions there must be a shift from the dependency on landfilling of waste which has multiple environmental impacts towards ISWM. Consequently, GHG mitigation techniques identified for WWT are phyto-remediation for WWT, thermal treatment of sewage sludge and electricity generation from gases produced as well as land application of sewage sludge as fertiliser. Effective risk and vulnerability assessment will assist with successful climate change and adaptation coping strategies.

CHAPTER 3

THE WASTE SECTOR AND CLIMATE CHANGE IN THE ETHEKWINI MUNICIPALITY

3.1 Introduction

The EM is located in the KwaZulu-Natal province of South Africa. The EM covers an area of approximately 2 297km^2 and has a population of 3.5 million people, which is a third of the provinces population (StatsSa, 2011). The largest city within the municipality is Durban; it is the largest port and city on Africa's east coast and is considered one of the economic drivers in the country (Roberts, 2010). Durban faces several developmental problems such as the rising levels of unemployment and the high levels of HIV/AIDS infection (Roberts, 2010). The service provision standards of the municipality are impressive with 86.1% of the population being provided weekly waste removal (StatsSa, 2011); however Fischer, (2013) stated that of this collected waste only 25% reaches the formal waste collection system. The main solid waste disposal sites in Durban are the Bisasar Road, Marrianhill and Buffelsdraai landfill sites with the Bisasar Road site being the largest in the area and possibly the busiest in South Africa (Fischer, 2013). Only the general and low hazard wastes are landfilled in the city, the high hazard waste is exported out of the province to high hazard landfills in the Eastern Cape and Gauteng (Fischer, 2013). The city is also responsible for the treatment of domestic and industrial wastewater which is discharged in to rivers or the ocean post treatment.

3.2 The waste sector in the EM

The continually growing population in EM results in increasing urbanisation and consumption and therefore contributes to the large volumes of waste and wastewater experienced by the municipality. The excessively growing waste and wastewater quantities have the potential to exacerbate the already existing environmental, economic, social and governance challenges the municipality already faces. Fischer, (2013) stated that there is a need to reduce waste production in the municipality through measures such as recycling thus decreasing the financial, environmental and social costs associated with waste disposal. The EM receives about 1.5 million tonnes of waste per annum (SAWIC, 2015). This waste contributes to the poor air quality and climate change in the city because of air pollutants emitted by discharged effluents and waste deposited (Fischer, 2013). The assessment of climate change adaptation and mitigation options in the waste sector could provide solutions or contribute to the alleviation of the existing environmental and developmental challenges.

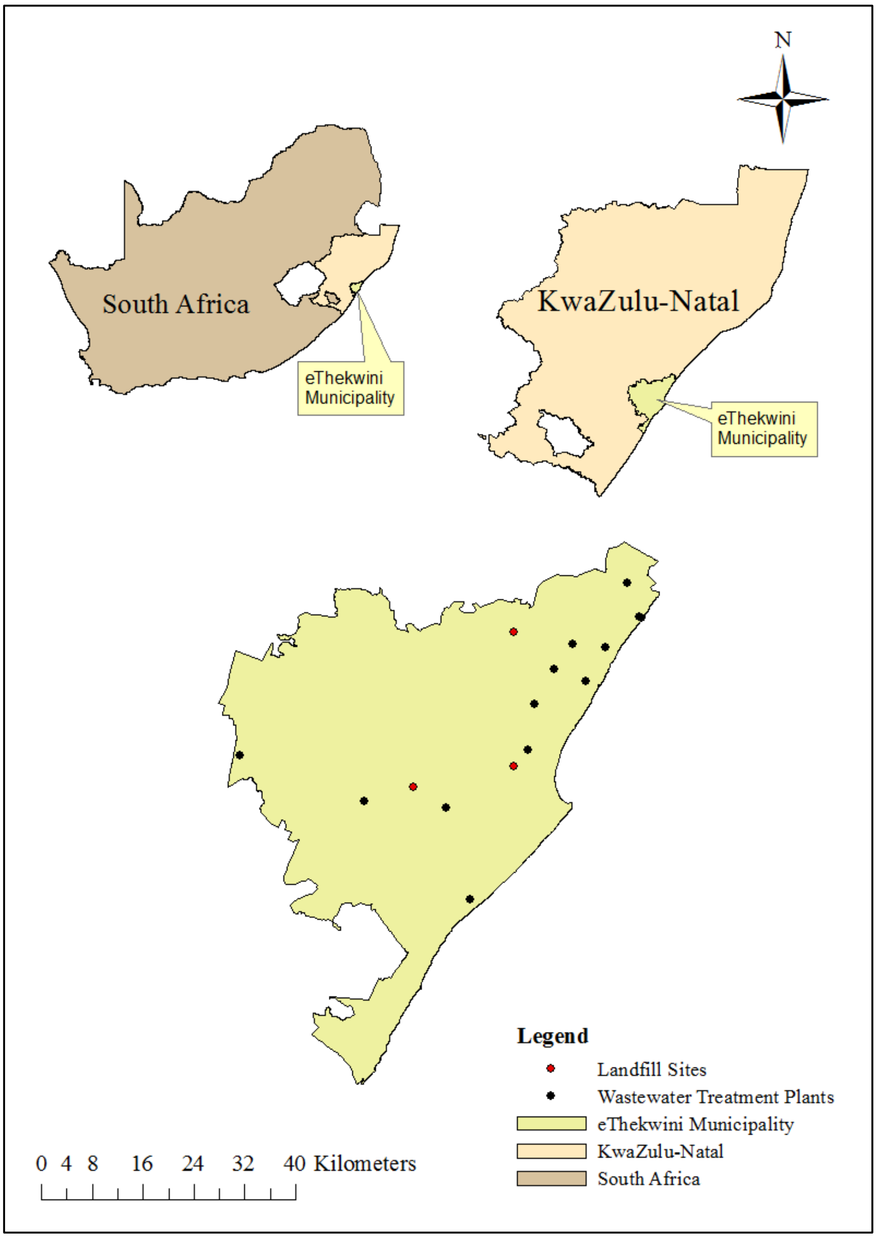


Figure 15: Location of the EM within South Africa and KwaZulu-Natal together with the landfills and wastewater treatment facilities.

3.2.1 Solid Waste

3.2.1.1 Landfill sites in the EM

The waste within the EM is managed by Durban Solid Waste (DSW) where immense volumes of solid waste are generated by residential, commercial and industrial sectors. The Bisasar Road landfill site is located 7km from the Durban Central Business District (CBD) and the Marianhill site is situated 20km west of Durban in the Pine Town Area (Couth *et al*. 2011). The Buffelsdraai landfill site is situated 8km to the west of small town Verulam (Payne, 2005). The Bisasar Road landfill site is close to reaching its maximum capacity and is expected to close shortly, most of the waste deposited in this landfill will be transferred to the newer Buffelsdraai landfill. The transfer of waste to this site will increase transport costs and emissions for the collection of waste for the city and increase environmental burden in the Buffelsdraai area. However, the Buffelsdraai site has a community reforestation project in order to offset emissions from the landfill which is expected to reduce environmental burdens especially in terms of emissions. This project is expected to offset about 50 000 tCO_2-e from the landfill through natural habitat restoration projects (BCRP, 2015). This project is also expected to increase climate change adaptation and resilience capacity locally, within ecosystems through sediment regulation, flood attenuation and biodiversity refuge conservation and within communities through the creation of jobs (BCRP, 2015). The communities that will benefit from the project are some of the most vulnerable and impoverished in Durban, this reforestation project highlights co-benefits for off-setting landfill emissions in the area.

The Marrianhill community was opposed to having the landfill site in their backyard because of health and environmental issues, however their monitoring committee convinced DSW to have a plant rescue process in 1998 (MLC, 2015). This process was driven by the Plant Rescue and Relocation Unit (PRUNT), the success of PRUNT lies in that the direct relocation of grasses, plants and topsoil is executed. The Marianhill landfill has a conservancy which was formed in 2002 and has numerous environmental successes, it has controlled alien plant invasion physically, this way creates jobs and it is environmentally friendly. The conservancy does not use herbicides and it enables the preservation of endangered species. The Marrianhill conservancy has several projects such as vegetating plants removed during construction of the landfill, rehabilitating degraded habitats and ecosystem and has a soil amelioration programme through the use of garden refuse (MLC, 2015). The success of rehabilitation is realised through the increasing wildlife in the area where the bird count has increased and continues to do so (MLC, 2015). The Marianhill conservancy site is considered an ecosystem best practice ecosystem restoration project (Van Schalkwyk, 2013). Furthermore more the landfill conservancy has successfully created a buffer zone to the landfill site thus decreasing any social or environmental impacts of this site. In improving the management of landfills the community and ecosystems will benefit. Figure 16 below depicts aerial views of the landfills which were created using Geographic Information Systems and Mr. Sids satellite images.

Figure 16: Arial view of the (a) Bisasar Road, (b) Mariahnhill, and (c) Buffelsdraai landfills.

Landfills differ from one another in terms of type, size, and their possible threat to the environment. The Bisasar Road, Marianhill and Buffelsdraai landfills are permitted sites in terms of the existing legislation because they have access control and engineering features such as lining (Friedrich and Trois, 2013a). Even though these sites are permitted in terms of legislation, there is little information regarding their compliance conditions for air, water and soil pollution. The Marianhill and Bisasar road sites collect and generate electricity from the use of LFG. Furthermore, the Mariannhill and Buffelsdraai landfills have completely engineered leachate treatment plants which include engineered reed beds that treat about 50 and 200 m^3 leachate daily (Strachan and Mzizi, 2010). Table 4 below depicts the characteristics of these landfill sites.

Table 4: Characteristics of the three main landfill sites in Durban (Source: IWMP, 2004; Couth *et al*. 2011).

	Bisasar Road	**Marianhill**	**Buffelsdraai**
Area	44ha	33ha	100ha
Date of establishment	1980	1997	2006
Location	Urban	Peri-urban	Rural
Waste deposited	General municipal solid waste, garden refuse and construction and demolition waste	General municipal solid waste, garden refuse and construction and demolition waste	General municipal solid waste, garden refuse and construction and demolition waste
Configuration	Deep valley landfill with lined cells on an old attenuation/unlined waste body	Valley landfill operated in 5 lined cells	Valley landfill operated in 2 lined cells
Capacity	21 million m^3	5 million m^3	50 million m^3
Average depth	40m	18m	30m
Deposition rate	3000 tonnes daily	550-700 tonnes daily	1200 tonnes daily
Expected closure time	2013	2022	2081
Biogas extraction system	Yes	Yes	No
Leachate treatment	No	Yes	Yes

3.2.1.2 Solid Waste Management

The waste in the EM is managed based on the National Environmental Management Act: Waste Act (NEMAWA) of 2008 (Act No. 59, 2008). The objectives of the NEMAWA (2008) are: to reduce and avoid the generation of waste; reduce, re-use, recycle and recover waste; and consider the treatment and safe disposal of waste as a last resort; ensure efficient delivery of waste services and the prevention of ecological degradation due to waste. Consequently, waste in the EM is managed based on the hierarchy of waste management (Figure 17), which is an approach towards the sustainable management of waste. According to Botes and McKenzie (2013) the focus should be on waste management options that are higher up in the hierarchy such as prevention, re-use and recycle because of greater impact than those below in the hierarchy. Botes and McKenzie, (2013) stated that a reduction in the quantity of waste produced will result in reduced costs and emissions from the transport of waste as well as a reduction in the quantity of waste being landfilled thus reducing resulting emissions and environmental and societal impacts. Therefore, indicating the co-benefits of the waste management options that are higher up in the waste hierarchy. Further the NEMAWA (2008) states that each municipality should develop an Integrated Waste Management Plan (IWMP). The most recent IWMP for the EM was published in 2004; this signifies the lack of recent information pertaining to waste within the municipality. It is therefore recommended that the municipality provide an updated IWMP as it will be beneficial for waste sector mitigation studies. However, from the IWMP (2004) it is clear that the objectives of the EM are in line with those of the NEMAWA (2008).

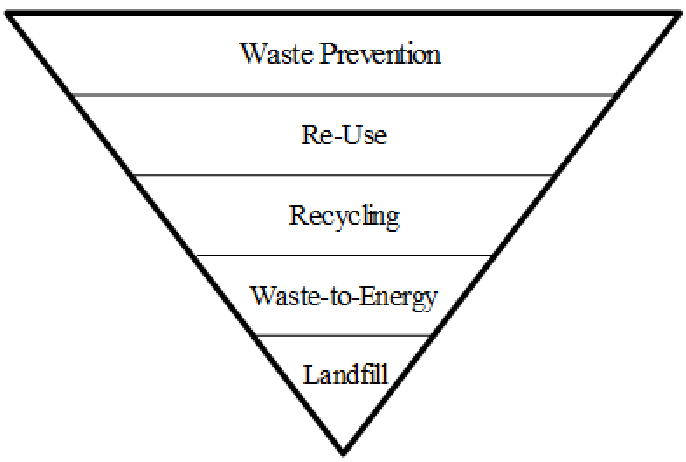


Figure 17: Waste Management Hierarchy (Source: NWMS, 2011).

DSW is the cleansing and solid waste unit of the EM and operates 3 active sanitary landfill sites (Bisasar Road, Mariannhill and Buffelsdraai landfill sites), 23 recycling and garden refuse drop-off centres, 6 major transfer stations, 2 LFG to electricity plants that are operated as CDM projects and 2 leachate plants (van der Merwe e*t al*. 2009; Botes and McKenzie, 2013). The Marianhill and Bisasar Road landfills are pioneers of LFG to electricity projects in South Africa, together generating 40 million kWh of electricity in 2011 (Botes and McKenzie, 2013). Even though there is significant electricity produced from the captured LFG, there are still significant quantities of GHG being released into the atmosphere as seen from the EM inventories. 1% of the CH_4 emissions within the EM in 2013 were attributed to solid waste and wastewater facilities (Botes and McKenzie, 2013). Thus, the use of other waste management options such as recycling, composting and incineration would result in ISWM and assist in the reduction of those GHG not being utilised for the generation of electricity within the municipality. However, Botes and McKenzie, (2013) state that even though GHG emissions from landfills are known there is limited information available on other emissions related to the waste sector such as: emissions from the transport of waste, emissions from the burning of waste as well as emissions that result from the wastewater sludge that is discharged into the ocean. Thus an investigation into these emissions could result in improved management as well as GHG mitigation mechanisms that would benefit the municipality

Recycling activities in the EM are, driven by numerous factors based on the legislated Waste Act (Act 59 of 2008). The recycling of business and household waste in the municipality occurs through: kerbside collection, drop off centres and buy back centres which are targeted at the low income groups that utilise recycling as a means of income generation (Freidrich and Trois, 2015). Further in order to reduce the quantity of landfilled waste and increase recycling within the EM, Mondi supplies orange bags for recyclables such as paper and plastic and has encouraged household level waste separation (van der Merwe *et al*. 2009). This initiative also results in reduced GHG emissions due to the decay of paper in landfills.

According to Freidrich and Trois (2013b) the EM has no composting facilities in place and aerobic composting is currently being performed for experimental purposes and as pilot activities. Freidrich and Trois (2013b) state that composting is being practised by community groups and households but there is little information pertaining to these projects. Thus, increased research, investigation and awareness on composting within the EM will result in reduced garden waste and organic waste in landfills thus significantly reducing landfill emissions. Further the high organic content of waste make composting a viable waste management option for the EM (Lehtila *et al*. 2007). Incineration is not practiced as a waste management option within the EM and country at large (Freidrich and Trois, 2015); this could be due to the high organic content of wet waste, the poor sorting of the waste or the lack of appropriate technology (Monnie *et al*. 2006).

In order to minimise environmental degradation due to waste, the EM encourages all its residence and industry to take responsibility and minimise or recycle their generated waste (van der Merwe *et al*. 2009).

3.2.2 Wastewater WWTPs

3.2.2.1 Wastewater Treatment Plants

The Durban Metro's wastewater management handles 435 million litres of domestic and industrial sewage. About 99% of the sewage is liquid waste which has to be treated to certain standards prior to it being released back into the rivers or the Indian Ocean. There are 27 WWTPs owned and operated by the EM with 10 sites treating industrial effluent and domestic effluent and the other 17 only treating domestic effluent. The location of some of the WWTPs within the municipality is illustrated in Figure 18 below. The **Northern**, **Kwamashu**, **Phoenix/Umhlanga**, Verulem, Isipingo, Mpumalanga, Umbilo and **Amanzimtoti** treatment plants combust their digester gas but only the WWTPs whose font is bold flare their biogas which can result in CO_2 and NO_x emissions. Only the Southern and Central WWTPs do not use the nitrification and denitrification processes. The Southern and Central WWTPs discharge their effluent into the Indian Ocean through outfall pipes that are 4km long. The effluent is released during the last 400m of the pipe through a series of diffusers at a depth of 60m.

Figure 18: Location some of the WWTPs within the EM.

A further discussion on wastewater management in the EM is provided below in order to develop a knowledge of the processes and systems in place. This will assist with the identification of any processes in place that result in GHG mitigation and contribute towards climate change adaptation.

3.2.2.2. Management of Wastewater Treatment

The Durban wastewater management is responsible for providing a sewage system that treats and safely disposes wastewater and it also carries out pollution monitoring (MWMD, 1997). The EM has 35 WWTP within the metropolitan area that collectively treats 435 million litres of wastewater daily. The Durban wastewater management department issues permits to industries in order to regulate the discharge of industrial effluents to the system. As part of the land based treatment, effluent is discharged into rivers and estuaries while partially treated effluent is discharged into the ocean via deep sea marine outfalls (MWMD, 1997). However the marine environment and rivers are continuously monitored and sampled to analyse the chemistry of the water and assess impacts of the effluent discharge.

According to the EM (2005) in order to reduce costs associated with electricity consumption the biogas produced during wastewater treatment will be used for generating electricity and the heat generated by these engines can be used to warm the digesters or to dry the sewage sludge The use of energy produced from biogas will result in energy savings and a reduction in the GHG emitted by the treatment process. Only four of the WWTPs in the municipality (Northern, Phoenix, Amanzimtoti and KwaMashu) combust their biogas and of these four, the Northern, KwaMashu and Phoenix generate heat which is consumed within the WWTP. The EM (2005) states that the generation of electricity from biogas could reduce the electricity bill of WWTPs by 50% because the power generated will be used internally. This will also reduce dependency of fossil fuel derived electricity from Eskom. However, the costs of implementation of this technology limits its availability and implementation for all treatment plants within the municipality. In order to maximise the implementation of the biogas capture technology, the KwaMashu WWTP has a sludge incinerator and dryer plant in place (Botha *et al.* 2011). The sludge incinerator and dryer are designed to complement each other through the use of combustion gas from the incinerator to dry the sludge into pellets (Botha *et al*. 2011). These pellets are then fed into the incinerator as supplementary fuel. The incineration of sludge reduces the quantity of sludge being disposed into rivers and oceans thus reducing the impacts of wastewater on water systems. Sludge incineration has multiple co-benefits such as fuel provision, heat generation, reduced biogas emissions and environmental impacts.

In addition, the EM has a water recycling plant that was commissioned in 2001 that was designed to treat 47.5 Ml/d of domestic and industrial wastewater to a near potable standard to be sold to industrial users such as Mondi Paper and Sapref for reuse (Gisclon *et al*. 2002). The Durban Water Recycling Works is the first water recycling project in the country and is located within the Southern WWTP, where the primary treated wastewater is discharged into the Indian Ocean. The reuse of wastewater will result in sustainable development of water resources, minimise water consumption, reduce the EMs wastewater output by 10% and consequently reduce environmental pollution in the oceans and rivers where treated wastewater is discharged (Gisclon *et al*. 2002). This water recycling initiative contributes to the preservation of natural water resources. Even though there is limited information available on wastewater treatment management within the EM, from the information gathered it is clear that the EM is aiming towards sustainable wastewater treatment.

3.3 Climate change

3.3.1 Climate change impacts

The EM is located in the eastern coastline of southern Africa, where its location increases its vulnerability since climate change is predicted to result in sea level rise. Sea-level rise along the EM coastline is predicted to be occurring at 2.7cm per decade and could possibly increase in the future (Lewis, 2011; EMIDP, 2013). The EM is largely dependent on tourism where rising sea-levels as well as other phenomena such as floods could affect this (Awuor *et al*. 2008, Hunt and Watkiss, 2011). This is because less people will be visiting the city due to undesirable weather conditions which will affect the economy also. However tourism could also be contributing to current climate alterations because of its ability to affect natural resources such as air, water, land, fauna and flora and it contributes to the emission of GHGs (Douglas *et al*. 2001). Climate is a significant driver of tourism; consequently a change in climates will impact tourism.

The projected impacts to be caused by climate changes are likely to increase malnutrition, increase the quantity of people suffering from disease, injury and death caused by heat waves, increase the occurrence of floods, droughts and storms and will continue to change the geographical range of infectious diseases such as malaria (Awuor *et al*. 2008; Mokoena, 2009; Ziervogell and Parnell, 2014). Furthermore, Mokoena (2009) stated that climate change effects such as declining economic output could adversely impact livelihoods as well as human security. The consequences of climate change in EM are expected to be increased soil erosion caused by flooding, declining agricultural productivity, loss of biodiversity, direct impacts on health due to increased heat waves as well as damage to infrastructure (Mokwena, 2009; Ziervogell and Parnell, 2014).

Climate change could possibly heighten existing problems such as food security, health and water availability (Awuor *et al*. 2008). It is predicted the city will experience shorter periods of rainfall and longer periods without together with changes in rainfall distribution (Awuor *et al*. 2008; Ziervogell and Parnell, 2014). This will have an impact on water availability and subsistence farming within communities. The challenge associated with the implementation of climate change strategies in the municipality increases its vulnerability to changing climates. These challenges have been identified as: inadequate coordination between the different spheres of government; lack of coordination between different departments within the municipality; inadequate knowledge and understanding of climate change issues amidst municipal officials and limited community awareness and involvement on climate change issues (Mokwena, 2009).

Climate change impacts that could be faced by the municipality and the waste sector include (Botes and McKenzie, 2013):

- The continuously rising temperatures due to climate change could increase the decomposition of landfilled waste and accelerate the rate of formation and release of CH_4.
- The storms severity is predicted to be intense and the increased rainfall could lead to more wastewater being released into rivers and the ocean if not collected timeously. Thus in order to avoid pollution of water bodies and blocking of drains, it will be necessary for waste collection services to collect waste more frequently.
- Due to increased storms, Durban storm water infrastructure is likely to experience an increase in storm water discharge and therefore increase the maintenance of the infrastructure. An infrastructure upgrade will be required to minimise impacts associated with blocking of drains and waste from unnecessary drainage.
- The rising temperatures could increase the already high air pollution produced by industry, where the concentration of pollutants such as ozone is enhanced by increased temperatures.

3.3.2 Climate change adaptation and mitigation in EM

In order to assist with climate change adaptation and mitigation the EM has developed the Municipal Climate Change Programme (MCCP) which was initiated in 2004 (Lewis, 2011; Walsh *et al*. 2013). In addition, the Durban Climate Change Strategy (DCCS) was developed by the Energy Office and the Environmental Planning and Climate Protection Department and was finalised in 2014. The DCCS involved an inclusive and participatory process aimed at producing a framework to be used by the EM and its residents for contributing towards climate change mitigation and adaptation. This programme focuses on climate change adaptation as well as improving the municipalities' ability to cope with the associated impacts. As part of climate change mitigation, the municipality provides annual GHG emissions inventories that are used to monitor emissions as well as identify those area that require effective mitigation. Furthermore, the EM developed Municipal Adaptation Plans (MAPs) that are aimed at assisting the various sectors with adapting to climate change impacts in order to decrease the costs associated with this change (Lewis, 2011). The adaptation interventions chosen by the EM are flexible and have numerous advantages that will ensure that many individuals profit from the interventions (Lewis, 2011). Adaptation will help reduce the vulnerability to climate change of the municipality. These MAPs were developed for the health, water and disaster management sectors because they were identified as high risk. Thus the municipality has not yet developed adaptation strategies that are specifically suited to the waste sector.

3.4 Summary

This chapter provides an overview of the EM and its significance as a study area while highlighting the landfills and wastewater treatment plants of interest. Following the overview, solid waste and wastewater management within in the municipality was discussed to enable the identification of practices resulting in GHG reduction and co-benefits. In addition climate change risk for the waste sector and the EM was outlined together with the adaptation strategies for the EM.

CHAPTER 4
DATA AND METHODOLOGY

4.1 Introduction

This work presents GHG emissions estimates from solid waste and wastewater management. The research methodology used was both qualitative and quantitative. Thus, this chapter describes the data, methods, assumptions and limitations of the emissions inventory that was developed for the solid waste and wastewater sector of the EM in order to achieve the aim and objectives of this study.

4.2 Methods Approaches: Solid Waste

4.2.1 Road Emissions

Emissions due to fuel use by DSW

The 2006 IPCC Guidelines for National Greenhouse Gas Inventories are a revised and updated version of the 1996 IPCC Guidelines. These guidelines enable all countries to compile reliable GHG inventories, regardless of resources. The IPCC (2006) guidelines were adopted for quantifying road transport emissions due to fuel use; this method considers emissions by diesel and petrol consumption by DSW. Further this approach is based on a tiered approach which ranges from Tier 1, 2 and 3. Tier 1 is the most basic, requires the least amount of data and it is the least accurate because of its extensive use of emission factors. The Tier 3 approach requires place specific data and is regarded as data intensive but it is the most accurate (IPCC, 2006). The Tier 1 approach includes the combustion of fuel from national energy statistics and default emission factors (IPCC, 2006). Tier 1 methodology often utilises IPCC country-level defaults, even though these are country-level defaults because the data to be used was municipality specific fuel consumption it enabled municipal level analysis with significant confidence. Furthermore, the Tier 1 approach is a sufficient estimation method for CO_2 emissions and does not require further calculation using Tier 2 methodology because the major gas emitted by vehicles is CO_2 (IPCC, 2006). This is because the impact of fuel emissions towards climate change lies in the emission of CO_2 with the other gases (CH_4 and N_2O) having minor impact. The total CO_2 emissions by fuel use were calculated using Equation 1 as adopted from IPCC (2006) GHG guidelines for inventories.

