

**UNIVERSITY OF VENDA**  
**SCHOOL OF ENVIRONMENTAL SCIENCES**  
**DEPARTMENT OF ECOLOGY AND RESOURCE MANAGEMENT**

Estimation of the emissions of gases from a two landfill sites using the LandGEM and Afvalzorg models: Case study of the Weltervenden (Polokwane) and Thohoyandou landfills

By

Njoku, Prince Obinna

Student Number: 16023634

.....  
Signature/Date

A Master's dissertation submitted to the Department of Ecology and Resource Management in the School of Environmental Sciences, University of Venda in partial fulfilment of the requirements for Masters of Environmental Sciences.

Supervisor: Prof. J.O. Odiyo

Co-supervisor: Dr. J.N. Edokpayi

September, 2018

### **Declaration**

I, NJOKU PRINCE OBINNA, hereby declare that this dissertation for Masters in Ecology and Resource Management at the University of Venda, hereby submitted by me, has not been previously submitted for a degree at this or any other institution. This is my work in design and execution; all reference materials contained herein have been duly acknowledged.

Signature \_\_\_\_\_

Date: \_\_\_\_\_

## Abstract

Over the years it has been observed that the solid waste sector has been an increasingly major contributor to the amount of Greenhouse gases (GHGs) in the atmosphere. To some extent a great chunk of these GHGs in the atmosphere is from Landfill gas (LFG). This study employs two theoretical models (LandGEM and Afvalzorg models) to estimate the amount of LFG emitted from Weltervenden and Thohoyandou landfill sites located in Limpopo province of South Africa. Furthermore, the study investigated the appropriate technique of the LFG utilisation as a source of electricity and the number of households using electricity. LFGcost model was used to estimate the cost and benefits related to the implementation of a LFG utilisation technology. Also, the possible health and environmental impacts of the landfill emissions on the people living closer to the landfill site were determined.

The LandGEM model's simulation concludes that CH<sub>4</sub> and CO<sub>2</sub> peaked in the year 2020 with values of  $3.323 \times 10^3$  Mg/year and  $9.118 \times 10^3$  Mg/year, respectively, for the Thohoyandou landfill. Results from the Afvalzorg model indicate that the CH<sub>4</sub> peaked in the year 2020 with value of  $3.501 \times 10^3$  Mg/year. Meanwhile the total emission of CH<sub>4</sub> from 2005-2040 by the LandGEM and Afvalzorg models are 66200 Mg/year and 69768 Mg/year, respectively. However, for the Weltervenden landfill, the total LFG peaked in the year 2023 while the CH<sub>4</sub> peak at 4061 Mg/year and 3128 Mg/year for LandGEM and Afvalzorg models, respectively.

Furthermore, results from the cost analysis and benefits for the implementation of a LFG utilisation technology in both landfills show that the implementation of such a utilisation technology will be economically feasible considering the sale of t CO<sub>2</sub> equivalent in the carbon market. However, without considering the sales of t CO<sub>2</sub> equivalent, not all the LFG engines are economically feasible for both landfills.

This study also shows that the residents living closer to the Thohoyandou landfill are at a higher risk of environmental pollution and could suffer negative impacts from the landfill than residents living far from the landfill site. However, the Weltervenden landfill did not have lots of communities living closer to the landfill and therefore it was not included in this study.

## **Acknowledgement**

I would like to express my deepest gratitude to God Almighty, who gave me life and strength to be able to conduct and complete this thesis.

I would like to thank my supervisor, Professor John Ogony Odiyo, who has the assertiveness and substance of a genius. He constantly guided and instilled in me a drive for research work. Without his tutelage and persistent help, this dissertation would have not been possible.

I also would like to show my gratitude to my co-supervisor, Doctor Joshua Edokpayi, who has been a source of encouragement and has made me a better person in terms of research.

I would like to thank my friends for their support throughout the period of this research.

In addition, I would like to thank my family, Njoku family, for their constant support and prayers, which was a pivotal point of commencing this study.

## **Dedication**

I dedicate this work to the Almighty God, who has given me life to begin and complete this dissertation and to my family.

## Table of Contents

### Front page

<b>UNIVERSITY OF VENDA</b> .....	<b>i</b>
<b>Declaration</b> .....	<b>i</b>
<b>Abstract</b> .....	<b>ii</b>
<b>Acknowledgement</b> .....	<b>iii</b>
<b>Dedication</b> .....	<b>iv</b>
<b>Table of Contents</b> .....	<b>v</b>
<b>List of Figures</b> .....	<b>viii</b>
<b>List of Tables</b> .....	<b>x</b>
<b>Scholarly Outputs from this study</b> .....	<b>xii</b>
<b>CHAPTER ONE: Introduction</b> .....	<b>1</b>
1.1 Background of the study .....	1
1.2 Statement of problem .....	3
1.3 Motivation .....	4
1.4 Objectives.....	5
1.4.1 Main Objective .....	5
1.4.2 Specific Objectives .....	5
1.5 Research Questions .....	5
1.6 Research Hypothesis .....	6
1.7 The Study Area.....	6
1.7.1 Weltevreden Landfill (Polokwane) .....	6
1.7.2 Thohoyandou Landfill .....	8
<b>CHAPTER TWO: Literature Review</b> .....	<b>11</b>
2.1 Solid waste.....	11
2.2 Landfill .....	14
2.3 Landfill gas (LFG) .....	17
2.3.1 Factors affecting the production of LFG .....	21
2.4 LFG Utilisations.....	22
2.5 Environmental and economic benefits of LFG .....	24
2.6 Models for Estimation of LFG .....	27

2.6.1 Application of LFG models for different studies .....	33
2.6.2 Energy potential from LFG in Africa .....	37
2.7 Cost analysis and benefits of LFG (LFGcost Web Model).....	41
<b>CHAPTER THREE: METHODOLOGY .....</b>	<b>45</b>
3.1 Research design.....	45
3.2 Models for the study.....	46
3.2.1 Landfill Gas Emission Models (LandGem).....	46
3.2.2 Multi-phase Afvalzorg model.....	47
3.2.3 Data input for the simulation of LFG in Thohoyandou and Weltervenden landfill sites .....	47
3.2.4 Procedure to run the LandGem and Afvalzorg models .....	51
3.3 Sensitivity analysis .....	52
3.4 Estimation of the cost analysis and benefit for the implementation of the LFG utilisation project.....	52
3.4.1 LFGcost Web Model .....	52
3.5 Investigation of the perception of health and environmental impacts of residents living closer to the landfill sites.....	54
3.6 Ethical Consideration .....	55
<b>CHAPTER FOUR: ESTIMATION OF LFG FROM THOHOYANDOU AND WELTERVENDEN LANDFILLS .....</b>	<b>56</b>
4.1 LandGEM simulation.....	56
4.2 Afvalzorg model simulation.....	60
4.3 Comparison of results from the LandGEM and Afvalzorg simulations .....	62
4.4 Comparison of the results from the two landfill sites .....	64
4.5 Sensitivity Analysis.....	66
4.6 Limitation of models .....	68
<b>CHAPTER FIVE: IMPLEMENTATION OF LFG UTILISATION TECHNOLOGY .70</b>	
5.1 Cost and benefits analysis .....	70
5.2 Environmental and Economic benefits .....	78
5.3 Electricity generated from the Thohoyandou and Weltervenden landfills .....	80
<b>CHAPTER SIX: EVALUATION OF THE PERCEPTIONS OF RESIDENTS LIVING CLOSER TO THOHOYANDOU LANDFILL .....</b>	<b>86</b>
6.1 Perception on health and environmental impacts due to the presence of a landfill site.	86

6.2 Perception of significance of environmental problems faced by the community .....	87
6.3 Perceptions on most reported illnesses encountered by the participants in both communities .....	98
6.4 Perception of most disturbing landfill site characteristics .....	101
6.5 Perception of life satisfaction with living in the community .....	104
<b>CHAPTER SEVEN: CONCLUSION AND RECOMMENDATIONS.....</b>	<b>107</b>
7.1 CONCLUSIONS .....	107
7.2 RECOMMENDATIONS .....	108
<b>REFERENCES.....</b>	<b>110</b>
<b>Appendix A: Results of the LFG generated from the Thohoyandou landfill site using the LandGEM model until 2040 .....</b>	<b>120</b>
<b>Appendix B: The total values of different odorous gas pollutants present in Thohoyandou landfill .....</b>	<b>121</b>
<b>Appendix C: Results of the LFG generated from the Weltervenden landfill site using the LandGem model until 2040.....</b>	<b>123</b>
<b>Appendix D: The total values of different odorous gas pollutants present in Weltervenden landfill .....</b>	<b>124</b>
<b>Appendix E: Results of the LFG generated from the Thohoyandou landfill site using the Afvalzorg model .....</b>	<b>126</b>
<b>Appendix F: Results of the LFG generated from the Weltervenden landfill site using the Afvalzorg model .....</b>	<b>127</b>
<b>Appendix G: Questionnaire for the study .....</b>	<b>128</b>
<b>Appendix H.....</b>	<b>132</b>
<b>Appendix I .....</b>	<b>133</b>
<b>Appendix J.....</b>	<b>134</b>
<b>Appendix K.....</b>	<b>135</b>
<b>Appendix L: Ethical Clearance certificate .....</b>	<b>136</b>

## List of Figures

Figure 1.1: Bell graph of extreme weather events (source: Lacynski, 2015).....	2
Figure 1.2: Study area map for Weltervenden Landfill.....	7
Figure 1.3: Study area map for Thohoyandou Landfill .....	8
Figure 1.4: The sign board of the Thohoyandou landfill situated at the main entrance .....	9
Figure 1.5: The already closed cells in the landfill. B: shows the current cell receiving waste in the landfill .....	10
Figure 1.6: Transportation of already sorted waste by reclaimers in the landfill .....	10
Figure 1.7: Residential community living closer to the landfill site.....	10
Figure 2.1: Solid waste hierarchy .....	14
Figure 2.2: An image of a modern sanitary landfill .....	15
Figure 2.3: Landfill gas composition against Time (ATSDR, 2001). .....	17
Figure 2.4: Some major components of LFG (US EPA, 2005).....	19
Figure 3.1: A design of the research process .....	46
Figure 3.2: Pie chart showing the average annual composition of waste present in the Thohoyandou landfill (Source: Thulamela Municipality and SAWIC website) .....	50
Figure 3.3: Pie chart showing the average annual composition of waste present in the Weltervenden landfill (Source: SAWIC website).....	51
Figure 4.1: Graphical representation of the total LFG, CH <sub>4</sub> , CO <sub>2</sub> and NMOC emitted from Thohoyandou landfill site using the LandGem model.....	57
Figure 4.2: Graphical representation showing the total LFG, CH <sub>4</sub> , CO <sub>2</sub> and NMOC emitted from the Weltervenden landfill site .....	59
Figure 4.3: Graphical representation of CH <sub>4</sub> emitted from Thohoyandou landfill site using the Afvalzorg model (k value = 0.5 year <sup>-1</sup> ).....	61
Figure 4.4: Graphical representation of the simulation of CH <sub>4</sub> emission from the Weltervenden landfill site using the Afvalzorg model .....	62
Figure 4.5: Comparison of the simulation of CH <sub>4</sub> using the Afvalzorg and LandGEM models for the Thohoyandou landfill site.....	63
Figure 4.6: Comparison of the simulation of CH <sub>4</sub> using the Afvalzorg and LandGEM models for the Weltervenden landfill site .....	64
Figure 4.7: The graphical representation of the LFG, methane, carbon dioxide and NMOC emitted from Thohoyandou and Weltervenden landfill sites using the LandGEM model. ....	65

Figure 4.8: The graphical representation of the LFG emitted from Thohoyandou and Weltervenden landfill sites using the Afvalzorg model.....	66
Figure 4.9: Graphical representation of Total LFG, CH <sub>4</sub> , CO <sub>2</sub> and NMOC emitted from Thohoyandou landfill site using the LandGEM model at k = 0.03 year <sup>-1</sup> . ....	67
Figure 4.10: Graphical representation of CH <sub>4</sub> emitted from Thohoyandou landfill site using the Afvalzorg model at k = 0.03. ....	68
Figure 5.1: Conversion of CH <sub>4</sub> (m <sup>3</sup> ) to t CO <sub>2</sub> equivalent (source: Couth et al., 2011).....	78
Figure 5.2: A graphical representation of the LFG generated, collected and utilised from the implementation of a LFG utilisation technology in Thohoyandou landfill site.....	83
Figure 5.3: A graphical representation of the LFG generated, collected and utilised from the implementation of a LFG utilisation technology in Weltervenden landfill site .....	85
Figure 6.1: Cross tabulation between the time the participant lived in the CL community and the seriousness of the disposal of solid waste.....	90
Figure 6.2 Cross tabulation between the time the participant lived in the CL community and the seriousness of the garbage and litters on the street .....	91
Figure 6.3: Cross tabulation between the time the participant lived in the CL community and the seriousness of unwelcomed location of the landfill to the community.....	92
Figure 6.4: Cross tabulation between the time the participant lived in the CL community and the seriousness of air pollution and bad odour in the community .....	93
Figure 6.5: Cross tabulation between the time the participant lived in the CL community and the seriousness of noise pollution in the community .....	95
Figure 6.6: Cross tabulation between the time the participant lived in the CL community and the seriousness of water pollution in the community.....	95
Figure 6.7: Cross tabulation between the time the participant lived in the CL community and the seriousness of dust pollution in the community.....	96
Figure 6.8: A graphical comparison between the participants response for both communities showing the seriousness of each landfill characteristic .....	97
Figure 6.9: A graphical comparison between the participants living in both communities showing how frequent the illnesses impact on them. ....	101
Figure 6.10: A graphical comparison between the participants living in both communities showing how disturbing the external factors associated with a landfill is to them.....	104
Figure 6.11: A graphical comparison between the participants living in both communities showing how satisfied the participants are in the community. ....	106

## List of Tables

Table 2.1: Waste generation rates in million tonnes/year in South Africa in 1992 and 1997 (Makgae, 2011).....	12
Table 2.2: Solid waste stream categorization (Hoornweg and Bhada-Tata, 2012) .....	12
Table 2.3 Typical LFG components (EPA, 2005) .....	20
Table 2.4: Summary of LFG utilisation (Terraaza and Willumsen, 2010; Global Methane Initiative, 2012).....	24
Table 2.5: Summary of LFG model evaluation .....	35
Table 2.6: Electricity consumption in some African countries (Karekezi, 2002) .....	37
Table 2.7: 2012 Potential energy recoveries from LFG recovery (TJ/year) in urban areas of Africa (Scarlat et al., 2015).....	39
Table 2.8: LFG project types and sizes (Jangikhatoonabad, 2015) .....	41
Table 2.9: Some cases of LFG project functional over the world .....	44
Table 3.1: Imputation data for the simulation of LFG with the LandGEM and Afvalzorg models.....	47
Table 3.2: MSW waste deposited in Thohoyandou landfill site from 2005 - 2019.....	49
Table 3.3: MSW deposited in Weltervenden landfill from 1999 – 2022.....	49
Table 3.4: Values of DOC in Southern African region .....	51
Table 3.5: Specific input parameters for the LFGcost Model for both landfills.....	53
Table 4.1 The simulations of LFG, CH <sub>4</sub> , CO <sub>2</sub> and NMOC using the LandGEM and Afvalzorg models for the Thohoyandou and Weltervenden landfill sites .....	64
Table 5.1: Economic and financial results for the implementation of a LFG Technology in Thohoyandou landfill site .....	71
Table 5.2: Economic and financial results for the implementation of a LFG Technology for Weltervenden landfill site .....	75
Table 5.3: The conversion of methane to tonnes of CO <sub>2</sub> e for Thohoyandou landfill.....	79
Table 5.4: The conversion of methane to t CO <sub>2</sub> e for Weltervenden landfill .....	80
Table 5.5: Annual electricity generated in kWh for the different LFG engines for Thohoyandou landfill.....	81
Table 5.6: Annual electricity generated in kWh for the different LFG engines for Weltervenden landfill.....	82
Table 5.7: The average electricity per year generated and the number of household beneficiaries from the Thohoyandou landfill site project .....	83

Table 5.8: The average electricity per year generated and the number of household beneficiaries from the Weltervenden landfill site project.....	84
Table 6.1: Social and demographic characteristics of respondents .....	86
Table 6.2: Respondents’ rating of significance of environmental problems in the community .....	88
Table 6.3: Respondents’ rating of how these illnesses are reported by the participants in both communities.....	100
Table 6.4: Respondents’ rating of how disturbing are the external characteristics observed by the participants living in both communities.....	102
Table 6.5: Respondents’ rating of how satisfied the participants are with living in both communities.....	105

## Scholarly Outputs from this study

TOPIC	ARTICLE	STATUS
A review of Landfill gas generation and utilisation in Africa.	Article. Njoku, P. O., Odiyo, J. O., Durowoju, O. S., & Edokpayi, J. N. (2018). A Review of Landfill Gas Generation and Utilisation in Africa. <i>Open Environmental Sciences</i> , 10(1).	Accepted in Open Environmental Sciences Journal
Evaluation of the total landfill gas and potential energy recovery from a landfill in Limpopo province, South Africa	Article	In progress
Estimation of landfill gas potential and potential energy recovery from Thohoyandou landfill site in Limpopo, South Africa	Article	Under going, to be published with Waste Management
Influence of risk perception on the health and environmental impacts of residents living closer to a landfill situated in Limpopo province, South Africa	Article	Under going, to be published with Waste Management

## CHAPTER ONE: Introduction

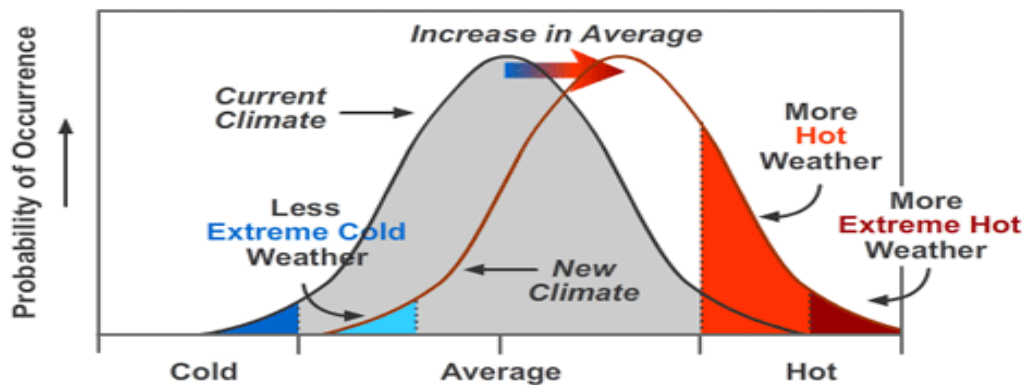
### 1.1 Background of the study

The world's Municipal Solid Waste (MSW) is about 1.3 billion tonnes/year with the expectations of its increase of 2.2 billion tons/year in 2025 (Hoornweg and Bhada-Tata, 2012). The need for this waste to be properly managed is of utmost importance. In Africa, some cities and regions generate MSW at approximately  $5 \times 10^{-4}$  tonnes per person per day and could reach  $8 \times 10^{-4}$  tonnes per person per day in extreme cases (EGSSAA, 2009). However, in developed countries, MSW generation is estimated to reach approximately  $10 \times 10^{-4} - 2 \times 10^{-3}$  tonnes per person per day (EGSSAA, 2009). Africa is lacking in the collection of most of their MSW because of poor forms of management, fiscal irresponsibility, lack of expertise and inadequacies to maintain the waste management system (EGSSAA, 2009).

South Africa generates approximately 100 million tonnes of general solid waste every year; an average person in South Africa generates about  $8 \times 10^{-4}$  tonnes of waste per day ( $3 \times 10^{-4}$  tonnes in low-income households and  $13 \times 10^{-3}$  tonnes in high-income households); which is almost the average amount of waste/person generated in developed countries (Ogola, et al., 2011). Waste management deals with the management of all processes and resources for appropriate handling of waste materials, from maintenance to waste transport trucks and dumping facilities to compliance with health codes and environmental regulations (Rushton, 2003). However, South Africa is focusing on waste management strategies, for example, the Polokwane declaration on waste management which is to stabilize waste generation and reduce the waste disposal by 50% in 2012 and by 2022 improve on a plan for zero waste generation (Phiri and Godfrey, 2012). Although, these strategies are in place, approximately 90% of South African's waste is deposited in landfills; while 85% of the world's municipal solid waste is deposited in landfills (DWAF, 1998; WWF, 2017).