CO_2 from road transport:

$$Emission = \sum_a \boldsymbol{Fuel_a} * \boldsymbol{EF_a} \quad \text{......Equation 1}$$

Where:

Emission	=Emissions of CO_2 (kg)
$Fuel_a$	= fuel sold (TJ)
EF_a	= emission factor (kg/TJ). This is equal to the carbon content of the fuel multiplied by 44/12
a	= type of fuel (e.g. petrol, diesel)

The CO_2 emission factor used accounts for all the carbon in the fuel including that which is emitted as CH_4, CO_2, CO and NMVOC as well as particulate matter (IPCC, 2006). The default IPCC emission factor for CO_2, CH_4 and N_2O used for calculating emissions is shown in Table 5. The total CH_4 and N_2O emissions by fuel use were calculated using Equation 2 adopted from IPCC (2006) guidelines for inventories.

Table 5: Road transport default emission factors of CO_2, CH_4 and N_2O (kg/TJ) (Source: IPCC, 2006).

Fuel Type	**CO_2**	**CH_4**	**N_2O**
Gasoline	69 300	33.0	3.2
Diesel	74 100	3.9	3.9

Tier 1 emissions of CH_4 and N_2O:

$$Emission = \sum_a [\boldsymbol{Fuel_a} * \boldsymbol{EF_a}] \quad \text{......Equation 2}$$

Where:

Emission	= emissions (kg)
EF_a	= emission factor (kg/TJ)
$Fuel_a$	= fuel consumed, (TJ) (as represented by fuel sold)
a	= fuel type a (e.g., diesel, gasoline, natural gas, LPG)

Emissions for the collection and transport of waste

The emission factors provided by Freidrich and Trois (2013a) have been developed specifically for GHG emissions associated with the collection and transport of waste for EM. The emission factors only consider emissions caused by the combustion of diesel by the collection trucks. Petrol is not considered because smaller vehicles do not collect and transport waste. The calculation of emissions from the collection and transport of waste using this method was considered because several studies on waste (Eisted *et al*. 2009; Moller *et al*. 2009; Trois and Jagarth, 2011; Freidrich and Trois, 2015) use this method for estimating emissions. GHG emissions from combusted diesel are CO_2, CH_4 and N_2O, but the amounts of CH_4 and N_2O produced are minor and insignificant when compared to CO_2 and were included in the calculation of the emission factor. This approach quantifies emissions in CO_2-e per tonne of waste transported. It was thus assumed that the landfilled waste is the waste that was collected and transported by each landfill site. The emission factor to be used is 0.01134 tCO_2-e (Freidrich and Trois, 2013a). The emission factor was converted to tCO_2-e in order to enable consistency with other calculations in this study. The equation to be used is shown below. The quantities for waste deposited used to calculate emissions were taken from Table 12.

GHG emissions from the collection and transport of waste (tCO_2-e):

GHG emissions = Activity data * Emission factor................................ Equation 3

Where:

Activity data = waste deposited in landfill at a certain year

Emission factor = default emission factor for the transport and collection of waste.

Comparison of methods used

The IPCC method is more inclusive as it considers emissions due to all fuel types used by DSW directly and indirectly. The IPCC (2006) guideline method is used for calculating CO_2 emissions for transport sector inventories globally and would be applicable when calculating overall transport sector emissions contributions of the waste sector so that it can be compared with other sectors. Fuel emissions calculated using emission factors are more specific to waste because emissions per tonne of waste deposited are considered whereas IPCC (2006) guidelines only consider fuel use emissions. The emission factor approach enabled the quantification of future emissions due to the transport and collection of waste because projected waste deposition data was available and this could not be conducted with the fuel consumption data only. When calculating emissions for the collection and transport of solid waste the emission factor approach proved to be the better method for this study. This is because it has been applied in other waste studies to quantify such emissions and therefore enables the comparison between different municipalities and cities. Furthermore, the use of emission factors shows that the emissions are also linked to the quantity of waste landfilled which is assumed to all have been collected and transported by the municipality.

4.2.2 Landfills

Approach using IPCC (2006) guidelines

The IPCC (2006) guidelines provide a comprehensive methodological framework to enable the preparation of consistent reports on GHG emissions inventories (Dodman, 2009). Further, the IPCC model used is a freely available spread-sheet format FOD model for quantifying solid waste emissions. FOD models account for the effect of ageing waste while the rate of LFG formation is assumed to decay exponentially with time (Scharff and Jacobs, 2006; Oonk, 2010). Thus, the IPCC model accounts for the effect that the depletion of carbon in the waste increases through time and better represents the pattern of the degradation process over time. The major assumption used is that the IPCC (2006) guidelines for emissions estimating are applicable to lower levels of the country such as municipalities. Thus emissions in this instance were made to be municipality specific using the available data provided. The impact of landfills on climate change lies in their emissions of CH_4 and CO_2 as well as other gaseous particles. It is discussed in Chapter 2 section 2.2.3.1.3 that CO_2 released by landfills does not contribute to overall GHG emissions and global warming because of its biogenic origin; hence only CH_4 emissions were calculated. The GWP of 21 and 310 (Santaalla *et al*. 2013) was used to determine the contribution of CH_4 and N_2O respectively to the greenhouse effect where final emissions were provided in tCO_2-e.

The order in which the IPCC equations were used enabled the calculation of the emitted tCO_2-e per annum. When using the spreadsheet, a specific set of parameters were followed. The region selected was southern Africa and the CH_4 generation constant was selected for a dry tropical environment. This is because the mean annual rainfall of Durban is less than 1 000 mm (Jury and Melice, 2000). The annual temperature assists with determining the CH_4 generation constant (Table 6) for each waste type and the default values were utilised as provided by the guidelines. The fraction of CH_4 developed in LFG is 55%, the fraction of dissimilated organic carbon (DOC) is 0.5, the conversion factor of carbon to CH_4 is 16/12 while the CH_4 correction factor used is 1 and since the landfill sites being referred to are considered to be sanitary and well managed, the oxidation factor used is 0.1 (IPCC, 2006; Manfredi *et al*. 2009; Freidrich and Trois, 2013).

Table 6: CH_4 generation rate constants (Source: IPCC, 2006).

CH_4 generation rate constant (K)	**Default value**
Food waste	0.085
Garden	0.065
Paper	0.045
Wood and straw	0.025
Textiles	0.045

The data for waste deposited annually in the landfill sites were provided by the municipality (Table 12) and the percentage composition of waste for the EM listed in Table 7 was adopted from Freidrich and Trois (2013a). The quantity of CH_4 recovered from the landfill sites was not included in the IPCC model although provided by the municipal inventories because data was only available for three years and would have skewed the outcome of the results. However, the recovered CH_4 was acknowledged and listed in the results section.

Table 7: Typical waste composition of eThekwini landfill sites

Waste Type	**Percentage Composition (%)**
Food	26
Garden	16
Paper	18
Wood	2
Textile	2
Metals	4
Glass	7
Plastics	12
Other inert	13

The CH_4 generated over the years is estimated based on the composition and quantity of waste deposited in the landfills where the waste composition is assumed to be constant throughout the entire time series for this study. Equations 4 equations 4-8 show the steps involved in the calculation of CH_4 generated in the landfill sites based on waste type and particular year.

Decomposable DOC from waste disposal:

$DDOC_m = W * DOC * DOC_f * MCF$ ……………………………………….. Equation 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, fraction, Gg C/Cg waste
DOC_f	= fraction of DOC that can decompose (fraction)
MCF	= CH_4 correction factor for aerobic decomposition in the year of deposition (fraction)

$DDOC_m$ accumulated at the end of year T:

$DDOCma_T = DDOCmd_T + (DDOCma_{T-1} * e^{-k})$ …………………………Equation 5

$DDOC_m$ decomposed at the end of year T:

$DDOCmdecomp_T = DDOCma_0 * (1 – e^{-k})$ ……………………………………...Equation 6

Where:

T	= inventory year
$DDOCma_T$	= DDOCm accumulated in the SWDS at the end of year T, Gg
$DDOCma_{T-1}$	= DDOCm accumulated in the SWDS at the end of year (T-1), Gg
$DDOCmd_T$	= DDOCm deposited into the SWDS in year T, Gg
DDOCm $decomp_T$	= DDOCm decomposed in the SWDS in year (T), Gg
k	= reaction constant, k =ln(2)/$t_{1/2}$ (y^{-1})
$t_{1/2}$	= half-life time (y)

k= 0.17 (Deafault value from 2006 IPCC guidelines for GHG inventories chose because half life less than 3 years is recommeded for tropical regions)

CH_4 generated from Decayed DDOCm:

$CH_4generated_T$ = $DDOCmdecomp_T * F * 16/12$ ……………………………Equation 7

Where

$CH_4generated_T$ = amount of CH_4 generated from decomposable material
$DDOCmdecomp_T$ = DDOCm decomposed in year T, Gg
F = fraction of CH_4, by volume, in generated LFG (fraction)
16/12 = molecular weight ratio CH_4/C (ratio)

Equation 8 represents the method of calculation of CH_4 emissions. In the IPCC (2006) guidelines this equation was listed first; however the results obtained from Equations 4-7 provide the necessary data for calculating emissions. Thus for the purpose of this study it was calculated and listed as the last equation.

CH_4 Emissions:

CH_4 Emissions = $[\sum_x CH4\ generated\ x.T - RT] * (1\text{-}0X_T)$ ………………...Equation 8

Where:

CH_4 Emissions = CH_4 emitted in year T.Gg
T = inventory year
x = waste category or type/material
R_T = recovered CH_4 in year T.Gg
OX_T = oxidation factor in year T, (fraction)

Approach using emission factors by Freidrich and Trois (2013a)

This section presents the calculation of GHG emissions from sanitary landfills with no LFG capture and flaring or electricity generation in place, thus it does not consider any mitigation options. This is representative of a majority of landfills in South Africa which do not have technologies for treatment of their waste. Equation 9 was used to calculate GHG emissions, the emission factor used for this landfill type is 1.01633 tCO_2-e/tonne wet waste (ww) (Freidrich and Trois, 2013a) and the activity data used for the quantity of waste deposited annually is listed in Table 12. In order to avoid the use of large numbers the units used for the emission factor were converted from $kgCO_2$-e/tonne ww to tCO_2-e/tonne ww. This emission factor calculates CH_4 emissions and considers carbon storage where CO_2 emissions from landfills are considered to not contribute to overall emissions because of their biogenic origin.

Emissions due to waste management (tCO_2-e):

GHG emissions = Activity data * Emission factor ………………………...Equation 9

Where:

Activity data = amount of waste deposited in each the landfill site at a certain year

Emission factor = is the default emission factor of a given waste management process.

Comparison of methods used

The calculation of GHG emissions from landfills using the IPCC (2006) guidelines is a commonly applied methodology for national level studies (Barton *et al*. 2008; Johari *et al*. 2012; Menikrupa *et al*. 2016). However, since these studies consider all landfills in municipalities within the country this tells us that IPCC (2006) guidelines are suitable for municipal level studies as well. This method requires significant amounts of historical data to increase accuracy which is lacking for most municipalities in developing countries such as the EM and often interpolations are made thus reducing the validity of input data. Nevertheless it does provide the better estimation because it considers the exponential decay factor of waste and shows that landfill emissions continue for years after closure of the landfill. This also highlights that other environmental impacts caused by landfilling such as leachate seepage, release of toxic odours and groundwater pollution continue post closure of the landfill.

The use of emission factors by Freidrich and Trois (2013a) has benefits because these emission factors were specifically designed for landfills in South Africa. However, several assumptions were also taken into account when developing these emission factors which could result in inaccuracies. Furthermore, the use of emission factors only considers the waste that was deposited in that particular year and does not consider that waste emissions grow over the years due to decay of waste which grows over the years. Both methods did however indicate the growing landfill emissions from the EM although different emissions were calculated. However, due to data limitations the use of emission factors proved to be the better method for this study.

4.2.3 Electricity (emissions and savings)

Electricity Consumption

The landfill sites utilise both renewable and non-renewable energy but the renewable energy is not considered to have GHG emissions associated with it. For calculating electricity consumption emissions, the Eskom Grid Emission Factor (GEF) was used. The GEF is the sum of GHGs emitted per unit of electricity generated and distributed by an electricity grid and it considers import and exports of electricity from the connection with other grids. The GHG emissions are comprised of CO_2, CH_4 and N_2O. The GEF of 1.07 tCO_2-e/MWh was used for calculating emissions associated with electricity use and it is based on the MWh sold by Eskom (EIR, 2014). This emission factor considers the electricity consumed throughout the generation process as well as that which is lost during transmission (McEnzie, 2012). Electricity consumption was calculated using the basic principle shown in Equation 10 below:

CO_2 emissions due to electricity consumption:

CO_2 emissions = Activity data * Emission factor……………………………. Equation 10

Where:

Activity data = amount of energy used by the landfill site

Emission factor = is the default emission factor of a given GHG by fuel type (tCO_2-e/MWh).

Electricity Sold

The municipality purchases electricity from the Bisasar Road and Marianhill landfill sites. The electricity provided is produced through implemented CDM projects. The total energy purchased by Eskom from the landfill sites is shown in Table 8 as provided by the eThekwini GHG inventories for 2010-2012. This information is used to calculate avoided emissions due to the use of renewable energy by the municipality where avoided emissions are calculated using Equation 10 above.

Table 8: Electricity purchased from landfills (MWh)

Year	LFG purchases
2010	53 701.91
2011	44 615.14
2012	44 875.42

4.2.4 Mitigation Scenarios

Each waste treatment option has variable GHG emissions associated with it due to the process and equipment utilised. The approach followed for creating these mitigation scenarios was adopted from Freidrich and Trois (2015) and Monnie *et al*. (2006). Freidrich and Trois (2015) provided emissions scenarios for the EM landfills for 2012, 2014 and 2020 while Monnie *et al*. (2006) provided guidance for continuous scenarios from 1990-2050 where a baseline scenario and other waste management scenarios were presented. The difference is that Freidrich and Trois (2015) used emission factors specific to South African municipalities while Monnie *et al.* (2006) utilised IPCC (2006) guidelines for all scenarios. However IPCC (2006) guidelines could not be used for mitigation because of the lack of data required for the IPCC Inventory which did not cover a minimum of 50 years as required. Consequently, the emission factors developed by Freidrich and Trois (2013a, b) using a carbon balance approach were employed for the mitigation scenarios. In order to avoid the use of large numbers the units used for the emission factors were converted from kgCO_2-e/tonne ww to tCO_2-e/tonne ww. Equation 11 shows the used technique when calculating emissions for the various scenarios. The activity data to be used and emission factor is dependent on the type of waste management technique used. Furthermore, it was assumed that the waste composition would remain the same until 2020 (Freidrich and Trois, 2015).

Emissions due to waste management (tCO_2-e):

GHG emissions = Activity data * Emission factor …………………………..Equation 11

Where:

Activity data = amount of waste deposited in each the landfill site at a certain year

Emission factor = is the default emission factor of a given waste management process.

The scenarios considered are, emissions from landfills without gas collection (baseline scenario); emissions from landfills with gas collection and flaring; emissions from landfills with gas collection and electricity generation; emissions due to increased recycling and emissions resulting from the introduction of composting. Incineration was not considered because waste is not incinerated in municipality (Freidrich and Trois, 2013a). The created scenarios highlight waste management options which could contribute towards climate change mitigation and adaptation. Each waste treatment option has variable GHG emissions associated with it due to the process and equipment utilised.

Scenarios are compiled from 2003-2014 for Bisasar Road, 2003-2020 for Marianhill and 2006-2020 for the Buffelsdraai landfill. These created scenarios consider the implications of GHG emissions in the future. Bisasar Road landfill scenarios are considered till 2014 because it is predicted to have closed at the end of that year (Freidrich and Troi, 2015). The quantity of waste deposited for all scenarios is taken from Table 12.

4.2.4.1 CH_4 emissions from landfills without gas collection (baseline scenario)

The aim of this scenario is to illustrate the effects of conventional landfills that do not employ other waste management criteria and the implications these would have on future GHG emissions. This scenario assumes no GHG reduction techniques are being used in the landfill. However, it does incorporate recycling since the landfilled waste is reduced due to current and historical recycling practices in the country. Calculations of emissions from this scenario are those which are shown in section 4.2.2.1 for the emission factor approach using Equation 9.

4.2.4.2 CH_4 emissions from landfills with gas collection and flaring

The Bisasar Road landfill has been combusting LFG since 1996 when the Hoffsetter extraction flare was installed, consequently LFG flaring began 2001 in Marianhill when a Realmside plant was installed (Couth *et al*. 2011). Since data for waste deposited were only available from 2003, for this scenario the effects of LFG capture and flaring were shown from 2003 onwards. The emission factor adopted from Freidrich and Trois (2013a) to be used for landfills with gas collection and flaring is 0.10120 tCO_2-e/tonne ww. The Buffeldraai landfill has no LFG capture system in place; it was however assumed that this would begin in 2015 after the closure of Bisasar Road landfill.

4.2.4.3 CH_4 emissions from landfills with gas collection and electricity generation

The emission factor for landfills with gas collection and energy recovery is -0.14452 tCO_2-e/tonne ww (Freiddrich and Trois, 2013a). This emission factor is negative because it shows emissions savings due to gas collection and energy generation. Even though LFG capture was commissioned in November 2006 in Marianhill and March 2008 in the Bisasar Road Landfill (DSW Office). For the purposes of this study it is assumed that LFG capture began in January 2007 in Marianhill and January 2008 in Bisasar Road. LFG recovery rate is assumed to remain constant over the years as in the study by Monni *et al*. 2006. The Buffeldraai landfill has no LFG capture and electricity generation system in place; it was however assumed that this would begin in 2015 after the closure of Bisasar Road landfill. The gas collection efficiency was assumed to be 75% while the gas energy recovery is assumed to be 30% (Manfredi *et al*. 2009; Freidrich and Trois, 2013a).

4.2.4.4 Increased Recycling

The increased recycling scenario is from 2012-2020. The landfills considered for increased recycling were the Marianhill and Buffelsdraai because the Bisasar Road was assumed to be closing in 2014 thus this would have minor impact. In order to show the impacts of recycling on landfills, the recycling rates are used to show the decrease in waste deposited in the landfills which results in reduced emissions. Therefore, the percentage increase in each of the materials was subtracted from the waste deposited, thus reducing the quantity of waste deposited. In addition, the percentages of waste recycled assisted with getting the exact quantity of waste recycled in tonnes. This is because if the recycling rate for paper in 2009 was 56%, this means that 44% of the paper was landfilled. Therefore, the 44% of landfilled paper in tonnes assisted in getting the 56% which was recycled (Table 9). This recycled amount is used to show GHG emissions savings due to recycling. This data were then modelled following the baseline approach.

Table 9: Percentage recycling rates (Source: Freidrich and Trois, 2015)

Material	**2009 Recycling Rate**	**2012 Recycling Rate**	**2014 Recycling Target**	**Potential future rates for 2020**
Paper	56%	59%	61%	66-71%
Metal	56%	60%	65%	70-75%
Glass	32%	40%	43%	48-53%
Plastic Overall	28%	30%	35%	40-45%

PVS and other plastics were excluded because they were not in the Freidrich and Trois (2013b) article. Further, the emission factors used for PEHD and PP taken from Freidrich and Trois (2013b), were different to those used by Freidrich and Trois (2015). All metals were considered to be steel because the percentage split between the two metal types is not known. It was further assumed that all paper is mixed paper since there was no percentage apportionment available for the different types of paper. The emission factors for recycling (Table 10) were used to show emissions savings due to recycling. These emissions savings were calculated using Equation 11 together with the emission factors for each product. The main recyclables considered are glass, paper, plastics and metals (Freidrich and Trois, 2013b; Freidrich and Trois, 2015).

Table 10: Recycling emission factors in tCO_2-e/tonne (Source: Freidrich and Trois, 2013b).

Material		**Emission Factor**
Paper		-0.5177
Metal	Aluminium	1.91107
	Steel	-2.5869
Glass		-0.290
Plastic overall	PELD (43%)	-0.8594
	PEHD (16%)	-0.7194
	PET (17%)	0.7894
	PP (16%)	-1.8324

4.2.4.5 Biological Treatment of Solid Waste (Composting)

The effects of composting on GHG emissions from landfills are computed considering that there is a reduction on the waste deposited. Only 8% of the current 18% of the garden waste stream is considered to be composted, garden waste includes wood waste. This 8% is garden waste which is separated by the municipality and this has not yet occurred for food waste (Freidrich and Trois, 2013b). The baseline waste stream was reduced of a percentage of the garden waste which will be composed, thus reducing the quantity of organic waste deposited. The percentage of garden waste composted is assumed to remain constant from 2015 to 2020. The resulting data were then modelled following the baseline approach. The emission factor of 0.185tCO_2-e/tonne of organic municipal waste (Freidrich and Trois, 2013b) was used to calculate emissions associated with composting the fraction of the waste stream.

4.3 Data Acquisition

4.3.1 Road Emissions

There was a challenge in obtaining specific data on the number of trucks that collect and transport waste and the distances travelled. However, data required for estimating fuel use emissions for DSW were requested and obtained freely from the eThekwini Fleet department. This department provided fuel use data in the form of invoices issued from BP garage to DSW for the years 2010 to 2014. The invoices provided were from BP because all DSW vehicles can only fill at certain BP garages because a BP fuel link system is used. The invoices included total diesel and petrol consumption for each of the DSW vehicles for that particular year. The fleet department also confirmed that diesel consumption was due to the use of trucks for the collection and transport of waste while petrol consumption was due to the smaller motor vehicles used by DSW. The total fuel consumption for DSW is shown in Table 11; the data were used as inputs into the IPCC equation to enable the calculation of CO_2, CH_4 and N_2O emissions caused by road transport.

Table 11: Total fuel consumption (kL) by DSW vehicles for the years 2010-2014

Fuel Type	**2010**	**2011**	**2012**	**2013**	**2014**
Petrol	114 340.31	191 778.47	201 230.90	832 954.52	236 103.57
Diesel	1 200 315.82	1 825 224.84	2 263 415.77	1 806 595.47	2 548 805.97

4.3.2 Landfills

The data required to determine GHG emissions from the landfill sites were acquired from the eThekwini Energy Office and DSW. There is a challenge with the availability of historically deposited waste for the landfill sites. Solid waste data for the landfill sites of interest were provided for the years 2009-2014 by DSW. The Bisasar Road landfill site is the largest landfill in Africa and has been operating since 1985 yet historical information on the quantity of waste deposited prior 2003 is not available (Freidrich and Trois, 2013a).

As a quality check measure, prior to use the data received from DSW was checked and analysed for any errors or missing data which could affect the outcome. The waste tonnage data received from DSW were averaged annually (Table 12) to enable the quantification of annual emissions from the landfill sites. The aggregated annual tonnage data were used as inputs into the IPCC equations to enable the quantification of CH_4 emissions. Waste deposited data for 2003 for the Bisasar Road and Marianhill landfills was taken from the 2003/2004 eThekwini Integrated Waste Management Plan, thus from this, the waste deposited data for 2004-2008 was obtained using linear interpolation. According to Payne and Ribbink (2011) the Buffelsdraai landfill was commissioned in 2006 and is predicted to receive 450 tonnes waste daily, this information was used to determine waste deposited for 2006-2008 using linear interpolation. The Bisasar road landfill is predicted to close at the end of 2014, thus the assumption was that there are no new waste deposits since then. According to Freidrich and Trois (2015) 75 % of the waste from Bisasar will be diverted to Buffelsdraai while the other 25% is sent to the Marianhill landfill. It was therefore assumed that 75% of the waste generated from 2015-2020 is sent to Buffelsdraai and the other 25% to the Marrianhill landfill. Waste is predicted to increase by 80% from 2014-2020 (Freidrich and Trois, 2015) and linear interpolation was applied to get the quantity of waste deposited from 2014-2020 for all the landfills.

Table 12: Annual waste (tonnes) deposited by DSW in the landfill sites

Year	Bisasar Road	Marianhill	Buffelsdraai
2003	636 784.00	115 414.00	-
2004	734 148.65	125 446.25	-
2005	831 513.30	135 478.51	-
2006	928 877.95	145 510.76	164 250.00
2007	1 026 242.60	155 543.02	109 518.46
2008	1 123 607.25	165 575.27	54 786.92
2009	1 220 971.90	175 607.53	55 373.82
2010	1 137 031.41	191 356.80	91 855.62
2011	1 086 433.88	210 109.81	57 950.90
2012	1 209 902.31	250 215.08	67 127.86
2013	1 099 701.37	280 564.41	78 221.09
2014	904 358.35	237 635.57	65 868.88
2015	-	527 435.18	848 980.98
2016	-	591 145.20	953 824.32
2017	-	654 855.21	1 058 667.66
2018	-	718 565.23	1 163 511.01
2019	-	782 275.25	1 268 354.35
2020	-	845 985.27	1 373 197.69

The EM population data (Table 13) to be used as inputs in the model IPCC (2006) model was sourced from Census data provided by StatsSA for the years 2001 and 2011. The population data for the years 2002-2010 and 2012-2014 were obtained using geometric interpolation as well as census mid-year estimates which were obtained from the StatsSA website. In addition, the waste per capita (kg/cap/year) for the years 2003-2009 was 182.5kg/cap/year (IWMP, 2004; EMSER, 2008) and the waste per generation rates for 2010-2014 is 189.93 (Freidrich and Trois, 2013a).

Table 13: Annual population for the EM

Year	**eThekwini Population**
2003	3169601
2004	3206498
2005	3242456
2006	3278095
2007	3468087
2008	3504006
2009	3537505
2010	3571324
2011	3605466
2012	3639935
2013	3461576
2014	3540196

4.3.3 Electricity (emissions and savings)

There is a challenge in the availability and access to activity data for electricity consumption of landfill sites within the municipality. Due to the lack of available raw data on the electricity consumed in each landfill site, the necessary electricity consumption data were extracted from the EM GHG emissions inventories for the years 2010, 2011 and 2012 for DSW (Table 14).

Table 14: DSW Electricity Consumption (MWh)

Year	**Renewable Energy**	**Non-renewable Energy**	**Total**
2010	3	653	656
2011	6	1 696	1 703
2012	7	1 796	1 803

4.4 Methods and data: Wastewater

4.4.1 Electricity Consumption

4.4.1.1 Methodological approach

The Eskom emission factor of 1.07 tCO_2-e/MWh was used to calculate electricity consumption emissions. Equation 10 shown in section 4.2.3.1 was used for the calculation.

4.4.1.2 Data and emissions estimates

There is a challenge in the availability and access to raw data for electricity consumption for WWTPs within the municipality. The electricity consumption data for WWT were not available, consequently the information in the provided municipality inventories was used to highlight consumption and emissions. Therefore the eThekwini GHG emissions inventories for 2010-2012 (EEO, 2014) assisted with filling the missing gaps. The annual electricity consumption for WWTPs in the municipality is shown in Table 15 where the renewable energy used by the EM is not considered to have GHG emissions contributions because of its biogenic origin.

Table 15: Electricity consumption (MWh) of WWTPs within the EM

Year	Renewable Energy	Non-Renewable Energy	Total
2010	105	22 760	22 865
2011	114	30 133	30 248
2012	222	55 436	55 658

4.4.2 Wastewater processing

4.4.2.1 Methodological Approach

Emissions from wastewater were quantified by the municipality based on Local Government GHG Emissions Analysis Protocols developed by the ICLEI, namely:

- The International Government GHG Emissions Analysis Protocol Version 1.0
- The Local Government Operations for the Quantification and Reporting of GHG Emissions Inventories Version 1.1

The municipality inventories state that in occurrences where the protocols where contradictory, the recent ICLEI Local Government Operations Protocol V1.1 was followed. These protocols were established in order to provide a standardised set of guidelines that will be of assistance to local governments when quantifying and reporting GHG emissions associated with the community and government operations. GHG emissions for the years 2010-2012 were provided by the municipality and the correctness of the information was checked for quality assurance purposes.

The ICLEI approach adopts equations from IPCC (2006) guidelines and it was adopted because the municipality used it to estimate emissions from previous years and it would enable continuation of results. Biological Oxygen Demand (BOD) values are generally used to quantify organic matter in wastewater; however the lack of specific data resulted in the use of emission factors for BOD values which were extracted from ICLEI protocols. The default fraction of CH_4 in the biogas was used because the municipality does not have gas quality instrumentation to enable monitoring, consequently the exact fraction of CH_4 gas cannot be determined. The limiting factor for this section is that there is extensive use of emission factors which could potentially result in potentially large error margins.

4.4.2.1.1 CH_4 emissions from the Incomplete Combustion of Digester Gas

$$\text{Annual } CH_4 \text{ emissions } (tCO_2\text{-e}) = (P \times \text{Digester Gas} \times F_{CH_4} \times \rho(CH_4) \times (1-DE) \times 0.0283 \times 365.25 \times 10^{-6}) \times GWP \quad \text{......Equation 12}$$

Where:

Term	Description	Value
P	population served by the WWTPs with anaerobic digesters	See Table 16
Digester Gas	cubic feet of digester gas produced per person per day [ft_3/person/day]	1.0
FCH_4	fraction of CH_4 in biogas	0.65
$\rho(CH_4)$	density of CH_4 (g/m^3)	662.00
DE	CH_4 Destruction Efficiency	0.99
	CH_4 Destruction Efficiency if gas is vented	0 (based on EM inventory)
0.0283	conversion from ft_3 to m_3 [m_3/ft_3]	0.0283
365.25	conversion factor [day/year]	365.25
10^{-6}	conversion from g to tonnes [tonnes/g]	10^{-6}
GWP	Global Warming Potential	21

Table 16: WWTPs that treat biogas using anaerobic digesters (Source: EM Inventories).

WWTP	**Population Served**				**Flaring**
	2010	**2011**	**2012**	**2013**	
Amanzimtoti	55 108	93 813	94 920	117 841	Yes
Isipingo	29 518	101 173	102 367	70 533	No
KwaMashu	140 675	323 117	326 930	277 875	Yes
Mpumalanga	3 640	35 840	36 263	11 425	No
Northern	132 593	229 935	232 648	320 529	Yes
Phoenix	47 033	124 996	126 471	118 569	Yes
Umbilo	36 225	23 186	23 460	66 395	No
Verulam	14 903	16 915	17 115	28 603	No

The Amanzimtoti, KwaMashu, Northern and Phoenix WWTP capture and flare the produced CH_4 gas, however further details on the quantity of gas flared and the resulting emissions could not be accessed. This factor limits the assessment of mitigation measures for wastewater.

4.4.2.1.2 CH_4 emissions from WWT lagoons

$$\text{Annual } CH_4 \text{ emissions } (tCO_2\text{-e}) = ((P \times F_{ind\text{-}com}) \times BOD_5 \text{ load} \times (1-F_P) \times Bo \times MCF_{anaerobic} \times 365.25 \times 10^{-3}) \times GWP \quad \text{……………….……Equation 13}$$

Where:

Term	Description	Value
P	population served by lagoons adjusted for industrial discharge, if applicable	See Table 17
F ind-com	factor for industrial and commercial co-discharge waste into the sewer system	1.25
BOD_5 load	amount of BOD_5 produced per person per day [kg BOD_5/person/day]	0.090
F_P	fraction of BOD_5 removed in the primary treatment if present	0.325
BO	maximum CH_4-producing capacity for domestic wastewater [kg CH_4/kg BOD_5 removed]	0.6
$MCF_{anaerobic}$	CH_4 correction factor for anaerobic systems	0.8
365.25	conversion factor (day/year)	365.5
10^{-3}	conversion from kg to tonnes [tonnes/g]	10^{-3}
GWP	Global Warming Potential	21

Table 17: WWT lagoon (Source: EM Inventories).

WWTP	Population Served			
	2010	**2011**	**2012**	**2013**
Cato Ridge	1 250	839	849	5 000

4.4.2.1.3 N_2O emissions from WWTPs with nitrification/denitrification

Annual N_2O emissions (tCO_2-e) = (($P_{total} \times F_{ind\text{-}com} \times EF\ nit/denit \times 10^{-6}$) $\times$ GWP ......Equation 17

Where:

Term	Description	Value
P_{total}	total population that is served by the centralised WWTP adjusted for industrial discharge where applicable	See Table 18
$F_{ind\text{-}com}$	factor for industrial and commercial co-discharge waste into the sewer system	1.25
EF nit/denit	emission factor for a WWTP with nitrification/denitrification [g N2O/person/year]	7
10^{-6}	conversion from g to tonnes (tonnes/g)	10^{-6}
GWP	N2O Global Warming Potential	310

Table 18: WWTPs with Nitrification/denitrification (Source: EM Inventories).

WWTP	Industrial Effluent	Population Served			
		2010	2011	2012	2013
Amanzimtoti	Y	68 885	93 813	94 920	117 841
Craigieburn	N	2 865	4 024	4 071	8 196
Dassenhoek	N	4 490	16 714	16 911	15 677
Genazano	N	4 013	5 769	5 837	6 575
Hammersdale	Y	21 379	9 422	9 533	113 442
Hillcrest	N	1 883	1 782	1 803	4 112
Kingsburgh	N	12 085	36 543	36 974	23 554
KwaMashu	Y	175 844	323 117	326 930	277 875
New Germany	Y	5 016	14 548	14 720	7 238
Northern	Y	165 741	229 935	232 648	320 529
Phoenix	N	47 033	124 996	126 471	118 569
Tongaat Central	Y	25 773	31 784	32 159	42 664
Umbilo	N	45 281	23 186	23 460	66 395
Umhlathuzana	N	30 673	48 822	49 398	52 691
Umdloti	N	2 543	3 541	3 583	5 269
Umkomaas	N	1 053	8 700	8 803	2 670
Verulam	Y	18 629	16 915	17 115	28 603

4.4.2.1.4 N_2O emissions from WWTPs without nitrification/denitrification

Annual N_2O emissions (tCO_2-e) = ((P_{total} × $F_{ind\text{-}com}$) × EF *w/o nit/denit × 10^{-6}) × GWP ……………………………………………..Equation 14

Where:

Term	Description	Value
P_{total}	population that is served by the centralised WWTP adjusted for industrial discharge where applicable	See Table 19
$F_{ind\text{-}com}$	factor for industrial and commercial co-discharge waste into the sewer system	1.25
EF w/o nit/denit	emission factor for a WWTP without nitrification/denitrification	3.2
10^{-6}	conversion from g to tonnes (tonnes/g)	10^{-6}
GWP	Global Warming Potential	310

Table 19: WWTPs without nitrification/denitrification (Source: EM Inventories).

WWTP	Industrial Effluent	Population Served			
		2010	2011	2012	2013
Central	Y	182 478	92 866	93 962	85 058
Isipingo	N	29 518	101 173	102 367	70 533
KwaNdengezi	N	2 825	15 032	15 209	9 842
Mpumalanga	N	3 640	35 840	36 263	11 425
Southern	Y	542 469	442 068	447 284	392 501

4.4.2.1.5 N_2O emissions from effluent discharge

Annual N_2O emissions (tCO_2-e) = (($P_{total} \times F_{ind\text{-}com}$) × (Total N Load – N uptake × BOD_5 load) × EF effluent × 44/28 × (1-F plant nit/denit) × 365.25 × 10^{-3}) …………………………..Equation 15

Where:

Term	Description	Value
P_{total}	population served	See Table 20
$F_{ind\text{-}com}$	factor for industrial and commercial co-discharge waste into the sewer system	1.25
Total N Load[27]	total nitrogen load [kg/N/person/day]	0.026
N uptake[28]	nitrogen uptake for cell growth in aerobic system (kg N/kg BOD_5)	0.05[1]
BOD_5 load	nitrogen uptake for cell growth in aerobic system (kg N/kg BOD_5)	0.090
EF effluent	emission factor [kg N2O-N/kg sewage-N produced]	0.005
44/28	molecular weight ratio N_2O to N_2	1.57
F plant nit/denit	fraction of nitrogen removed for the centralised WWTP with nitrification/denitrification	0.7[1]
365.25	conversion factor [day/year]	365.25
10^{-3}	conversion from kg to tonnes [tonnes/kg]	10^{-3}
GWP	global Warming Potential	310

Table 20: WWTP outlets (Source: EM Inventories).

Name of WWTP outlet	Industrial Effluent	Population Served			
		2010	2011	2012	2013
Ocean	Y	616 453	770 566	632 147	1 328 799
Umhlatuzana River	N	32 555	32 555	33 384	57 003
Umbilo River	Y	45 281	45 281	37 147	66 395
Amanzimtoti River	N	12 085	12 085	12 393	23 554
Mohlongwa River	N	2 865	2 865	2 938	8 196
Umkomaas River	N	1 053	1 053	1 080	2 670
Ngane River	N	625	625	641	2 100
Mbokodweni River	Y	68 885	68 885	56 511	117 841
Isipingo River	N	29 518	29 518	30 270	70 533
Umgeni River	Y	165 741	165 741	135 969	320 529
Aller River	Y	5 016	5 016	4 115	7 238
Umhlangane River	Y	175 844	175 844	144 256	277 875
Mlaas River	N	3 640	3 640	3 733	149 943
Sterspruit	Y	21 379	21 806	17 538	113 442
Ohlanga River	N	60 050	60 050	61 579	167 815
Umdloti	Y	21 806	21 806	17 889	33 872
Tongaati River	Y	25 773	25 773	21 143	42 664
Genazzona Stream	N	4 013	4 013	4 115	6 575

4.4.2.2. Data acquisition

The provided eThekwini GHG emissions inventory for the years 2010-2012 assisted with filling the missing gaps. Emissions from wastewater for 2013 were not provided, however the necessary raw data were provided by the eThekwini Energy Office to enable calculation of emissions. The wastewater information received included a list of the municipal owned WWTPs, those treatment plants that treat industrial effluent, those sites with and without nitrification/denitrification systems; the population served by the treatment plants as well as the WWTPs that combust their digester gas. This information was used as inputs into the equations for each particular process during emissions estimation.

4.5 Approach to understanding adaptation in the waste sector

A qualitative assessment of climate change adaptation for the waste sector in the EM was undertaken in this study. This qualitative assessment was conducted with the aim of developing an understanding of how the waste sector can contribute towards climate change adaptation in the EM. This analysis placed emphasis on the society's interaction and construction as well as their possible responses to climate change, and is considered as subjective and contextual (Whittemore *et al*. 2001). This approach had to be undertaken because quantitative methods for adaptation analysis are not well established due to the complexities and uncertainties involved. Extensive analysis of existing literature provided the necessary information on local cases which were used to assess the adaptive capacity of the waste sector and municipality.

4.6 Summary

This section provides an outline of how GHG emissions from the waste sector have been calculated using several methodologies namely: IPCC 2006 guidelines, International Council for Local Environmental Initiatives (ICLEI) protocol and emission factors developed specifically for South African municipalities. GHG emissions were calculated for fuel use by DSW, collection and transport of solid waste, electricity consumption in landfills and landfilling due to the waste deposited. Emissions calculated for wastewater were electricity consumption and those caused by the treatment of wastewater. For the mitigation scenarios, the emission factors developed by Freidrich and Trois (2013a, b) for South African municipalities were used to determine emissions from landfills without gas collection, landfills with gas collection and flaring, landfills with gas capture and electricity generation, recycling and composting. Only those waste treatment technologies carried out in the EM were considered and thus flaring was not included. Emissions associated with the acquisition of raw material, manufacturing and use were not considered because of the difficulty associated with access to data and the high level of complexity therein. Furthermore, a qualitative approach was adopted to assess the contribution of GHG mitigation in the waste sector towards climate change adaptation in the EM.

CHAPTER 5
RESULTS AND DISCUSSION

5.1 Introduction

This study seeks to quantify and develop an understanding of GHG emissions associated with the waste sector in the EM as well as highlight the opportunities available to reduce these emissions which will simultaneously increase the adaptive capacity of the municipality. In order to achieve this aim, GHG emissions were quantified for solid waste and wastewater management and the outcome then analysed. In addition this chapter presents GHG mitigation scenarios for various solid waste management options that could reduce GHG emissions with co-benefits that contribute towards climate change adaptation.

5.2 Solid Waste

5.2.1 Road Emissions

5.2.1.1 Emissions due to fuel use by DSW

Road emissions in the waste sector are caused by the combustion and evaporation of fuel by heavy and light duty vehicles (DSW, 2015). The fossil fuels consumed by vehicles directly translates into the emission of GHGs when combusted. Although minor, these road emissions contribute to national road transport emissions which are responsible for a majority of emissions in the transport sector as discussed in section 2.2.3.1.1 of Chapter 2. Thus, road transport is a major source of CO_2 emissions (Popa *et al*. 2015) and the collection and transport of waste is a contributor towards these emissions. Overall DSW fuel consumption emissions for the years 2010-2014 are shown in Figure 19. Petrol emissions are lower than diesel emissions because diesel is consumed more than petrol due to the number of waste collection trucks as well as the size of the trucks which contributes to the larger fuel consumption. CO_2 emissions based on fuel use for DSW have increased by more than 100% from 2010 to 2014 for both diesel and petrol. The growing emissions could be attributed to increased fuel use because of improving waste management in the municipality where more households have waste collected. Specifically, the weekly waste removal of waste in the municipality has increased from 85.7% in 2001 to 86.1% in 2011 (StatsSA, 2015).

The results obtained were compared with those from Freidrich and Trois (2015) for 2012 and 2014 where the results shown in Figure 19 were lower than those from the Freidrich and Trois (2015) study. The different results are attributed to the different methodology used for emissions calculations, where in this study emissions were calculated based on fuel use for the entire DSW versus the emission factor based on diesel consumption per tonne of waste collected. Furthermore, the results shown in Figure 19 could be lower because there were no data available for the quantity of fuel obtained from the municipality sites and it was thus excluded.

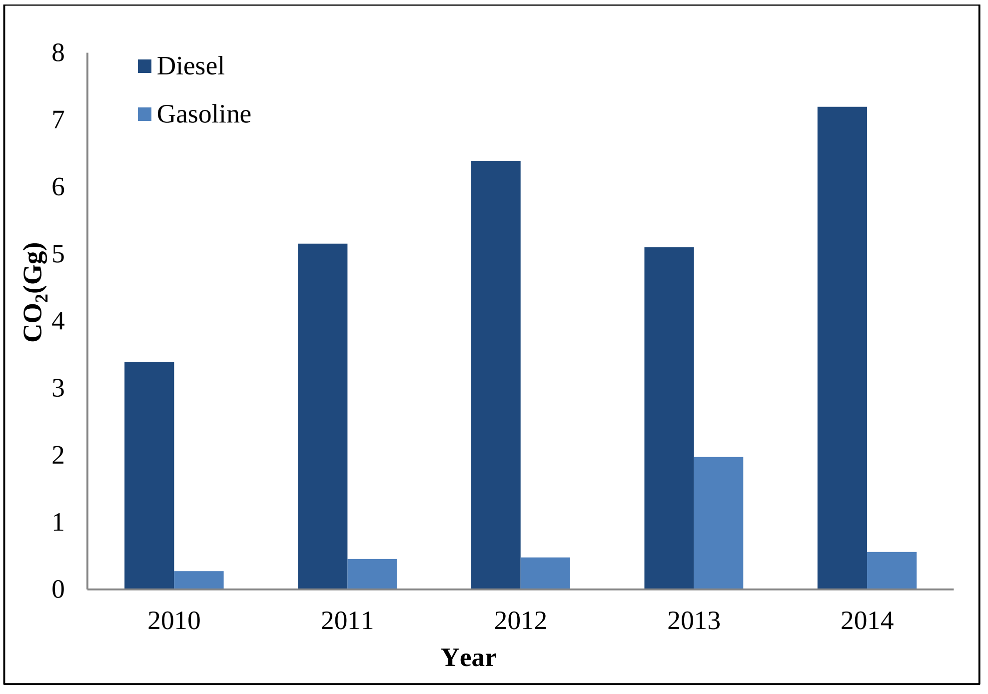


Figure 19: Emissions from DSW fuel consumption.

5.2.1.2 Emissions for the collection and transport of waste

From the results in illustrated in Figure 20, there is an increase in GHG emissions from 2003-2014 for all landfills and a projected increase from 2014-2020 for the Marianhill and Buffelsdraai landfills. However, a decline is also visible from 2012 -2014 for the Bisasar Road landfill which could be attributed to the landfill nearing closure thus resulting in a decline of waste deposited there. The GHG emissions associated with Marianhill and Buffelsdraai landfill increased steadily until 2014 where a sharp growth is visible from then till 2020. This is due to the diversion of waste from the Bisasar Road landfill to those sites. The closure of the Bisasar Road landfill will result in increased collection and transport emissions because the Buffelsdraai landfill is situated 34km north of Durban CBD and Marianhill is situated 20km west of Durban CBD while Bisasar Road was only 7km away from the CBD. Consequently, waste will be transported longer distances to get to the landfills. This increased distance will not only increase associated GHG emissions but it will also increase the costs associated with the collection and transport of solid waste. The costs associated with the collection and transport of waste make u 80-90% of municipal solid waste budgets in developing countries (Akhatar *et al*. 2015; Das and Bhattacharyya, 2015; Kinobe *et al*. 2015). In order to reduce the costs and pollutants emitted due to collecting and transporting waste, the path has to be minimised and the routes used optimised. The collection of waste is a significant part of the waste management system and an efficient collection system will result in shorter collection routes, lower operating hours and labour costs. Further, the conversion of vehicles to cleaner burning fuels or regular maintenance of vehicles should be a priority in order to reduce emissions (Hounsome and Iyer, 2006).

The results were compared with those from Eisted *et al*. (2009) which calculated GHG emissions for the collection, transfer and transport of waste based on data from Europe and North America. The results obtained in this study were much higher than those obtained by Eisted *et al*. (2009); this is caused by the lower emission factors for waste collection used by Eisted *et al*. (2009) and that developed countries have better waste management systems than developing countries. In addition, Eisted *et al*. (2009) considered various factors such as the type of waste being transported and the distance travelled by the truck. This type of assessment is not applicable yet for developing countries because of data limitations. However, with continuing research there will be gaps filled and a database developed which will enable more detailed studies. In addition the results shown in Figure 20 were also compared with those from Freidrich and Trois (2015) for 2012, 2014 and 2020; the results obtained were higher than the study in comparison (about 40% higher). This difference is caused by the different data used for waste deposited in landfills where the overall tonnage for waste deposited in the three landfills used in this study is higher than that used by Freidrich and Trois (2015) even though both data sets were provided by DSW.

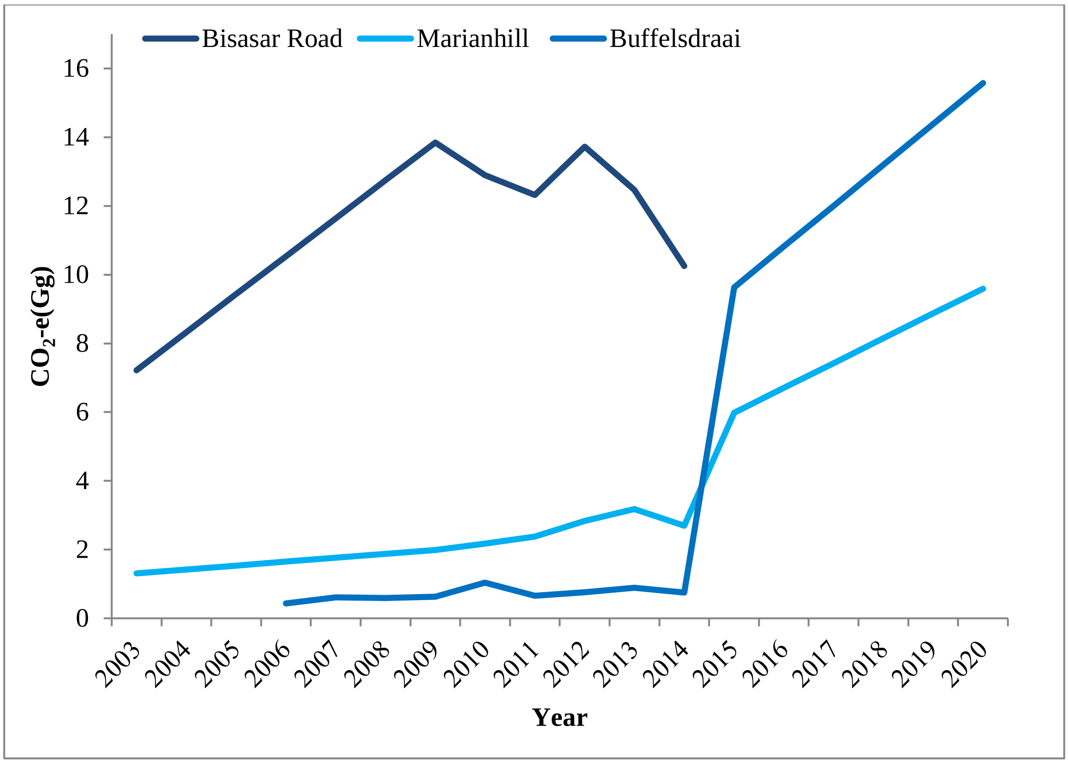


Figure 20: Emissions due to the collection and transport waste.

5.2.2 Landfill Emissions and Savings

5.2.2.1 Emissions derived using IPCC (2006) guidelines

The default starting year for CH_4 emissions for Bisasar Road and Marianhill landfills is 2005 while that of the Buffelsdraai landfill is 2008 this is because the IPCC (2006) assumes that the decay of organic material begins 6 months post deposition of waste. The emissions from 2004 for Bisasar Road and Marianhill and 2007 for Buffelsdraai were very small and could not be shown in the presented graph, but can be seen in Appendix B1. Figure 21 shows the cumulative CH_4 generated by each landfill; the Bisasar Road landfill is responsible for the highest emissions because it is the largest landfill in the municipality and has the largest waste deposition. Even though the GHG emissions for Buffelsdraai are least compared to the other landfills, an increase in emissions is expected upon closure of the Bisasar Road landfill in 2014 since 75% of the waste will be diverted there (IWMP, 2004; Couth *et al*. 2011; Freidrich and Trois, 2015). There is a clear increase in CH_4 emissions particularly for Bisasar Road 2005-2015 due to the application of the FOD model used and a decline after 2015 because the landfill was assumed to have closed in 2014 and no new depositions were made. The CH_4

emissions from Marianhill and Buffelsdraai continued to increase from the initial time till 2021 because waste deposited projections were made till 2020 and began decreasing from 2021-2030. The decrease in emissions is caused by the lack of data to be input into the model. Consequently, this shows us that the impacts of landfill emissions occur even when the landfill site has been closed (Füssel and Klein, 2006; Chalvatzaki and Lazaridis, 2009; CSIR, 2011; Rezaee *et al*. 2013). The FOD highlights that even though there will be no new waste deposited, emissions will still occur due to the waste already deposited. Therefore, the impacts of waste deposited today will affect future generations unless effectively mitigated.

The increase in CH_4 emissions shows that the municipal emissions due to increasing waste deposition are growing. This is because landfilling is a cheaper option when compared to other waste treatment options (Godfrey, 2015). Therefore, the growing quantities of waste deposited in landfills should not be ignored because as these continue to increase solid waste emissions will continue to grow and contribute to global climate change and its associated impacts. The emissions results obtained are larger than emissions calculated in the eThekwini GHG inventories (2010-2012) even though the same FOD principle was used. The difference in results particularly with the eThekwini inventory is that the eThekwini inventories considered LFG collection for the Bisasar Road and Marianhill landfills which reduce the results. Therefore the exclusion of the quantity of LFG recovered and lack of data is limiting factor towards the accuracy of the results obtained. The use of the FOD approach will result in an accumulation of data which will be beneficial to future GHG mitigation studies in the eThekwini waste sector.