Landfill gas (LFG) is a mixture of different gases formed by the biodegradation action of microorganisms on waste deposited within a landfill (Heyer et al., 2013). Mismanagement of landfill can lead to uncontrolled emissions of LFG such as  $\text{CH}_4$  and  $\text{CO}_2$  which contribute enormously to climate change; pungent odours, litters and dust in the vicinity; seepage of leachate formed in the landfill into groundwater and surface water (Health Protection Agency, 2011).  $\text{CH}_4$  and  $\text{CO}_2$  are Greenhouse gases (GHGs), which pose serious threat to different spheres of the environment, which include unimaginable forms of flooding, sea level rise, distortion of rainfall patterns, unpredictable and powerful hurricanes, gigantic heat

waves and loss of glaciers among others (Woudhuysen and Kaplinsky, 2009). One of the key effects of LFG is air pollution which is one of the leading potentials to global warming and extreme climate change (CSIR, 2011). The United States Environmental Protection Agency (USEPA) (2005) predicts from recent scientific assessments that, as the global temperature continues to increase due to climate change; the number and intensity of extreme events will increase (Figure 1).



**Figure 1.1: Bell graph of extreme weather events (source: Lacynski, 2015)**

According to the technical report carried out by The Long-Term Adaptation Scenarios (LTAS): climate trends in South Africa (2013), it was observed that the mean average temperature increased by at least 1.5 times, the observed global average of  $0.65^{\circ}\text{C}$ . In addition, South Africa experienced a series of heat waves, which were  $5^{\circ}\text{C}$  higher than the maximum mean of the hottest month in 2015 (South African Weather Service, 2018). The Water Research Commission (South Africa) reported the intensity of drought increases in South Africa as the years increase. In 2015, South Africa suffered a major drought that was the same magnitude as the highest drought recorded in South Africa in 1991-1992 (Renault and Richard, 2013). These anomalies in the climatic condition will continue to persist and grow worse, if the continuous release of GHG from both landfill and other anthropogenic sources are not monitored and regulated (Parker et al., 2002).

One of the prevailing ways in managing the continuous emissions of LFG into the environment is by proper utilisation of the LFG. LFG can be utilised in various forms, which are direct use of the LFG in the landfill site; electrical power generation; fuel for vehicles and bio-methane production (Dudek et al., 2010).

## 1.2 Statement of problem

Landfill is one of the prevailing solid waste management techniques, though it is accompanied by both environmental and health problems. If there are no forms of LFG collection and utilisation technology installed in a landfill, the LFG migrates freely into the atmosphere thereby causing harm to the environment and endangering lives (Dudek et al., 2010). South Africa records show that it is one of the most vulnerable parts of the world in relation to probable climate change (Rogerson, 2016). Since the prevailing global warming, South Africa has been reported to be approximately 2% hotter and at least 6% drier over the ten years interval from 1997-2006 compared to the 1970s (Blignauta et al., 2009). If the climate change persists by 2050, it could lead to a fall in South Africa's GDP to about 1.5%, which is approximately the annual foreign investment in South Africa (Turpie and Visser, 2012). The Weltervenden landfill and Thohoyandou landfill have no form of LFG collection and utilisation of technology installed in the landfills. Therefore, these landfills emit GHG into the atmosphere that contributes considerably to the GHG generated from South Africa.

LFG is a renewable source of energy that is essential for development and it is a crucial part of social, environmental and economic challenges in any country. Both developed and developing countries are now looking at any locally available, renewable and alternative energy options in order to address the issues of climate change and the provision of cleaner energy and security. However, LFG has been underutilised in South Africa (Couth et al., 2011), Weltervenden and Thohoyandou LFG emissions have not been utilised in any form. However, some form of flaring system has been installed in Weltervenden landfill site (Bhailall, 2015). This study will be the first of its kind to simulate the total LFG emission from landfill in the Limpopo province (including Thohoyandou and Weltervenden landfills); it also be the first to derive the cost analysis and benefits for the utilisation of the LFG. This study, if properly implemented, will help in provision of electricity, create jobs for the people of South Africa and reduce global warming associated health hazards from the landfills.

LFG are highly flammable gases and pose great threat of fire outbreaks in the landfill sites and around the vicinity. CH<sub>4</sub> is highly explosive in air if about 5-15% by volume or concentration is exposed to the air. On 10<sup>th</sup> August 2016, in Pietermaritzburg, South Africa, part of the New England road landfill engulfed into flames and produced pungent odour. This caused about 70 informal settlement houses to be burned down; at least 140 people were left homeless at the Woodstock road informal settlement. The cause of fire was attributed to

prevailing LFG emitted from the waste piles and dry weather condition (Nsele, 2016). Therefore, because there are no forms of proper management and control of LFG generated from the Weltervenden and Thohoyandou landfills, there is high tendency of fire outbreaks in the landfills and its vicinity. Weltervenden landfill has suffered from some series of fire outbreaks over the years (key informant: traders).

People living close to the landfill site face a lot of problems (Thada, 2012). Research shows that people living close to the landfill site mainly suffer medical conditions such as asthma, cuts, diarrhoea, stomach pain, recurring flu, cholera and tuberculosis more than people living far away from the landfill site (Thada, 2012). The causes of the health problems are as a result of continuous exposure to chemicals; inhalation of toxic fumes and dust from the landfill sites. Despite the harmful effects, not much research on LFG emissions has been conducted in Limpopo Province.

### **1.3 Motivation**

The emissions associated with landfill operations (LFG, leachates, dust, odour and litters) are dangers to the earth's ecosystem (DWAF, 1998). A little emission of CH<sub>4</sub> from landfills or any other sources is of great danger to the earth's stability (Nikiema et al., 2007). As a result of the continuous increase of CH<sub>4</sub> in the atmosphere, the need to estimate the total amount of LFG emitted is of great importance. South Africa is still behind in the availability of data on LFG emission due to poor landfill management; and reduced research focus in the area of LFG emissions. It is therefore paramount for this study to be conducted as the data determined can help fill the data gap which already exists in South Africa.

Various studies have shown LFG to be a major contributor to health and environmental problems facing people living close to the landfill site (Vrijheid, 2000; Hamer, 2003; Durmusoglu et al., 2010; Thada, 2012). This study therefore takes into consideration settlements close to a landfill site, identify various prevailing health and environmental problems and recommends possible solutions. In addition, a study shows adverse effects of exposure to landfill site on pregnancy with an increase in infant's low birth weight as a result of continuous contact of parents with chemical substances (dioxins) present in the landfill site (Vrijheid, 2000). According to the UN's fourth report (2007), Africa is the most vulnerable continent to climate change (Wild, 2015). Although many developed nations utilise LFG emissions, in 2001 the world recorded approximately 950 landfill gas plants, where approximately 90% are from developed nations (Willumsen, 2001). South Africa is still

behind in policies and technology concerning LFG utilisation, however, in eThekweni Municipality (Durban South Africa); three sanitary landfills (Bisasar 6.5MW, Mirianhill 1 MW and LaMercy 0.5MW) made progress in the first CDM LFG utilisation project in Africa (Couth et al., 2011). The Durban LFG technology generates electricity of about 50000 MWh per year, which is enough to power about 3750 small homes (eThekweni Municipality, 2017). This study focuses on the estimation of LFG emitted; its benefits and association with landfill operation.

## **1.4 Objectives**

### **1.4.1 Main Objective**

The main objective of this study is to estimate the amount of LFG emitted from the Weltervenden and Thohoyandou Landfill sites using the LandGEM and Afvalzorg models, and to evaluate potential utilisation of the gases emitted.

### **1.4.2 Specific Objectives**

- i. To investigate the amount of GHGs emitted from Weltervenden and Thohoyandou landfill sites using the LandGem and Afvalzorg models.
- ii. To evaluate the best technique for the utilisation of LFG from the Weltervenden and Thohoyandou landfill sites as a source of energy.
- iii. To evaluate the number of households that are able to utilise the electricity generated, and determine the cost and benefits related to the implementation of the LFG utilisation technology with the use of the LFGcost Web model.
- iv. To evaluate the perception of people living closer to the landfill site, concerning the health and environmental impacts of the LFG emissions in the community.

## **1.5 Research Questions**

- i. What is the total estimated amount of LFG emitted from the Weltervenden and Thohoyandou landfill sites?
- ii. What is the best technique for the utilisation of the LFG as a source of energy from the Weltervenden landfill and Thohoyandou landfill?
- iii. What are the perception of the people living closer to the landfill site concerning their health and environmental challenges posed by the landfill's presence in the community?

## 1.6 Research Hypothesis

- i. The total amount of LFG emitted from the landfill sites is high and can be estimated with the use of the LandGEM and Afvalzorg models.
- ii. The LFG (CH<sub>4</sub>) emitted from the Weltervenden landfill site and Thohoyandou landfill can be useful as an alternative source of energy (electricity).
- iii. The electricity produced from the implementation of LFG can be used to power households living in the province and the LFG utilization technology can be beneficial based on cost analysis using the LFGcost model.
- iv. The people living closer to the landfill site are concerned due to the presence of the landfill site.

## 1.7 The Study Area

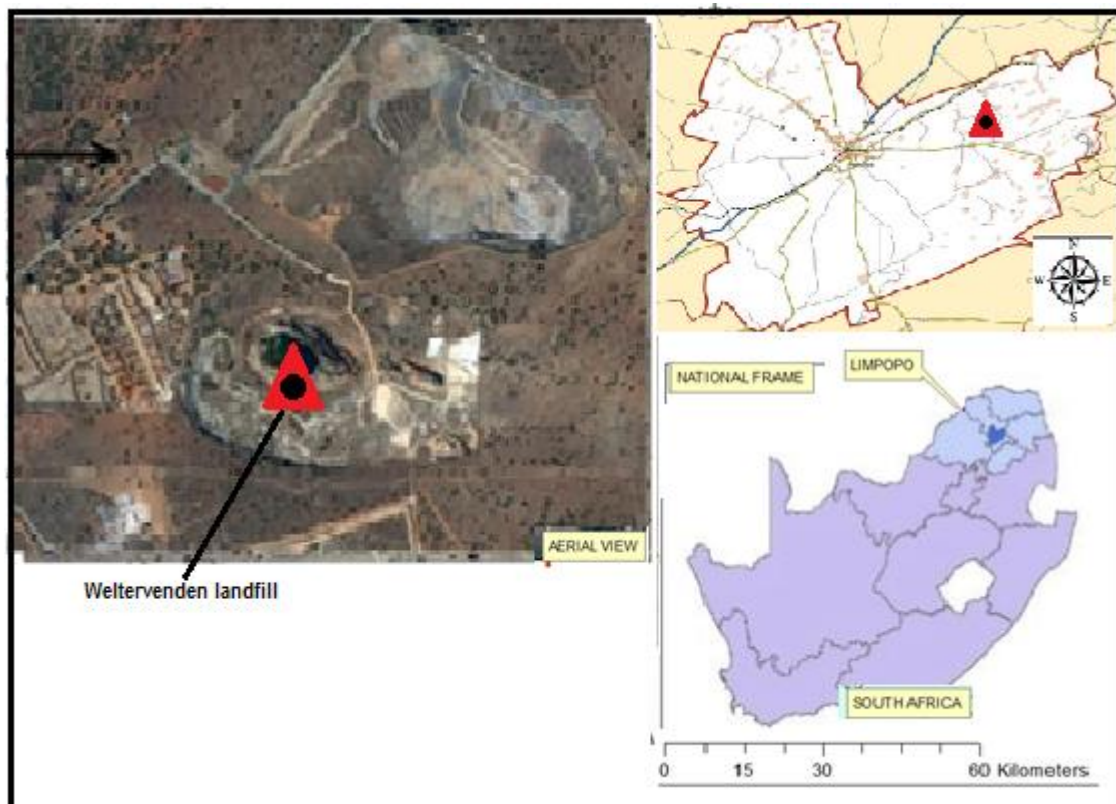
### 1.7.1 Weltervenden Landfill (Polokwane)

The landfill is located in Polokwane. The site started off as a quarry before it was licensed in the year 1998 by the then Department of Water affairs and Forestry. The landfill occupies 35 ha of land with the current slope of 56% from the base. The height of the landfill above the ground is 14 m (28% slopes) western side and 11 m high southern side. The landfill has an eligible notice board displayed in front of the landfill. The landfill is fenced round to avoid unauthorized entry into the landfill site and waste inspections are done by the security guard and the transporter who confirm the type of waste it is carrying before they are allowed into the landfill. There is a water tanker spray system which sprays the ground with water often to avoid dust percolation in the landfill area. The landfill currently allows reclaimers on site and most of the reclaimers have their protective clothes on to avoid health and safety hazards in the landfill. Also, there is a weighbridge at the entrance of the landfill, this weighbridge gives an accurate result on the amount of waste disposed into the landfill. Weltervenden landfill is the main landfill that manages MSW in Polokwane Municipality. Figure 1.2 shows a map of Weltervenden landfill site. Polokwane Municipality is under the jurisdiction of Capricorn District in Limpopo Province. The Weltervenden landfill is located on longitudes 23° 57' 00.75''S and latitude 29° 29' 48.21''E (Polokwane municipality, 2011).

Polokwane Municipality has an estimated population of 508,967 which makes up 10% of the total population living in Limpopo Province (Polokwane Municipality, 2011). Polokwane Municipality experiences 3.27% annual population growth rate, while the internal migration

to cities increase annually at 1.7% (Polokwane Municipality, 2011). About 71% of the spatial composition of Polokwane Municipality is considered to be rural, while 23% is said to be urban, the remaining 6% is characterised to be demarcated into small buildings, recreational centres and industrial site (Polokwane Municipality, 2011). Polokwane lies in the summer rainfall region with warm climate, with maximum temperature during December and January in the range of 28.1°C-36.8°C (Polokwane Municipality, 2011).

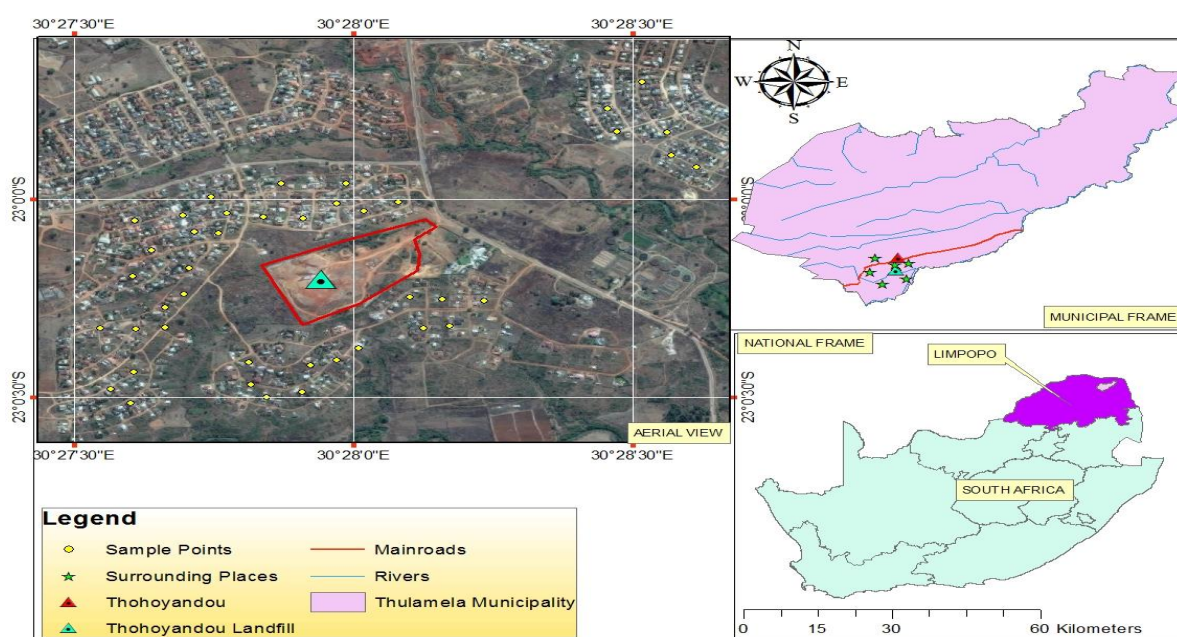
Polokwane receives approximately 389 mm of rainfall every year, with the greatest amount of rainfall occurring during summer (Saexplorer, 2017a).



**Figure 1.2: Study area map for Weltervenden Landfill**

## 1.7.2 Thohoyandou Landfill

The landfill is located in the Thulamela Municipality. It is the main landfill that accepts and manages MSW in the Thulamela Municipality and it is currently receiving waste. Figure 1.3 gives the map of Thohoyandou landfill. Thulamela Municipality is located 180 km from Polokwane, it is a gateway to Kruger National Park. It is located on longitudes  $23^{\circ}00'13.0''S$  and latitude  $30^{\circ}27'55.3''E$ . The population of Thulamela Municipality is about 584,257 people and it is characterised mostly of rural settlements (Thulamela local Municipality, 2017). Thohoyandou receives approximately 752 mm of rain every year, with most rainfall occurring during mid-summer (Saexplorer, 2017b).



**Figure 1.3: Study area map for Thohoyandou Landfill**

The landfill had its permit to commence operation in 2004 by the then Minister of Water Affairs and Forestry. Figure 1.4 shows the sign board and some notices at the entrance of the landfill site. When visited during the study on 5th June 2017, the landfill only received general MSW. Waste that were inorganic or organic which could have definite acute chronic effects on human's health and the environment because of its physical, chemical and toxic features and which corresponds to the UNDP's definition of hazardous waste were not allowed to be deposited in the landfill. The landfill currently accepts majority of its MSW generated in the Thulamela Municipality area and it is currently the only landfill accepting MSW in the area. The landfill has about 4 cells which have been closed up and a current functioning cell which is still receiving waste. Figures 1.5A and 1.5B show the closed cells

and the functioning cell in the landfill, respectively. The management of the landfill is constructing a proper weighing bridge for proper calculation of waste being deposited in. Waste like nappies and tyres are currently basic challenges faced by the landfill operators because of their inability to degrade quickly, these wastes can stay for years before they degrade. On visit to the landfill site, the garden waste is separated for composting and permitted reclaimers sort for plastic bottles and aluminum cans for recycling.



**Figure 1.4: the sign board of the Thohoyandou landfill situated at the main entrance**



A



B

**Figure 1.5: A: shows the already closed cells in the landfill. B: shows the current cell receiving waste in the landfill**

Figure 1.6 shows a reclaimer arranging his already sorted and packaged plastics bottles and aluminum cans. The landfill is majorly faced with challenges like; poor technology and machineries, loose particles of dust in the atmosphere; excessive mosquitoes, flies and rodents; air pollution/odour. However, Figure 1.7 shows the residential community residing close to the landfill site. This study also sought the perception of the residents in the area concerning health, environment, and social risk of living closer to the landfill site. It was observed that residential area is approximately 100 m from the landfill site.



**Figure 1.6: Transportation of already sorted waste by reclaimers in the landfill**



**Figure 1.7: Residential community living close to the landfill site**

## CHAPTER TWO: Literature Review

### 2.1 Solid waste

Waste production is an unavoidable outcome of the developmental activities, with the concept of urbanisation and industrialisation becoming major factors in national economy. Although waste seems unavoidable in a conceptual sense, it can be as useful as the original product. White et al. (2012) define waste as end-products of human activity, substances that have the need to be thrown away. Waste can be classified by physical state (solid, liquid and gas), and in context to solid waste by original use (packaging waste, food waste etc.); and physical property (combustible, recyclable and compostable); by origin (Industrial, Agricultural, domestic, commercial, etc.); or safety levels (hazardous and non-hazardous).

According to South Africa's legislation, the National Environmental Management Waste Act (DEA, 2012), waste is any substance, whether or not that substance can be reduced, reused, recycled and recovered;

- i. that is surplus, unwanted, rejected, discarded, abandoned or disposed of;
- ii. where the generator has no further use of for the purposes of production, reprocessing or consumption.
- iii. that must be treated or disposed of; or
- iv. that is identified as a waste by the Minister, but
  - a. a by-product not considered waste, and
  - b. any portion of waste once reused, recycled or recovered.

The Council for Scientific and Industrial Research (CSIR), conducted a study on waste streams in South Africa from 1992-1997, and realised that the total volume of both hazardous and non-hazardous waste generated by South Africa between 1992 and 1997 accrued up to about 500 million tons with the mining industry leading the waste stream sector. Table 2.1 shows the research summary of the CSIR (Makgae, 2011).

**Table 2.1: Waste generation rates in million tonnes/year in South Africa in 1992 and 1997 (Makgae, 2011)**

Waste stream	1992	1997
Mining	378	468.2
Industrial	23	16.3
Power generation	20	20.6
Agriculture and forestry	20	20
Domestic and trade	15	8.2
Sewage sludge	12	0.3
Total	468	533.6

Solid waste is categorized based on their sources, type of waste generated and type of solid waste. Table 2.2 shows some different category of solid waste.