The apportionment of emissions per waste category for each landfill is shown in Appendix (B1, 2 and 3) where it is obvious that food, garden and paper waste are responsible for most of the emissions. These wastes which are responsible for the highest emissions can be diverted from landfills through initiatives such as recycling and composting. The results obtained could not be compared to international studies which followed the same approach (Hoa and Matsouka, 2015) because these studies applied the IPCC model on a national level whilst for this study it was applied on a municipal level. Thus, the IPCC (2006) guidelines can be applied at municipal level provided the relevant municipal data are available.

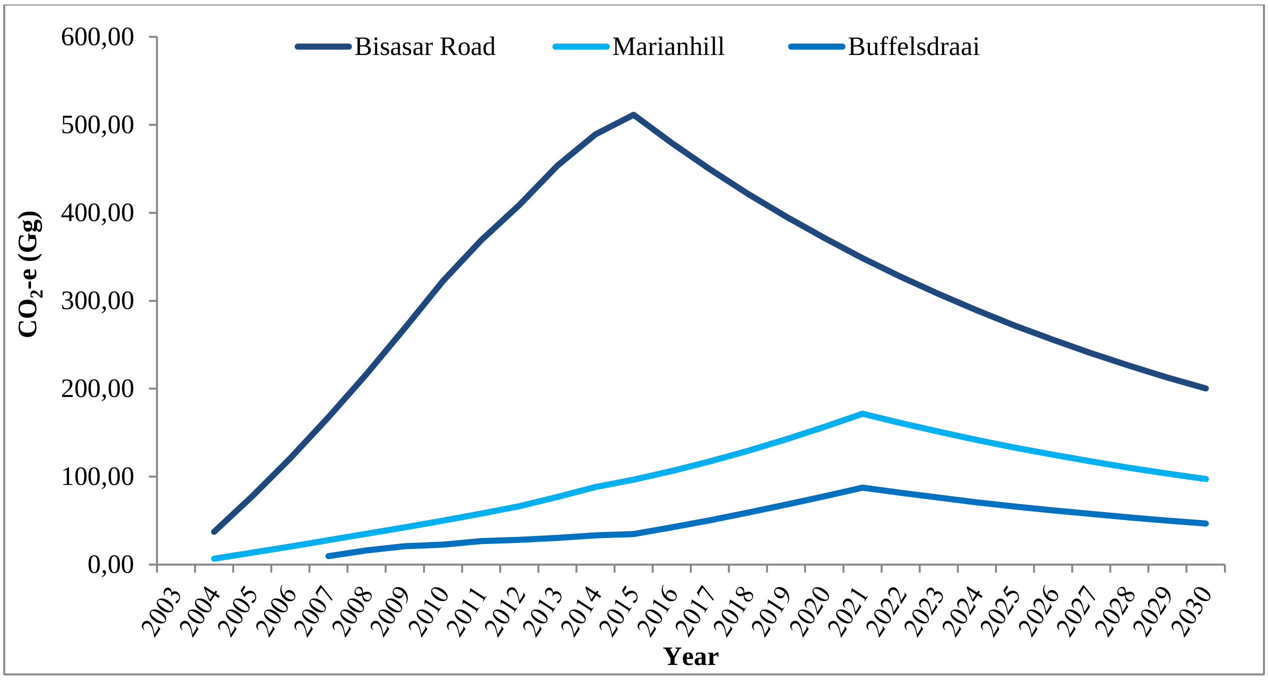


Figure 21: Annual CH_4 emissions for landfills

5.2.2.2 Emissions derived using emission factors for landfills in South Africa

The Bisasar Road landfill is responsible for the highest emissions because it is the largest landfill in the municipality and has the largest waste deposition. Figure 22 below shows GHG emissions from landfills without any GHG mitigation technology in place and it shows the continuously growing emissions from the landfills in the EM. The Bisasar Road landfill is predicted to have been closed in 2014 (IWMP, 2004; Couth *et al*. 2011; Freidrich and Trois, 2015) hence there are no future projections on landfill emissions. Figure 22 shows a sharp growth in emissions from Marianhill and Buffelsdraai landfills, which is caused by the diversion of waste as discussed in detail in section 4.2.2.1. The results obtained were compared with the results by Freidrich and Trois (2015) and were slightly higher (18%) but this is because the data used was 18% higher. The results were compared using the Buffelsdraai emissions for 2012 without LFG collection because it was presented in the article. Emissions from the Buffelsdraai landfill will continue to increase unless effective GHG reduction technologies are implemented. The results obtained from the Marianhill landfill could be lower when considering that this site has LFG capture and electricity generation systems in place. The results below show a business as usual scenario which could have negative impacts on the municipality and country at large. Furthermore, the results shown below show the GHG reduction potential of emissions from solid waste which contributes to 12% of the municipalities GHG emissions.

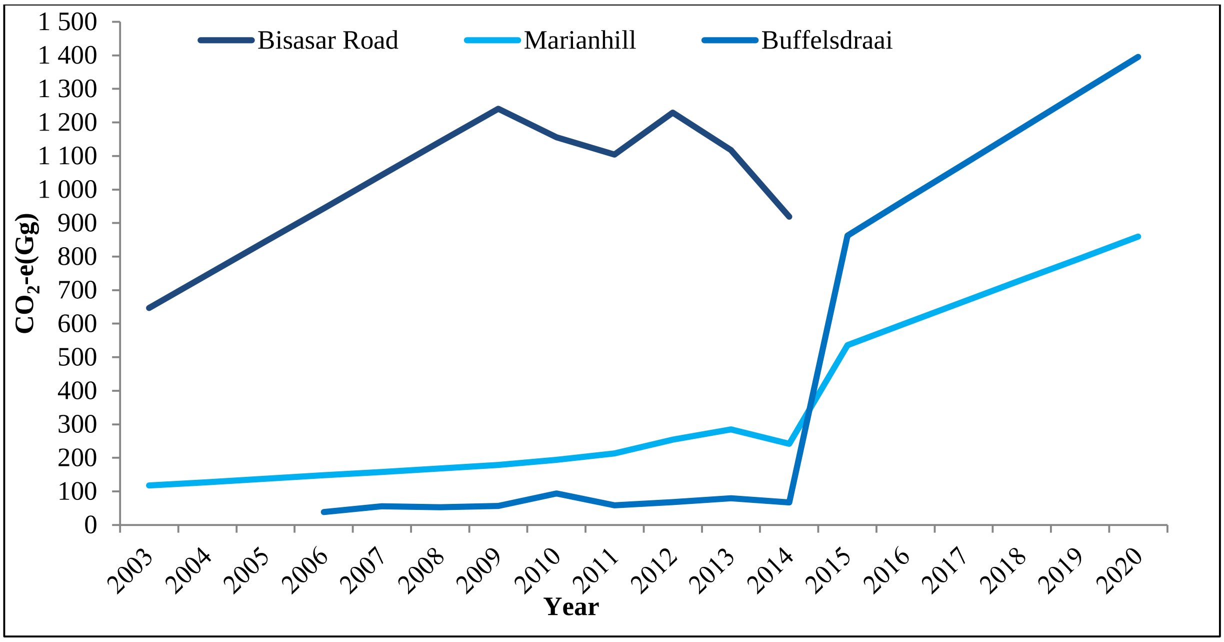


Figure 22: Annual CH_4 emissions for landfills

5.2.2.3 Landfill Emissions Savings

Table 21 shows the carbon emissions reductions that were claimed by the municipality. The emissions savings were not included in the model because LFG recovery began in 2007 in the Marianhill landfill and in 2008 in the Bisasar Road landfill yet the only information available was for 2010-2012. The CH_4 recovered shown highlights CH_4 emissions savings due to gas recovery from the CDM technology that is in place in the Bisasar Road and Marianhill landfills. The CH_4 recovered is the CH_4 destroyed from the landfills and converted to electricity and this electricity is sold to the municipality and claimed as CERs. According to Bond and Shariffe (2012) the Bisasar Road CDM project has 3.1 million CERs that are valued at US$15 million; therefore each CER is worth US$4.84. Using this information, it was calculated that the EM has generated US$3 453 380 from CDM-CER technology from the Bisasar Road and Marianhill landfills from 2010-2012. CDM technology is contributing to GHG mitigation and is recommended for the Buffelsdraai landfill which will take over from Bisasar Road when it reaches its maximum capacity. Furthermore, gas recovery should continue even when the landfill is closed because deposited materials will continue to decay even after closure of the landfill even though emissions will decline with time.

Table 21: CDM-CER Emissions savings ($GgCO_2$-e)

Landfill site	2010	2011	2012
Bisasar Road	232	200	193
Marianhill Park	26	34	26

The Bisasar Road and Marianhill landfills supply electricity to the municipality (Table 22) thus contributing to the Eskom grid. The electricity from landfills is being purchased from the Bisasar Road and Marianhill landfills because they are the only landfills with CDM technology in place within EM. Thus electricity generation contributes to the alleviation of electricity shortages in the EM (Gumbo and Simelane, 2015) and it provides an income for the municipality. It can further be said that electricity supplied by CDM projects results in overall emissions savings for the municipality's electricity consumption because of the reduced use of coal based electricity. Although this electricity supplied by Bisasar Road and Marianhill landfill sites contributes a minor percentage to the Eskom grid (Table 22), this however highlights the available potential for solid waste to be a significant contributor to the Eskom grid while reducing GHG emissions. This will be useful as it can provide households with electricity thus reducing the effects of load shedding to local communities. Furthermore, the renewable energy provided by landfills will reduce air pollution as well as other environmental problems caused by the use of fossil fuel based energy.

Table 22: Renewable energy purchase from LFG ($GgCO_2$-e/MWh)

Year	LFG purchases	% contribution to EM grid
2010	55	0.46
2011	46	0.38
2012	46	0.37

5.2.3 Electricity Consumption Emissions

The electricity emissions from all 3 landfills covered in this study are adopted from the eThekwini GHG inventories for 2010-2012 (Table 23). Individual landfill consumption was not available. There is a clear increase in electricity emissions by the landfills caused by increased electricity use where emissions have tripled from 2010 to 2012. These electricity emissions also include the electricity that is used while converting CH_4 to electricity (Trois and Jagarth, 2011). Electricity consumption emissions from landfills are minor when compared to transport and landfilling emissions; this is because electricity is used for basic purposes such as lighting and cooling in the offices. Waste studies often consider electricity produced from waste and not electricity consumed during solid waste management (Cherubbini *et al*. 2008; Tian *et al*. 2013; Freidrich and Trois, 2015). This is because the electricity consumed during solid waste management is minor compared to emissions from landfills. Electricity emissions not only result in GHG emissions but because South Africa uses coal derived energy, there are several environmental impacts associated with it that have been discussed in section 2.2.3.1.2 of the literature review. Therefore, the electricity produced from LFG should also be used within DSW because electricity consumption emissions could be zero since electricity is generated in the landfills. The use of electricity produced within landfills will also reduce the costs of electricity thus resulting in financial savings for the landfill sites.

Table 23: CO_2 emissions due to electricity consumption for DSW ($GgCO_2$-e/MWh)

Year	Electricity Emissions
2010	1
2011	2
2012	2

5.3 Wastewater

5.3.1 Emissions from wastewater processing

Based on the presented equations in section 4.3.2.1 emissions were estimated for the activities listed below during WWT within the EM where the BOD value was used to estimate the organic fraction in the wastewater. Tables 24 and 25 present estimated emissions from wastewater processing while Appendix B shows a breakdown of emissions caused by each WWT plant. The quality and quantity of the effluent and emissions depends on the population serviced, number of industries served by each treatment plant, the weather and population habits (Meneses *et al*. 2010; Salsabil *et al*. 2010). Thus, the former statement is used to explain why there are higher CH_4 emissions produced by the incomplete combustion of digester gas than from WWT lagoons. The extent of CH_4 and N_2O emissions varies depending on the country and the characteristics of the wastewater together with the treatment processes used (Cziepel *et al*. 1995).

Table 24 shows WWT lagoons, however GHG emissions from WWT lagoons are small because smaller quantities of wastewater are sent to lagoons. The majority of the CH_4 emissions are generated from anaerobic systems such as lagoons as well as anaerobic digesters where the captured biogas is not completely combusted (GHGISA, 2013). The large growth in emissions from the incomplete combustion of digester gas from 2010 to 2011 is caused by the growth in population serviced by some of the WWTPs during this period. From the results in Table 24 it is clear that emissions from the incomplete combustion of digester gas are responsible for the highest CH_4 emissions.

Table 24: CH_4 emissions due to wastewater processing ($GgCO_2$-e)

Process	2010	2011	2012	2013
Stationary emissions from Incomplete Combustion of Digester Gas	8	17	17	17
Process emissions from WWT lagoons[1]	0	0	0	0
Total	**8**	**17**	**17**	**18**

Table 25 indicates clearly that emissions from effluent discharge to rivers are responsible for the highest N_2O emissions. In addition emissions from WWTPs with nitrification/denitrification are higher than emissions from WWTPs without nitrification/denitrification. This was shown in other wastewater studies where Kampschreur *et al*. (2009) and Fine and Haddas, (2012) stated that process emissions for treatment plants with nitrification/denitrification are higher because a higher mass sludge is allocated to the digester therefore producing more biogas. Furthermore, nitrification and denitrification contribute to higher CO_2 emissions due to increased electricity usage. N_2O does not only contribute to global warming but according to Ravishankara *et al*. (2009) it also contributes to ozone depletion. This signifies the importance of reducing N_2O emissions from WWT thus minimising the effect on ozone depletion as well. The CH_4 emissions are produced when wastewater is handled under anaerobic conditions (El-Fadel and Massound, 2001; Daelman *et al*. 2013).

[1] The actual values are not presented as the emissions were negligible considering that decimal places were not used

Table 25: N_2O emissions estimated due to wastewater processing ($GgCO_2$-e)

Process	2010	2011	2012	2013
Process emissions from WWTPs with nitrification/denitrification	1	3	3	3
Process emissions from WWTPs without nitrification/denitrification	1	2	1	1
Process emissions from effluent discharge to rivers	8	9	9	20
Total	**12**	**13**	**13**	**24**

The EM discharges its effluent into rivers and the oceans which not only contributes GHG emissions but the ecotoxicity of the water as well. The discharge of wastewater into rivers which includes pollutants such as lead, mercury and manganese into water could result in cancer impacts for communities (Niero *et al*. 2014). In order to minimise the atmospheric and environmental impacts of WWT; a move from pollutant removal to resource recovery could potentially reduce the associated emissions (Meneses *et al*. 2010; Niero *et al*. 2014). This is because energy recovery from the resulting sludge does not only reduce the GWP of CH_4 and N_2O emissions but it also reduces GHG emissions associated with electricity production (Cziepel *et al*. 1995). Energy recovery from wastewater sludge is currently not practiced by the municipality; however the Northern, KwaMashu and Phoenix sites generate heat which is consumed within the WWTPs. In addition, the Northern, KwaMashu, Amanzimtoti and Phoenix treatment sites flare their biogas and release it into the atmosphere but the volume of biogas flared was not provided because according to the wastewater inventories there is no instrumentation which would enable them to determine the CH_4 fraction of the biogas and this limited the estimation of CH_4 converted into CO_2 which contributed to GHG mitigation. The flaring of sludge where electricity generation is not available is encouraged because CO_2 has a lower GWP than CH_4.

The Isipingo and Amanzimtoti treatment plants did in 2014 begin to quantify their biogas production rate and the average CH_4 selling price for electricity production and at the time there was insufficient data available to be used for this study. The flaring of sludge biogas is not the only GHG reduction option for WWT plants but land application of sewage sludge and the use of phyto-remedial technologies which could reduce the already high electricity consumption emissions can also be considered. According to Kalmykova *et al*. (2015) the spreading of sewage sludge on land has low environmental impact because it only requires machinery to transport and spread. However, the composition of the sludge must be thoroughly tested in order to test the phosphorus ontent to make sure that it would not be harmful to humans and the ecosystems (Niero *et al*. 2014; Kamlykova *et al*. 2015). These technologies have currently not been explored in South Africa however they have the potential to reduce emissions and provide associated benefits such as improved soil quality. Although often ignored, CH_4, CO_2 and N_2O emissions contribute to overall GHG emissions from the country. Several studies (Fine and Haddas, 2012; Risch *et al*. 2015; Niero *et al*. 2014) have considered the LCA assessment of the wastewater system which is recommended for future studies within the municipality.

5.3.2 Emissions due to electricity consumption

Table 26 shows CO_2 emissions caused by the consumption of coal derived electricity for all WWTPs in the EM where there is a clear increase in emissions from 2010-2012. GHG emissions from electricity use in WWTPs are the largest source of emissions for WWTPs when compared to process emissions from treatment. Even though CO_2 emissions from electricity consumption are the highest emissions for WWT, the higher GWP of non-carbon emissions increases the magnitude and impact of CO_2-e emissions. Fine and Haddas (2012) stated that CO_2 emissions due to electricity consumption are the main source of emissions from WWTPs in developed countries. Electricity in WWTPs is used for lights and buildings and the technology and processes used for treatment such as pumping, disinfection and aeration. Energy is also used for transporting the wastewater to the plant and the transport of treated wastewater to the distribution system (USEPA, 2013). The technology used for WWT is responsible for the large quantity of electricity used which results in a significant amount of emissions. The electricity used in WWTPs uses 27% of the municipality's' wastewater budget (Scheepers and vd Merwe-Botha, 2013).

Table 26: Electricity consumption emissions (GgCO_2-e)

Year	Emissions
2010	23
2011	31
2012	57

These high electricity emissions could be reduced by the use of electricity derived from the conversion of the biogas produced during treatment. Capturing energy in wastewater to generate heat and electricity will reduce the amount of fossil fuel derived energy to treat wastewater. Keller and Hartley (2003) and Fine and Haddas (2012) reported that the recovery and reuse of biogas generated in anaerobic processes could be a significant source of energy for WWTPs because the recovery and reuse of the produced biogas which contains CH_4 will minimise extra GHG emissions while providing a highly beneficial source. The use of biogas for electricity to be used in WWTPs can turn WWTPs into net zero users of energy. Thus wastewater is a significant resource and should no longer be regarded as a waste. Energy consumption in WWTPs can also be reduced by repairing sewer systems to prevent groundwater infiltration, improving equipment being used and water conservation (USEPA, 2013). Water conservation improves energy efficiency because there will be lower quantities of wastewater to be treated. Reducing energy use has environmental co-benefits because it will reduce the emission of GHG associated with fossil fuel derived electricity, save on electricity costs and conserve water. According to the USEPA (2013) improvements in the technology used can also reduce the emissions of GHG which will improve air and water pollution. WWTPs need to have energy improvement goals which will reduce their electricity use, such as implementing community educations programmes that will result in less water use. Equipment upgrades could result in energy efficiency. Further, an improvement of the infrastructure will help prepare for climate change related impacts thus assisting with adaptation for the infrastructure of WWTPs. WWTPs need to identify those processes that consume the most electricity so that energy use can be reduced. Aeration during secondary treatment of wastewater and pumping have been identified as the largest consumers of electricity in WWTPs (Scheepers and vd Merwe-Botha, 2013; USEPA, 2013).

5.3.3 Overall Emissions from WWT

The overall GHG contribution could be shown for the years 2011/2012 because there was sufficient information was available for all processes. The percentage contribution of each process towards the carbon footprint of WWTPs in the EM is seen in Figure 23. CO_2 emissions from electricity consumption were the highest contributors followed by CH_4 emissions and lastly N_2O emissions. Process emissions from WWT lagoons were very small in comparison and amounted to infinitesimals when considering significant figures and were thus not included in the graph. WWT lagoons do not only result in small CH_4 emissions but they utilise the least amount of electricity also (USEPA, 2013). In terms of GHG reduction WWT lagoons are regarded as the best method. Since electricity consumption is responsible for the highest emissions it highlights the need to develop methods that require less mechanisation which could be used to reduce these emissions and reducing a significant portion of WWT GHG emissions.

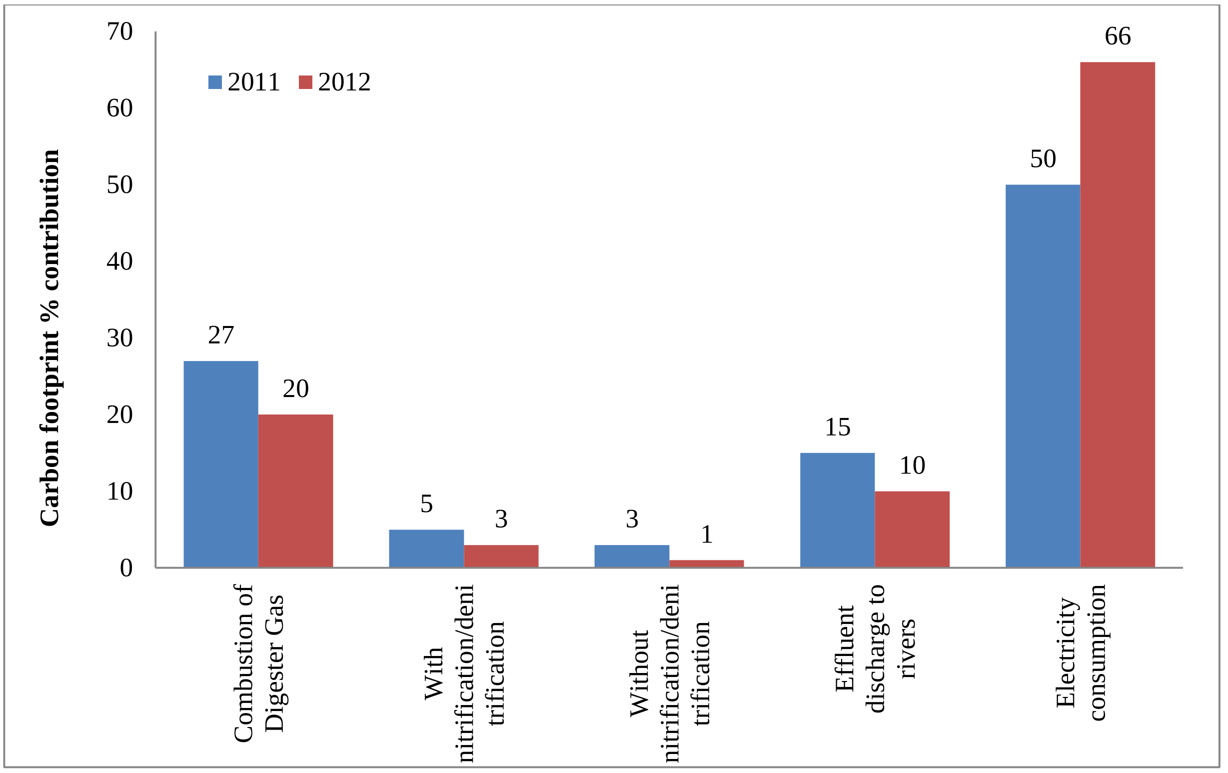


Figure 23: Percentage apportionment for WWT GHG emissions contributions

Even though scenario analysis for wastewater was not possible, some of the opportunities for climate change adaptation are discussed. Improved treatment of wastewater will reduce possible contamination of rivers it is discharged into, where with reduced water, rivers will have less ability to neutralise the incoming wastewater. River flooding is also an expected impact of climate change, where the reduced wastewater discharged and improved quality being discharged into rivers will lessen the impacts of river flooding on the surrounding environment due to contamination by heavy metals and other pollutants contained in the wastewater. Thus, the reduction of the quantity and improvement in the quality of wastewater reaching rivers could result in reducing loss of aquatic species. Furthermore, the effective treatment of wastewater and its recycling can reduce the burden of water scarcity during times of drought as it can be reused.

5.4 GHG mitigation scenarios

This section provides an assessment of GHG mitigation scenarios for the EM solid waste management by considering various factors that could potentially influence the reduction of emissions. Whilst the estimates produced within these scenarios may contain uncertainty due to data limitations, these scenarios provide useful indications of the potential for mitigation using different interventions. Furthermore, due to data limitations discussed earlier, scenarios were only established for municipal solid waste and not wastewater.

From the scenarios presented in Figures 24 to 26 it is clear that conventional landfills (baseline) are responsible for the highest emissions and this is in line with several other studies (Monnie *et al*. 2006; Chen and Lin, 2007; Menikrupa *et al*. 2013; Dedinec *et al*. 2015). The scenarios shown in the graphs below show the GHG emissions associated with each waste management option for the landfills considered. These mitigation scenarios presented show that all waste management scenarios (except the baseline) have associated environmental benefits especially in terms of GHG reduction. The Bisasar Road landfill is responsible for the largest CH_4 emissions because it is the largest landfill in the municipality and has the most waste deposited there. The decline in the emissions for 2012-2014 in the Bisasar Road landfill (Figure 24) is because it is nearing closure and thus less waste is being deposited there. From the projections made, the Buffelsdraai landfill will have the most emissions because of the diversion of waste to that site.