**Table 2.2: Solid waste stream categorization (Hoornweg and Bhada-Tata, 2012)**

Waste type generated	Generator of waste	Source of waste
Food wastes, paper, cardboard, plastics, textiles, leather, yard wastes, wood, glass, metals, ashes, special wastes (e.g. bulky items, consumer electronics, white goods, batteries, oil, tires), and household hazardous waste	Immediate family and extended family	Residential, commercial
Housekeeping wastes, packaging, food wastes, construction and demolition materials, hazardous wastes, ashes, special waste	Heavy and light machines, Power generator plants, construction sites.	Industrial
Paper, cardboard, plastics, wood, food waste, glass, metals, hazardous waste	Store, hotels, office building, schools, churches, market places, malls	Commercial
Dirts, wood, steel, concrete, dust, glass.	Construction sites, road repairs, renovations, demolitions	Construction and Demolition
Leaves, dust, tree trimmings, sludge, food waste	Street cleaning, landscaping, parks, recreational areas, waste water treatment plants.	Municipal services
Food waste, pesticides, manure, hazardous waste, animal dumps	Crops, farms, dairies, vineyards, grazing animals	Agricultural
Electronic waste: computers, mobile phones, photocopiers house hold electronics,	Domestic, offices, industries etc.	Residential, commercial

Population growth, urbanization and globalization have been attributed to the rapid increase of waste generation in the globe. The handling, storage, collection and disposal of MSW is very important, hence the need for solid waste management strategies (Zurbrugg, 2002). Solid waste management is the collection, transportation, disposal, monitoring of garbage, sewage, and other waste products (Sharholy et al., 2008). Waste management practices consist of the management of all processes and resources for appropriate handling of waste materials. This includes maintenance of waste transport trucks and dumping facilities in compliance with health codes and environmental regulations. There are eight dominant types of waste management techniques around the world. They include incineration, landfill, recycling, composting, fermentation, source reduction, reuse, and land application (Rushton, 2003). Waste management can be planned in advance given the ability to predict the nature, composition and quantities of waste generated over a period of time. Figure 2.1, shows the different solid waste hierarchy and the most favoured approach towards solid waste management. There are innovative plans that can be put in place for proper waste management which include:

Waste prevention – the avoidance of some waste generated either by government regulations and laws. Waste generation sensitization and awareness in schools and households about the advantages of low waste generation. Promoting the use of cleaner technology in the industrial sector to prevent the production of gaseous emissions into the atmosphere. Waste prevention has the highest priority because, if there is no waste generated, then there is no need for waste management and the problems associated with waste (USEPA, 2005). However, with the rapid rise in global industrialization and increasing population, it will be very difficult to completely prevent waste.

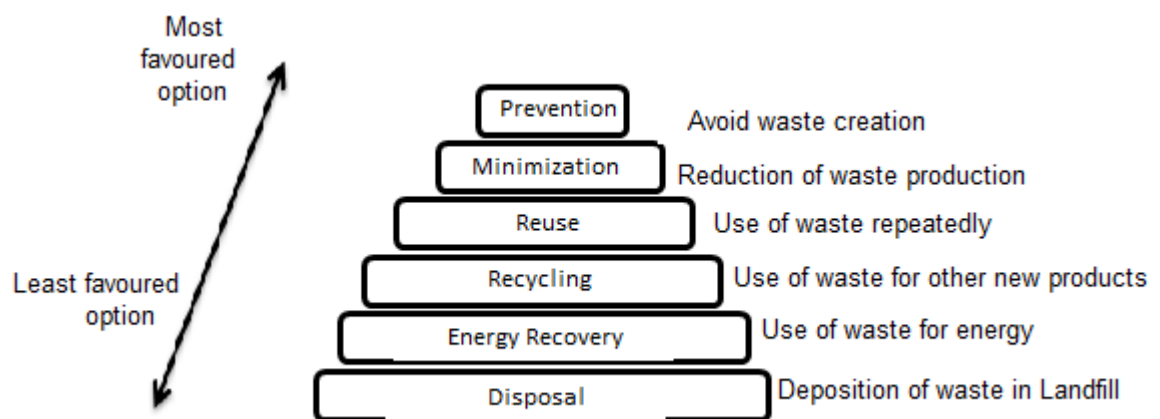
Waste minimization is the systematic method for reduction of sources of waste production. For instance, the reduction of volume of waste during manufacturing process such as reduction of package materials during packaging of goods (Makgae, 2011).

Reuse – This entails the use of waste material again after it has been used before. Reuse of water bottle for storage of other liquid contents in the home; or the use of plastic bags for storage purposes (Rakib et al., 2014).

Recycle – this is the breakdown of used waste product as raw materials for production of new product. Some types of recyclable materials include paper, glass, and degradable waste (Makgae, 2011).

Waste to energy recovery – consist of any waste treatment procedure that generates energy in the form of electricity, heat or transport fuels (e.g. diesel) from a waste source (Willumsen, 2001). An example is the use of gases emitted from landfill site as a source of fuel.

Disposal – this comprises of the dumping of waste material for example the use of Landfill. Waste disposal approach is the least of waste management planning procedure (Figure 2.1) because the end-product has an adverse effect on the environment (Makgae, 2011). Gases generated from the landfills or dumpsites contribute to global warming and climate change.



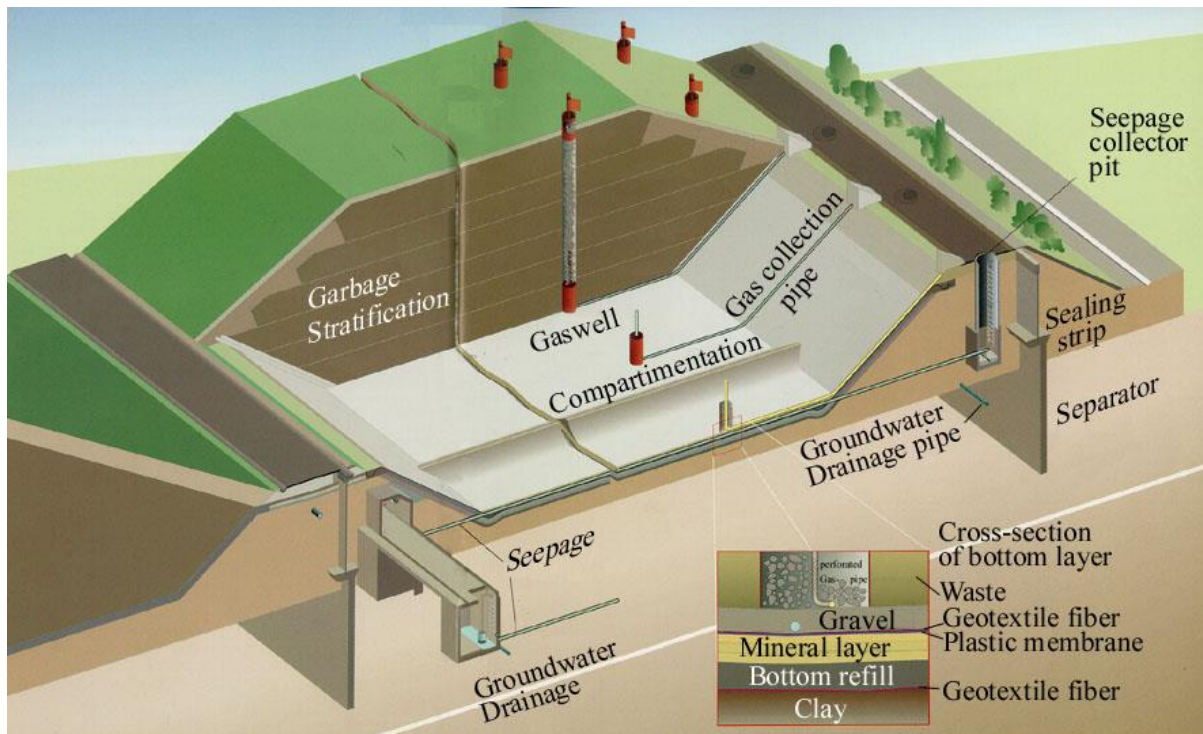
**Figure 2.1: Solid waste hierarchy (Njoku et al., 2018)**

In South Africa, waste management has been uncoordinated and poorly funded (Achankeng, 2003). There have been major issues in relation to waste management in South Africa which include lack of financial resources, insufficient waste collection system, unlawful dumping and unlicensed disposal facilities (Guerrero et al., 2013). The Department of Environmental Affairs (DEA) highlighted the need for combined waste management strategies in the waste hierarchy. That is tackling the issues of waste from the top of the waste hierarchy while the main focus should be on waste prevention and minimisation (to reuse) in order to avoid greater impacts from waste disposal (Makgae, 2011).

## 2.2 Landfill

Landfill has been a common acceptor for waste in the past decades, as stated earlier till to date about 90% of South African's waste and 85% of the world's waste is deposited in a

landfill (DWAF, 1998). In the operation of a landfill site, one should understand the processes, organizations and managements in landfill site selection, design and operations in order to avoid the danger associated with environmental media and human health. Figure 2.2 shows a typical landfill site and its different components.



**Figure 2.2: An image of a modern sanitary landfill (Source: <http://biophysics.sbg.ac.at/waste/landfill.htm>).**

**Landfill site selection** – This is a vital stage in the development of a landfill. In the selection of a landfill site, the criteria should meet the economic, environmental and public standards of the government. The selection process should not infringe on the constitutional right of the people living within the vicinity (DWAF, 1998).

Also, in selecting a landfill site - the natural, social, political, economic and technical factors must be considered. Landfill experts should ensure that the following landfill site selection precautions are taken into consideration;

- i. A proper hygienic and safe environment for the people living closer to the proposed landfill site and the personnel working at the landfill.
- ii. The air, water and land are protected from the proposed landfill emissions.
- iii. Reasonable use of land and proper land use.

- iv. Consider the maximum number of machines to be used in the site (Josimovic & Maric, 2012).

**Landfill design** - is an interactive process incorporating a conceptual design proposal; the findings of the environmental assessment; risk assessment and conclusions reached in the investigations to minimize the negative impacts on the environment and human health (Carey et al., 2000). The aim of having a landfill design constructed is to eliminate any form of adverse effect found during site investigation and environmental impact assessment. In addition, it prevents possible leachate discharge into ground or surface water. The provision of enough cover materials to avoid odour, seepage of rain water, litters, and provide good aesthetics to the environment (US Environmental Protection Agency, 2010).

**Landfill daily operation** - The MSW is collected by the landfill trucks, on reaching the landfill site the trucks are weighed on a weighing scale. The landfill operator inspects the solid waste to check for inappropriate waste for the landfill according to the codes of the landfill and inappropriate waste is separated from the total solid waste. The landfill trucks then offload the remaining solid waste into the appropriate landfill for the day. Immediately a landfill bulldozer quickly compacts and spreads the waste to avoid wind scattering the waste and odour (Carey et al., 2000). Meanwhile, the landfill truck is reweighed before leaving the landfill site to estimate the amount of waste carried by the truck; and this data is kept by the landfill operators. At the end of the day, a landfill bulldozer compacts and spreads soil or other cover materials over the solid waste to about 6 inches. Water trucks sprays water into the atmosphere to reduce dust in the atmosphere. Also, authorized scavengers or recycling companies come and search for recyclable materials for recycling. Finally, at the end of the day's operation, a landfill supervisor inspects the daily operations of the landfill and certifies the day's work. This often helps in identifying any loop holes that might have occurred during the day (Carey et al., 2000).

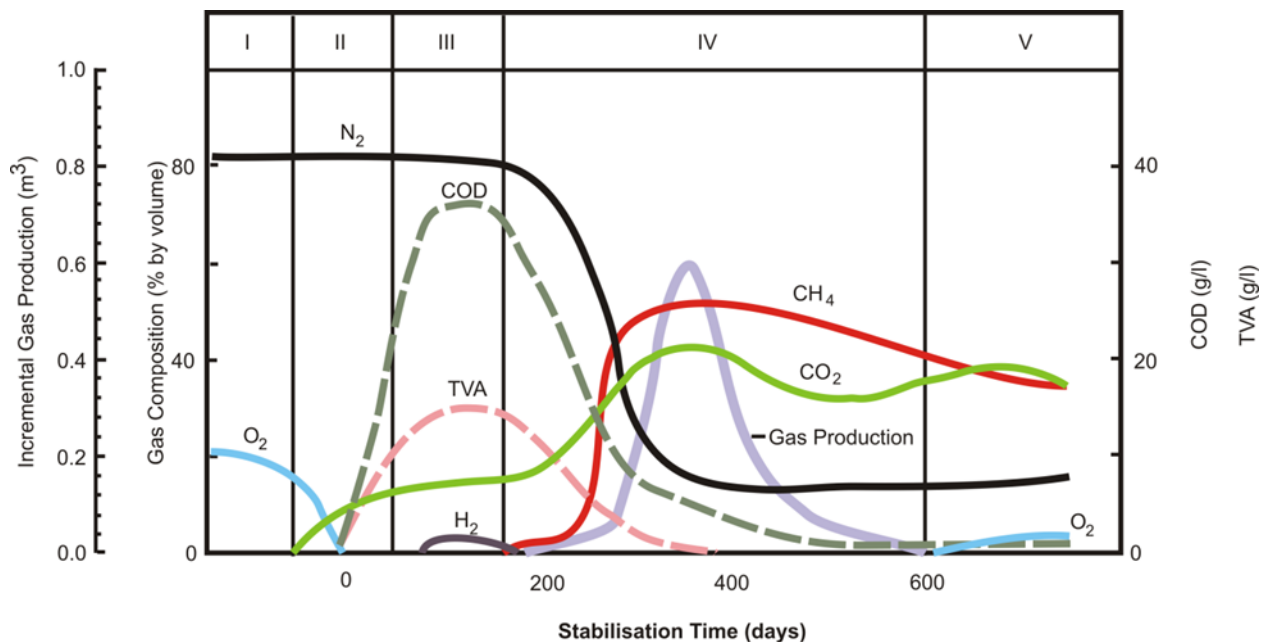
In South Africa, MSW is managed through landfill technique (CSIR, 2011). Gauteng province has the largest share with about 42%. Mpumalanga and KwaZulu-Natal provinces generate more than 5 million cubic meters of hazardous waste annually because of high rate of mining and fertilizer production activities present in the areas (DWAF, 1997). An average person in South Africa generates about  $0.7 \times 10^{-4}$  tonnes of waste, which is almost the average amount of waste/person generated in the developed countries. Various sources of pollution associated with landfill emissions include waste generated from the emission of landfill

vehicles and power generators; scattering of waste by wind while it is deposited in the landfill site e.g. litters, dust; emissions of gases due to break down of organic waste e.g. CH<sub>4</sub>, CO<sub>2</sub>, and Non-Methane Organic Compounds (NMOC) (Health Protection Agency, 2011).

### 2.3 Landfill gas (LFG)

The production of LFG involves bacterial decomposition, chemical reactions and volatilization of organic waste present in a solid waste landfill (Heyer et al., 2013).

**Bacterial decomposition** – this is largely the main process in LFG production, whereby bacteria decomposes organic waste into various by-products at the end of the process (Heyer et al., 2013). The different stages of bacterial decomposition are shown in Figure 2.3.



**Figure 2.3: Landfill gases present during the decomposition process of MSW (ATSDR, 2001).**

Phase I – aerobic bacteria decompose the long molecular chains of carbohydrates, protein and lipids found in the organic waste in the presence of available oxygen, this phase can go on for days or months until the total oxygen is used up. The oxygen present in this phase is as a result of loose compaction of solid waste when buried. The end –products of this phase are CO<sub>2</sub>, heat and water. Nitrogen content is high but will continue to undergo decay as the phase continues (ATSDR, 2001).

Phase II - this phase starts after the oxygen in the landfill is exhausted. In this anaerobic process, the bacteria change the compounds derived from the phase I process into acetic,

lactic, formic acids and alcohols such as methanol and ethanol. This is a very acidic process in which the acid present mixes with moisture which makes the nutrients dissolve. This makes the presence of nitrogen and phosphorus available to the bacteria in the landfill. Carbon dioxide and hydrogen (by products) are also generated, if the landfill is disturbed and air enters, then the phase goes back to the phase I process (LMOP, 2015).

Phase III – this is mainly where the methanogenous process starts. The anaerobic bacteria use the acid generated in phase II to form acetate. Then methane producing bacteria begins to emerge. Acid producing bacteria generates compounds for the methanogenic producing bacteria for use. At this phase, hydrogen peaks, chemical oxygen demand (COD) and total volatile acid concentration peaks as well in the concentration of the leachate (ATSDR, 2001).

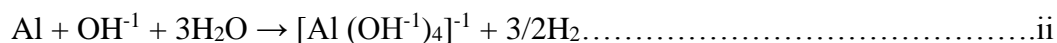
Phase IV – This is the equilibrium phase where production rate and composition are constant. Approximately 55% methane, 45% CO<sub>2</sub>, and 10% other gases are produced. Gas production could still occur for a period of 20 years after the landfill has been closed (Brindley, 2012).

Phase V – most landfill gas emissions occur at this phase, the pressure in the landfill waste compartment is higher than pressure of the ambient atmosphere. In this long-term phase, the volume of CO<sub>2</sub> decreases with respect to the methane emissions, the ratio can range up to 4:1 of CH<sub>4</sub> to CO<sub>2</sub> emissions (Bialowiec, 2011).

**Chemical reaction** – different chemical substances present in the landfill waste compartment react together chemically in the presence and absence of moisture, O<sub>2</sub>, CO<sub>2</sub> to give rise to different forms of LFG (LMOP, 2015). For example, anhydrous oxidation of aluminum:



Molecular enthalpy of the oxidation of aluminum = -1675.7KJ/mole (Calder and Stark, 2010). Aluminum from raw trash or metals reacts with oxygen with or without the presence of water. Amphoteric reaction – aluminum reacts with alkaline water at pH ≥ 8;



Also, aluminum nitrite reacts with water to give ammonium gas;



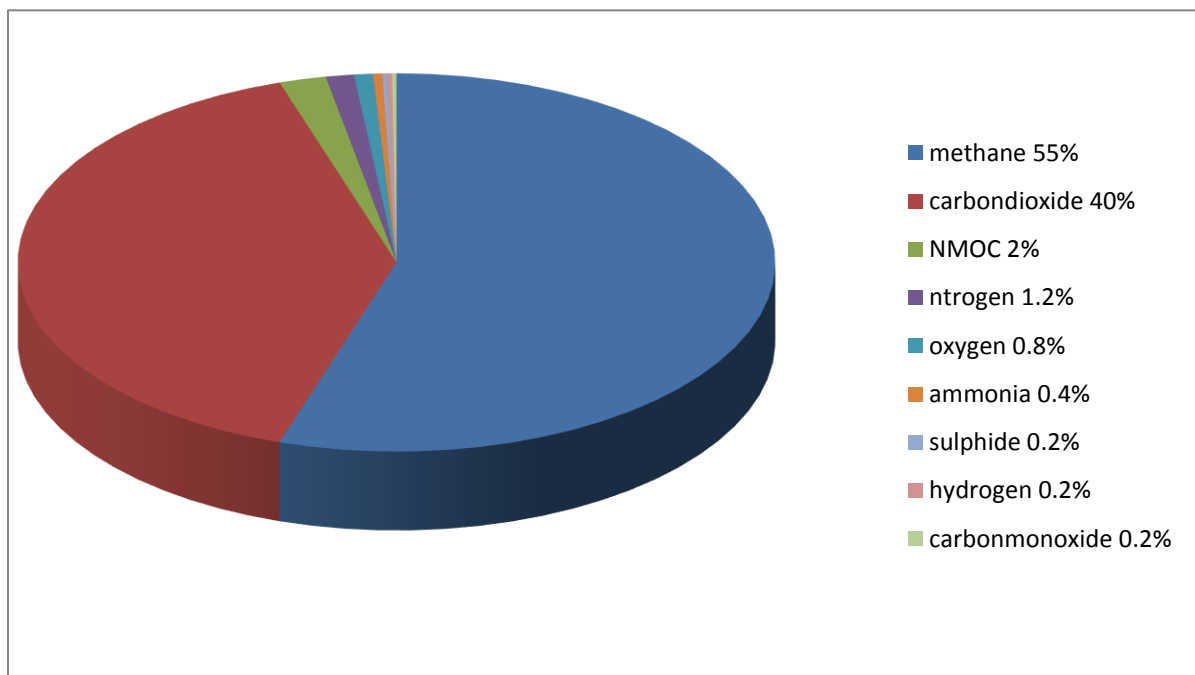
The odour of ammonia gas indicates the landfill is alkaline in nature.

Aluminum sulfide and water;



These end products are characterized by pungent odour (Lide, 2003).

**Volatilisation** – chemical substances vaporize into the atmosphere from a solid or liquid state. These chemical substances are usually characterized with low boiling point which mainly consists of NOMCs found in the landfill (ATSDR, 2001). Feldmann (2003) identified volatile compounds like permethylated compound of tin, bismuth, arsenic, tellurium, antimony, selenium and mercury, aromatic compounds – benzene, toluene, xylenes), alkalines, chlorinated hydrocarbons (chloromethane and chloro benzenes) and terpenes ( $\alpha$ -pinene, camphene and limonene) in landfills. Polystyrene plastic waste was considered as the major source of the volatile chemical compound. Urase et al. (2008) identified similar volatile compounds present in a landfill like benzene and trim ethyl benzene. Table 2.3 shows various components, effects and composition of LFG and Figure 2.4 shows the LFG components in percentage.