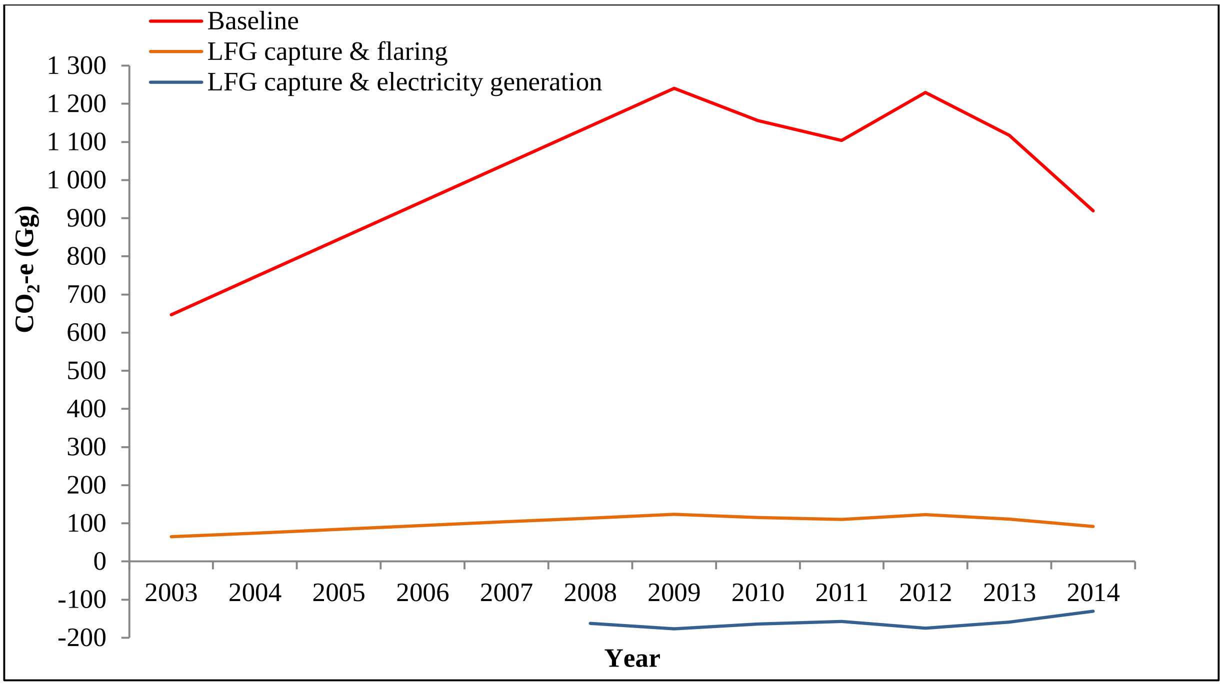


Figure 24: Annual CH_4 emission scenarios for the Bisasar Road landfill

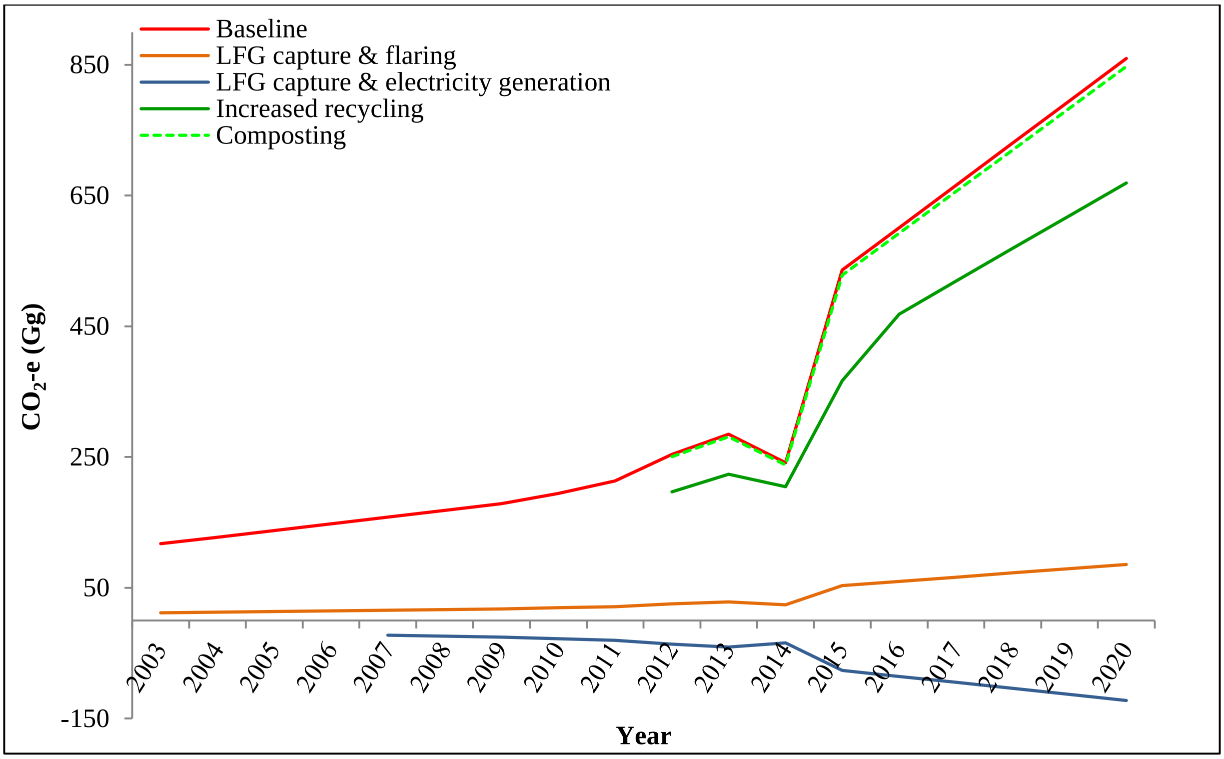


Figure 25: Annual CH_4 emission scenarios for the Marianhill landfill

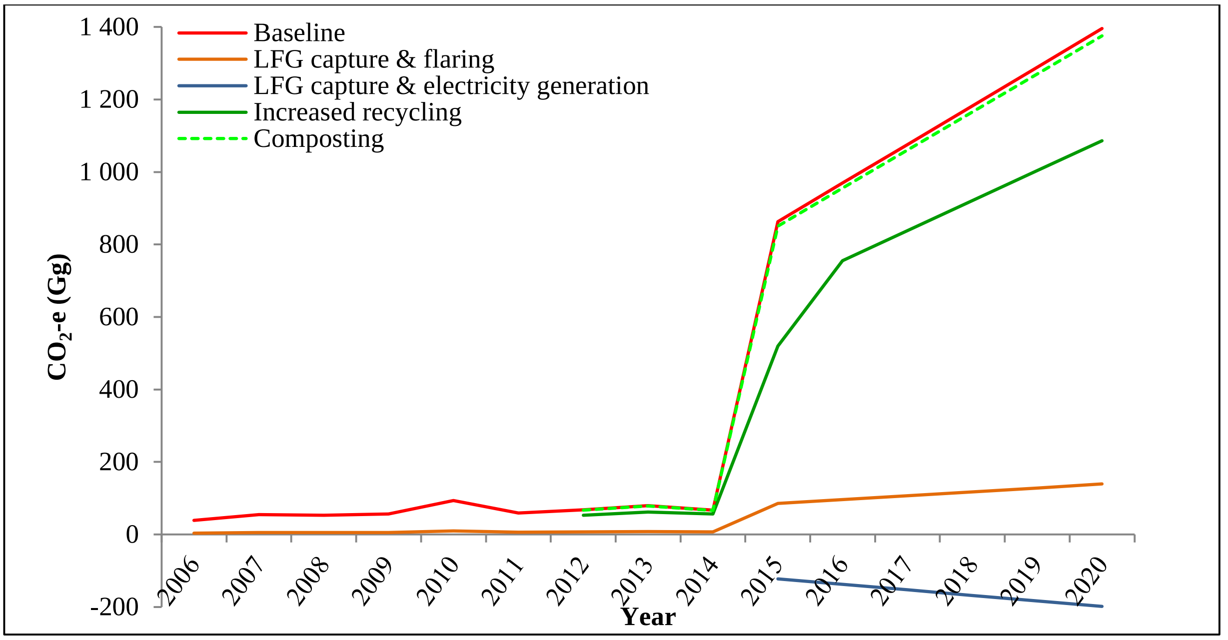


Figure 26: Annual CH_4 emission scenarios for the Buffelsdraai landfill

5.4.1 LFG Capture and Flaring

From the results presented in Figures 24-26 for all 3 landfills, LFG capture and flaring yields the second best results in terms of GHG reduction. LFG flaring was implemented in the Bisasar Road and Marianhill landfills without CDM/CER income in order to control the spread of LFG around facilities within the sites (Couth *et al*. 2011). However this has resulted in significant results for GHG reduction as seen in Figures 24-26. Thus LFG capture and flaring has co-benefits in that it not only reduces the spread of LFG as an odour but significantly reduces GHG emissions and other air pollutants released by LFG. Consequently LFG capture and flaring improves the air quality surrounding the landfill and reduces the spread of odour which can be an irritation to surrounding communities. The CO_2 released from flaring does not contribute to overall CO_2 emissions because it comes from the organic fraction of the waste which is biogenic in origin. Since CH_4 emission contributes to ozone depletion (Johari *et al*. 2012) the flaring of LFG has significant benefits for the absorption of ultra violet radiation by ozone in the upper levels of the atmosphere.

5.4.2 LFG Capture and Electricity Generation

LFG capture and electricity generation produces the best results in terms of GHG mitigation for solid waste management. This scenario yields the best results because of the negative value of the emission factor which indicates the possible savings. LFG capture and electricity generation also creates an income for the municipality due to CDM-CER income and it reduces the impacts associated with conventional fossil fuel derived electricity through the displacement of air pollutants and other GHGs thus improving air quality in surrounding area. Thus the implementation of CDM technologies such as LFG capture with electricity generation would be beneficial to the Buffelsdraai landfill which currently has no CDM in place whereas failure to implement will result in increased emissions. The implementation of LFG capture and electricity generation technology is extremely costly and can only occur through the assistance of CDM in developing countries (Trois and Jagarth, 2011); however it is also very effective for assisting towards adaptation through improved air quality which will be beneficial to those members of the community that are vulnerable to air pollution impacts. Further, electricity demand for the municipality continues to increase thus the electricity generated from LFG is a means of adaptation because it contributes to electricity supply thus alleviating the burden of demand on the municipality. Increased heat is predicted as a climate change impact for the municipality where hospitals and households utilise more electricity for cooling purposes, thus the electricity generated from LFG could for example be supplied to hospitals to improve conditions.

Although costly, this option proves to be the best particularly because of its associated co-benefits. In this study the use of LFG focused on electricity generation, however Ahmed *et al*. (2015) states that other means of utilising LFG such as combined heat and power generation, steam generation, LFG piping, methanol and H_2 and production are also viable options which need to be further explored and considered. The profitability, implementation costs and social and environmental benefits need to be evaluated where the most suitable option is implemented within each municipality.

5.4.3 Recycling

Increased recycling produces the third best results for reducing GHG emissions when compared to the other scenarios. The effects of increased recycling are seen from 2012 as per the data used. Recycling results in GHG reduction because of the avoidance of the production of raw materials (Carvahlo and Marques, 2014). Recycling reduces emissions by reducing the quantity of waste particularly organic waste being landfilled thus extending the lifespan of the landfill. Monnie *et al*. (2006) stated that the effects of recycling are seen by reducing the quantity of waste deposited. Recycling certain materials such as glass is more costly than conventional landfilling but it is preferred because of the environmental and social benefits such as job creation for informal recyclers (Nahman, 2011). This is why it is at the top of the waste management hierarchy. Recycling of materials will be beneficial to the Buffelsdraai landfill which currently has no gas capture and flaring or electricity generation facilities in place. The recycling of materials such as paper will reduce the organic component of waste that is responsible for CH_4 emissions. Therefore, the recycling of paper is encouraged because the landfilling of paper results in higher emissions than when it is recycled (Lehtila *et al*. 2007; Freidrich and Trois, 2015). The implementation of the DSW and Mondi orange recycling bags initiative has contributed to increased recycling within the municipality and it has also encouraged separation of waste by households. The recycling of materials encourages community education and it promotes waste separation thus contributing to increased composting rates also. Further, recycling reduces the quantity of landfilled waste thus contributing towards sustainable landfilling and consequently results in operation costs savings for the municipality (Couth and Trois, 2010). GHG emissions savings due to recycling the fraction of municipal solid waste are seen in Table 27, therefore does not only reduce emissions in landfills but offsets and reduces overall GHG emissions.

Table 27: Overall emissions savings due to recycling ($GgCO_2$-e)

Year	Bisasar Road	Marianhill	Buffelsdraai	Total
2012	-439	-90	-24	-546
2013	-413	-105	-29	-548
2014	-352	-92	-25	-470
2015	0.00	-208	-335	-544
2016	0.00	-237	-382	-619.
2017	0.00	-266	-431	-697
2018	0.00	-296	-480	-776
2019	0.00	-327	-531	-858
2020	0.00	-379	-616	-991

5.4.4 Biological Treatment of Solid Waste (Composting)

Composting has the lowest GHG reduction potential from the scenarios shown in Figures 24-26. The effects of composting are seen from 2012 onwards because this is when it is assumed to have begun within the municipality. Only the Marianhill and Buffelsdraai landfills were considered to have composting. In order to maximise composting the source separation of waste is encouraged from household level. As seen in Table 28 composting of the fraction of garden waste resulted in net emissions, however Barton *et al*. (2007) states that the offset in terms of GHG reduction for composting is seen in its application as a soil conditioner. Lehtila *et al*. (2007) stated that GHG emissions from landfilling and composting of yard waste are slightly comparable as can be seen in the baseline and composting scenarios, however composting results in notably lower emissions compared to conventional landfilling and it provides a product which can be sold thus providing an income for the municipality. Emissions caused by composting are less than those that would have occurred had the garden waste been landfilled. For instance if 8% of the garden waste was landfilled in 2020 it would have resulted in higher emissions of 12 381and 20 096tCO_2-e for Marrianhill and Buffelsdraai respectively versus the 2 and 4 $GgCO_2$-e produced from composting. Even though the GHG reduction capacity of composting is small, Dedinec *et al*. (2015) states that it has other benefits such as reducing the use of inorganic fertilisers and air pollution. Further, the reduction of organic landfilled waste will reduce the leachate being produced in landfills where the seepage of this leachate could contaminate groundwater (Baker *et al*. 2015; Hong *et al*. 2015) thus resulting in less water available for use and improved costs for the purification of water. Thus composting contributes towards risk and vulnerability support and would support adaptation. When comparing the projected emissions for 2020 with those from Freidrich and Trois (2015), the results shown is Table 30 are lower because the data used were smaller.

Table 28: GHG emissions due to composting of waste ($GgCO_2$-e)

Year	Marianhill	Buffelsdraai
2012	1	0[1]
2013	1	0[1]
2014	1	0[1]
2015	1	2
2016	2	3
2017	2	3
2018	2	3
2019	2	3
2020	2	4

The fraction of waste which can be composted is one of the largest sources of GHG emissions from landfills, therefore composting not only reduces GHG emissions but it reduces nuisances such as landfill leachate, odour as well as vectors such as rats which are attracted by this waste type (Tian *et al*. 2013). Composting of the organic fraction of waste not only reduces emissions but also creates landfill space and extends the lifespan of the landfill. However, composting requires great capital investment where an anaerobic digestion plant costs less to implement and will make a larger profit (Trois and Jagarth, 2011). The profit however depends on the established market for composting. Thus due to less costs anaerobic digestion plants have more advantage over composting plants. According to Tian *et al*. (2013) the most significant problem associated with composting is the discharge of odorous gases mainly emitted by anaerobic composting processes. The costs and environmental benefits associated with composting make it a preferred treatment method to be implemented within the EM. Thus the creation of a market for composting within the EM will ensure long-term economic viability and sustainability thereof (Trois and Jagarth, 2011). Composting is suitable for the EM because of the large fraction of organic waste in the municipal waste stream. Furthermore, composting does not only have to occur at composting plants but it can also occur at household level and it will improve soil conditions for subsistence farming while it promotes source separation of waste.

5.5 Summary

The outcomes of the calculated emissions from solid and wastewater are based on the IPCC (2006) guidelines, ICLEI principles as well as the use of municipality specific emission factors by Frederich and Trois (2013a, b). Where the appropriate data could not be accessed the results from the EM inventories were used in order to show waste sector emissions. Landfills were responsible for the highest emissions, followed by the collection and transport of waste with electricity consumption having the lowest emissions for solid waste emissions. Consequently electricity consumption was responsible for the highest emissions due to WWT followed by emissions from the incomplete combustion of digester gas, then emissions from WWTPs without nitrification/denitrification while WWTPs with nitrification/denitrification and WWT lagoons had were responsible for the lowest emissions. GHG mitigation scenarios were developed for solid waste in order to show the GHG reduction potential of the different waste management scenarios and the associated co-benefits. These mitigation scenarios showed that with no intervention GHG emissions from the Marianhill and Buffelsdraai landfills will increase by 60% in 2020. LFG capture with electricity generation gave the best GHG reduction results, but the costs associated with implementation are a major disadvantage particularly for cities in developing countries. This is why other solid waste treatment options such as LFG capture with flaring, increased recycling and composting which also result in a reduction of emissions have to be considered. GHG mitigation scenarios were not created for WWT but the growing emissions show that mitigation is required particularly because it could have associated co-benefits with it also. GHG mitigation scenarios were not presented for wastewater due to the lack of data.

Furthermore, the contribution of climate change mitigation in the waste sector towards climate change adaptation was highlighted Although a minor contributor of emissions the waste sector also contributes to climate change adaptation in the city where improved wastewater management could result in more water available.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

This research is aimed at providing useful information to waste managers within the municipality that will encourage the assessment of alternatives to landfilling while highlighting the environmental and social benefits that will assist with adapting to climate change. This study also provides information pertaining to the treatment of wastewater and the emissions associated with it. Furthermore, various means of climate change adaptation in the municipality were assessed for how the waste sector can contribute towards adaptation. This chapter will provide and outline of the findings of this study, to show that the specified objectives were met and it will provide recommendations for future studies in the waste sector.

6.2 Summary of results

6.2.1 Characterisation of GHG emissions from the waste sector

The first objective of this research was to develop a comprehensive understanding of GHG emissions related to the waste management sector in EM. In order to achieve this, data were collected from the DSW and the eThekwini Energy Office for the quantification of these emissions and the identification of the major sources of emissions for both solid waste management and WWT.

In order to quantify emissions for solid waste management, the IPCC (2006) guidelines were used together with the emission factors developed by Freidrich and Trois (2013a, b) for South Africa. Chapter 2 of the IPCC guidelines was used to calculate GHG emissions associated with transport in DSW based on fuel use while Chapter 3 was used to calculated landfill emissions based on FOD principle. From analysis of the data from solid waste it was shown that landfills are responsible for the highest emissions within this sector while emissions caused by collection and transport of solid waste or fuel use and electricity consumption were relatively small. However the emissions caused by landfilling showed that is great potential for GHG mitigation with associated benefits.

In order to achieve this objective for WWT, data was adopted from the EM inventories which used ICLEI principles for quantification. GHG emissions from WWT were quantified for electricity production and the WWT processes. Electricity consumption is responsible for the highest wastewater GHG emissions due to the treatment processes. CH_4 emissions were the second highest contributors of emissions from WWT, mostly due to the incomplete combustion of digester gas. N_2O emissions were the lowest emissions; the processes responsible for the production of this gas in descending order are effluent discharge into rivers, WWTPs without nitrification/denitrification and WWTPs with nitrification/denitrification. The emissions from WWT plants are linked to the number of people serviced by each treatment plant where those plants with servicing the most people had the most emissions. This is why those treatment plants with nitrification/denitrification had lower emissions than those plants without nitrification/denitrification.

6.2.2 Identification of interventions to reduce GHG emissions in the waste sector

The second objective of this study was to identify interventions that can be implemented in the city that will contribute to the reduction of GHG emissions from the waste sector by using innovative technologies that will help build climate change resilience and improve waste management. In order to do this, GHG mitigation scenarios were created for solid waste management which showed the benefits of various waste management options that reduced GHG emissions. Landfilling with LFG capture and electricity production provided the best results in terms of GHG reduction. LFG capture with electricity generation within the EM has been successful and even contributes to the municipalities Eskom grid. However, other methods of waste management such as LFG capture with flaring, recycling and composting also showed GHG reduction with co-benefits that could assist the municipality with adapting to climate change or reducing the impacts thereof at a lower cost. Increased recycling proved to have the second lowest GHG reduction capability even though it would reduce emissions by 37%. However, recycling is at the top of the waste management hierarchy because of its associated co-benefits namely: the reduction of fossil fuel use due to the production of virgin materials and job creation for the informal sector. Consequently, composting and recycling both encourage the source separation of waste thus resulting in integrated and more effective waste management. Composting is a method which needs further exploration for both solid waste and wastewater sludge because of its relatively low cost implementation and the avoidance of the use of inorganic fertiliser.

Table 29: Table showing the co-benefits of GHG mitigation from solid waste

Waste Management Type	**Benefit**	**Co-benefit**	**Disadvantage**
LFG capture and flaring	Reduces CH_4 emissions in the atmosphere	• Reduces odours from landfills • Reduces air pollutants from LFG	Implementation is costly
LFG capture and electricity generation	GHG mitigation	• Reduces odours from landfills • GHG mitigation • Produce electricity • Municipality generates income through CDM-CER • Reduces air pollutants from LFG • Reduces impacts associated with fossil fuel produced electricity	Costly, requires CDM funding
Recycling	GHG mitigation	• Extend lifetime of landfill site • Job creation (informal workers) • Cleaner communities • Reduces electricity used at production stage	Costly to implement
Composting	CH_4 and CO_2 emissions reduction	• Cheaper priced compost • Combats land degradation • Reduce air pollution • Job creation • Carbon sink • Mitigate groundwater contamination	• Overemphasis on mechanised labour • No market for compost

Although various mitigation options were presented for solid waste management, an integration of these different waste management options will yield better results for the environment and society at large. Integrated waste management will produce the best GHG reduction and waste management.

In order to achieve this second objective for WWT no mitigation scenarios were explored due to the lack of available data, however the Amanzimtoti, Northern and WWTPs that flare their biogas and some of it is also used to generate heat that is used within the WWTPs. This minimises the emission of CH_4 being released in the atmosphere. However, sufficient data was not available to quantify the advantages of these processes where only the Amanzimtoti began collating data on the quantity of biogas flared in January 2014. Thus future studies will benefit from this. There lies great potential for further research on the various WWT options such as phyto-remediation, composting of sewage sludge and incineration of wastewater sludge with electricity production which could potentially reduce GHG emissions while providing significant co-benefits for the municipality.

6.2.3 Climate change risk, vulnerability and adaptation in the EM

The third objective of this study was to develop an understanding of climate change risk and vulnerability and the adaptation measures required to build the resilience of communities. In order to achieve this an extensive analysis of literature and available information of climate change adaptation was undertaken. This enabled the identification of the risks and vulnerabilities experienced by the municipality and communities at large. Since the EM is a coastal municipality it is highly vulnerable to climate related impacts, sea level rise and storm surges. Furthermore, the waste sector is also at risk of climate change impacts particularly due to increased heat, extreme rainfall and drought. In addition, the contribution of the waste sector towards climate change adaptation was highlighted where the provision and use of inorganic fertiliser to rehabilitate the soil during could significantly benefit subsistence farming. The provision of electricity by landfills and possibly WWT plants in the future could help ease the energy demand from Eskom. ISWM and improved WWT will reduce the environmental and socio-economic impacts caused by the waste sector. The integrated management of solid waste and wastewater will reduce GHG emission thus slowing down the process of climate change. Furthermore, it was shown that the co-benefits of climate change mitigation in the waste sector assist with climate change adaptation for the entire municipality and country thus supporting the notion of "think globally and acting locally".

6.3 Study limitations and recommendations

6.3.1 Limitations

A major limitation to the use of the IPCC spreadsheet (software) for this study is that it requires data for at least 50 years to increase the accuracy of the results, which was not available for the EM. The lack of data for previous years introduces a significant degree of uncertainty, thus the gathering of historical and current data from municipal landfill sites is recommended as it will strengthen GHG quantification as well as mitigation and adaptation studies overall.

For WWT, when quantifying these emissions only the operational stage was considered because often wastewater studies (Foley *et al*. 2010; Niero *et al*. 2014) consider only the operational stage due to data limitations. Furthermore, residual sludge produced after the WWT process was not included in this study as there was no information pertaining to it. Information on the residual sludge would have enabled the calculation of the electricity production capacity of biogas produced by the wastewater sludge thus reducing the non-renewable energy used during treatment or whether or not this sludge could be substituted for inorganic fertiliser. In addition, GHG mitigation scenarios on existing biogas flaring and heating within some WWTPs could not be conducted due to data limitations.

6.3.2 Recommendations

6.3.2.1 Interventions needed in EM

In the EM as in many other municipalities within developing countries, the availability and quality of data are major limitations for studies in (Bogner *et al*. 2007; Freidrich and Trois, 2013a). It is recommended that managers at all levels of government develop policies that will result in the collation of data for solid waste and WWTPs. This will benefit future studies in this sector.

LFG capture and electricity generation is not available in most South African landfills because it requires the assistance of CDM funding it is recommended that awareness is created for other options such as composting which has lower implementation costs. Furthermore, LFG capture and flaring is also recommended because of its lower implementation costs compared to electricity generation and because of its ability to reduce GHG emissions.

ISWM is recommended because it will result in extensive contribution towards climate change mitigation and resource recovery (Menikrupa *et al*. 2013). This is because each waste management process complements and impacts the other process.

The adoption of incentives and awareness programmes to the public will improve participation of the community particularly towards waste separation which encourages activities such as recycling, composting and waste incineration (Carlson *et al*. 2015; Morgadinho *et al.* 2015).

Since waste management budgets are insufficient (Trois and Jagarth, 2011), waste management practices that will result in an income or other indirect benefits for the waste sector are recommended for the EM.

The development of an appropriate framework that would enable the prioritisation of waste management practices and technologies that would maximise GHG reduction and be suitable for local socioeconomic conditions is needed for developing countries (Dedinec *et al*. 2015).

6.3.2.2 Future research

There is a lack of studies on the GHG mitigation potential of WWT in the EM and South Africa and therein lies great potential for further research which could lead to implementation of improved WWT practices.