**Figure 2.4: Some major components of LFG (US EPA, 2005)**

**Table 2.3 Typical LFG components (EPA, 2005)**

<b>Component</b>	<b>Percent (%) by Volume</b>	<b>Characteristics</b>	<b>Effects</b>
Methane	45–60	Methane is a naturally occurring gas. It is colourless and odourless. Largest LFG emitted from landfill, it is GHG, highly flammable.	Global warming, major cause of landfill fire
Carbon dioxide	40–60	Carbon dioxide is colourless, odourless, and slightly acidic. It exists in the earth's atmosphere at a concentration of 0.04 (400ppm) percent by volume. It is a GHG.	Global warming, major source of ocean acidity
Nitrogen	2–5	Nitrogen comprises approximately 79% of the atmosphere. It is odourless, tasteless, and colourless.	Oxides of Nitrogen (NO <sub>x</sub> ) are toxic gases, source of smog and acid rain; respiratory problems, lung damage. Nitrites and nitrates can cause cancer, thyroid problems.
Oxygen	0.1–1	Oxygen comprises approximately 21% of the atmosphere. It is odourless, tasteless, and colourless.	Iron rusting, supports combustion in landfill fires, excess oxygen at partial pressure can lead to severe health problem like cells damage, brain damage.
Ammonia	0.1–1	Ammonia is a colourless gas with a pungent odour. Corrosive gas, highly irritating	Burning of nose, throat and respiratory tract, coughing, skin and eye irritation. Pungent and suffocating odour. Eutrophication, soil acidification.
NMOCs (non-methane organic compounds)	0.01–0.6	NMOCs are organic compounds (i.e., compounds that contain carbon). (Methane is an organic compound but is not considered a NMOC.) NMOCs may occur naturally or be formed by synthetic chemical processes. NMOCs most commonly found in landfills include acrylonitrile, benzene, 1,1-dichloroethane, 1,2-cis trichloroethylene, dichloromethane, carbonyl sulfide, ethyl-benzene, hexane, methyl ethyl ketone, tetrachloroethylene, toluene, trichloroethylene, vinyl chloride, and xylenes.	Carcinogenic, leukaemia, headaches, nausea. Some of the gases are highly flammable, pungent odour.
Sulfides	0–1	Sulfides (e.g., hydrogen sulfide, dimethyl sulfide, mercaptans) are naturally occurring gases that give the landfill gas mixture its rotten-egg smell. Sulfides can cause unpleasant odour even at very low concentrations.	Irritation to the eye, nose and throat, breathing difficulty, poor memory, tiredness. Pungent odour,
Hydrogen	0–0.2	Hydrogen is an odourless, colourless gas, tasteless, highly combustible, light gas.	Supports burning in landfill fires.
Carbon monoxide	0–0.2	Carbon monoxide is an odourless, colourless gas.	Reduces oxygen circulation in the body, vision problems, reduced manual dexterity and even death. formation of smog.

### 2.3.1 Factors affecting the production of LFG

The production of LFG is influenced by different factors such as waste composition, moisture content, temperature, oxygen and age of refuse (ATSDR, 2001).

- i. **Composition and type of organic waste** – the higher the composition of organic waste present in the landfill, the more LFG is generated. According to the IPCC model, the composition of waste in a Municipal Solid Waste includes; food, garden, paper, wood, textile, nappies, domestic and plastic wastes. A Study has shown that in domestic waste the landfill contains lower amount of halogenated hydrocarbon concentration than industrial or co disposal waste (Parker et al., 2002). Organic waste contains certain nutrients like sodium, potassium, calcium, magnesium, which serve as enhancer for bacterial activities and helps in the degradation process. Hence the increase in organic waste in a landfill contributes to faster degradation of the waste and LFG emission. However, some waste are composed of compounds that impede bacterial growth and are harmful to the bacteria, such as compounds with high salts concentrations impede methane – producing bacterial activities (ATSDR, 2001).
- ii. **Moisture content** – increase in moisture content will enhance microbial growth, thus increase LFG production (Global Methane Initiative, 2012). Moisture content in the landfill supports the reproduction of bacteria. Trace LFG like ammonia in the landfill are highly soluble, if the moisture content increases it dissolves ammonia in the waste and reduces the amount of ammonia gas generated (Parker et al., 2002). Lays et al., (1997) found that reduced moisture content reduces methanogenic activities (methane formation) in organic waste. Lays et al. (1997) also discovered that the reduction of moisture content from 96% - 90% saw a reduction in methanogenic activity from 100% to 53% at a neutral pH.
- iii. **Oxygen in the landfill** – the presence of oxygen in the landfill aids aerobic bacteria in waste decomposition. It increases degradation process; rate of waste decomposition and settlement; and decreases the production of CH<sub>4</sub> and supports CO<sub>2</sub> formation. When the landfill is closed there is blockage of oxygen into the landfill, therefore, this brings about the reduction of oxygen. The presence of anaerobic bacteria emerges (helps in CH<sub>4</sub> production) in the landfill and it is dependent on the lack of oxygen content present in the landfill (ATSDR, 2001). Anaerobic process (absence of oxygen), in landfill promotes slow stabilization of waste; stimulates the formation of

CH<sub>4</sub>; and enhances the formation of Non-Metallic Organic Compounds (NMOC) (through chemical or volatilization reaction) (Themelis and Ulloa, 2007).

- iv. **Temperature** – Change in temperature has great effects on the LFG generation. Warm temperature (15°C - 45°C) encourages bacterial activity which increases LFG generation. A stable temperature is experienced when the landfill is capped for about 25°C and 45°C. Increase in temperature improves volatilization and chemical reactions (ATSDR, 2001). Lanini et al., (2001), conducted research to investigate the role of temperature rise in a landfill and the effects in the landfill. The laboratory experiment showed that high thermal temperature at 70°C could be reached if there is free flow of oxygen in the landfill. Therefore, a landfill should be closed properly after dumping of waste to avoid high temperature. However, temperature should not exceed certain limits to avoid landfill fire, a temperature range of 15°C - 45°C in the landfill is most convenient for LFG production (Lanini et al., 2001).
- v. **Age of waste deposited** – New deposited MSW will generate more LFG than older deposited, MSW because newly deposited waste is still fresh in organic content and degradation process of the MSW is still beginning. Landfill emissions reach its peak at the year of closure of landfill because of the continuous deposition of solid waste in the landfill. However, 20 years down the line the landfill still continues to experience LFG emission, some landfills experience emission of LFG for 50 years or more after closure (Global Methane Initiative , 2012).

## 2.4 LFG Utilisations

This is the process of collecting, processing and treating the LFG collected during the decomposition of MSW from a landfill. There are more than 1000 LFG utilisation technologies which are functioning around the world with more LFG being utilised every year (Terraaza and Willumsen, 2010). However, some major factors are considered before an appropriate landfill utilisation technology is constructed include the following:

- i. There should be assurance of continuous flow of municipal solid waste.
- ii. The best or type of LFG utilisation system for the proposed landfill.
- iii. The availability of potential end users for the technology.
- iv. The quality and duration of the potential LFG generation.
- v. The capital, expenditure and operating costs for the utilisation technology.
- vi. Availability of expertise for proper operations of the heavy machines.

The different forms of LFG utilisation can be in various forms which include direct use as a form of electricity, boiler system, fuels for vehicle, natural gas network, various chemical compounds and leachate evaporation.

**Source of natural gas network** – This involve the utilisation and refining of LFG to natural gas quality (Terraza and Willumsen, 2010). Rasi et al. (2014) investigated on the upgrading of LFG using a high-pressure water absorption process. The study showed that using high pressure gas absorption technique, LFG can be improved to  $87.9 \pm 2.0\%$  methane contents. The authors suggested that the refined LFG can be used in the natural gas network for domestic purposes.

**Boiler system** – This is the second most common use of LFG. Boiler systems use LFG as a source of fuel for production of steam and hot water. The steams formed from the process can be used in heating buildings, schools, hospitals and for large manufacturing industries (pulp and paper industries). Examples of landfills that use LFG for boiler system are the Gaoantun landfill (Beijing, China) and three rivers regional landfill in South Carolina, USA (Global Methane Initiative, 2012).

**Furnace, dryers and kilns** – This involves the direct use of raw LFG generated from landfills as a direct source of fuel for kilns (Terraza and Willumsen, 2010). Manufacturing companies that produce cements, ceramics, iron, wood and steel use the LFG directly from the landfill site as a source of fuel for infra-red heating mechanism. The infra-red heating can reach up to  $800^{\circ}\text{C}$  -  $1000^{\circ}\text{C}$  with efficiency of up to 93%. LFG can also be used as supplementary sources of fuel for larger industrial companies, where the raw LFG cannot cover the entire fuel needed for operations (Global Methane Initiation, 2012).

**Fuel for vehicles** – The LFG is compressed and used as a source of fuel for powering vehicles. Pattersson et al. (2006) study showed that fuel for vehicles from LFG is produced by purification and compression of raw LFG. This process is used in some developed nations but the process is not favourable in all nations. It is advisable to check the tax system to calculate if the process will be profitable or not (Terraza and Willumsen, 2010).

**Electricity** – The LFG can be used for power generation. This can generate electricity up to 45 megawatts for a steam engine. The LFG utilisation technology is mostly used for electricity generation (Terraza and Willumsen, 2010). Boodhan (2014) analysed different methods to generate electricity with recent innovative technologies. Some of these technologies include reciprocating internal combustion engine gas or steam turbine, power

plant with organic rankine cycle, stirling cycle engine. These forms of utilisation have been shown to be reliable environmentally and economically as well as friendly to their users (Global Methane Initiative, 2012). Table 2.4 indicates the summary of the different uses of LFG.

**Table 2.4: Summary of LFG utilisation (Terraaza and Willumsen, 2010; Global Methane Initiative, 2012)**

<b>LFG utilisation</b>	<b>Uses</b>	<b>Characteristics</b>
As a source of natural gas	Can be used domestically for cooking and industries. Can be used in generation of revenue for the government, when sold.	The technique for conversion of raw LFG to natural gas is relatively expensive.
Boiler system	Relatively not expensive Does not require large amount of LFG when processing. Can be used in landfill sites, schools, hospitals for heating the system. Can make use of maximum amount of LFG generated from the landfill.	Accessibility of end-users must be close by. The cost is tied to length of pipe lines.
Furnace, dryers and kilns	The raw LFG can be used directly from the kilns in some manufacturing companies. Inexpensive and easy to install. Can be coupled with other energy products.	Constraint of LFG utilisation, if used seasonally.
Use as vehicle fuel	Use as source of fuel to landfill vehicles and trucks. Can also be sold as a source of income to the government.	Can be expensive due to the processing of the raw LFG collected into vehicle fuels
Use as a source of electricity	Can be a source of electricity. Can be used as a source of revenue to the government due to the sale of the electricity. Maximum use of LFG, when LFG is collected from the landfill site.	Relatively high cost of operations. Requires high level of expertise and technology. Cost may be negligible with countries with low electricity costs.

## 2.5 Environmental and economic benefits of LFG

LFG are major contributors of world's GHG, because enormous amount of CH<sub>4</sub> and CO<sub>2</sub> is generated from the degradation process of deposited waste in landfills. However, the issue of contamination of surface and ground water by leachate from the landfill, pungent odour, to

loud disturbing noise from landfill bulldozers, power generator machines and trucks is very common landfill effects (Environment Victoria, 2013). Litters, excess rodents, unexpected landfill fires and the harmful health effects on humans working and living closer to the landfill site caused by various emissions from the landfill site are also concerns from landfill emission. The amount of GHG present in the atmosphere occupies 0.04% of the earth's atmosphere and contributes greatly to the earth's warming. According to the IPCC, future effects of GHGs on the environment involves continuous rise of earth's temperature, frost free seasons (and growing season) will lengthen; precipitation patterns will continue to change; increased amount of drought and heat wave; stronger and more intense hurricanes; rise in sea level about 1-4 feet by the year 2100; arctic likely to become ice free. Furthermore, this will pose catastrophic consequences on the generations yet unborn (The Center for a Competitive Waste Industry, 2016). Also, continuous inhalation of CH<sub>4</sub> can cause loss of coordination, nausea, vomiting and at high concentration can cause death (Health Protection Agency, 2011). Acidic gases like nitrogen dioxide, sulphur dioxide and halides have harmful effects on the health and environment when introduced. Acidic gases are emitted from degradation process of waste or chemical reaction within the landfill. Nitrogen dioxide when inhaled by humans can cause inflammation, bronchoconstriction and respiratory infections. Sulphur dioxide has effects on asthmatic patients; it can trigger asthma attacks (Health Protection Agency, 2011). Furthermore, when these acidic gases reach the atmosphere, they tend to acidify the moisture in the atmosphere and fall down as acid rain. Padhi et al. (2013) identified that Sulphur dioxide has harmful effects on plants growth and productivity.

Landfill generates different kinds of trace toxic elements which include carbon monoxide, hydrogen sulphide, xylene, dioxin, etc. Toxic organic micro pollutants also include polychlorinated dibenzo-para-dioxins and polychlorinated dibenzofurans (PCDDs and PCDFs) which are all called dioxins; and polycyclic aromatic hydrocarbons (PAHs). Dioxin can be formed from the presence of chlorine-containing substances in the landfill and from landfill fire (Roots et al., 2004). Vrijheid, (2000) found that breast feeding mothers are exposed to dioxin from a landfill as low as 19 ppt could cause their children permanent reduction in sperm count when they grow old. PAHs are considered to have some form of potential carcinogenic properties, when in contact with humans could lead to tumor of the lungs, skin and other parts of the body (Health Protection Agency, 2011).

Hydrogen Sulphide ( $H_2S$ ) is a colourless and highly flammable gas. It has an odour of rotten egg and this contributes immensely to the odour of emissions experienced from landfill sites. It is formed when high sulphate containing compounds (gypsum and plaster board) are mixed with the degradable waste in the landfill site. When humans are exposed to high  $H_2S$  it could lead to malfunction of the central nervous system and respiratory paralysis (Li and Moore, 2008).

Marilyn et al. (2000) conducted a study on the effects of the immune system associated with living near a super fund site which contains Organochlorine pesticides, volatile Organic compounds and metals. The study seeks to know if living near this site can lead to higher plasma organochlorine levels, immune suppression or DNA damage. Series of test was conducted on the blood specimen, skin test and focused interviews. This study conducted in six locations in Aberdeen and North Carolina shows that Age-adjusted mean plasma DDE levels were 4.05 ppb for residents living in Aberdeen and 2.95 ppb ( $p = 0.01$ ) for residents living farther away. Residents who were between the ages of 40–59 years and lived closer to the site, especially the Farm Chemicals site, had higher plasma DDE levels than residents who lived farther away. Also, residents who lived closer to the Farm Chemicals site before 1985 also had higher plasma DDE levels than residents who lived farther away. Also, residents who lived closer to the dump sites had statistically significantly lower mitogen-induced lymphoproliferative activity than residents who lived farther away ( $p < 0.05$ ). However, Residential location was not consistently associated with frequency of micronuclei or skin test responses.

A review study was conducted by Porta et al. (2009) on epidemiological studies on health effects associated with management of solid waste. Peer reviewed paper (49 papers in total) on the health effects of waste management from 1983 – 2008 were reviewed extensively. Health related illnesses like different types of cancer, different birth defects and reproductive disorder, respiratory diseases and skin disorder were considered. Porta et al. (2009) concluded that a lot of limitations were observed and overall evidences were inadequate to establish the results from the various studies. This was as a result of poor exposure assessment, ecological level of analysis and lack of information on relevant cofounders. This notwithstanding, some effects estimates were established as drivers to the assessment of health impacts from old landfills and incineration plants.

Jarup et al. (2002) carried out a study on the cancer risks in residents living closer to landfill sites in Great Britain. This was a nation-wide research which consists of a population living within 2 km of 9656 landfills out of a total of 19196 landfills, which have been operational from 1982 to 1997. The national post coded registers provided a total of 341856640 persons – year for adult cancer analysis and 113631443 persons – year of childhood leukemia. The results shows that 89786 persons cases of bladder cancer, 36802 person cases of brain cancer, 21773 person cases of hepatobiliary cancer, 37812 person cases of adult leukemia and 3973 cases of childhood leukemia. This study concludes that no excess risks of cancers of the the bladder and brain, hepatobiliary cancer or leukemia were associated with residents living within 2 km of the landfills. Therefore, it concludes that the results does not support that there is excess risk to cancer when living closer to a landfill site.

Sankoh et al. (2013) conducted an environmental health impact of solid waste disposal in developing cities, case study was Graville brook dumpsite Freetown Sierra lone. Samples were collected from 398 residents living within 50 meters away from the dumpsite. While, 233 residents were sampled that lived far away from the dumpsite. With the help of structured and self-administered questionnaires, interviews and personal observations, data was collected. The study then concludes that both nearby residents and far away residents suffered from related diseases such as malaria, chest pains, diarrhea and cholera, due to the location of the dumpsite closer to their settlements. As a result, this study highlights the need for the Freetown City Council to properly manage and relocate the dumpsite to a safe distance from all human settlements, and provide resettlement and environmental education programmes for all persons living less than 50 meters away from the dumpsite.

## **2.6 Models for Estimation of LFG**

The different models used in the estimation of LFG can be categorized into Zero order, first order and second order generation models.

*Zero order generation models* assume that LFG generated remains steady against time. Therefore, age and type of waste has no effect on the LFG production. Examples of zero order models include the following:

European Pollution Emission Register (EPER) Germany– The model only measures LFGs which are of similar waste type or unconditioned residential waste (Rajaram et al., 2011). Mathematically, it can be described in equation 2.1 below.

$$Me = M \times BDC_F \times F \times D \times C \dots\dots\dots (2.1)$$

Where Me is the amount of diffused methane emission ( $\text{MgCH}_4 \cdot \text{y}^{-1}$ ); M is the annual amount of landfill waste ( $\text{Mg waste} \cdot \text{y}^{-1}$ ); BDC is the proportion of degradable carbon 0.15 ( $\text{MgC} \cdot \text{Mg waste}^{-1}$ );  $BDC_f$  is the proportion of C converted, 0.5; F is the calculation factor of carbon converted into  $\text{CH}_4$ , 1.33 ( $\text{MgCH}_4 \cdot \text{MgC}^{-1}$ ); D is the collection efficiency; and C is the methane concentration 50% (Rajaram et al., 2011). Thompson et al., (2009) conducted research on building a better LFG model, with 35 Canadian landfills as a case study. Although the EPER German model was widely inaccurate from the research, the model has been used in other parts of the world.

Solid Waste association of North America (SWANA) zero order. It is characterized by equation 2.2;

$$Q = \frac{ML_0}{(t_0 - t_1)} \dots\dots\dots (2.2)$$

Where, Q is methane generation ratio; M is the waste in place;  $L_0$  is the methane generation potential;  $t_0$  is the lag time;  $t_1$  is the time to end point of generation (Kamalan et al., 2011). SWANA developed this model to calculate the amount of LFG emitted from a landfill. Staub et al., (2010), in his experiment on ‘influence of landfill cap cover characteristics on the mitigation of GHG emissions’ used the SWANA model to calculate the total LFG. The results show that the total emission of LFG is dependent on the nature of the cap cover of the landfill.

IPCC Waste Model - The model is used in calculating LFG in national emission inventories. The model carries out estimations of LFG yield as a single-phase model or multi-phase model, based on the available waste data. The single-phase model waste data centres on bulk waste. The multi-phase model is centred on the different waste composition data (IPCC, 1996). The model assumes that the emissions of  $\text{CH}_4$  begin the same year waste is deposited in the landfill. This is a simple approach to estimate LFG. The IPCC guidelines provided default values for countries-specific data, which are not available especially in cases where the countries lack solid waste statistics i.e. in developing and under-developed countries.

***Factors imputed into the IPCC model***

1. ***Degradable Organic Carbon DOC*** - Is the organic carbon that is accessible to biochemical decomposition and it is the carbon content found in MSW. It can be

calculated from weighed average of the carbon content of the MSW. Equation 2.3 shows how the DOC content is calculated (Penteado et al., 2012).

$$\text{DOC} = (0.4 * A) + (0.17 * B) + (0.15 * C) + (0.3 * D) \dots\dots\dots (2.3)$$

Where A = fraction of MSW in textile and paper

B = fraction of MSW in garden waste, park waste,

C = fraction MSW in food waste

D = fraction of MSW in straw or wood

DOC content data is determined by any of these methods;

Using own national data.

By calculating based on country's waste composition and using the default DOC values given in the model (Revised IPCC workbook, 1996).

2. **Fraction of Degradable Organic Carbon DOC<sub>f</sub>** - Shows that in the model not all organic carbon present in the landfill degrades and has the ability to generate CH<sub>4</sub>. Moisture content, pH, temperature and composition of waste determine the value of DOC<sub>f</sub>. The default value in the IPCC model is 0.5; which means, approximately 50% of all DOC<sub>f</sub> contributes to CH<sub>4</sub> generation (Larsson, 2014).
3. **Methane Correction Factor MCF** considers a sanitary landfill. An unmanaged landfill produces less CH<sub>4</sub> because most of the waste decomposes aerobically at the top layer of the landfill, which tends to decrease CH<sub>4</sub> emission. A managed landfill on the other hand tends to generate more CH<sub>4</sub> (IPCC, 2006).
4. **Fraction of CH<sub>4</sub> (F) generated LFG** identifies the total amount of CH<sub>4</sub> produced from the LFG throughout the anaerobic degradation of organic material. The default value for the IPCC model is 0.5; which means approximately 50 % of all DOC<sub>f</sub> contributes to methane generation (Penteado et al., 2012).
5. **Oxidation factor OX** identifies the amount of CH<sub>4</sub> emitted from the landfill, which oxidizes in the soil or other covering material in the landfill. When the OX factor is zero, it means no oxidation occurred during the degradation, but if the OX factor is one then, 100% CH<sub>4</sub> oxidized. However, IPCC's default value is zero (IPCC, 2006).
6. **Methane Generation Constant (k)** - IPCC recommends k = 0.08 - 0.1 for bulk Municipal Solid waste. This means that 50 % of the CH<sub>4</sub> potential forms after

approximately 9 years. Half-life is derived by calculation of a weighted average for half time for a bulk solid waste mix (i.e. single-phase) or by dividing the waste into categories of waste according to the rate of degradation (i.e. multi-phase). The single-phase approach will be used in the IPCC model (Larsson, 2014).

**First order generation models** – These models consider waste quantity, condition of landfill and quality of waste as well as reduction of carbon effect in waste over time (Amini et al., 2012). Some examples of first order model include the following:

Netherlands Organisation for Applied Scientific Research (TNO) model – It calculates LFG generation based on the effects of depletion of organic carbon in waste. Same waste composition is preferred to be used, when calculating the LFG yield in model calibration. This reduces error during estimation of waste composition (Rajaram et al., 2011). It is represented by this equation 2.4;

$$\alpha_t = \zeta 1.87 A C_0 k_1 e^{-k_1 t} \dots\dots\dots (2.4)$$

Where,  $\alpha_t$  is the LFG production at a given time ( $\text{m}^3\text{LFG.y}^{-1}$ );  $\zeta$  is the dissemination factor 0.58; 1.87 is the conversion factor ( $\text{m}^3\text{LFG.kgCdegraded}^{-1}$ ); A is the amount of waste in place (Mg);  $C_0$  is the amount of organic carbon in waste ( $\text{kg C.Mg waste}^{-1}$ );  $k_1$  is the degradation rate  $0.094 (\text{year}^{-1})$ ; and t is the time elapsed from the first deposition of waste (year). The TNO model was applied in Thompson et al., (2009) research on the validation of LFG models with methane recovery rates using 35 Canadian landfill sites. The TNO overestimated the LFG emission when the fraction of degradable organic compound ( $\text{DOC}_f$ ) was 0.5, although the TNO model did not produce the best of results when compared to the other models used.

Multi-phase Afvalzorg model - The model was developed by R. Gronert and H.Scharff (NV Afvalzorg Holdings) with the support of the Dutch Environmental Agency. The model is based on a first order decay. The model simulates the total LFG and  $\text{CH}_4$  recovery and emission from landfills for which limited data of waste composition is available. The IPCC (2006) guideline for solid waste disposal sites is used and the IPCC default values are used for running the model. It is advised to use default values provided by the model unless the value can be derived by experts with understanding of anaerobic degradation process in a landfill. Therefore, it is recommended that a comparison of the results be done with the default values provided by the model. The model has eight waste categories and three

fractions are distinguished when calculating LFG generation (Jacobs and Scharff, 2001). The model is represented by equation 2.5;

$$\alpha_t = \zeta \sum_{i=1}^3 1.87 A C_{0,i} K_{1,i} e^{-k_{1,i}t} \dots\dots\dots (2.5)$$

Where,  $\alpha_t$  is the landfill gas formation at certain time ( $m^3.y^{-1}$ );  $\zeta$  is the dissemination factor;  $i$  is the waste fraction with degradation waste  $k_{1,i}$  ( $kg.kg_{waste}^{-1}$ );  $A$  is the amount of waste in place (tons);  $C_0$  is the amount of organic carbon in waste ( $kg.tonnewaste^{-1}$ );  $k_{1,i}$  is the degradation rate constant of fraction  $i$  ( $y^{-1}$ ); and  $t$  is the time elapsed during deposition ( $y$ ) (Kamalan, 2011). The Afvalzorg model is a multiphase model and considers different waste composition in its LFG estimation, while the TNO model is developed to consider waste with the same waste composition for its estimation of LFG.

GasSIM model – The model was developed by Golder Associates for the Environment agency (England and Wales). The model uses a first order kinetic approach for the simulation of LFG. It also incorporates the simplified sequential biodegradation by classifying the biodegradability of various waste streams as slow, medium and fast (equation 2.6) (Donovan et al., 2011).

$$C_t = C_0 - (C_{0,1}e_1^{(-kt)} + C_{0,2}e_2^{(-kt)} + C_{0,3}e_3^{(-kt)}) \text{ and } C_x = C_t - C_{t-1} \dots\dots\dots (2.6)$$

The imputation data for the model are the total amount of waste (Mg), moisture content, landfill site geometry, rainfall and specific waste composition breakdown during a particular year of disposal. Each waste category is made up of different fractions, each fraction is assigned a degradability class ( $k$  value) (Kamalan et al., 2011). Scheutz et al., (2001) used the GasSIM model for the estimation of LFG. Also researches like Donovan et al., (2011) and Attenborough et al., (2002) used the GasSim model to estimate the total LFG emitted from a landfill site. The result from the GasSim model shows the estimation of the LFG over a period of 159 years. The model was convenient for the research work.

EPER France model– This model can estimate LFG using two approaches. The first approach is the LFG that is connected to a LFG extraction system, which can be calculated with equation 2.7.

$$A = F * H * [CH_4] \dots\dots\dots (2.7)$$

Where,  $A$  is the amount of methane recovered ( $m^3.y^{-1}$ );  $F$  is the extraction rate of the LFG ( $m^3 h^{-1}$ );  $H$  is the compressor yearly hours in operation ( $h$ ); and  $[CH_4]$  is the methane

concentration in LFG (%) (Rajaram et al, 2011). A is corrected to (m<sup>3</sup>STP.y<sup>-1</sup>) at standard temperature and pressure, when monitoring the gas quality sample.

The second approach is the LFG generated from landfill sites that are not connected to a LFG extraction system and it is calculated by equation 2.8.

$$FE_{CH_4} = \sum_x FE_0 * (\sum_{1,2,3} A_i * p_i * k_i * e^{-k_i t}) \dots\dots\dots (2.8)$$

Where FE<sub>CH<sub>4</sub></sub> is the annual methane production (Nm<sup>3</sup>y<sup>-1</sup>); FE<sub>0</sub> is the LFG generation potential; p<sub>i</sub> is the waste fraction with degradation rate k<sub>i</sub> (kg:kg<sub>waste</sub><sup>-1</sup>); k<sub>i</sub> is the degradation waste fraction i (y<sup>-1</sup>); t is the time of waste deposited; and A<sub>i</sub> is the normalization factor (Jacobs and Scharff, 2001).

Landfill Gas Emission Models (LandGEM) - This model was developed by the U.S. Environmental Protection Agency (EPA). It is a programmed tool for the calculation of emissions of total LFG, CO<sub>2</sub>, CH<sub>4</sub>, NMOCs and other air pollutants emitted from a landfill. The model is based on first order decomposition reaction rate for the estimation of LFG. It is a comparatively simple means of estimating LFG. Default empirical data is found from the model, however; field test data is used in place of the default data. The U.S. EPA provides an explicit users' guide at their website. The United State Environmental Protection Agency (US EPA) created the LandGem model in September 1998 and it is accessed from this website <http://www.epa.gov/ttn/catc/>. Equation 2.9 shows the mathematical calculations for the LandGEM model (Wang et al., 2013).

$$Q_{CH_4} = \sum_{i=1}^n \sum_{j=0.1}^1 kL_0 \left(\frac{M_1}{10}\right) e^{-kt_{ij}} \dots\dots\dots (2.9)$$

Q<sub>CH<sub>4</sub></sub> = annual methane generation in the year of the calculation (m<sup>3</sup>/year)

i = increment in one year time

n = (year of the calculation) – (initial year of waste acceptance)

j = increment in 0.1 year time

k = methane generation rate (year<sup>-1</sup>)

L<sub>0</sub> = potential methane generation capacity (m<sup>3</sup>/Mg)

M<sub>i</sub> = mass of waste accepted in the i<sup>th</sup> year (Mg)

t<sub>ij</sub> = age of the j<sup>th</sup> section of waste mass M<sub>i</sub> accepted in the i<sup>th</sup> year.

Almost all LFG models simulate CH<sub>4</sub> generation based on three important input parameters, which are, the annual disposal of waste in a landfill from the opening to closure of landfill; Degradable Organic Content (DOC) and decay rate constant  $k$ . However, the LandGEM and Scholl Canyon models require methane generation potential  $L_0$ .

### **2.6.1 Application of LFG models for different studies**

Scharff and Jacobs (2006) used the TNO, Afvalzorg, GasSim, LandGEM, EPER France model and EPER Germany models to simulate the LFG generation from three Dutch landfills. From the results, it showed that the difference in results from the models were too far apart (from the highest estimation to the lowest). In the case of one landfill, the results gave more than a factor of 20. Scharff and Jacobs believed that the LFG models are diverse and have a lot of uncertainties among the models. However, the discrepancies among these models, when compared will give a better LFG simulation result; transparency of data and consistency.

Corti et al. (2007) used the Scholl canyon model to estimate the amount of LFG produced by the Casa Rota landfill in Italy. The result was compared with observed data which was previously carried out in 2004. A 40% LFG collection efficiency was recorded in 2004 and in 2005 the LFG collection efficiency rose up to 60%, because of the implementation of improved collection technology. The Scholl Canyon model was efficient in the estimation of LFG production.

Thompson et al., (2009) used the German EPER model, TNO model, Belgium model, Scholl model and LandGem (2.01) model to predict LFG production and the results were compared with the observed LFG generation in 35 Canadian landfills. Belgium, Scholl canyon and LandGem (2.01) models had standard errors of 91%, 71% and 89%, respectively. However, the TNO and German EPER models overestimated the LFG generation, in which the results were generally not good compared to the other models. According to Thompson et al. (2009), from the results, only LandGEM model underestimated LFG generation and gave the best result while the other four models overestimated gas generation.

Donovan et al., (2009) used the GasSIM model to simulate the LFG (CH<sub>4</sub>) emitted from a biological treated municipal solid waste landfill. The study identified the total methane generation of the landfill over a 150 years' simulation period. It was further observed that CH<sub>4</sub> emitted was peak at closure of landfill and CH<sub>4</sub> continued to reduce over time. However,

LFG continued to evolve over a long period of time (Donovan et al., 2009). The GasSIM model estimated the total amount of CH<sub>4</sub>, but the results from the GasSim model was different from the results achieved during field analysis because of different environmental factors affecting the field calculations (Donovan et al., 2009).

Bhailall (2010) in Johannesburg, South Africa, conducted research using the LandGem, GasSim and IPCC models to estimate LFG production. The three models simulations showed an increase in LFG generation as waste deposition increases. The results from LandGem estimate a higher value than the other two models, while IPCC model records the lowest results because of its ability to calculate LFG emissions from waste fraction.

Bella et al. (2011) simulated the potential CH<sub>4</sub> emitted from Bellolampo Landfill (Italy) using the flux chamber method and compared the results with the LandGEM and Erigh models. The result of the LandGEM showed a CH<sub>4</sub> emission of  $2.72 \times 10^5$ , the Erigh model was  $2.57 \times 10^5$  and flux chamber was  $2.54 \times 10^5$ . The results showed an almost similar result, although the models showed slightly higher results than the flux chamber's result.

Larsson, (2014) simulated the total LFG from a Swedish landfill using the LandGem, IPCC and Afvalzorg models from 1950 - 2050. The landfill simulations showed a total remaining gas potential of 2100 – 3250 tons CH<sub>4</sub> from year 2015 – 2035, which is very important to global warming effects. The comparison of the models showed that CH<sub>4</sub> production peaked from the years 1974 - 1980. However, the total simulated CH<sub>4</sub> emission potential for the LandGEM, IPCC and Afvalzorg model from the years 1950 – 2050 was 109331, 35289 and 26255, respectively. The result showed a significant difference in LandGEM compared to the IPCC and Afvalzorg models.

Mou et al. (2015) used Afvalzorg, LandGem and IPCC models to estimate LFG from the Danish waste disposal site receiving low organic waste content. The results showed that the LandGem model estimates the largest amount of CH<sub>4</sub> emitted from the landfill, the IPCC model estimates 25% - 33% of the LandGEM's results. The Afvalzorg model estimated 10% of the LandGEM's results. The Afvalzorg model was found to be more convenient in the estimation of LFG from landfills receiving low organic waste because of its multi-phase category abilities. Nonetheless, the Afvalzorg model requires a lot of data, which are easily accessible from most landfills in developed countries from landfill operators (Mou et al., 2015).

Taherian et al., (2016) used the LandGEM and the Afvalzorg models to simulate the LFG potential generation in Halgheh-Darreh landfill (Iran). The results show that the LandGEM's results, by the mean of practical value of methane potential was closer to realistic situation than the Afvalzorg model. The result obtained from the run of the LandGEM model was 1426.94 m<sup>3</sup>/h and 901.82 m<sup>3</sup>/h (for theoretical and practical results of estimated methane generation rate (L<sub>0</sub>)), respectively. While the results obtained from the Afvalzorg's model simulations are 5200 m<sup>3</sup>/h and 4000 m<sup>3</sup>/h (theoretical and practical values of L<sub>0</sub>, respectively).

Although there are various models for the estimation of LFG, as shown above, this study focused on the use of the Afvalzorg and LandGEM models for the estimation of LFG for reasons explained using Table 2.5. However, the examples were based on one or few landfills, different regions, different waste composition type and different landfill types. Hence the uncertainty of the use of the different models (Scharff and Jacobs, 2006). Therefore, for the validation of the models for this study, a larger set of parameters were used (Oonk, 2010). For the different models given above, parameters such as availability, ease of operation, required input, waste changes, climatic zone, scientific basis, transparency, accuracy and validation were used to validate the models for this study (Oonk, 2010); the evaluation is summarised below. Table 2.5, gives a summary of some available model validation for LFG simulation.

**Table 2.5: Summary of LFG model evaluation**

Parameters	Models						
	IPCC	LandGEM	GasSim	Afvalzorg	EPER finnish	EPER France	TNO
Availability	++	++	+	++	+	+	+
Ease of Operation	+	++	-	++	-	-	+
Transparency	+	+	-	+	-	+	+
Waste input	-	-	+	++	+	-	+
Widely used	+	++	+	+	-	-	+
Different climatic conditions	-	++	-	-	-	-	-

According to Table 2.5, the parameters for validation of the models are explained below.

**Availability** – Although all the models are freeware models, some models like the GasSim requires some amount of money to access the full version of the model. Table 2.5, shows a “++”, signifies the model can be directly downloaded from the internet and it is easily

accessible by a user. A “–” means the users will add more effort in the accessibility of the models. The LandGem, IPCC and Afvalzorg models are easily accessible on the internet.

**Ease of Operation** – It shows the expertise of the user with the specific model. It also involves the number of different manipulations before the results are obtained. From Table 2.5, the GasSim got a “–” because of some data imputations that are not used for calculating methane emission (Oonk, 2010). The finnish EPER got a “–” because the model is set in finnish and less easy to work with. The LandGEM and Afvalzorg models are easy to operate and do not require complex manipulations of results (Thompson et al., 2009; Larsson 2014).

**Transparency** is based on the actual description of the models, assumptions by the developers, and efforts to validate outcome of the model. All the models are assumed to have good outcomes based on the developers. Spread sheet based models are transparent than executable based models (e.g. GasSIM). This is because the method of calculation for spread sheet and default values can be referenced back to the authors (Oonk, 2010). LandGEM, Afvalzorg, IPCC models got a “+” because they are spread sheet based models.

**Required waste input data** – this data is considered very important in LFG simulations, because the more input of data for waste is considered the better the advantage of the models. This allows a better simulation of the LFG emissions. From Table 2.5, the Afvalzorg, GasSim, TNO and finnish EPER models give opportunities for imputation of waste data according to waste source (household, commercial, office waste, etc.), which also enhances result outputs of the model. The IPCC and LandGEM models got a “–” sign because the models did not give room for waste source imputation data. Although the IPCC model gives room for the waste composition imputation (like paper, plastic, etc.) but the source of waste seems to be more realistic since it shows the way results are recorded in the landfill by the operator (Oonk, 2010). However, the waste source data for South African landfills is insufficient, a comprehensive waste data for landfills are mostly found in developed countries.

**Widely Used** – this indicates the acceptability of the model worldwide and how frequently it has been used based on literature. From Table 2.5, the LandGEM, got a “++” because it is one of the models that is globally acceptable and has ability to simulate LFG in different conditions, has easy accessibility and provides a better result output design of the different LFG components. The LandGEM also simulates various LFG components (like total LFG, CH<sub>4</sub>, CO<sub>2</sub>, NMOC, Hydrogen Sulphide, etc.) from a landfill. The LandGEM also provides a

well-documented graphical illustration of the result output. The Afvalzorg model got a “+” because it simulates only the total LFG and CH<sub>4</sub> generation and does not go further to simulate other components of the LFG. Although for relevance of this study for the utilisation of LFG, CH<sub>4</sub> is the gas used in the utilisation project.

According to the illustration above the LandGEM and Afvalzorg, models are good enough models for the simulation of LFG, the IPCC and TNO are also good for LFG simulations. The Afvalzorg model’s most strength lies in the ability to simulate waste from different sources and the high ability to under estimate LFG simulations (Oonk, 2010). The LandGEM’s strength lies on its simplicity and the ability to simulate all the components of the LFG generated. However, this study did not use the IPCC model because it is used to estimate nation-wide LFG emissions.

### 2.6.2 Energy potential from LFG in Africa

Energy is important for the development of a nation. African countries generate energy mainly from oil, hydro, gas and coal. South Africa’s energy (electricity) generation is 90% powered by coal. Oil-producing African countries like Nigeria (holds about 30% of oil reserves in Africa) mainly rely on oil and gas as a source of energy (Karekezi, 2002). As of 1995, South Africa produced 50% of total electricity generated in Africa, followed by Northern African with about 30% and the rest of the continent accounts for 20%. The consumption of electricity in Africa is very low with exceptions of South Africa and Northern Africa. Table 2.6, shows a summary of some Africa countries and their electricity consumption rates (Karekezi, 2002).

**Table 2.6: Electricity consumption in some African countries (Karekezi, 2002)**

Countries	KWh per capita
Angola	63.9
Benin	43.9
Cameroon	180.7
Congo (Kinshasa)	120.4
Congo (Brazzaville)	197.2
Cote D’Ivoire	181.3
Ethiopia	21.4
Gabon	752.2

Countries	KWh per capita
Kenya	128.7
Mozambique	46.8
Nigeria	84
Senegal	107.2
Sudan	48.5
Tanzania	54.3
North Africa	772.9
South Africa	3800.2

African governments have failed to make LFG utilisation a priority in their agenda. Scarlat et al. (2015) conducted a research on the potential energy from utilisation of LFG and incineration of MSW in urban areas of Africa (with efficiency of 20% and 30% for incineration and LFG plants efficiency, respectively). The results show that the energy obtained was approximately 1125 PJ in 2012 and estimated to be 2198 PJ in 2025 (assuming all waste generated is collected).

Nigeria has the highest population in Africa and generates about 17.4 million tonnes/year of MSW at a range of 0.00021-0.00035 tonnes/person/day and deposits 74% of its MSW in dumpsites and landfills (Adewumi et al., 2005). There are no effective guidelines and regulations on MSW management, hence the number is not properly documented. A study was conducted by the Center for People and Environment (CPE) on four different landfills in Nigeria to estimate the potential electricity that can be obtained from the collected LFG. The result shows that the utilization of the LFG in the four different landfills was economically viable and at a minimum electricity cost of \$0.2 KW/h. Therefore, if most of the LFG from landfills and dumpsites are utilized, some economic challenges the country faces on electricity generation can be minimized.