Several LCA studies on WWT have identified data quality and availability as problems when compiling the lifecycle inventory (Corominas *et al*. 2013; Niero *et al*. 2014). Further, the lack of sufficient data limited analysis and exploration of the extent to which the wastewater sector can contribute towards GHG mitigation. Therefore the development of country specific emission factors could reduce this gap caused by insufficient data.

LCA studies and life cycle impacts assessments on solid waste and wastewater management are recommended for South African municipalities because they would show areas responsible for the most impacts and those areas with the most GHG reduction potential which would simultaneously reduce social, economic and environmental impacts/burden.

Other waste management options such as incineration, gasification and pyrolysis were not considered because they are not carried out in South African municipalities however future studies on their impacts are encouraged as these options could be beneficial to waste management.

References

Ackerman, F. 2000. Waste management and climate change. *Local Environment,* 5, 223-229.

Adger, W. N. 2006. Vulnerability. *Global Environmental Change.*16, 268–281.

Agamuthu, P. 2013. Landfilling in developing countries. *Waste Management & Research.* 31, 1-2.

Ahmed, S. I., Johari, A., Hashim, H., Mat, R., Lim, J. S., Ngadi, N. and Ali, A. 2015. Optimal landfill gas utilization for renewable energy production. *Environmental Progress & Sustainable Energy.* 34, 289-296.

Al-Amin, A.Q. and Leal Fihlo, W. 2014. A return to prioritising needs: Adaptation or mitigation alternatives? *Progress in Development studies*. 14, 359-371.

Al-Amin, A. Q., Rasiah, R. and Chenayah, S. 2015. Prioritizing climate change mitigation: An assessment using Malaysia to reduce carbon emissions in future. *Environmental Science & Policy.* 50, 24-33.

Alley, R., Bernsten, T., Bindoff, N.L., Chen, Z., Chidthaisong, A., Friedlingstein, P., Gregory, J., Hegerl, G., Heimann, M., Hewitson, B., Hoskins, B., Joos, F., Jouzel, J., Kattsov, V., Lohmann, U., Manning, M., Matsuno, T., Molina, M., Nicholls, N., Overeck, J., Qin, D., Raga, G., Ramaswamy, V., Ren, J., Rusticucci, M., Solomon, S., Somerville, R., Stocker, T.F., Stott, P., Stouffer, R.J., Whetton, P., Wood, R.A. and Wratt, D. 2007. Climate change 2007: The physical science basis, Summary for Policy Makers. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change / IPCC WGI Fourth Assessment Report.*

Angelini, T., Gardiner, A., Wesselink, B. and Bates, J. 2009. Methane emissions in the waste sector. Sectoral Emission Reduction Potentials and Economic Costs for Climate Change (SERPEC-CC).

Ashfaq, A., Mohammad, S., Kaifiyan, M. and Maheshwari, A. 2015. Evolution, impacts and sustainability assessment of renewable energy. *International Journal of Current Microbiology and Applied Sciences.* 4, 610-616.

Ashton, P.J., Roux, S.P., Oelofse, S.H.H. and Hill, L. 2012. An Overview of Water and Wastewater Treatment in South Africa (Version 2.0). Contract Report – dated February 2012 – to the Chief Directorate: Science & Technology for Economic Impact, Department of Science and Technology, Pretoria, South Africa, by CSIR – Natural Resources and the Environment, Pretoria, South Africa. Report No. CSIR/NRE/WR/ER/2012/0002/A. ii + 34 pp.

Awuor, C. B., Orindi, V. A. and Adwera, A. O. 2008. Climate change and coastal cities: the case of Mombasa, Kenya. *Environment and Urbanization.* 20, 231-242.

Ayers, J.M. and Huq, S. 2008. The Value of Linking Mitigation and Adaptation: A Case Study of Bangladesh. *Environmental Management*. 43, 753–764.

Ayers, J. 2010. Understanding the Adaptation Paradox: Can Global Climate Change Adaptation Policy be Locally Inclusive. Doctor of Philosophy, Department of International Development. The London School of Political Economics and Political Science. [Online] Available: http://etheses.lse.ac.uk/393/1/Ayers_Understanding%20the%20Adaptation%20Paradox.pdf [Accessed: 22/05/2015].

Barr, R., Fankhauser, S. and Hamilton, K. 2010. Adaptation investments: a resource allocation framework. *Mitigation and Adaptation Strategies for Global Change.* 15, 843-858.

Barton, J.R., Issaias, I. And Stentiford, E.I. 2007. Carbon-Making the right choice for waste management in developing countries. *Waste Management.* 28, 690-698.

Bebb, J. and Kersey, J. 2003. Potential impacts of climate change on waste management. Environment Agency. [Online] Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/290358/sx1-042-tr-e-e.pdf [Accessed: 07/08/2014].

Baker, R.J., Reilly, T.J., Lopez, A., Romanok, K. and Wengrowski, E.W. 2015. Screening tool to evaluate the vulnerability of down-gradient receptors to groundwater contaminants from uncapped landfills. *Waste Management*. 43, 363-375.

Biesbroek, G. R., Termeer, C. J., Klostermann, J. E. and Kabat, P. 2014. Analytical lenses on barriers in the governance of climate change adaptation. *Mitigation and adaptation strategies for global change.* 19, 1011-1032.

Blaikie, P., Cannon, T., Davis, I. and Wisner, B. (Eds.). 2014. *At risk: natural hazards, people's vulnerability and disasters.* London and New York. Routledge.

Blake, S., Davidson, P., Greenwood, D. and Wade, N. 2015. *Climate change risks in electricity networks*.

Blengini, G.A. 2008. Using LCA to evaluate impacts and resource conservation potential of composting: a case study of the Asti District in Italy. *Resources, Conservation and Recycling.* 52, 1373–1381.

Blight, J. and Mussane, I. 2007. Sustainability and recycling in poor communities: a case study in the Eastern Cape, South African. In: Managing Solid Wastes in Developing Countries. Diaz, L.F., Eggerth, L.L. and Savage, G.M. (Eds.). CISA Publisher, Padova, Italy, 202–213.

Bock, E., Schmidt, I., Stuven, R. and Zart, D. 1995. Nitrogen loss caused by denitrifying nitrosomonas cells using ammonium or hydrogen as electron donors and nitrite as electron acceptor. *Archives of Microbiology.* 163, 16–20.

Bogner, J., Abdelrafie Ahmed, M., Diaz, C., Faaij, A., Gao, Q., Hashimoto, S., Mareckova, K., Pipatti, R. and Zhang T. 2007. Waste Management. In*: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Metz, O.R.D., Bosch, P.R., Dave R. and

Meyer, L.A. (Eds.). Cambridge University Press, Cambridge.

Bogner, J., Pipatti, R., Hashimoto, S., Diaz, C., Mareckova, K., Diaz, L., Kjeldsen, P., Monni, S., Faaij, A. and Gao, Q. 2008. Mitigation of global greenhouse gas emissions from waste: conclusions and strategies from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. Working Group III (Mitigation). *Waste Management & Research.* 26, 11-32.

Boldrin, A., Andersen, J. K., Moller, J., Faviono, E. and Christensen, T. H. 2009. Composting and compost utilization: accounting of greenhouse gases and global warming contributions. *Waste Management & Research*.00, 1-13.

Bond, P. and Sharife, K. 2012. Africa's biggest landfill site: the case of Bisasar Road. Le Monde Diplomatique. [Online] Available: http://mondediplo.com/blogs/africa-s-biggest-landfill-site-the-case-of [Accessed 01/20/2015 2015].

Boonsong, K. and Chansiri, M. 2008. Domestic wastewater treatment using vetiver grass cultivated with floating platform technique. *Assumption University: Journal of Technology.* 12, 73-80.

Botes, A. and McKenzie, M. 2013. Durban Climate Change Strategy Waste and Pollution Theme Report. Environmental Planning and Climate Protection Department. eThekwini Municipality: Energy Office. [Online] Available: http://www.durban.gov.za/City_Services/energyoffice/Documents/DCCS%20Waste%20and%20Pollution%20Theme%20Report.pdf [Accessed: 03/03/2015].

Botha, M.F., Biyela, S.L., Fry, M.R. and Paladh, R. 2011. Sewage-sludge incineration in South Africa using a fluidized-bed reactor. A paper in the proceedings of a conference on fluidization 315. 16–17 November 2011, Johannesburg, South Africa

Boughedir, S. 2015. Case study: disaster risk management and climate change adaptation in Greater Algiers: overview on a study assessing urban vulnerabilities to disaster risk and proposing measures for adaptation. *Current Opinion in Environmental Sustainability.* 13, 103-108.

Bovea, M.D., Ibanez-Fores, V., Gallardo, A. and Colomer-Mendoza, F.J. 2010. Environmental assessment of alternative municipal solid waste management strategies. A Spanish case study. *Waste management.* 30, 2383-2395.

Bowyer, P., Schaller, M., Bender, S. and Jacob, D. 2014. Adaptation as Climate change Risk Management: Methods and Approaches. *Handbook of Climate Change Adaptation.* Springer. 1-8.

Brion, N., Verbanck, M.A., Bauwens, W., Elskens, M., Chen, M. and Servais, P. 2015. Assessing the impacts of wastewater treatment implementation on the water quality of a small urban river over the past 40 years. *Environmental Science and Pollution Research*. 22, 12720-12736.

Brown, K., Adger, W.N., Boyd, E., Corbera-Elizalde, E. and Shackley, S. 2004. How do CDM projects contribute to sustainable development? Technical Report 16. Tyndall Centre for Climate Change Research, Manchester, UK.

Brooks, N. 2003. Vulnerability, risk and adaptation: A conceptual framework. Tyndall Centre for Climate Change research. Working Paper 38.

Brooks, N.,_Neil Adger, W. and Mick Kelly, P. 2005. The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. Global Environmental Change. 15, 151–163.Broto, V. C., Boyd, E. and Ensor, J. 2015. Participatory urban planning for climate change adaptation in coastal cities: lessons from a pilot experience in Maputo, Mozambique. *Current Opinion in Environmental Sustainability,* 13**,** 11-18.

Buffelsdraai Community Reforestation Project (BCRP). 2015. The official website of the eThekwini Municipality. [Online] Available: http://www.durban.gov.za/City_Services/development_planning_management/environmental_planning_climate_protection/Projects/Pages/Buffelsdraai-Community-Reforestation-Project.aspx [Accessed 07/04/2015].

Bulkeley, H. and Newell, P. (Eds.) 2015. Introduction. In*: Governing Climate Change.* Second edition. New York: Routledge.

Cakir, F. and Stenstrom, M. 2005. Greenhouse gas production: a comparison between aerobic and anaerobic wastewater treatment technology. *Water Research,* 39**,** 4197-4203.

Carapina, H. S., Stepanov, J., Prokic, D. C., Curcic, L., Zugic, N. V. and Mihajlov, A. N. 2014. Importance of Municipal Waste Data Reliability in Decision Making Process Using LCA Model-Case Study Conducted in Timok County (Serbia). *International Journal of Waste Resources*. 4, 166.

Care International in Vietnam (CARE Vietnam). 2013. Climate vulnerability and capacity of ethnic minorities in the northern mountainous region of Vietnam. [Online] Available: http://www.care.org/sites/default/files/documents/CC-2013-VNM-CARE_ClimChg_Vietnam.pdf [Accessed: 07/09/2015].

Cavan, G., Bultin, T., Gill, S., Kingston, R. and Lindley, S. 2015. Web-GIS Tools for Climate Change Adaptation Planning in Cities. *Handbook of Climate Change Adaptation*. W. Leal Filho, W. (Ed.). 2161-2191.

Chalvatzaki, E. and Lazaridis, M. 2009. Assessment of air pollutant emissions from the Akrotiri landfill site (Chania, Greece). *Waste Management and Research*. 00, 1-11.

Chapman, L. 2007. Transport and climate change: a review. *Journal of transport geography.* 15, 354-367.

Cheng, H. and Hu, Y. 2010. Municipal solid waste (MSW) as a renewable source of energy: Current and future practices in China. *Bioresource Technology.* 101, 3816-3824.

Chen, T.C. and Lin, C.F. 2007. Greenhouse gases emissions from waste management practices using Life Cycle Inventory model. *Journal of Hazardous Material.* 155, 23–31.

Chen, T. and Lin, C. 2010. CO_2 Emissions from municipal solid waste incinerator: IPXX formula estimation and flue gas measurement. J*ournal of Environmental Engineering and Management*. 20, 9-17.

Clark, N. N., Kern, J. M., Atkinson, C. M. and Nine, R. D. 2002. Factors affecting heavy-duty diesel vehicle emissions. *Journal of the Air and Waste Management Association.* 52, 84-94.

Couth, R. and Trois, C. 2010. Carbon emissions reduction strategies in Africa from improved waste management: A review. *Waste Management.* 30, 2336–2346.

Couth, R., Trois, C., Parkin, J., Strachan, L., Gilder, A. and Wright, M. 2011. Delivery and viability of landfill gas CDM projects in Africa—A South African experience. *Renewable and Sustainable Energy Reviews.* 15, 392-403.

Cramer. W., Yohe, G.W., Auffhammer, M., Huggel, C., Molau, U., Dias, M.A.F.S. and Leemans, R. In: *Climate Climate Change 2014: Impacts, Adaptation, and Vulnerability*. Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L., Cambridge, United Kingdom and New York, NY, USA : Cambridge University Press, 2014 - ISBN 9781107058071 - p. 979 - 1038.

Crichton, D. 1999. The Risk Triangle. In*: Natural Disaster Management.* Ingleton, J. (Ed.) Tudor Rose.

Consonni, S., Giugliano, M. and Grosso, M. 2005. Alternative strategies for energy recovery from municipal solid waste: Part B: Emission and cost estimates. *Waste Management*. 25, 137-148.

Cunningham, S. D. and Ow, D. W. 1996. Promises and prospects of phytoremediation. *Plant physiology.* 110, 715.

Damodaran, A. 2015. The Co-benefit Principle and the Durban Platform: Towards an Inclusive Framework for Negotiating Climate Finance. *In: The G20 Development Agenda*. Parthasarathi, S. (Ed.). Dehli, India: Cambridge University Press.

Danas, K., Kurdi, B., Stark, M. and Mutlaq, A. 2012. Climate change effects on waste water treatment. CEE Jordan Group Presentation, Jordan, 18. [Online] Available: http://courses.washington.edu/cejordan/CC%20AND%20WWT.pdf [Accessed: 07/05/2015].

Das, S. and Bhattacharyya, B. K. 2015. Optimization of municipal solid waste collection and transportation routes. *Waste Management,* 43, 9-18.

Davis, M. and Clemmer, S. 2014. Power Failure: How Climate Change Puts Our Electricity at Risk— and What We Can Do. [Online] Available: http://www.ucsusa.org/sites/default/files/legacy/assets/documents/Power-Failure-How-Climate-Change-Puts-Our-Electricity-at-Risk-and-What-We-Can-Do.pdf [Accessed 07/09/2015 2014].

Daze, A., Huong, V.L., Phuong, D.T., Yen, N.T., Hanh, D.M., Webb, J., Gyang, R., Awuor, C., Ambani, M., Fontenla, G., Dela Vega, R. and Dela Vega, T.F. 2011. Understanding Vulnerability to Climate Change: Insights from Application of CARE's Climate Vulnerability and Capacity Analysis (CVCA) Methodology. CARE Poverty, Environment and Climate Change Network (PECCN). [Online] Available: http://careclimatechange.org/wp-content/uploads/2015/05/CARE_Understanding_Vulnerability.pdf [Accessed: 15/04/2015].

Dedinec, A., Markovska, N., Ristovski, I., Velevski, G., Gjorgjievska, V. T., Grncarovska, T. O. and Zdraveva, P. 2015. Economic and environmental evaluation of climate change mitigation measures in the waste sector of developing countries. *Journal of Cleaner Production.* 88, 234-241.

Department for Environment, Food and Rural Affairs (DEFRA). 2013. Advanced Thermal Treatment of Municipal Solid Waste. [Online] Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/221035/pb13888-thermal-treatment-waste.pdf [Accessed: 24/04/2015].

Dechezleprêtre, A., Glachant, M. and Ménière, Y. 2008. The Clean Development Mechanism and the international diffusion of technologies: An empirical study. *Energy Policy*. 36, 1273-1283.

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) and the Ministry of Environment, Forests and Climate Change (MoEF&CC). 2014. A Framework for Climate Change Vulnerability Assessments. [Online] Available: http://www.ccarai.org/files/va_guide_ccarai_final_lowres.pdf [Accessed: 14/04/2015].

Dincer, I. 2000. Renewable energy and sustainable development: a crucial review. *Renewable and Sustainable Energy Reviews.* 4, 157-175.

Di Maria, F. and Micale, C. 2015. Life cycle analysis of incineration compared to anaerobic digestion followed by composting for managing organic waste: the influence of system components for an Italian district. *The International Journal of Life Cycle Assessment*. 20, 377-388.

Di Trapani, D., Mannina, G., Vivian, G. and Babikova, K. 2015. A quantity-quality mathematical model for municipal solid waste landfill: Model calibration and sensitivity analysis. *Proceedings Sardinia 2015, Fifteenth International Waste Management and Landfill Symposium.* S. Margherita di Pula, Cagliari, Italy; 5 – 9 October 2015.

Dodman, D. 2009. Blaming cities for climate change? An analysis of urban greenhouse gas emissions inventories. *Environment and Urbanization.* 21, 185-201.

Domingo, J.l. and Nadal, M. 2009. Domestic waste composting facilities: A review of human health risks. Environment International. 35, 382–389.

Douglas, N. and Derrett, R. (eds). 2001. *Special interest tourism*. John Wiley and Sons Australia, Ltd.

Dow, K., Berkhout, F., Preston, B.L., Klein, R.J.T., Midgely, G. and Shaw, R.M. 2013. Limits to adaptation. *Nature Climate Change.* 3, 305–307.

Eakin, H., Lemos, M. and Nelson, D. 2014. Differentiating capacities as a means to sustainable climate change adaptation. *Global Environmental Change.* 27, 1-8.

Eisted, R., Larsen, A. W. and Christensen, T. H. 2009. Collection, transfer and transport of waste: accounting of greenhouse gases and global warming contribution. *Waste Management & Research*. 00, 1-8.

El-Fadel, M. and Massound, M. 2001. Methane emissions from wastewater management. *Environmental Pollution.* 114, 177-185.

Ellison, J. C. 2015. Vulnerability assessment of mangroves to climate change and sea-level rise impacts. *Wetlands Ecology and Management.* 23, 115-137.

Enete, I. 2010. Potential impacts of climate change on solid waste management in Nigeria. *Journal of Sustainable Development in Africa.* 12, 101-110.

Eskom Integrated Report (EIR). 2014. Eskom Powering your world 2014. [Online] Available: http://integratedreport.eskom.co.za/supplementary/app-environmental.php [Accessed 07/09/2015.

eThekwini Energy Office (EEO). 2014. eThekwini Municipality Emissions Inventory. [Online] Available: http://www.durban.gov.za/City_Services/energyoffice/Pages/GHG-Inventory.aspx [Accessed: 08/11/2014].

eThekwini Municipality (EM). 2005. Energy from Biogas: eThekwini Municipality, Durban, South Africa. [Online] Available: http://www.wrc.org.za/Lists/Knowledge%20Hub%20Items/Attachments/10297/SA-EM5%20-%20Ethekwini%20-%20Biogas%20energy%20production.docx. [Accessed: 15/10/2015].

eThekwini Municipality State of the Environment Report (EMSER). 2008. eThekwini Municipality. Headline Indicators Report: 2007/2008 Financial Year. [Online] Available: http://www.durban.gov.za/City_Services/development_planning_management/environmental_planning_climate_protection/Publications/Documents/SOE%20Headline%20indicators%20report%202007%202008.pdf [Accessed: 08/07/2015].

eThekwini Municipality: 2012/2013 Integrated Development Plan Review (EMIDP). 2013. [Online] Available: http://www.durban.gov.za/City_Government/City_Vision/IDP/Documents/eThekwini%20IDP%202013_14.pdf [Accessed: 26/05/2015].

Fankhauser, S. and McDermott, T. K. 2014. Understanding the adaptation deficit: why are poor countries more vulnerable to climate events than rich countries? *Global Environmental Chang.* 27, 9-18.

Ferreria, R., Buttell, F. and Ferreria, S. 2015. Ethical Considerations for Conducting Disaster Research with Vulnerable Populations. *Journal of Social Work Values and Ethics.*3, 379-384.

Finnveden, G., Albertsson, A., Berendson, J., Eriksson, E., Hoglund, L.O., Karlsson, S. and Sundqvist, J. 1995. Solid waste treatment within the framework of life-cycle assessment. *Journal of Cleaner Production.* 3, 189-199.

Fischer, T. 2013. Durban Climate Change Strategy Introductory Report Theme Waste and Air Pollution. eThekwini Municipality: Energy Office. [Online] Available: http://www.dccs.org.za/wp-content/uploads/2013/02/DCCS-Introductory-Report-Waste-and-Pollution.pdf [Accessed: 22/4/2015].

Fine, P. and Hadas, E. 2012. Options to reduce greenhouse gas emissions during wastewater treatment for agricultural use. *Science of the Total Environment*. 416, 289–299.

Friedrich, E., Pillay, S. and Buckley, C. 2009. Carbon footprint analysis for increasing water supply and sanitation in South Africa: a case study. *Journal of Cleaner Production.* 17, 1-12.

Friedrich, E. and Trois, C. 2011. Quantification of greenhouse gas emissions from waste management processes for municipalities – A comparative review focusing on Africa. *Waste Management.* 31, 1585-1596.

Friedrich, E. and Trois, C. 2013a. GHG emission factors developed for the collection, transport and landfilling of municipal waste in South African municipalities. *Waste Management.* 33, 1013-1026.

Friedrich, E. and Trois, C. 2013b. GHG emission factors developed for the recycling and composting of municipal waste in South African municipalities. *Waste management.*33, 2520-2531.

Friedrich, E. and Trois, C. 2015. Current and future greenhouse gas (GHG) emissions from the management of municipal solid waste in the eThekwini Municipality – South Africa. *Journal of Cleaner Production*. 1-13.

Foley, J., de Haas, D., Yuan, Z. and Lant, P. 2010. Nitrous oxide generation in full-scale biological nutrient removal wastewater treatment plants. *Water Research*. 44, 831-844.

Funfgeld, H. and McEvy, D. Framing Climate Change Adaptation in Policy and Practice [Online] Available: http://www.academia.edu/5574949/Framing_Climate_Change_Adaptation_in_Policy_and_Practice [Accessed 04/09/2015].

Garibaldi, J. A., Winkler, H., La Rovere, E. L., Cadena, A., Palma, R., Sanhueza, J. E., Tyler, E. and Torres Gunfaus, M. 2014. Comparative analysis of five case studies: commonalities and differences in approaches to mitigation actions in five developing countries. *Climate and Development.* 6, 59-70.

Gisclon, A., McCarley, S. and McNally, K. 2002. The Durban water recycling project- The vision becomes reality.

Gentil, E. C., Aoustin, E. and Christensen, T. H. 2009. Greenhouse gas accounting and waste management. *Waste Management & Research*. 00, 1-12.

Giusti, L. 2009. A review of waste management practices and their impact on human health. *Waste Management*. 29, 2227–2239.

Godfrey, L. 2015. Finding value in waste: Identifying opportunities for growth in a secondary resources economy. The 5th CSIR Conference ideas that work. 8-9 October 2015. CSIR ICC.

Greenhouse Gas Inventory for South Africa (GHGISA): 2000-2010. 2013. Witi, J., Stevens, L., Manzini, L., du Toit, L. and Musee, N. Department of Environmental Affairs, South Africa. [Online] Available: http://www.saaqis.org.za/ Accessed: 15/06/2014.

Guerrero, L. A., Mass, G. and Hogland, W. 2013. Solid waste management challenges for cities in developing countries. *Waste management.* 33, 220-232.

Gumbo, T. and Simelane, T. 2015. Innovations in Municipal Solid Waste Management: Experiences from eThekwini Municipality, South Africa. In*: Future Directions of Municipal Solid Waste Management in Africa.* Mohee, R. and Simelane, T. (Eds.). Pretoria, South Africa: Africa Institute of South Africa.

Haites, E., Duan, M. and Seres, S. 2006. Technology transfer by CDM projects. *Climate policy*.6, 327-344.

Halsnael, K. and Shukla, P. 2009. Sustainable development as a framework for developing country participation in international climate change policies. *Mitigation and Adaptation Strategies for Global Change.* 13,105–130.

Hartman JR, W. J. 1975. An evaluation of land treatment of municipal wastewater and physical siting of facility installations. DTIC Document.

Hengchaovanich, D. 2000. VGT: A bioengineering and phytoremediation option for the new millennium. Proceedings of the Second International Conference on Vetiver. Office of the Royal Development Projects Board, Bangkok, 2000. Citeseer, 25-30.

Hong J., Shi, W., Wang, Y., Chen, W. and Li, X. 2015. Life cycle assessment of electronic waste treatment. *Waste Management*. 38, 357-365.

Hoornweg, D., Thomas, L. and Otten, L. 1999. Composting and its applicability in developing countries. Published for the Urban Development Division. *World Bank working paper series 8*. Urban Waste Management.

Hoornwenweg, D., Sugar, L. and Gomez, C. L. T. 2011. Cities and greenhouse gas emissions: moving forward. *Environment and Urbanization*. 1-21.

Hoornweg, D. and Bhada-Tata, P. 2012. What a waste: a global review of solid waste management. [Online] Available: https://www.wdronline.worldbank.org/handle/10986/17388 [Accessed: 15/7/2015].

Hou, J., LV, J., CHEN, X. and Yu, S. 2015. China's regional social vulnerability to geological disasters: evaluation and spatial characteristics analysis. *Natural Hazards*. 1-15.

Hounsome, R. and Iyers, K. 2006. Climatic future for Durban: Phase 2. Headline climate change adaptation strategy. CSIR Report.