Furthermore, in Africa, data from Scarlat et al., (2015), shows that if waste generated and collected in urban areas of Africa is properly utilized the potential energy recovery from the waste is as shown in Table 2.7.

**Table 2.7: 2012 Potential energy recoveries from LFG recovery (TJ/year) in urban areas of Africa (Scarlat et al., 2015)**

<b>Countries</b>	<b>Potential electricity generation (TJ/year)</b>	<b>Potential electricity generated using the total CH<sub>4</sub> captured (TJ/year)</b>
Algeria	24,663	22,690
Angola	4808	2067
Benin	1692	389
Botswana	1152	496
Burkina Faso	1905	762
Burundi	437	175
Cameroon	7799	3353
Cape Verde	130	124
Central African Rep.	704	281
Chad	1325	265
Comoros	449	90
Congo Rep	9911	3965
Congo	1166	501
Cote d'Ivoire	4013	1605
Djibouti	291	125
Egypt	41502	26146
Equatorial Guinea	200	86
Eritrea	492	197
Ethiopia	3450	1380
Gabon	532	229
Gambia	450	180
Ghana	949	806
Guinea	1340	536
Guinea-Bissau	168	67
Kenya	2288	915
Lesotho	260	112
Liberia	723	289
Libya	5297	2278
Madagascar	4237	763

<b>Countries</b>	<b>Potential electricity generation (TJ/year)</b>	<b>Potential electricity generated using the total CH<sub>4</sub> captured (TJ/year)</b>
Malawi	1289	541
Mali	3095	1238
Mauritania	594	178
Mauritius	1102	1080
Mayotte	144	137
Morocco	23,354	20,085
Mozambique	1069	449
Namibia	383	165
Niger	1106	465
Nigeria	37275	15656
Rwanda	888	373
Réunion	1639	1557
Saint Helena	4	4
Sao Tome	42	40
Senegal	2286	480
Seychelles	127	121
Sierra Leone	841	370
Somalia	881	370
South Africa	55420	27710
Sudan	13084	5626
Swaziland	116	55
Tanzania	2953	1240
Togo	1142	1085
Tunisia	5143	2006
Uganda	1445	433
Western Sahara	203	41
Zambia	918	386
Zimbabwe	2361	1170
Total Africa	282,602	154,520
Sub-Saharan Africa	182,439	81,275

## 2.7 Cost analysis and benefits of LFG (LFGcost Web Model)

The cost and benefit of a LFG energy project show how LFG generated from a landfill will benefit the people and the environment through utilisation. Couth et al. (2011) state that LFG utilisation technology is not usually an economically viable venture to embark on. Based on the capital cost of implementation and the rate on returns on sales of electricity, the LFG utilisation ends in deficit. However, the sales of carbon credits in the international market can be profitable for the LFG utilisation project to be considered. For example, the Durban LFG utilisation project, component one (Mariannahill and La Mercy landfill sites) sold a 700,000 Certified Emission Reduction (CER) in 2005 for 14 years to the Prototype Carbon funds of the World bank for \$3.95 per tonne of CO<sub>2</sub> (Couth et al., 2011). However, component 2 (Bisasar landfill) produced 3.1 million CER, the eThekweni Municipality signed a deal with Trading Emission PLC till 2012, which sold to the international market. In 2009, the price of CO<sub>2</sub> emission increased in the international carbon market and ranged from \$11 - \$16.3 per tonne of CO<sub>2</sub> equivalent (CO<sub>2</sub>e), but the price is determined based on the highest bidder (Couth et al., 2011).

This study uses the LFG cost model to analyse the cost and benefit analysis of the projected amount of LFG from the landfills. The different options for the electricity generation include internal combustion (reciprocating) engines, gas turbines, micro turbines and combined heat and power systems (Jangikhatoonabad, 2015).

The LFGcost Model is a spread sheet tool developed for EPA's Landfill Methane Outreach Programme (LMOP) to simulate the costs of LFG energy project. The Model is useful in obtaining an initial economic feasibility analysis for a specific type of LFG energy project. LFG projects include electricity generation, direct use, boiler retrofit, combined heat and power, leachate evaporation, Compressed Natural Gas (CNG) and high Btu production (US EPA, LFGcost Web model, Version 3.1, 2016). Table 2.8 shows the different LFG energy project types and their sizes.

**Table 2.8: LFG project types and sizes (Jangikhatoonabad, 2015)**

LFG Energy project type	Project size
Direct use (boilers)	400-3000 ft <sup>3</sup> /min LFG
Boiler Retrofit	Less than or equal to 3000 ft <sup>3</sup> /min LFG
High Btu processing plant	1000-10000 ft <sup>3</sup> /min LFG
Onsite CNG production and fueling station	50-600 ft <sup>3</sup> /min LFG
Leachate evaporator	5000 gallons leachate/day and greater

<b>LFG Energy project type</b>	<b>Project size</b>
Standard turbine generator set	Greater than 3 MW
Standard reciprocating engine generator set	800 kW and greater
Small reciprocating engine generator set	100 kW-1 MW
CHP reciprocating engine generator set	800 kW and greater
CHP turbine generator set	Greater than 3 MW
CHP micro turbine generator set	30-300 Kw

Jangikhatoonabad (2015) used the LFG cost model to investigate the economic feasibility, environmental and social impacts of a LFG utilisation project in Tema and Tamale landfills situated in Ghana. The study revealed, based on the LFG cost model that the Tamale landfill was not environmentally feasible for a LFG utilisation project instalment. However, the Tema landfill would be economically feasible only if a microturbine engine was installed in the landfill. The Tema LFG project would produce an average annual electricity of 13.2 million kWh and a payback period of 3 years after commencement of project.

Ahmed et al. (2015) developed a Mixed Integer Linear Programming model for LFG utilisation as a sustainable source of energy based on economic and environmental conditions by maximising profit and greenhouse gas reduction. The study shows that the utilisation of LFG in the area was high in profit that is 7.6 times that which is currently gained. The Combined Heat and Power CHP generation was estimated to generate about 2420 tonnes of oil equivalent. The potential utilisations of LFG in this study could lead to Malaysia's greenhouse gas reduction of about 0.007%.

According to Boodhan (2014), an economic analysis of landfill gas to energy projects in the island state of Trinidad and Tobago used the LFGcost model to simulate the economic feasibility of an implementation of a LFG utilisation project in Trinidad and Tobago. Beethan. Forres park and Guanapo landfills were suitable landfills for the study. The study showed that the implementation of a LFG utilisation project in these landfills was economically feasible. However, the study also served as a yard stick for the government of Trinidad and Tobago instrumental policies and recommendations on LFG emissions, collections and utilisation.

Cooley et al. (2013) used the LFG cost model to simulate the LFG collection cost which was dependent on the area of the landfill and electricity generated from the landfills. The study assumed a 10% discount rate and 15 years lifespan for the project. The results of the study

showed that some landfills are economically feasible for the implementation of a LFG utilisation project if low-end pipelines cost are used for the study. However, with the use of high-end pipeline cost, none of the landfills were economically feasible. Also, when the results were compared to the conventional sources of gases and electricity production, none of the landfill production i.e. the pipeline ingestion or the electricity generation were more economically feasible. More money was, however, recommended to be invested in the LFG utilisation project to make the project economically feasible. Nevertheless, the study showed that 10 out of 25 landfills in the North Carolina are currently capturing LFG. Moreover, if the cost of equipment for LFG projects can be reduced, then the implementation of a LFG utilisation project in these landfills may be economically viable. Table 2.9 shows some cases of LFG utilization technology functional around the world.

Karapidakis et al. (2010) conducted research on the investigation of LFG in the generation of electricity. The study firstly evaluated if the active extraction of LFG would produce enough electricity. The Long Range Energy Alternatives Planning System (LEAP) software and Technology and Environmental Database (TED) were used to estimate the potential LFG electricity generated. The study showed that the potential total utilisation of LFG for electricity generation will save 4933.86 tonnes of oil equivalent (TOE) and contribute to of 57.9 tonnes of CO<sub>2</sub> reduction. This study concludes that electricity generation was enough for the biogas plant consumption and also enough power was transported to the national grid despite the short comings of the landfill.

Shin et al. (2005) conducted a research on the assessment of LFG for electricity generation in Korea using the LEAP model and TED, and compared with existing electricity generating facilities (business as usual scenario of existing power plants). The gas engine, gas turbine and steam turbines were considered. The study concludes that LFG utilisation with other forms of energy utilisation reduces global warming potential by a maximum of 75% when compared to spontaneous CH<sub>4</sub> emission. LFG electricity generation would be the good solution for CO<sub>2</sub> displacement over the medium term and additional energy profit.

Several methods have been reported for modelling the utilisation of LFGs, some of which includes: Long-range Energy Alternatives Planning system (LEAP), Technology and Environmental Database model (TED) and mixed linear programming model (LP) (Ahmed et al., 2015; Shin et al., 2005; Karapidakis et al., 2010). The most commonly used are LFGcost web model and LEAP. However, these other models estimate LFG emission and utilization

for electricity generation only and does not consider other LFG utilization options and cost in implementation of a LFG utilization technology (Ahmed et al., 2015). In this study, we used the LFGcost model because it is compactable with the LandGEM. It is only and mainly developed for the evaluation of LFG technology, cost analysis and has several advantages such as its wide application than the other models.

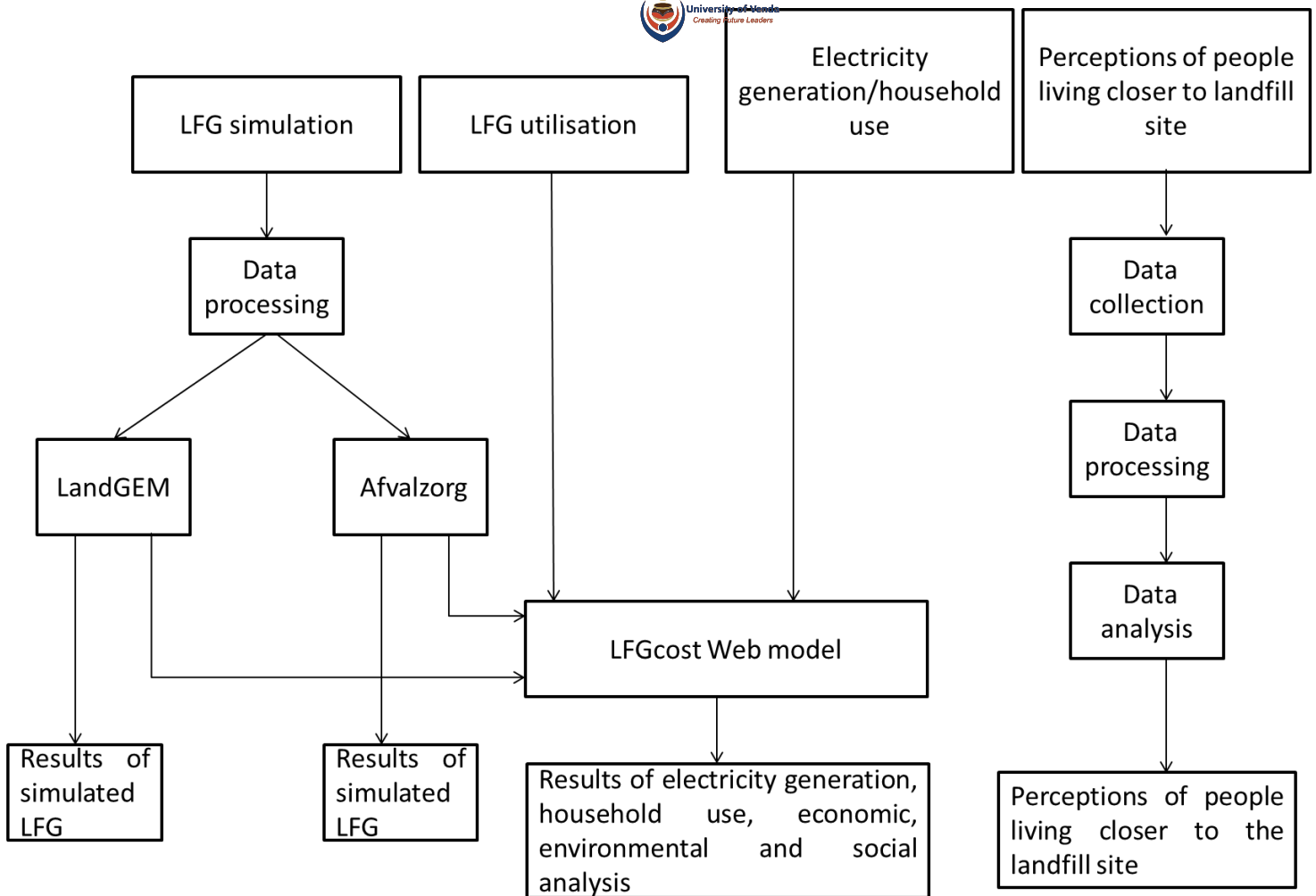
**Table 2.9: Some cases of LFG project functional over the world**

<b>Countries</b>	<b>Projects</b>	<b>LFG utilisation project type</b>
Australia	Belrose LFG project	Electricity
Argentina	Olavaria LFG project	Electricity
Belgium	Vharzera	Electricity
Brazil	Bandeirantes LFG energy project	Electricity
	Novagenar LFG energy project	Electricity
Canada	Greater Sudbury and halton region	Electricity
Columbia	Lapradera LFG project	Electricity, gas flaring
China	Suzhou Qizi Mountain LFG recovery project	Electricity
	Chengdu LFG energy project	Electricity
	Gaoantun LFG energy project	Electricity
	Mentougou LFG energy	Electricity
Ecuador	Zambisa LFG energy project	Electricity
Greece	Anoliossia LFG energy project	Electricity
India	Okhla LFG project	Electricity
	Goria LFG project	Electricity
Indonesia	Batulayang Pontianak landfill project	Electricity
Ireland	Arthurstown LFG energy project	Electricity
New Zealand	Horotiu Hamilton LFG project	Electricity
Norway	City of Bergen	Electricity
Poland	Lubna Sosnowiec and legajny LFG project	Electricity
	Torun LFG energy project	Electricity
Romania	Targu Mures LFG utilisation project	Thermal energy, natural gas
Russia	Chelyabinsk LFG utilisation project	Electricity
South Africa	eThekwin Municipality LFG project	Electricity
Sweden	Kristianstad LFG project	Electricity
Ukraine	Khmeluitsky LFG project	Electricity
United Kingdom	Wingmoor Farm LFG project	Electricity
	Drumee LFG utilisation project	Electricity
USA	Mckinney LFG project	Electricity
	Puente hills	Electricity

## CHAPTER THREE: METHODOLOGY

### 3.1 Research design

The study calculated the total LFG emitted from the Weltervenden and Thohoyandou landfills. It also determined the best approach for LFG utilisation when CH<sub>4</sub> emitted from the landfills is used as a source of energy for electricity generation. The study also investigated the possible perceptions and attitudes; health and environmental impacts associated with the landfill site's workers and the community living closer to the landfill sites. Furthermore, it also identified the number of households the electricity estimated from the LFG technology can supply. Cost analysis, environmental and economic benefits related to the implementation of LFG technology were also evaluated. This study adopted two models (Afvalzorg and LandGEM models) to calculate the total LFG emitted from the landfill sites. The LFGcost Web model was used to calculate the cost analysis and benefits of the LFG utilisation project. In addition, with the aid of the landfill workers and people living closer to the landfill site, a research questionnaire was used to collect data on the perceptions and attitudes; health and environmental effects associated with the landfill sites. IBM Statistical Package for Social Sciences (SPSS) software version 23 was used to analyse the data collected. Figure 3.1 gives a graphical summary of the research process.



**Figure 3.1: A design of the research process**

### 3.2 Models for the study

The LandGEM and Afvalzorg models were used to estimate the amount of LFG emitted from the landfills. It is essential to consider waste volumes and composition, local climate and other parameters that are required as input data for the models.

#### 3.2.1 Landfill Gas Emission Models (LandGem)

The input data for the LandGem model included the following:

- i. The total amount of the MSW deposited in the landfill annually.
- ii. The year the landfill commenced operation and closing year of landfill.
- iii. The design capacity of the landfill – the total amount of waste that will be disposed in the landfill.
- iv. Potential methane generation capacity  $L_0$ .
- v. The methane generation rate  $k$ .
- vi. The concentration of the total Non-metallic Organic Compounds NMOC.
- vii. Methane content by volume in percentage.

The model output comprises of the annual emission rate of CH<sub>4</sub>, carbon dioxide, NMOC and some trace gases during the life time of the landfill and even after closure of the landfill site. However, some of the LFG simulated from the landfill site to be considered in this study by the LandGEM model includes; methane (CH<sub>4</sub>), carbon dioxide (CO<sub>2</sub>), Benzene, carbon monoxide, ethyl mercaptans (CH<sub>3</sub>CH<sub>2</sub>S), hydrogen sulphide, NMOC, Vinyl Chloride (CH<sub>2</sub>CHCl) and mercury.

### 3.2.2 Multi-phase Afvalzorg model

Data imputation necessary to run the Afvalzorg model included:

- i. Start year of waste disposal
- ii. Waste mass deposal every year
- iii. Methane Correction Factor MCF
- iv. Waste composition of the landfill in percentage
- v. Degradable Organic Carbon DOC in MSW
- vi. Methane generation rate constant
- vii. LFG recovery efficiency

The model output includes the total LFG and CH<sub>4</sub> generated.

### 3.2.3 Data input for the simulation of LFG in Thohoyandou and Weltervenden landfill sites

The data for the simulation of the LFG was collected from the (waste management sector) Thohoyandou Municipality, Polokwane Municipality and the South African Waste Information system (SAWIC) website for the LandGEM and Afvalzorg models. Table 3.1 shows the imputation data required for the simulation of LFG with the LandGEM and the Afvalzorg models.

**Table 3.1: Imputation data for the simulation of LFG with the LandGEM and Afvalzorg models**

Data	Thohoyandou Landfill	Weltervenden landfill
Year landfill commenced operation	2004	1999
Proposed year of closure of landfill operation	2020	2022
Degradation constant k (year <sup>-1</sup> )	0.05	0.05
Potential Methane Generation Capacity L <sub>0</sub> (m <sup>3</sup> /Mg)	100	100
Methane concentration (%)	50	50
Methane correction factor MCF (managed)	1	1

anaerobic landfill)		
<b>Data</b>	<b>Thohoyandou Landfill</b>	<b>Weltervenden landfill</b>
Oxidation Factor OX (managed and covered landfill with oxidising material)	0.1	0.1
Recovery efficiency	0	0

The total amount of solid waste deposited in the landfill shows the annual amount of waste deposited in the Thohoyandou and Weltervenden landfills from the starting year to expected closure year. The total waste deposition in the landfill was an essential input data to run the model. Data on yearly waste deposited from the Municipalities in Thohoyandou and Weltervenden landfills started in the years 2004 and 2012, respectively. However, Thohoyandou and Weltervenden landfills officially commenced operations in the years 2005 and 1999, respectively. Therefore, equation 3.1 was used to calculate the missing data from both landfills.

Kalantarifard and Yang (2012) showed a positive correlation with population increase and socioeconomic level increase with waste generation and used the population size to estimate the amount of future waste generation. However, certain factors can lead to the reduction of waste in a landfill as population increases. Factors like government policies on waste deposition in a landfill; increase in recycling; increase in incineration and increase in waste composting.

$$\text{Past}_g = \text{Present}_g (1 - i)^n \text{ (Polokwane Municipality)} \dots \dots \dots (3.1)$$

$\text{Past}_g$  = past waste generation;  $\text{Present}_g$  = present waste generation;  $i$  = rate of growth which is 0.62%;  $n$  = period of year; using the population census of 2011 for Thulamela and Polokwane, Municipalities, 618,462 and 628999 people, respectively (Thulamela Municipality, 2014; City of Polokwane, 2018). Table 3.2 and 3.3 show the amount of waste deposited in the Thohoyandou and Weltervenden landfills, respectively. Equation 3.1 was used to estimate the potential waste generated in the area based on the potential population size for both landfills. The results were applied in this study to fill in the missing data that were not acquired from the SAWIC and Municipalities.