Howden, S. M., Soussana, J.F., Tubiello, F. N., Chhetri, N., Dunlop, M. and Meinke, H. 2007. Adapting agriculture to climate change. *Proceedings of the National Academy of Sciences.* 104, 19691-19696.

Hunt, A. and Watkiss, P. 2011. Climate change impacts and adaptation in cities: a review of the literature. *Climatic Change.* 104, 13-49.

Illman, J., Halonene, M., Rinee, P., Huq, S. and Tveitdaal, S. 2013. Scoping study on financing adaptation-mitigation synergy activities. Copenhagen: Nordic Council of Ministers. 1-52.

Inglezakis, V. J., Rojas–Solorzano, L., Kim, J., Aitbekova, A. and Ismailova, A. 2015. Comparison between landfill gas and waste incineration for power generation in Astana, Kazakhstan. *Waste Management and Research.* 33, 486-494.

Integrated Waste Management Plan for the eThekwini Municipality (IWMP). 2004. eThekwini Municipality. [Online] Available: http://www.durban.gov.za/Documents/CityServices/Cleansing%20and%20Solid%20Waste/Integrated_Waste_Management_Plan.pdf [Accessed: 18/04/2014].

Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories. 2006. [Online] Available: http://www.ipcc-nggip.iges.or.jp/public/2006gl/ [Accessed: 15/05/2014].

IPCC 2014a. Climate Change 2014: Impacts, Adaptation, and Vulnerability.Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: Barros, V. R., Field, C.B., Dokken, D.J., Mastratndrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., Maccracken, S., Mastrandrea, P.R. and White, L.L. (Eds.). 5th ed. United Kingdom and New York, NY, USA.

IPCC 2014b. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, , K., Adler, A., Baum, I., Bruner, S., Eickemeier, P. Kriemann, B. Savolainen, J., Schlomer, S., Von Stechow, C., Zwickel, T. and Minx, J.C. (Eds.). Cambridge, United Kingdom and New York, NY, USA.

Jewaskiewitz, B.L., Mills, B.L., Barratt, B.J., 2008. Landfill gas to electricity CDMprojects – design, implementation and the CDM verification process.In:Proceedings of Wastecon 2008 – Nineteenth Waste Management Conferenceand Exhibition, 6–10th October 2008. Durban, South Africa.

Johari, A., Ahmed, S. I., Hashim, H., Alkali, H. and Ramli, M. 2012. Economic and environmental benefits of landfill gas from municipal solid waste in Malaysia. *Renewable and Sustainable Energy Reviews.* 16, 2907-2912.

Johnson, J. and Marshall. P.A. (Eds). 2007. *Climate Change and the Great Barrier Reef.* Australia, Great Barrier Reef Park Authority and Australian Greenhouse Office.

Jury, M. and Melice, J.L. 2000. Analysis of Durban rainfall and Nile river flow 1871–1999. *Theoretical and applied climatology.* 67, 161-169.

Kalmykova, Y., Palme, U., Yu, S., and Karlfeldt Fedje, K. 2015. Life Cycle Assessment of Phosphorus Sources from Phosphate ore and urban sinks: Sewage Sludge and MSW Incineration fly ash. *International Journal of Environmental Research*. 9,133-140.

Kampschreur, M.J., Tan, N.C.G., Kleerebesem, R., Picioreanu, C., Jetten, M.S.M. and Van Losdrecht, M.C.M. 2008. Effect of dynamic process conditions on nitrogen oxide emission from a nitrifying culture. *Environmental Science and Technology*. 42, 429-435.

Kampschreur, M.J., Temminkb, H., Kleerebezema, R., Jettena, M.S.M. and van Loosdrecht, M.C.M. 2009. Nitrous oxide emission during wastewater treatment. *Water Research*. 43, 4093–4103.

Karakurt, I., Aydin, G. and Aydiner, K. 2012. Sources and mitigation of methane emissions by sectors: A critical review. *Renewable Energy*. 39, 40-48.

Karl, T. R. and Trenberth, K. E. 2003. Modern global climate change. *Science*. 302, 1719-1723.

Karl, T.R., Arguez, A., Huang, B., Lawrimore, J.H., McMahon, J.R., Menne1, M.J., Peterson, T.C., Vose, R.S. and Zhang, H. 2015. Possible artifacts of data biases in the recent global surface warming hiatus. *Science*. 348, 1469-1472.

Keller, J. and K. Hartley. 2003. Greenhouse gas production in wastewater treatment: process selection is the major factor. *Water Science and Technology*. 47, 43-48.

Kinobe, J., Bosona, T., Gebresenbet, G., Niwagaba, C. and Vinneras, B. 2015. Optimization of waste collection and disposal in Kampala city. *Habitat International.* 49, 126-137.

Kinnear, S., Rose, A. and Rolfe, J. 2015. Emissions reporting in the Australian road freight transport sector: is there a better method than the default option? International Journal of Sustainable Transportation. 9, 93-102.

Koetse, M. J. and Rietveld, P. 2009. The impact of climate change and weather on transport: An overview of empirical findings. *Transportation Research Part D: Transport and Environment*, 14, 205-221.

Kraemer, H. C., Stice, E., Kazdin, A., Offord, D. and Kupper, D. 2014. How do risk factors work together? Mediators, moderators, and independent, overlapping, and proxy risk factors. *American Journal of Psychiatry*. 158, 848-85.

Kumar, A. and Prasad, R. 2015. Production of Renewable Energy and Waste Water Management from Vetiver Grass. In: *Management of Water, Energy and Bio-resources in the Era of Climate Change: Emerging Issues and Challenges.* Raju, N.J. *et al*. (Eds.). Springer.

Lalet, A., Magnien, P. and Penaud, O. 2010. Protocol for the quantification of greenhouse gas emissions from waste management activities. Developed by Enterprises pout I′Environnement working group. [Online] Available: http://www.epe.asso.org / http://www.GHGprotocol.org [Accessed: 04/18/2014].

Lam, P. T., Chan, E. H., Ann, T., Cam, W. C. and Jack, S. Y. 2015. Applicability of clean development mechanism to the Hong Kong building sector. *Journal of Cleaner Production*. 1-13.

Law, Y., Ye, L., Pan, Y. and Yuanm, Z. 2012. Nitrous oxide emissions from wastewater treatment processes. *Philosophical Transactions of the Royal Society.* 367, 1265–1277.

Le, S., Yuangpho, N., Threrujirapapong, T., Khanitchaidecha, W. and Nakaruk, A. 2015. Synthesis of Mesoporous Materials from Vetiver Grass for Wastewater Treatment. *Journal of the Australian Ceramic Society Volume.* 51, 40-44.

Lehtoranta, J., Ekholm, P., Wahlström, S., Tallberg, P. and Risto, U. 2015. Labile organic carbon regulates phosphorus release from eroded soil transported into anaerobic coastal systems. *Ambio*. 44, 263-273.

Lewis, M. 2011. Durban's Municpal Climate Change Protection Programme: Climate Change and Adaptation Planning. eThekwini Municipality. [Online] Available: http://www.durban.gov.za/City_Services/development_planning_management/environmental_planning_climate_protection/Publications/Documents/Durbans%20Municipal%20Climate%20Protection%20Programme_Climate%20Chan.pdf [Accessed: 04/09/2015].

Li, P., Li, Y.P., Huang, G.H. and Zhang, J.L. 2015a. Modeling for waste management associated with environmental-impact abatement under uncertainty. *Environmental Science*, *Pollution and Research*. 23, 5003-5019.

Li, C., Shi, H., Cao, Y., Wang, J., Kuang, Y., Tan, Y. and Wei, J. 2015b. Comprehensive review of renewable energy curtailment and avoidance: A specific example in China. *Renewable and Sustainable Energy Reviews.* 41, 1067-1079.

Liamsanguan, C. and Gheewala, S. H. 2008. The holistic impact of integrated solid waste management on greenhouse gas emissions in Phuket. *Journal of Cleaner Production.* 16, 1865-1871.

Lieske, D. J., Roness, L. A., Phillips, E. A. and Fox, M. J. 2015. Climate Change Adaptation Challenges Facing New Brunswick Coastal Communities: A Review of the Problems and a Synthesis of Solutions Suggested by Regional Adaptation Research. *Journal of New Brunswick Studies/Revue d'études sur le Nouveau-Brunswick.* 6,1.

Lishenga, I., Nyaanga, D., Owino, J. and Wambua, R. 2015. Efficacy of Hydroponic and Soil-

Based Vetiver Systems in the Treatment of Domestic Wastewater. *International Journal of Pure and Applied Sciences and Technology*. 26, 53-63.

Major, D. C., Omojola, A., Dettinger, M., Hanson, R.T. and Sanchez-Rodriguez, R. 2011. Climate change, water, and wastewater in cities. *In: Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network*. Rosenzweig, C., Solecki, W. D., Hammer, S.A. and Mehrotra, S. (Eds.) Cambridge University Press, Cambridge, UK. 113–143.

Manfredi, S., Scharff, H., Tonini, D. and Christensen, T. H. 2009. Landfilling of waste: accounting of greenhouse gases and global warming contributions. *Waste Management and Research*. 00, 1-12.

Marianhill Landfill Conservancy (MLC). 2015. Landfill Conservancy. [Online] Available: http://landfillconservancies.com/sus_proj.htm [Accessed 15/04/2015].

Marshall, N. A., Marshall, P. A., Tamelander, J., Obura, D., Malleret-King, D. and Cinner, J. (Eds.). 2010. *A Framework for Social Adaptation to Climate Change: Sustaining Tropical Coastal Communities [sic] and Industries*. IUCN.

Marshall, N. A., Tobin, R. C., Marshall, P. A., Gooch, M. and Hobday, A. J. 2013. Social vulnerability of marine resource users to extreme weather events. *Ecosystems*. 16, 797-809.

Martin, C., O'Donnell, A., Joseph, G., and Wodon, Q. 2015. Three approaches to climate change adaptation. In*: Climate change adaptation and social resilience in the Sundarbans*. O'Donnell, A. and Wodon, Q. (Eds.). London and New York: Routledge.

Matete, N.O. and Trois, C. 2008. Towards zero waste in emerging countries – a South African experience. *Waste Management. 28*, 1480–1492.

Meneses, M., Pasqualino, J. C. and Castells, F. 2010. Environmental assessment of urban wastewater reuse: Treatment alternatives and applications. *Chemosphere*. 81, 266-272.

Menikrua, S., Sang-Arun, J. and Bengtsson, M. 2013. Integrated solid waste management: an approach for enhancing climate co-benefits through resource recovery. *Journal of Cleaner Production*. 58, 34-42.

Menikrupa, S., Sang-Arun, J. and Bengtsson, M. 2016. Assessment of environmental and economic performance of Waste-to-Energy facilities in Thai cities. *Renewable Energy*. 86, 576-584.

Mergenthaler, S. 2015. Mitigating climate change. In: *Managing Global Challenges*. Springer. 143-165.

Mesjasz-Lech, A. 2014. Municipal Waste Management in Context of Sustainable Urban Development. *Procedia-Social and Behavioral Sciences*. 151, 244-256.

Metz, B. 2001.Summary for Policy Makers. Climate Change 2001: Mitigation: Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Metz, B. Eds. Cambridge University Press. 1-14.

Michaelowa, A. and Jotzo, F. 2005. Transaction costs, institutional rigidities and the size of the clean development mechanism. *Energy policy.* 33, 511-523.

Mideksa, T. K. and Kallbekken, S. 2010. The impact of climate change on the electricity market: A review. *Energy Policy.* 38, 3579-3585.

Minghua, Z., Xiumin, F., Rovetta, A., Qichang, H., Vicentini, F., Bingkai, L., Giusti, A. and Yi, L. 2009. Municipal solid waste management in Pudong New Area, China. *Waste management.* 29, 1227-1233.

Mohareb, A. K., Warith, M. A. and Diaz, R. 2008. Modelling greenhouse gas emissions for municipal solid waste management strategies in Ottawa, Ontario, Canada. *Resources, Conservation and Recycling.* 52, 1241-1251.

Mokwena, L. 2009. Municipal responses to climate change in South Africa: the case of eThekwini, the City of Cape Town, and the City of Johannesburg. Centre for Policy Studies. [Online] http://www. cps. org. za/cps% 20pdf/RR113. Pdf [accessed 5 December 2010].

Møller, J., Boldrin, A. and Thomas H. Christensen, T.H. 2009. Anaerobic digestion and digestate use: accounting of greenhouse gases and global warming contribution. Waste *Management and Research*. 00, 1-12.

Monnie, S, Pipatti, R., Lehtila, A. and Syri, S. 2006. Global climate change mitigation scenarios for solid waste management. VTT Technical Research Centre of Finland 2006. Espoo 2006. VTT Publications 603.

Morgadinho, L., Oliveira, C. and Martinho, A. 2015. A qualitative study about perceptions of European automotive sector's contribution to lower greenhouse gas emissions. *Journal of Cleaner Production*. 106, 644-653.

Morgan, C. 2011. *Vulnerability assessments: a review of approaches.* Gland, Switzerland-IUCN.

Moser, S.C. and Boykoff, M.T. (Eds.). 2013. Climate change and adaptation success: the scope of the challenge. In: *Successful Adaptation to climate change*: *Linking Science and Policy in a Rapidly Changing World.* USA and Canada: Routledge. 1-34.

Moss, R. H., Meehl, G., Lemos, M. C., Smith, J., Arnold, J., Arnott, J., Behar, D., Brasseur, G. P., Broomell, S. and Busalacchi, A. 2013. Hell and high water: practice-relevant adaptation science. *Science.* 342, 696-698.

Municipal Wastewater Management Department (MWMD). 1997. Monitoring and control of sewage disposal and treatment. July 1997 Guideline/Policy Document 3. [Online] Available: http://www.durban.gov.za/City_Services/water_sanitation/Policies_Plans_Guidelines/Documents/guideline3.pdf [Accessed: 16/10/2015].

Nahman, A. 2011. Pricing landfill externalities: emissions and disamenity costs in Cape Town, South Africa. *Waste Management.* 31, 2046-2056.

National Environment Management: Waste Act, 2008.Act No. 59 of 2008. Government Gazzette, Republic of South Africa, 10 March 2009. No. 32000. [Online] Available: https://www.environment.gov.za/sites/default/files/legislations/nema_amendment_act59.pdf [Accessed: 04/10/2015].

National Waste Management Strategy (NWMS). 2011. Department of Environmental Affairs. [Online] Available: https://www.environment.gov.za/sites/default/files/docs/nationalwaste_management_strategy.pdf [Accessed: 15/10/2015].

Noble, I.R., Huq, D., Anokhin, Y.A., Carmin, J., Goudou, D., Lansigan, F.P., Osman-Elasha, B. and Villamizar, A. 2014. Adaptation needs and options. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability*. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., Barros, V.R., Dokken, D.J. Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R. and White, L.L. (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 833-868.

Nzeadibe, T. C. 2015. Moving up the Hierarchy: Involving the Informal Sector to Increase Recycling Rates in Nigerian Cities. *In: Future Directions of Municipal Solid Waste Management in Africa.* Mohee, R. and Simelane, T (Eds.). Pretoria: Africa Institute of South Africa.

O'Connor, D. J., Daly, S. M. and Sodeau, J. R. 2015. On-line monitoring of airborne bioaerosols released from a composting/green waste site. *Waste Management*. 42, 23-30.

Oonk, H. 2010. Literature review: methane from landfills. Methods to quantify generation, oxidation and emission. *Sustainable Landfill Foundation*.

Oppenheimer, M., Campos, M., Warren, R., Birkmann, J., Luber, G., O'Neill, B. and Takahashi, K. 2014. Emergent risks and key vulnerabilities. *In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Field, C. B., Barros, V. R., Dokken, D. J., Mach, K. J., Mastrandrea, M. D., Bilir, T. E., Chatterjee, M., Ebi, K. L., Estrada, Y. O., Genova, R. C., Girma, B., Kissel, E. S., Levy, A. N., Maccracken, S., Mastrandrea, P. R. and White, L. (Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Pachauri, R., Allen, M., Barros, V., Broome, J., Cramer, W., Christ, R., Church, J., Clarke, L., Dahe, Q. and Dasgupta, P. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change. IPCC Geneva, Switzerland.

Park, H.D., Wells, G.F., Bae, H., Criddle, C.S. and Francis, C.A. 2006. Occurrence of ammonia-oxidizing Archaea in wastewater treatment plant bioreactors'. *Applied and Environmental Microbiology*. 72, 5643–5647.

Payne, G. J. 2005. Buffelsdraai Landfill: A New Regional Landfill for the eThekwini Council. [Online] Available: http://landfillconservancies.com/docs/gjp_lig_paper_sept_2005.pdf [Accessed: 03/05/2014].

Pyane, G.J. and Ribbink, K. 2011. The Buffelsdraai landfill experience. [Online] Available: http://www.mile.org.za/Come_Learn/Capacity%20Enhancement/Master%20Class/Multimedia%20Library/Solid%20Waste%20Management%20Master%20Class%202931%20July%202013/GCLs-The%20Buffelsdraai%20Landfill%20Experience.pdf. [Accessed: 18/04/2015].

Pegels, A. 2010. Renewable energy in South Africa: Potentials, barriers and options for support. *Energy policy*. 38, 4945-4954.

Penna, C. C. and Geels, F. W. 2015. Climate change and the slow reorientation of the American car industry (1979–2012): An application and extension of the Dialectic Issue Life Cycle (DILC) model. *Research Policy*. 44, 1029-1048.

Perlaviciute, G. and Steg, L. 2015. The influence of values on evaluations of energy alternatives. *Renewable Energy*. 77, 259-267.

Pilli, S., Yan, S., Tyagi, R. and Surampalli, R. 2015. Thermal Pretreatment of Sewage Sludge to Enhance Anaerobic Digestion: A Review. *Critical Reviews in Environmental Science and Technology*. 45, 669-702.

Popa, ME., Vollmer, M.K., Jordan, A., Brand, W. A., Pathirana, S. L., Rothe, M. and Röckmann, T. 2015. Vehicle emissions of greenhouse gases and related tracers from a tunnel study: $CO:CO_2$, $N_2O:CO_2$, $CH_4:CO_2$, $O_2:CO_2$ ratios, and the stable isotopes 13C and 18O in CO_2 and CO. *Atmospheric Chemistry and Physics*. 14, 2105–2123.

Rattanachot, W., Wang, Y., Chong, D. and Suwansawas, S. 2015. Adaptation strategies of transport infrastructures to global climate change. *Transport Policy*. 41, 159-166.

Ravindra, K., Kaur, K. and Mor, S. 2015. System analysis of municipal solid waste management in Chandigarh and minimization practices for cleaner emissions. *Journal of Cleaner Production*. 89, 251-256.

Reddy, P. P. (Ed.). 2015. Causes of Climate Change. *In: Climate Resilient Agriculture for Ensuring Food Security*. India: Springer.

Rettenberger, G., 2009. Recovery of landfill gas under conditions of landfills indeveloping countries. In: *Sardinia 2009 Twelfth International Waste Management and Landfill Symposium*. October 2009, Santa Margherita diPula, Cagliari, Sardinia, Italy.

Rezaee, R., Nasseri, S., Mahvi, A. H., Jafari, A., Mazloomi, S., Gavami, A. and Yaghmaeian,

K. 2014. Estimation of gas emission released from a municipal solid waste landfill site through a modeling approach: A case study, Sanandaj, Iran. *Journal of Advances in Environmental Health Research.* 2, 13-21.

Rezania, S., Ponraj, M., Talaiekhozani, A., Mohamad, S. E., Din, M. F. M., Taib, S. M., Sabbagh, F. and Sairan, F. M. 2015. Perspectives of phytoremediation using water hyacinth for removal of heavy metals, organic and inorganic pollutants in wastewater. *Journal of environmental management.* 163, 125-133.

Risch, E., Gutierrez, O., Rouz, P., Boutin, C. and Corominas, L. 2015. Life cycle assessment of urban wastewater systems: Quantifying the relative contribution of sewer systems. *Water Research.* 77, 35-48.

Roberts, D. 2008. Thinking globally, acting locally—institutionalizing climate change at the local government level in Durban, South Africa. *Environment and Urbanization.* 20, 521-537.

Roberts, D. 2010. Prioritizing climate change adaptation and local level resilience in Durban, South Africa. *Environment and Urbanization.* 22, 397-413.

Robertson, L.A., Dalsgaard, T., Revsbech, N.P.andKuenen, J.G., 1995.Confirmation of aerobic denitrification in batch cultures, usinggas-chromatography and N-15 mass-spectrometry. FEMS. *Microbiology Ecology.* 18, 113–119.

Romieu, E., Welle, T., Schneiderbauer, S., Pelling, M. and Vinchon, C. 2010. Vulnerability assessment within climate change and natural hazard contexts: revealing gaps and synergies through coastal applications. *Sustainability Science.* 5, 159-170.

Roongtanakiat, N., Tangruangkiat, S. and Meesat, R. 2007. Utilization of vetiver grass (Vetiveria zizanioides) for removal of heavy metals from industrial wastewaters. *Science Asia.* 33, 397-403.

Sabbasa, T., Polettinib, A., Pomib,R., Astrupc, T., Hjelmard, O., Mostbauera, P., Cappaie, G., Magelf, G., Salhofera, S., Speiserg, C., Heuss-Assbichlerf, S., Kleinh, R. and Lechnera, P. 2003. Management of municipal solid waste incineration rules. *Waste Management*. 23, 61–88.

Saharan, V. K., Pinjari, D. V., Gogate, P. R. and Pandit, A. B. 2014. Advanced Oxidation Technologies for Wastewater Treatment: An Overview. In*: Industrial Wastewater Treatment, Recycling and Reuse.* Ranade, V. V. and Bhandari, V. M. (Eds.). Unighted Kingdom: Elsevier, Butterworth, Heinemann.

Salsabil, M. R., Laurent, J., Casellas, M. and Dagot, C. 2010. Techno-economic evaluation of thermal treatment, ozonation and sonication for the reduction of wastewater biomass volume before aerobic or anaerobic digestion. *Journal of Hazardous materials.* 174, 323-333.

Santaalla, E., Cordoba, V. and Blanco, G. 2013. Greenhouse gas emissions from the waste sector in Argentina in business-as-usual and mitigation scenarios. *Journal of the Air and Waste Management Association.* 63, 909-917.

Sarewitz, D., Roger, R. and Keykhah, M. 2003. Vulnerability and Risk: Some Thoughts from a Political and Policy Perspective. *Risk Analysis.* 23, 805-810.

Scharff, H. and Jacobs, J. 2006. Applying guidance for methane emission estimation for landfills. *Waste Management.* 26, 417-429.

Schaubroeck, T., De Clippeleir, H., Weissenbacher, N., Dewulf, J., Boeckx, P., Vlaeminck, S. E. and Wett, B. 2015. Environmental sustainability of an energy self-sufficient sewage treatment plant: Improvements through DEMON and co-digestion. *Water research.* 74, 166-179.

Scheepers, R. and vd Merwe-Botha, M. 2013. Wastewater treatment plants in South Africa - a realistic perspective of energy optimisation considerations: wastewater. *Resource.* 15, 56-58.

Schipper, E. L. F. 2009. Meeting at the crossroads?: Exploring the linkages between climate change adaptation and disaster risk reduction. *Climate and Development.* 1, 16-30.

Schneider, M., Holzer, A. And Hoffmann, V.H. 2008. Understanding the CDM's contribution to technology transfer. *Energy Policy.* 36, 2930-2938.

Schneiderbauer, S. and Ehlrich, D. 2006. Social levels and hazard (in)dependence in determining vulnerability. *In:* Measuring vulnerability to natural hazards: Towards disaster resilient societies. Birkmann, J. (Ed.). United Nations Publications.

Schwartz, H. G., Meyer, M., Burbank, C. J., Kuby, M., Oster, C., Posey, J., Russo, E. J. and Rypinski, A. 2014. Transportation. In*: Climate Change Impacts in the United States: The Third National Climate Assessment*. Melillo, J. M., Richmond, T.C. and Yohe, G. W. (Eds.). U.S. Global Change Research Program.

Sebri, M. and Ben-Salh, O. 2014. On the causal dynamics between economic growth, renewable energy consumption, CO 2 emissions and trade openness: Fresh evidence from BRICS countries. *Renewable and Sustainable Energy Reviews.* 39, 14-23.

Serrao-Neumann, S., Crick, F., Harman, B., Schuch, G. and Choy, D. L. 2015. Maximising synergies between disaster risk reduction and climate change adaptation: Potential enablers for improved planning outcomes. *Environmental Science and Policy.* 50, 46-61.

Singh, R. and Agrawal, M. 2008. Potential benefits and risks of land application of sewage sludge. *Waste management.* 28, 347-358.

South African Waste Information Centre (SAWIC). 2015. [Online] Available: http://sawic.environment.gov.za/ [Accessed 15/03/2015].

Statistics South Africa (StatsSA). 2011. Population Demographics. [Online] Available: http://www.statssa.gov.za [Accessed: 26/04/2015].

Stern, N. 2008. The economics of climate change. *The American Economic Review*, 1-37.

Stern, N. and Taylor, C. 2008. Climate change: Risk, ethics, and the Stern review. In*: Science Magazine's State of the Planet 2008-2009: with a Special Section on Energy and Sustainability.* Kennedy, D. (ed.) Washington DC: Island Press.

Stone, D., Auffhammer, M., Carey, M., Hansen, G., Huggel, C., Cramer, W., Lobell, D., Molau, U., Solow, A. and Tibig, L. 2013. The challenge to detect and attribute effects of climate change on human and natural systems. *Climatic Change.* 121, 381-395.

Strachan, L. and Mzizi, M. 2010. Credence in clear landfill water: landfill. *ReSource.* 12, 20-23.

Strauch, R., Raymond, C., Rochefort, R., Hamlet, A. and Lauver, C. 2015. Adapting transportation to climate change on federal lands in Washington State, USA. *Climatic Change.* 130, 185-199.

Taiyab, N. 2006. Exploring the market for voluntary carbon offsets. IIED, London.

Taylor, S. A., Larson, E. L. and Harrison, R. G. 2015. Hybrid zones: windows on climate change. *Trends in Ecology and Evolution.* 30, 398-406.

Thambiran, T. and Diab, R.D. Air pollution and climate change co-benefit opportunities in theroad transportation sector in Durban, South Africa. *Atmospheric Environment* (2011), doi:10.1016/j.atmosenv.2011.02.059.

Tian, H., Gao, J., Hao, J., Lu, L., Zhu, C. and Qiu, P. 2013. Atmospheric pollution problems and control proposals associated with solid waste management in China: A review. *Journal of Hazardous Materials*. 252–253, 142–154.

Trois, C., Marcello, A., Pretti, S., Trois, P. and Rossi, G. 2007. The environmental risk posed by small dumps of complex arsenic, antimony, nickel and cobalt sulphides. *Journal of Geochemical Exploration.* 92, 83-95.

Trois, C. and Simelane, O. T. 2010. Implementing separate waste collection and mechanical biological waste treatment in South Africa: A comparison with Austria and England. *Waste management.* 30, 1457-1463.

Trois, C. and Jagath, R. 2011. Sustained carbon emissions reductions through zero waste strategies for South African municipalities. INTECH Open Access Publisher.

Truong, P., Hart, B., Chomchallow, N., Sombtpanit, S. and Network, P. R. V. 2001. Vetiver system for wastewater treatment. Office of the Royal Development Projects Board.

Turner, S., Moloney, S., Glover, A. and Fungveld, H. 2014. A Review of the Monitoring and Evaluation literature for Climate Change Adaptation. Melbourne: Centre for Urban Research, RMIT University.

Turpie, J. H., Winkler, H., Spalding-Fecher, R. and Midgely, G. 2002. Economic Impacts of Climate Change in South Africa: A Preliminary Analysis of Unmitigated Damage Costs. Southern Waters and Energy and Development Research Centre. [Online]

Available: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.203.2218&rep=rep1&type=pdf. [Accessed: 28/07/2015].

United States Agency for International Devlopment (USAID). 2012. Solid Waste Management. Addressing climate change impacts on infrastructure: Preparing for change. [Online]. Available: https://www.usaid.gov/sites/default/files/documents/1865/Infrastructure_SolidWasteManagement.pdf [Accessed 07/09/2015].

United Nations Environment Programme (UNEP). 2010. Waste and Climate Change: Global Trends and Strategy Framework. [Online] Available: http://www.unep.or.jp/ietc/Publications/spc/Waste&ClimateChange/Waste&ClimateChange.pdf [Accessed: 25/06/2015].

United Nations Framework Convention on Climate Change (UNFCCC). 2006. Handbook. [Online] Available: http://unfccc.int/resource/docs/publications/handbook.pdf [Accessed 07/09/2015].

United Nations Framework Convention on Climate Change (UNFCCC). 2007. Climate Change: Impacts, Vulnerabilities and Adaptation in Developing Countries. [Online] Available: http://unfccc.int/resource/docs/publications/impacts.pdf [Accessed: 14/04/2015].

United States Environmental Protection Agency (USEPA). 2013. Local government climate an energy strategy guides. [Online] Available: http://www3.epa.gov/statelocalclimate/documents/pdf/wastewater-guide.pdf [Accessed 14/10/2015].

Van Den Berg, M., Hof, A. F., Van Vliet, J. and Van Vuuren, D. P. 2015. Impact of the choice of emission metric on greenhouse gas abatement and costs. *Environmental Research Letters.* 10, 024001.

Van Der Linden, S. 2015. The social-psychological determinants of climate change risk perceptions: towards a comprehensive model. *Journal of Environmental Psychology.* 41, 112-124.

van der Merwe, M., Lombard, J., Lomard, R. and lobard R. 2009. Sustainable Waste Management Guideline. Environmental Planning and Climate Protection Department: Biodiversity, Climate, People. [Online] Available: http://www.durban.gov.za/City_Services/development_planning_management/environmental_planning_climate_protection/Publications/Documents/Waste%20guide%20low%20res.pdf [Accessed: 2015/10/27].

Van Schalkwyk, C. 2013. Modern and mechanised waste transfer station-eThekwini: solid waste. *ReSource.* 15, 18-20.

Venema, H.D. and Rehman, I.H. 2007.Decentralized renewable energy and the climate change mitigation-adaptation nexus. *Mitigation and Adaptation Strategies for Global Change*.12, 875–900.

Walsh, C., Roberts, D., Dawson, R., Hall, J., Nickson, A. and Hounsome, R. 2013. Experiences of integrated assessment of climate impacts, adaptation and mitigation modelling in London and Durban. *Environment and Urbanization.* 25, 1-20.

Wang, X., Chen, T., Ge, Y. and Jia, Y. 2008. Studies on land application of sewage sludge and its limiting factors. *Journal of Hazardous Materials.* 160, 554-558.

Wang, X.H., Wang, X., Huppes, G., Heijungs, R. and Ren, N.Q. 2015. Environmental implications of increasingly stringent sewage discharge standards in municipal wastewater treatment plants: case study of a cool area of China. *Journal of Cleaner Production.* 94, 278-283.

Watkins, P. and McKendry, P. 2015. Assessment of waste derived gases as a renewable energy source – Part 1. *Sustainable Energy Technologies and Assessments.* 10, 102-113.

Wilson, D.C., Velis, C. and Cheeseman, C. 2006. Role of informal sector recycling in waste management in developing countries. *Habitat International.* 30, 797-808.

Whittemore, R., Chase, S. K. and Mandle, C. L. 2001. Validity in qualitative research. *Qualitative health research.* 11, 522-537.

Yusuf, R.O., Noor, Z. Z., Abba, A.H., Abu Hassan, M.A. and Mohd Din, M.F. 2012. Methane emission by sectors: A comprehensive review of emission sources and mitigation methods. *Renewable and Sustainable Energy Reviews*. 16, 5059–5070.

Zeng, X., Sun, Q., Huo, B., Wan, H. and Jing, C. 2010. Integrated Solid Waste Management Under Global Warming. *The Open Waste Management Journal.* 3, 13-17.

Zhang, D. Q., Tan, S. K. and Gersberg, R. M. 2010. Municipal solid waste management in China: status, problems and challenges. *Journal of Environmental Management.*91, 1623-1633.

Zhao, W., van der Voet, E., Zhanga, Y. and Huppesb, G. 2009. Life cycle assessment of municipal solid waste managementwith regard to greenhouse gas emissions: Case study ofTianjin, China. *Science of the total environment*. 407, 1517 – 1526.

Zhou, C., Huang, H., Cao, A. and Xu, W. 2014. Modeling the carbon cycle of the municipal solid waste management system for urban metabolism. *Ecological Modelling*.

Zorpas, A. A., Vlyssies, A. G., Zorpas, G. A., Karlis, P. K. and Arapoglou, D. 2001. Impact of thermal treatment on metal in sewage sludge from the Psittalias wastewater treatment plant, Athens, Greece. *Journal of hazardous materials.* 82, 291-298.

Zotos, G., Karagiannidis, A., Zampetoglou, S., Malamakis, A., Antonopoulos, I.S., Kontogianni, S. and Tchobanoglous, G. 2009. Developing a holistic strategy for integrated waste management within municipal planning: Challenges, policies, solutions and perspectives for Hellenic municipalities in the zero-waste, low-cost direction. *Waste Management.* 29, 1686-1692.

Zouboulis, A. and Tolkou, A. 2015. Effect of Climate Change in Wastewater Treatment Plants: Reviewing the Problems and Solutions. In. *Managing Water Resources under Climate Uncertainty*. Shresta, S. *et al*. (Eds.).Springer. 197-220.

Zuberi, M. J. S. and Ali, S. F. 2015. Greenhouse effect reduction by recovering energy from waste landfills in Pakistan. *Renewable and Sustainable Energy Reviews*. 44, 117-131.

Appendices

Appendix A: Transport emissions

A1: DSW fuel consumption emissions ($GgCO_2$)

	2010	2011	2012	2013	2014
Diesel	3.39	5.15	6.39	5.10	7.20
Petrol	0.27	0.45	0.48	1.97	0.56
Total	**3.66**	**5.61**	**6.87**	**7.07**	**7.76**

A2: GHG emissions for the collection and transport of solid waste ($GgCO_2$-e)

Year	Bisasar Road	Marianhill Park	Buffelsdraai
2003	7.22	1.31	-
2004	8.33	1.42	-
2005	9.43	1.54	-
2006	10.53	1.65	0.43
2007	11.64	1.76	0.62
2008	12.74	1.88	0.59
2009	13.85	1.99	0.63
2010	12.89	2.17	1.04
2011	12.32	2.38	0.66
2012	13.72	2.84	0.76
2013	12.47	3.18	0.89
2014	10.26	2.69	0.75
2015	-	5.98	9.63
2016	-	6.70	10.82
2017	-	7.43	12.01
2018	-	8.15	13.19
2019	-	8.87	14.38
2020	-	9.59	15.57

Appendix B: Solid waste emissions

B1: CH_4 emissions from landfill sites using emission factors by Freidrich and Trois (2013a, b) ($GgCO_2$-e)

Year	Bisasar Road	Marianhill Park	Buffelsdraai
2004	647.18	117.30	-
2005	746.14	127.49	-
2006	845.09	137.69	38,85
2007	944.05	147.89	55,13
2008	1 043.00	158.08	52,86
2009	1 141.96	168.28	56,28
2010	1 240.91	178.48	93,36
2011	1 155.60	194.48	58,90
2012	1 104.18	213.54	68,22
2013	1 229.66	254.30	79,50
2014	1 117.66	285.15	66,94
2015	919.13	241.52	862,84
2016	-	536.05	969,40
2017	-	600.80	1 075,96
2018	-	665.55	1 182,51
2019	-	730.30	1 289,07
2020	-	795.05	1 395,62

B2: CH_4 emissions from landfill using IPCC (2006) guidelines ($GgCO_2$-e)

Year	Bisasar Road	Marianhill Park	Buffelsdraai
2004	-	-	-
2005	37.13	6.57	-
2006	77.53	13.46	-
2007	121.09	20.56	-
2008	167.65	27.67	9.53
2009	216.87	34.99	16.31
2010	268.67	42.30	20.73
2011	322.74	49.89	22.65
2012	368.69	57.94	26.68
2013	408.81	66.52	28.36
2014	453.68	76.90	30.48
2015	489.29	88.39	33.12
2016	511.38	96.67	34.87
2017	479.37	106.30	42.33
2018	449.50	117.18	50.37
2019	421.63	129.24	58.97
2020	395.61	142.40	68.07
2021	371.31	156.59	77.65
2022	348.61	171.74	87.68
2023	327.41	161.02	81.67
2024	307.58	151.02	76.09
2025	289.05	141.68	70.91
2026	271.72	132.95	66.11
2027	255.50	124.81	61.65
2028	240.33	117.20	57.51
2029	226.12	110.09	53.66
2030	212.82	103.44	50.08

B3: Annual emissions for Bisasar Road landfill per to waste type ($GgCO_2$-e)

Year	Food	Garden	Paper	Wood	Textile
2004	17.38	8.99	13.81	0.04	1.04
2005	36.00	18.78	29.06	0.09	2.21
2006	55.76	29.33	45.80	0.15	3.49
2007	76.57	40.63	63.98	0.21	4.89
2008	98.38	52.53	83.39	0.28	6.38
2009	121.03	65.10	104.12	0.35	7.93
2010	144.48	78.20	125.97	0.42	9.53
2011	163.77	89.33	145.09	0.49	10.98
2012	180.08	99.06	162.26	0.55	12.29
2013	198.43	109.93	181.42	0.62	13.70
2014	212.27	118.54	197.29	0.68	14.88
2015	219.66	123.86	208.26	0.73	15.69
2016	201.76	116.07	199.09	0.71	15.00
2017	185.32	108.76	190.33	0.69	14.34
2018	170.22	101.92	181.96	0.67	13.71
2019	156.35	95.51	173.95	0.66	13.11
2020	143.61	89.50	166.30	0.64	12.53
2021	131.90	83.86	158.98	0.62	11.98
2022	121.16	78.59	151.98	0.61	11.45
2023	111.28	73.64	145.30	0.59	10.95
2024	102.21	69.01	138.90	0.58	10.47
2025	93.89	64.66	132.79	0.56	10.01
2026	86.23	60.59	126.95	0.55	9.57
2027	79.21	56.78	121.36	0.54	9.15
2028	72.75	53.21	116.02	0.52	8.74
2029	66.82	49.86	110.92	0.51	8.36
2030	61.38	46.72	106.03	0.50	7.99

B4: Annual emissions for Marianhill landfill per waste type (GgCO_2-e)

Year	Food	Garden	Paper	Wood	Textile
2004	3.11	1.59	2.44	0.01	0.16
2005	6.24	3.25	5.04	0.02	0.40
2006	9.40	4.99	7.80	0.03	0.63
2007	12.59	6.70	10.58	0.04	0.84
2008	15.80	8.48	13.50	0.05	1.05
2009	19.03	10.24	16.43	0.05	1.25
2010	22.28	12.07	19.50	0.07	1.52
2011	25.64	14.04	22.84	0.08	1.78
2012	29.29	16.19	26.39	0.09	1.95
2013	33.73	18.78	30.66	0.10	2.17
2014	38.64	21.65	35.39	0.11	2.42
2015	41.98	23.71	38.99	0.12	2.60
2016	45.91	26.02	43.11	0.14	2.93
2017	50.38	28.63	47.74	0.16	3.29
2018	55.36	31.53	52.86	0.18	3.68
2019	60.79	34.68	58.43	0.20	4.11
2020	66.65	38.09	64.45	0.22	4.58
2021	72.89	41.73	70.89	0.24	5.07
2022	66.95	39.10	67.77	0.24	4.85
2023	61.50	36.64	64.79	0.23	4.64
2024	56.49	34.34	61.94	0.22	4.43
2025	51.88	32.18	59.21	0.22	4.24
2026	47.66	30.15	56.61	0.21	4.05
2027	43.77	28.25	54.12	0.21	3.87
2028	40.21	26.47	51.74	0.20	3.70
2029	36.93	24.81	49.46	0.20	3.54
2030	33.92	23.25	47.28	0.19	3.38

B5: Annual emissions for Buffelsdraai landfill per waste type (GgCO_2-e)

Year	Food	Garden	Paper	Wood	Textile
2007	0.00	0.00	0.00	0.00	0.00
2008	0.00	0.00	0.00	0.00	0.00
2009	0.00	0.00	0.00	0.00	0.00
2010	4.52	2.29	3.52	0.01	0.24
2011	7.63	3.91	6.08	0.02	0.48
2012	9.55	4.99	7.84	0.03	0.62
2013	10.28	5.47	8.72	0.03	0.67
2014	11.98	6.45	10.37	0.04	0.81
2015	12.59	6.88	11.17	0.04	0.84
2016	13.39	7.41	12.13	0.04	0.89
2017	14.44	8.08	13.30	0.04	0.94
2018	15.06	8.52	14.14	0.05	0.98
2019	20.86	9.89	15.14	0.09	1.06
2020	27.01	11.40	16.28	0.13	1.15
2021	33.49	13.04	17.56	0.18	1.25
2022	40.27	14.81	18.98	0.23	1.36
2023	47.32	16.68	20.52	0.28	1.48
2024	54.62	18.66	22.19	0.34	1.60
2025	50.17	17.49	21.22	0.33	1.53
2026	46.08	16.39	20.28	0.32	1.47
2027	42.33	15.36	19.39	0.32	1.40
2028	38.88	14.39	18.54	0.31	1.34
2029	35.71	13.49	17.72	0.30	1.28
2030	32.80	12.64	16.94	0.29	1.22

Appendix C: Wastewater emissions

Appendix C1: Stationary CH_4 from Incomplete Combustion of Digester Gas per WWTP ($GgCO_2$-e)

WWTP	2010	2011	2012	2013
Amanzimtoti	0.05	0.09	0.088	0.11
Isipingo	2.76	9.45	9.56	6.59
KwaMashu	0.12	0.30	0.31	0.26
Mpumalanga	0.34	3.35	3.39	1.07
Northern	0.12	0.21	0.22	0.30
Phoenix	0.44	0.11	0.12	0.11
Umbilo	3.39	2.17	2.20	6.20
Verulam	1.40	1.56	1.60	2.67
Total	**8.22**	**17.26**	**17.47**	**17.67**

Appendix C2: CH_4 emissions from wastewater WWTP with nitrification/denitrification ($GgCO_2$-e)

WWTP	Industrial Effluent	2010	2011	2012	2013
Amanzimtoti	Y	0.15	0.25	0.17	0.21
Craigieburn	N	0.00	0.00	0.00	0.00
Dassenhoek	N	0.01	0.36	0.00	0.00
Genazano	N	0.00	0.12	0.00	0.00
Hammersdale	Y	0.05	0.26	0.00	0.21
Hillcrest	N	0.00	0.00	0.00	0.00
Kingsburgh	N	0.03	0.79	0.21	0.39
KwaMashu	Y	0.38	0.88	0.60	0.51
New Germany	Y	0.01	0.39	0.21	0.00
Northern	Y	0.36	0.62	0.43	0.58
Phoenix	N	0.10	0.27	0.19	0.17
Tongaat Central	Y	0.06	0.86	0.00	0.50
Umbilo	N	0.10	0.50	0.00	0.00
Umhlathuzana	N	0.07	0.10	0.00	0.60
Umdloti	N	0.00	0.00	0.00	0.00
Umkomaas	N	0.00	0.19	0.21	0.21
Verulam	Y	0.04	0.49	0.43	0.43
Total	Y	1	**3**	**3**	**3**

Appendix C3: N_2O emissions from WWTP without nitrification/denitrification ($GgCO_2$-e)

WWTP	**2011**	**2011**	**2012**	**2013**
Central	0.22	0.12	0.12	0.11
Isipingo	0.02	0.13	0.13	0.09
Kwandengezi	0.00	0.02	0.02	0.01
Mpumalanga	0.00	0.04	0.04	0.01
Southern Works	0.54	0.55	0.05	0.49
Total	**0.80**	**0.85**	**0.86**	**0.71**

Appendix C4: N_2O emissions from effluent discharge ($GgCO_2$-e)

WWTP outlet	**Industrial Effluent**	**2010**	**2011**	**2012**	**2013**
Ocean	Y	4.42	4.42	4.53	9.52
Umhlatuzana River	N	0.19	0.23	0.24	0.41
Umbilo River	Y	0.26	0.26	0.27	0.48
Amanzimtoti River	N	0.07	0.09	0.09	0.17
Mohlongwa River	N	0.02	0.02	0.02	0.06
Umkomaas River	N	0.00	0.00	0.00	0.02
Ngane River	N	0.00	0.00	0.00	0.02
Mbokodweni River	Y	0.39	0.39	0.40	0.84
Isipingo River	N	0.17	0.21	0.22	0.50
Umgeni River	Y	0.95	0.95	0.97	2.30
Aller River	Y	0.29	0.03	0.03	0.05
Umhlangane River	Y	1.01	1.01	1.03	1.99
Mlaas River	N	0.02	0.03	0.03	1.07
Sterspruit	Y	0.02	0.41	0.13	0.81
Ohlanga River	N	0.03	0.43	0.44	1.20
Umdloti	Y	0.12	0.13	0.13	0.24
Tongaati River	Y	0.34	0.15	0.15	0.31
Genazzona Stream	N	0.13	0.03	0.03	0.05
Total		**8.34**	**8.79**	**8.72**	**20.04**

Appendix D: Mitigation Scenarios

Appendix D1: CH_4 emissions for the baseline scenario ($GgCO_2$-e)

Year	Bisasar Road	Marianhill	Buffelsdraai
2004	647,18	117,30	-
2005	746,14	127,49	-
2006	845,09	137,69	38,85
2007	944,05	147,89	55,13
2008	1 043,00	158,08	52,86
2009	1 141,96	168,28	56,28
2010	1 240,91	178,48	93,36
2011	1 155,60	194,48	58,90
2012	1 104,18	213,54	68,22
2013	1 229,66	254,30	79,50
2014	1 117,66	285,15	66,94
2015	-	241,52	862,84
2016	-	536,05	969,40
2017	-	600,80	1 075,96
2018	-	665,55	1 182,51
2019	-	730,30	1 289,07
2020	-	795,05	1 395,62

Appendix D2: CH_4 emissions for landfills with LFG capture and flaring ($GgCO_2$-e)

Year	Bisasar Road	Marianhill	Buffelsdraai
2004	64,44	11,68	-
2005	74,30	12,70	-
2006	84,15	13,71	-
2007	94,00	14,73	3,87
2008	103,86	15,74	5,49
2009	113,71	16,76	5,26
2010	123,56	17,77	5,60
2011	115,07	19,37	9,30
2012	109,95	21,26	5,86
2013	122,44	25,32	6,79
2014	111,29	28,39	7,92
2015	-	24,05	6,67
2016	-	53,38	85,92
2017	-	59,82	96,53
2018	-	66,27	107,14
2019	-	72,72	117,75
2020	-	79,17	128,36

Appendix D3: CH_4 emissions for the landfills with LFG capture and electricity generation ($GgCO_2$-e)

Year	Bisasar Road	Marianhill	Buffelsdraai
2004	-92,03	-16,68	0,00
2005	-106,10	-18,13	0,00
2006	-120,17	-19,58	0,00
2007	-134,24	-21,03	-5,52
2008	-148,31	-22,48	-7,84
2009	-162,38	-23,93	-7,52
2010	-176,45	-25,38	-8,00
2011	-164,32	-27,65	-13,27
2012	-157,01	-30,37	-8,38
2013	-174,86	-36,16	-9,70
2014	-158,93	-40,55	-11,30
2015		-34,34	-9,52
2016		-76,22	-122,69
2017		-85,43	-137,85
2018		-94,64	-153,00
2019		-103,85	-168,15
2020		-113,05	-183,30

Appendix D4: Emissions from landfills considering increased recycling ($GgCO_2$-e)

Year	Marianhill	Buffelsdraai
2013	250.64	67.24
2014	281.04	78.35
2015	238.04	65.98
2016	528.33	850.42
2017	592.15	955.44
2018	655.97	1,060.46
2019	719.78	1,165.48
2020	783.60	1,270.50

Appendix D5: Emissions savings from increased recycling for each material ($GgCO_2$-e)

Year	Emissions Savings											
	Bisasar Road				Marianhill				Buffelsdraai			
	Paper	Metal	Glass	Plastic	Paper	Metal	Glass	Plastic	Paper	Metal	Glass	Plastic
2012	-178.16	-187.79	-16.38	-56.75	-36.85	-38.84	-3.39	-11.74	0.00	-10.42	-0.91	-3.15
2013	-164.68	-177.80	-15.45	-55.88	-42.01	-4.36	-3.94	-14.26	-0.01	-12.65	-1.01	-3.97
2014	-137.69	-152.07	-13.16	-49.49	-36.18	-39.96	-3.46	-13.00	--0.01	-11.08	-0.96	-3.60
2015	-	-	-	-	-81.35	-89.78	-7.82	-29.52	-0.03	-144.52	-12.59	-47.52
2016	-	-	-	-	-92.36	-102.00	-8.94	-33.83	-0.15	-164.58	-14.43	-54.58
2017	-	-	-	-	-103.78	-114.35	-10.08	-38.40	-0.17	-184.86	-16.30	-62.07
2018	-	-	-	-	-115.32	-126.96	-11.26	-43.03	-0.19	-205.58	-18.23	-69.67
2019	-	-	-	-	-127.30	-139.84	-12.47	-47.94	-0.21	-226.72	-20.22	-77.74
2020	-	-	-	-	-36.85	-38.84	-3.39	-52.91	-0.00	-10.42	-0.91	-85.88

Appendix D6: Emissions savings from increased recycling of plastic ($GgCO_2$-e)

Year	Emissions Savings											
	Bisasar Road				Marianhill				Buffelsdraai			
	PELD	PEHD	PET	PP	PELD	PEHD	PET	PP	PELD	PEHD	PET	PP
2012	-22.99	-7.16	-8.35	-18.24	-4.76	-1.48	-1.73	-3.77	-1.28	-0.40	-0.46	-1.01
2013	-22.64	-7.05	-8.22	-17.96	-5.78	-1.80	-2.10	-4.58	-1.61	-0.50	-0.58	-1.28
2014	-20.90	-6.25	-7.28	-15.91	-5.27	-1.64	-1.91	-4.18	-1.46	-0.45	-0.53	-1.16
2015	-	-	-	-	-11.96	-3.73	-4.34	-9.49	-19.25	-6.00	-6.99	-15.28
2016	-	-	-	-	-13.71	-4.27	-4.98	-10.87	-22.12	-6.89	-8.03	-17.55
2017	-	-	-	-	-15.56	-4.85	-5.65	-12.34	-25.15	-7.83	-9.13	-19.95
2018	-	-	-	-	-17.43	-5.43	-6.31	-13.83	-28.23	-8.79	-10.25	-22.40
2019	-	-	-	-	-19.42	-6.05	-7.05	-15.41	-31.50	-9.81	-11.44	-24.99
2020	-	-	-	-	-21.44	-6.68	-7.78	-17.01	-1.28	-0.40	-0.46	-1.01

Appendix D7: Quantity of composted waste (Gg)

Year	Marianhill	Buffelsdraai
2015	7.60	12.23
2016	8.51	13.74
2017	9.43	15.24
2018	10.34	16.75
2019	11.76	18.26
2020	12.19	19.77

Appendix D8: Emissions from landfills due to composting ($GgCO_2$-e)

Year	Buffelsdraai	Marianhill
2013	79.49	285.15
2014	65.98	239.14
2015	850.39	527.48
2016	955.41	589.28
2017	1 060.43	650.70
2018	1 165.45	711.73
2019	1 270.45	787.96
2020	1 375.48	851.69