**Table 3.2: MSW waste deposited in Thohoyandou landfill site from 2005 - 2019**

<b>Years</b>	<b>Population</b>	<b>Waste deposited (tonnes)</b>
2005	595,809	56,072*
2006	599,526	56,414*
2007	603,267	56,759*
2008	607,030	57,109*
2009	610,817	57,463
2010	614,628	70,666
2011	618,462	92,637
2012	622,296	104,617
2013	626,155	97,967
2014	630,037	210,000
2015	633,943	298,705.9
2016	637,874	83,719
2017	641,828	84,238*
2018	645,801	84,759*
2019	649,806	85,285*

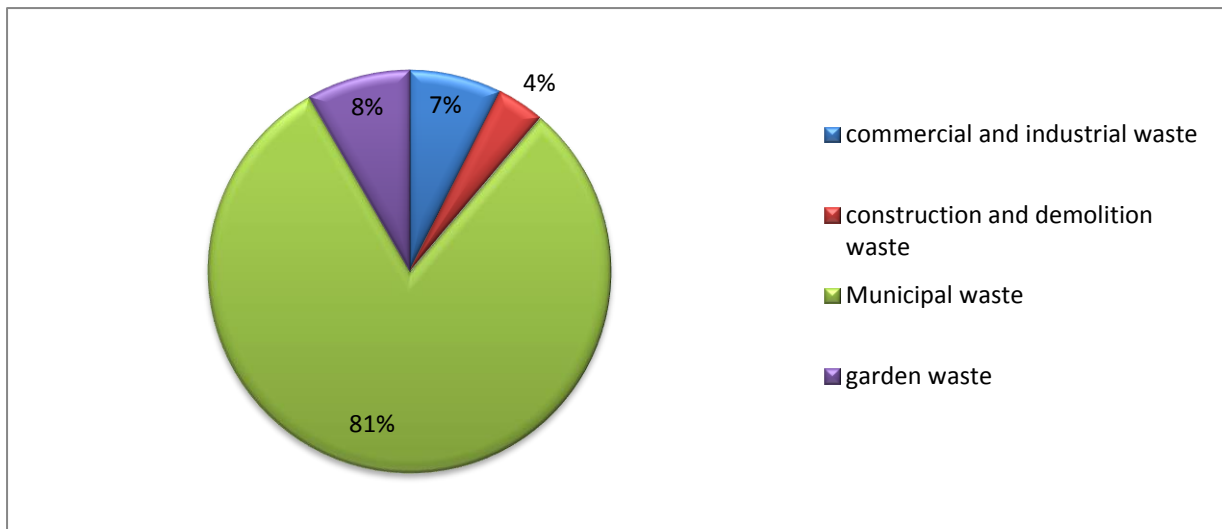
Note: \* shows the expected amount of waste deposited in the landfill, while amount of waste deposited from year 2009 to 2016 was obtained from SAWIC.

**Table 3.3: MSW deposited in Weltervenden landfill from 1999 – 2022**

<b>Years</b>	<b>Population</b>	<b>Waste deposited (tonnes)</b>
1999	485786	39667.16*
2000	496359	40340.08*
2001	507161	41036.21*
2002	518,199	41756.80*
2003	529,477	42503.15*
2004	541,000	43276.66*
2005	552,774	44078.84*
2006	564,804	44911.33*
2007	577,096	45775.87*
2008	589,656	46674.35*
2009	602,489	47608.8*
2010	615,601	48581.43*
2011	628,999	49594.63*
2012	642,397	50651
2013	656,080	44487
2014	670,054	204914
2015	684,326	182716
2016	698,903	129017
2017	713,789	131765.1*
2018	728,993	134513.1*
2019	744,520	137261.2*
2020	760,379	140938.2*
2021	776,575	142757.3*
2022	793,116	145505.4*

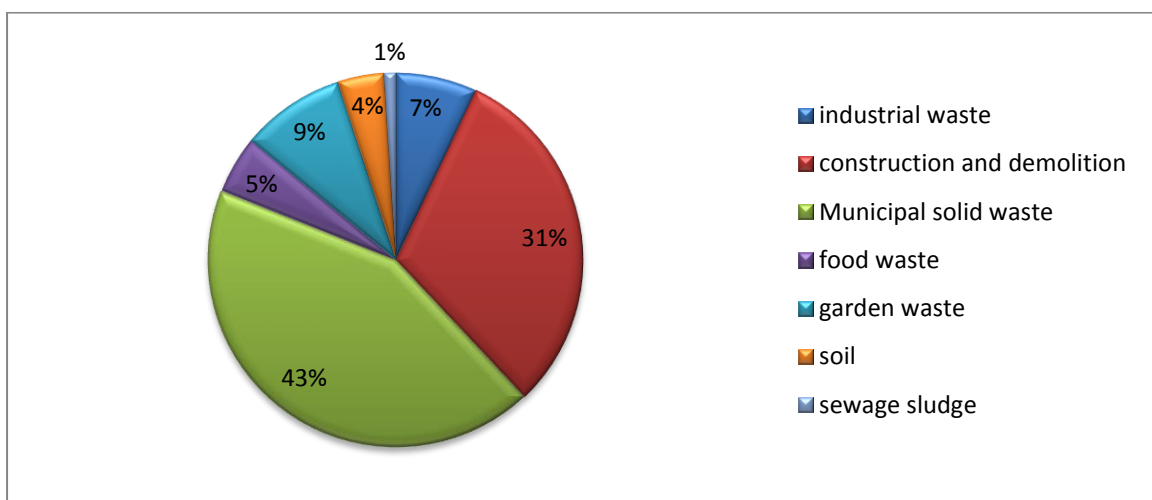
Note: \* shows the expected amount of waste deposited in the landfill, while amount of waste deposited from year 2012 to 2016 was obtained from SAWIC.

The general waste composition for both landfills were obtained from the SAWIC website, Thulamela and Polokwane Municipalities. Figure 3.2 and 3.3 show the waste composition in Thohoyandou and Weltervenden landfills, respectively.



**Figure 3.2: Pie chart showing the average annual composition of waste present in the Thohoyandou landfill (Source: Thulamela Municipality and SAWIC website)**

It is important to indicate that, 10% of the total composition of solid waste deposited in the Thohoyandou landfill is considered to be inert waste and it includes; sand, ceramics, tiles, gravels, bricks etc., (SAWIC website). Thus, only 90% of total waste deposited in the landfill was imputed in the LandGEM model.



**Figure 3.3: Pie chart showing the average annual composition of waste present in the Weltervenden landfill (Source: SAWIC website)**

It is also important to indicate that 12% of annual waste deposited in the Weltervenden landfill was inert waste (SAWIC website). Thus, 88% of total annual waste generated was imputed in the LandGEM model.

Degradable Organic Compound (DOC) the Afvalzorg model gives different default values for different regions in the world. The default value of DOC for the Southern African region is shown in Table 3.4.

**Table 3.4: Values of DOC in Southern African region**

DOC (by weight wet basis)	Default	Range
Food waste	0.15	0.08-0.20
Garden	0.20	0.18-0.22
Bulk MSW	0.20	0.12-0.28
Sewage sludge	0.05	0.04-0.05
Industrial waste	0.15	0-0.54

**3.2.4 Procedure to run the LandGem and Afvalzorg models**

***LandGEM***

Procedure 1 – insert the name of the landfill in the landfill identifier column of the model.

Procedure 2 – insert the opening year of the landfill site in Table 1 of the model

Procedure 3 – insert the closing year of the landfill in Table 1 of the model

Procedure 4 – insert the k value, Lo value, NMOC concentration and methane content in Table 2 of the model.

Procedure 5 – select the LFG to be simulated in Table 3 of the model.

Procedure 6 – insert the annual MSW deposited in the landfill in Table 4 of the model.

***Afvalzorg model***

Procedure 1 – insert the start year of waste disposal in cell A47 of the model.

Procedure 2 – insert the k value of MSW in cell D41 of the model.

Procedure 3 – insert the OX value for the cover area of the landfill in cell D42 of the model.

Procedure 4 – insert the DOC value in Table 1 of the model.

Procedure 5 – insert the waste composition of the MSW in Table 1 of the model.

Procedure 6 – insert the values of the annual MSW deposited

Procedure 7 – insert the MCF value in column D of the model

Procedure 8 – insert the LFG recovery efficiency in column J of the model

### 3.3 Sensitivity analysis

Also k value is calculated by  $k = 3.2 \times 10^{-5} (x) + 0.01$  ..... (3.2);

From equation 3.2, x is the average annual rainfall of the area (Daura et al., 2014). The average rainfall in Thulamela and Polokwane Municipalities are 500 mm and 521 mm, respectively, according to the IDP 2016/2017 financial report for Thulamela and Finch et al, (2003). Therefore,  $k = 0.026 \text{ year}^{-1}$  and  $0.027 \text{ year}^{-1}$  for Thohoyandou and Weltervenden landfills, respectively.

### 3.4 Estimation of the cost analysis and benefit for the implementation of the LFG utilisation project

#### 3.4.1 LFGcost Web Model

The landfill gas energy cost model (version 3.1) was used to determine economic analysis and the feasibility of implementing the LFG utilisation technology. The software was created in Microsoft Excel to make the computations transparent and determine the initial economic feasibility in the conversion of LFG to energy project (LFGcost Web user manual). The model is grounded on default characteristics of a landfill, as well as additional user input data which produces outputs in various proportions for the LFG utilisation project.

The model was implemented on five types of electricity-generating technologies, which are internal combustion engines (15-year lifetime), gas turbines (15-year lifetime), micro turbines (10-year lifetime), Combined Heat and Power engine (CHP) turbines and CHP microturbines. The main tools for determining the feasibility of the LFG to energy project are the net present value (NPV) and the internal rate of return (IRR), which are the main criterion used for either accepting or rejecting projects in cost-benefit analysis. The NPV is the present value of net cash flow and the project can be executed if the NPV is equal to zero or greater than zero, and rejected if the NPV is less than zero. Also IRR value can also be used to determine the viability of a LFG utilisation project. If the IRR is greater than the discount rate, the project is viable.

*Imputation data to run the LFGcost Web model for the Thohoyandou and Weltervenden landfill sites.*

Table 3.1, shows some of the imputed data to run the LFGcost Web model for the Thohoyandou and Weltervenden landfills, with the specific input requirements as shown in Table 3.5:

**Table 3.5: Specific input parameters for the LFGcost Model for both landfills**

Parameters	Thohoyandou landfill	Weltevenden Landfill
Landfill Opening and closure	Refer to Table 3.1	Refer to table 3.1
Area of Landfill wellfield to supply project	20 or 40	20 or 40
The total amount of MSW deposited in the landfill annually	Refer to Table 3.2	Refer to table 3.3
Landfill energy project types	Standard turbine, standard engine, microturbine, combined heat and power system (CHP) turbine and CHP microturbine.	Standard turbine, standard engine, microturbine, combined heat and power system (CHP) turbine and CHP microturbine.
Year LFG project begins operation	2018	2021
Methane generation rate constant $k$ (year <sup>-1</sup> )	Refer to table 3.1	Refer to Table 3.1
Potential methane generation capacity $L_0$ (ft <sup>3</sup> /ton)	Refer to Table 3.1	Refer to Table 3.1
Methane content of LFG in %	50	50
Average depth (ft)	65	65
LFG collection efficiency	85%	85%
Expected LFG energy project time (years)	15 years but 10 years for microturbine engines	15 years but 10 years for microturbine engines
Loan lifetime (years)	10	10
Interest rate (%)	6.75	6.75
Inflation rate (%)	4.5	4.5
Marginal tax rate (%)	35	35
Discount rate (%)	1	1
Down payment for the project (%)	50 and 100	50 and 100
Electricity purchase price for the projects not generating electricity (R/kWh)	\$0.08 at a rate of \$14.21 to 1 rand	\$0.08 at a rate of \$14.21 to 1 rand
Annual electricity purchase price escalation rate (%)	2.2	2.2

### **3.5 Investigation of the perception of health and environmental impacts of residents living closer to the landfill sites**

Weltervenden landfill is located far away from residential areas, but some old government buildings and some few business enterprises are located close to the landfill. However, the Thohoyandou landfill is situated very close to the residential areas at approximately 100 m away from the landfill. Therefore, this study sought to find out the perceptions of health impact and the way of life for the residents living closer to Thohoyandou landfill. The study focused on residents living approximately 50 m to 2 km away from the landfill. The households living closer to the landfill were identified to be approximately 100 households around the landfill, with an average of 4 people per household (SA Stat, 2016). However, a total of 100 people were identified as the sample size. Stratified random sampling was used to identify approximately 50 participants who lived approximately 100 m to 500 m, while 50 participants who lived 1 km to 2 km away from the landfill were identified as the control for the study (Brewer, 1999). This study strategically identified participants based on how long they have lived in the community. A landfill operator manager and three university students were trained and recruited for data collection.

A five page questionnaire was pretested with 30 participants, to identify errors and limitations of the survey tool (Appendix G). Furthermore, after adjustments, the questionnaire was administered to a total of 100 participants (50 participants – people living closer to landfill while 50 participants – people living far away from the landfill). Topical issues on perception of neighbourhood problems, significance of environmental problems, most frequently experienced sickness and life in general in the landfill were identified. The data acquired from the field study was analysed with the aid of SPSS to obtain possible results and findings from the data acquired. Also a comprehensive Independent Sample Test was conducted for the variables in this study.

At the start of the administration of questionnaires majority of the residents were very willing to cooperate in filling the questionnaire. Additional information, suggestions and recommendations were also given to the researchers by the participants based on the environmental challenges faced by the community. During the field work, four households expressed scepticism and refused to participate in the study. Two other households expressed less concern because they felt the study was not beneficial to them as they were not house owners and not fully responsible for the environmental issues in the community.

### **3.6 Ethical Consideration**

This study was submitted to the Ethical committee of the University of Venda, to ascertain the avoidance of harm to participants; the Informed consent of the participants and the avoidance of deception and invasion of privacy of the participants. The dissertation was approved by the ethics committee to commence the study. A copy of the ethical clearance approval certificate can be found in Appendix L.

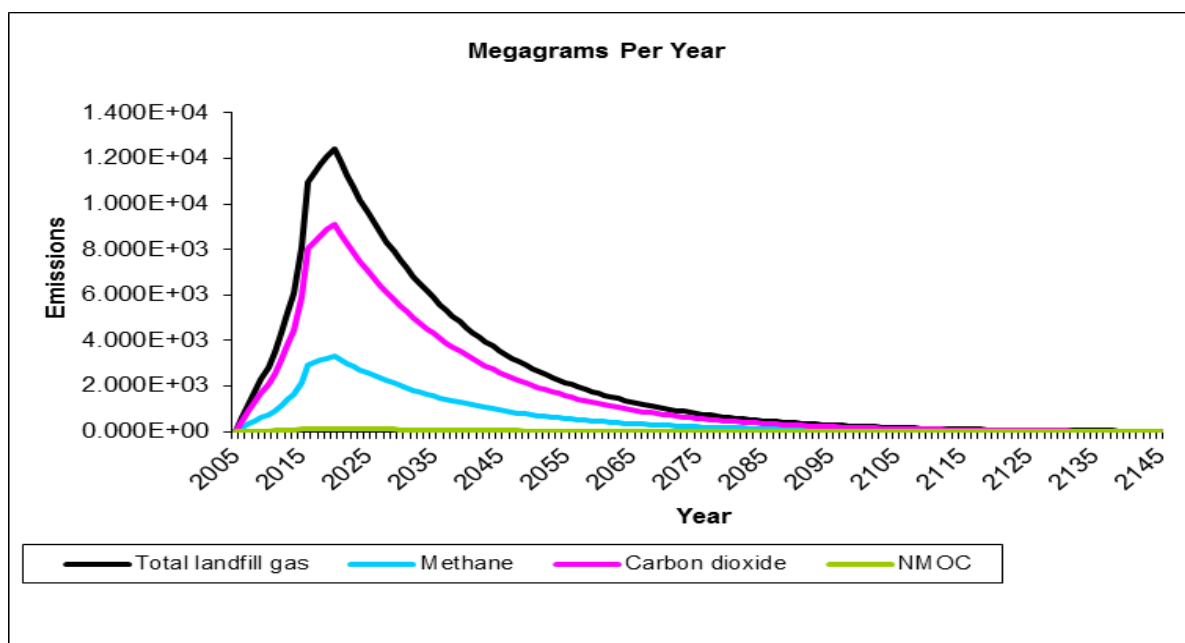
## CHAPTER FOUR: ESTIMATION OF LFG FROM THOHOYANDOU AND WELTERVENDEN LANDFILLS

### 4.1 LandGEM simulation

The LandGEM simulated the total LFG emissions from both landfills. As stated earlier in chapter three, the LFG is as a result of anaerobic decomposition of waste in the landfill. The LFG simulated by the LandGEM includes total LFG, CH<sub>4</sub>, CO<sub>2</sub> (which are the most dominant gases emitted from the landfill) and NMOC (which comprises of Volatile Organic Compound (VOC) and odorous emissions like benzene, hydrogen sulphide, carbon monoxide etc.). Appendix A shows the results obtained for the Thohoyandou landfill using the LandGEM; Appendix B shows the results of other trace gases found in the landfill and Appendix C shows the results obtained for the Welteervenden landfill using the LandGEM.

The LandGem model simulated the total LFG emission over a period of about 120 years after closure of landfill. The results obtained from the model after processing includes; Total LFG, CH<sub>4</sub>, CO<sub>2</sub> and NMOC generated from the Thohoyandou landfill site until 2145 (Figure 4.1) and different trace gas pollutants emitted from the landfill (Appendix B). Figure 4.1 shows the rate of gases emission over the years for different LFG, simulated by LandGEM.

The LandGem model results show that CH<sub>4</sub> and CO<sub>2</sub> are the major gases found in the landfill. The LFG emitted from Thohoyandou landfill increases with increase in waste deposition over time and it peaks with closure of the landfill. The maximum projected emission of CH<sub>4</sub> and CO<sub>2</sub> was in 2020 with values of  $3.323 \times 10^3$  Mg/year and  $9.118 \times 10^3$  Mg/year, respectively. This is because in 2020, the Thohoyandou landfill is expected to be closed, therefore the deposition of solid waste in the landfill will cease. The LFG production then starts declining until all degradable waste buried in the landfill is degraded. This inference is in line with results obtained from Liphoto (2001); Bhailall et al., (2010); Kalantarifard and Yang (2012); Aydi (2012). However, Aydi (2012) conducted a subsurface estimation of LFG using the LandGEM model; the results show that the total LFG emitted from the landfill peaked one year after closure of landfill site. This study disagrees with the results derived from Aydi (2012).



**Figure 4.1: Graphical representation of the total LFG, CH<sub>4</sub>, CO<sub>2</sub> and NMOC emitted from Thohoyandou landfill site using the LandGem model.**

In this study, the CO<sub>2</sub> emitted was recorded to be greater than the CH<sub>4</sub> using the LandGEM, although this is contrary to expectations because during the run of the LandGem model CH<sub>4</sub> was estimated to be 50% of the total LFG emitted. Gardner et al. (1993) showed that the total rate of emission of CH<sub>4</sub> is usually less than CO<sub>2</sub> emissions from a landfill. Hence this supports the results from the LandGEM model derived for this study, because large quantities of CH<sub>4</sub> oxidises microbiologically to CO<sub>2</sub> within the landfill cover soil before reaching the atmospheric environment, which leads to the loss of CH<sub>4</sub>. Liphoto (2001) compared CH<sub>4</sub> and CO<sub>2</sub> emission from three landfills in Durban, South Africa using the LandGEM model. Liphoto results show that the CH<sub>4</sub> emitted from the three landfills were lower than the CO<sub>2</sub> emissions from the landfills. Liphoto concludes that the surface emissions of CO<sub>2</sub> are always higher than the CH<sub>4</sub> emissions as a result of the microbial oxidation of CH<sub>4</sub> into CO<sub>2</sub> within the landfill before it reaches the atmosphere. The total CO<sub>2</sub> and CH<sub>4</sub> emitted from the Thohoyandou landfill between the years 2005 to 2040 is 181717.6 Mg and 66229.7 Mg, respectively. However, factors contributing to the CH<sub>4</sub> oxidation capacity of the soil include; soil moisture content (optimum oxidation occurs at 15% - 20% moisture content), soil temperature (optimum oxidation occurs at 30°C - 35°C in soil), presence of methanogenic bacteria in the landfill, soil type and thickness of cover.

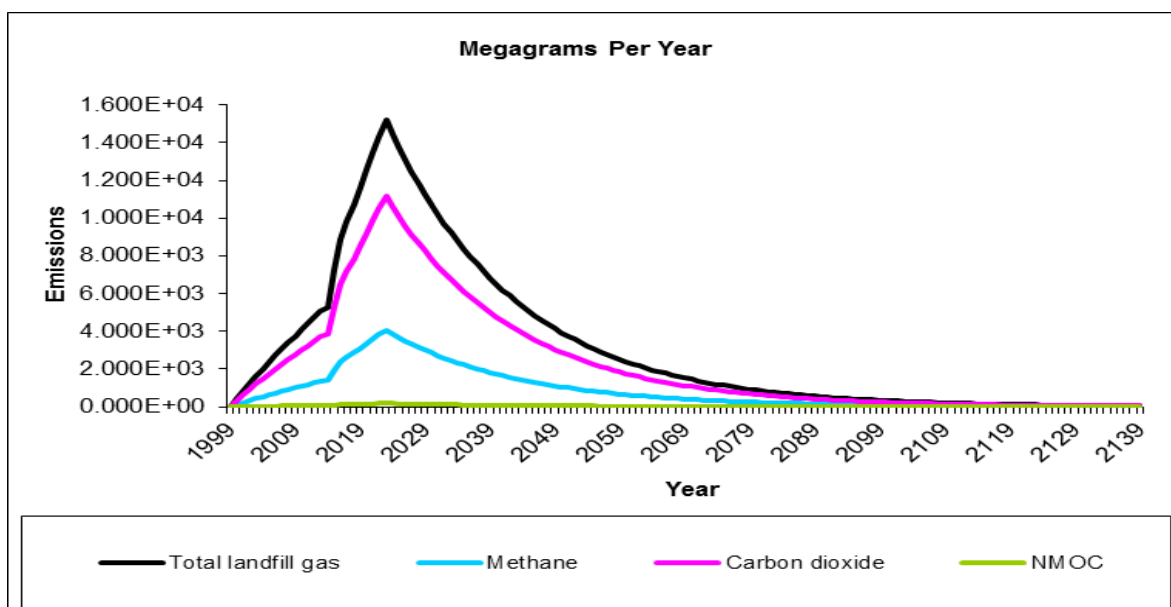
During the post closure years of the landfill, the LFG generated declined over a period of 120 years and the LFG became insignificant at around 80 to 100 years. Therefore, it shows that from the landfill site, traces of LFG still evolve over the years after closure. The drop of LFG generation is due to the insufficient or no degradable waste compound found in the landfill. The continuous emission of LFG from the landfill after closure is due to the slow biogasification of biodegradable waste. Figure 4.1 shows LFG generated was estimated to continue emission up to 2145 using the LandGem model. This result agrees with Rezaee (2014) who estimated the LFG from year 2000-2143; Bhillal et al. (2010) estimated the total LFG from 2025/2026 (peak year of LFG emission) to year 2143; also Liphoto (2001) estimated the LFG emissions up to 200 years after opening of landfill.

During our entire site visit, we noticed the huge amount of pungent smell evolving from the landfill from a distance most especially during humid weather condition. LFGs like hydrogen sulphide, methyl mercaptans and ethyl mercaptans were identified to be major sources of the pungent odour from landfills (Liphoto, 2001). Appendix B gives graphical representation of the odorous gases emission from years 2005 to 2160 from the Thohoyandou landfill. These gases will reach their peaks in the year 2020 at ethyl mercaptans ( $5.921 \times 10^{-2}$  Mg/year) and hydrogen sulphide ( $5.084 \times 10^{-1}$  Mg/year), etc. (Appendix B); the gases decline afterwards as the years go by. The air pollutants as explained above will reach their peak in 2020 which is similar to other LFGs emitted. However, these trace LFGs also continue to reduce after closure of landfill just like the other LFGs. These odorous pollutants can be referred to as trace gases because of their small quantity when compared to the amount of CH<sub>4</sub> and CO<sub>2</sub> emitted. The odorous pollutants follow a similar trend to that of the total LFG, i.e. perhaps the total composition of LFG follow an overall LFG emission process. Air pollutants like NMOC which includes Chlorinated Hydrocarbons, benzene, vinyl chloride, carbon monoxide, CFCs and some other trace compounds were simulated by the LandGEM model. These gases are air pollutants that contribute to the earth's global warming and also some of these trace gases are carcinogenic to humans.

The total LFG, CH<sub>4</sub>, CO<sub>2</sub> and NMOC from the Weltervenden landfill site was emitted until 2139. The Weltervenden's LFG emissions increase with increase in waste deposition in the landfill and the LFG peaks a year after closure of the landfill. The results of the LandGEM simulation of LFG from the Weltervenden landfill are shown in Appendix C and Figure 4.2. The emissions of CH<sub>4</sub> and CO<sub>2</sub> will peak in the year 2023 with values of  $4.061 \times 10^3$  Mg/year

and  $1.114 \times 10^4$  Mg/year, respectively. The peak emissions of the LFG were as a result of the closure of the landfill in 2022, i.e. the landfill stopped receiving waste hence the reduction in LFG emission. The CO<sub>2</sub> emitted from the Weltervenden landfill was also recorded to be greater than the CH<sub>4</sub> emitted as explained earlier.

According to the Weltervenden landfill operators, the landfill still has about five more years to continue operations until closure, although strategic plans have been put in place to expand the landfill so as to accommodate more MSW. However, the LFG simulated is recorded to decline over a period of 115 years with the Total LFG becoming very insignificant from 2081 to 2139. As said earlier the decline in LFG is due to the insufficient MSW deposition in the landfill and almost all the remaining waste buried under the ground have all decayed. Figure 4.2, illustrates the graphical representation of the total LFG, CH<sub>4</sub>, CO<sub>2</sub> and NMOC emitted from the Weltervenden landfill which is derived from LandGEM model's simulations.



**Figure 4.2: Graphical representation showing the total LFG, CH<sub>4</sub>, CO<sub>2</sub> and NMOC emitted from the Weltervenden landfill site**

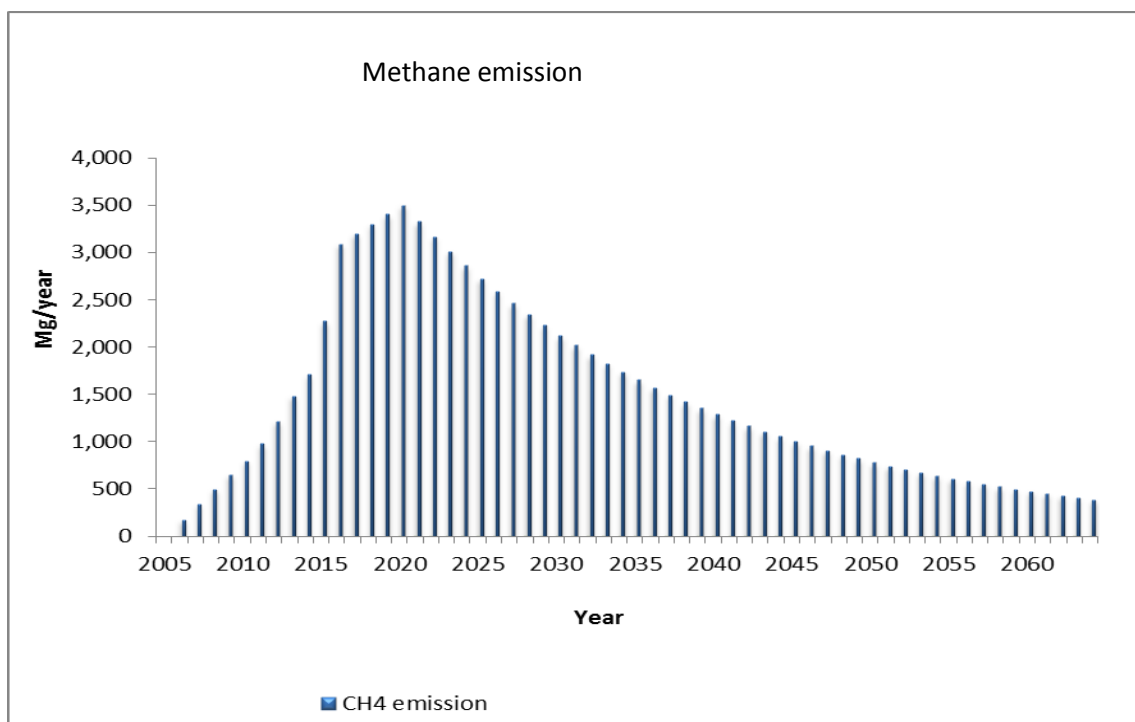
Appendix D shows the graphical representations of some of the pollutant gases simulated by the LandGEM model, gases like hydrogen sulphide, benzene, ethyl mercaptans, etc., contribute significantly to the emanating odour from the landfill site. These gases are found in smaller quantities when compared to the CH<sub>4</sub> and CO<sub>2</sub> emitted and can also be called trace gases. The peak amount of trace gases includes benzene (0.07515 Mg/year), ethyl mercaptans (0.07236 Mg/year) and hydrogen sulphide (0.6212 Mg/year) continue to increase from the

opening of the landfill and these gases will reach their peak in the year 2023 and continue to decline as the years go by. These gases also follow similar trend of total LFG emitted, which leads to deduction that these trace gases are components of the total LFG emissions. Furthermore, appendix D illustrates some air pollutants emitted from the Weltervenden landfill which includes; chlorinated Hydrocarbons, benzene, vinyl chloride, carbon monoxide, CFCs and some other trace compounds, which contribute significantly to the South African air pollution.

#### **4.2 Afvalzorg model simulation**

Appendix E shows the results derived from the Afvalzorg model's simulations for Thohoyandou landfill. The Afvalzorg model simulated the total LFG emission over a period of 60 years from the opening of the landfill until 2060. Unlike the LandGEM, Afvalzorg model only simulates the total LFG and CH<sub>4</sub>. The model shows that LFG emitted from the Thohoyandou landfill increases with increase in waste deposition over time and the LFG peaks as the landfill closes. Appendix E gives the results of the LFG generated by the Afvalzorg model. It shows the maximum projected emission of the total LFG and CH<sub>4</sub> will be in 2020 with values of 1119 m<sup>3</sup> STP/h and 3501 Mg/year, respectively.

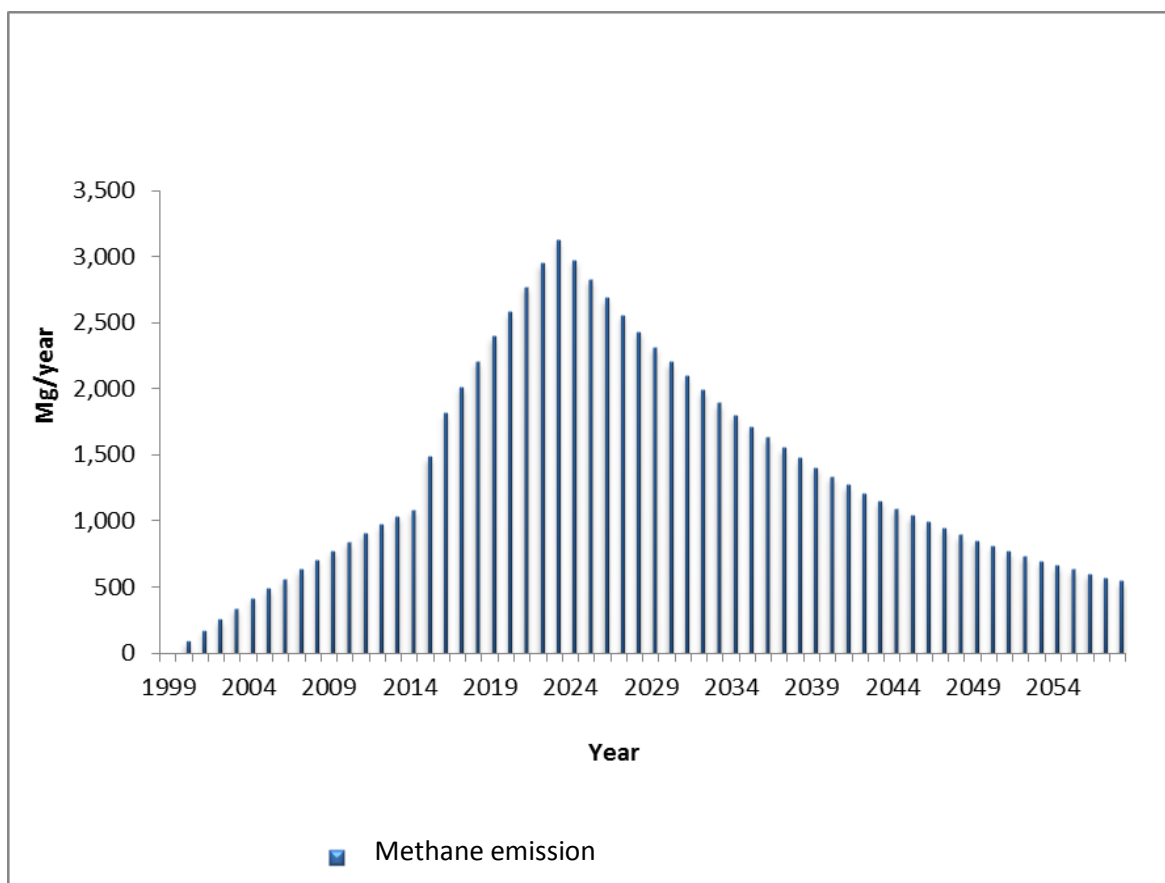
After closure of the landfill, the total LFG emitted will begin to reduce over a period of about 50 years and the LFG will become insignificant. The drop of LFG generation can be attributed to the lack of MSW deposition in the landfill, therefore the reduction of biodegradable substances present in the landfill. The continuous emission of LFG from the landfill after closure is due to the slow bio gasification of biodegradable waste as explained earlier. Figure 4.3 shows the graphical representation of the CH<sub>4</sub> generated from the Thohoyandou landfill site and the CH<sub>4</sub> generated was estimated to continue emission up to 2060 using the Afvalzorg model.



**Figure 4.3: Graphical representation of CH<sub>4</sub> emitted from Thohoyandou landfill site using the Afvalzorg model (k value = 0.5 year<sup>-1</sup>).**

Appendix F shows the results derived from the Afvalzorg model from the Weltervenden landfill site.

As stated earlier the Afvalzorg model simulates LFG only for about 60 years from the time the landfill opened. The model simulated the total LFG and CH<sub>4</sub> only emitted from the Weltervenden landfill until 2066. Figure 4.4 shows that as the waste deposition increased the increase in CH<sub>4</sub> emission increased and will peak in the year 2023. The year of peaking of the LFG and CH<sub>4</sub> is similar to the year of peaking simulated by the LandGEM model. Appendix F shows the maximum emitted values of LFG and CH<sub>4</sub> from the Weltervenden landfill are 1000 m<sup>3</sup>STP/h and 3128 Mg/year, respectively.



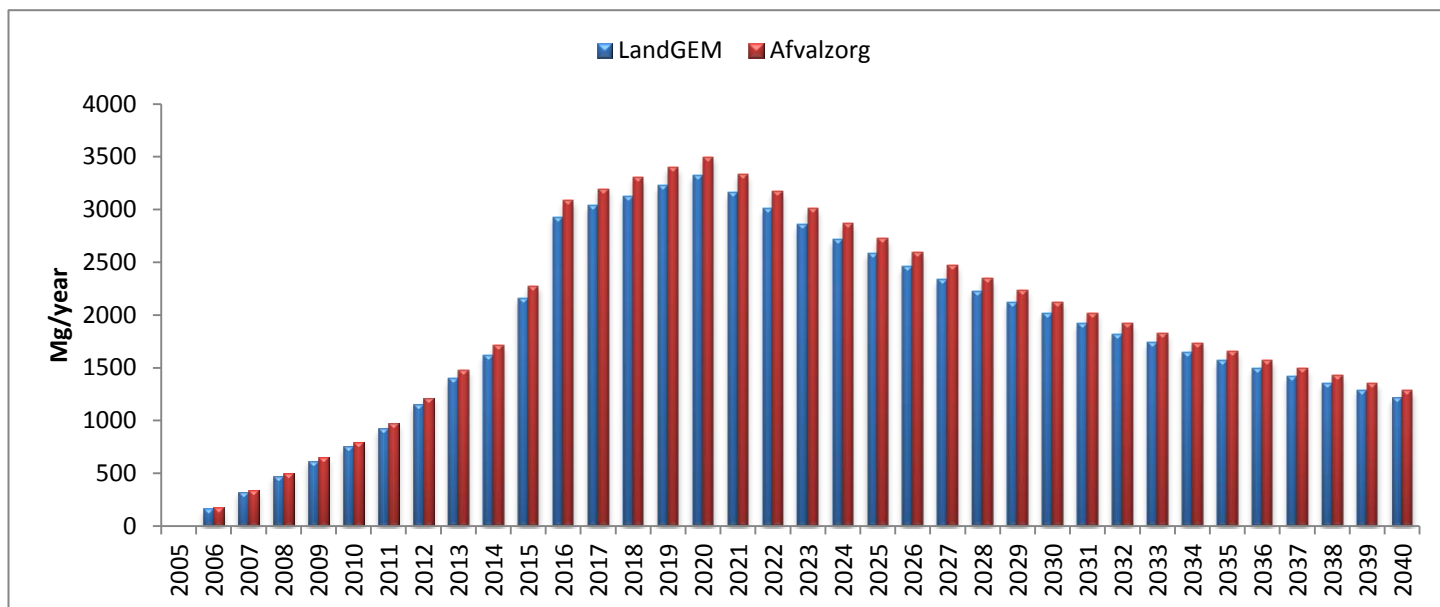
**Figure 4.4: Graphical representation of the simulation of CH<sub>4</sub> emission from the Weltervenden landfill site using the Afvalzorg model**

The Weltervenden landfill will reach closure in the year 2023; the result from the Afvalzorg simulation shows a rapid reduction after the estimated closure of the landfill site until the CH<sub>4</sub> became insignificant. The reduction of the LFG emission as stated earlier is as a result of reduction in the deposition of MSW in the landfill, therefore there is limited amount of waste to generate the LFG. Therefore, the amount of waste deposition is a very fundamental characteristic for LFG emission from a landfill site.

### 4.3 Comparison of results from the LandGEM and Afvalzorg simulations

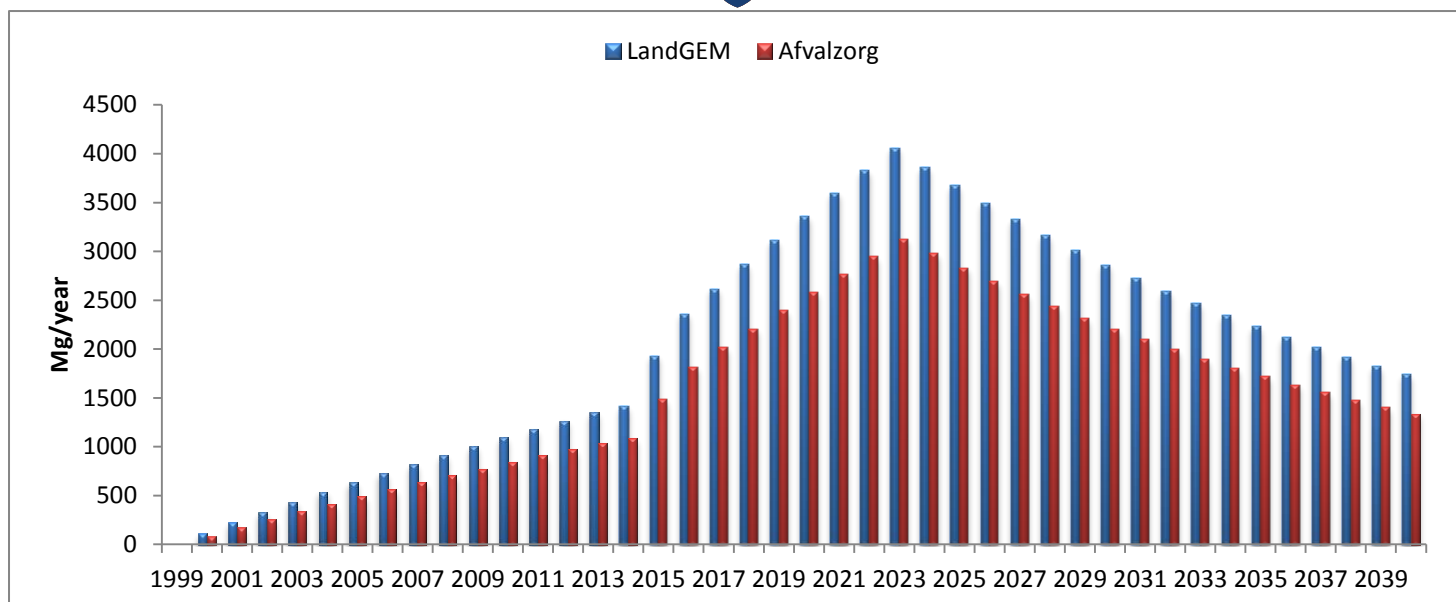
The comparison of the two models is based on the ability to get a more and precise or exact simulation of the LFG. The two most dominant gases simulated by the LandGEM are CH<sub>4</sub> and CO<sub>2</sub> which are also very strong GHG present in the atmosphere. However, the Afvalzorg model only simulates the total LFG and the CH<sub>4</sub> emissions. Therefore, the comparison will be based on the CH<sub>4</sub> emitted using the two models. The models show for Thohoyandou landfill that the CH<sub>4</sub> peaked in the year 2020 with the LandGEM reaching a peak CH<sub>4</sub> emission of 3323 Mg/year and Afvalzorg model reaching 3501 Mg/year. However, the total potential

emission of CH<sub>4</sub> from year 2005 - 2040 recorded by the LandGEM and the Afvalzorg models are 66200 Mg/year and 69768 Mg/year, respectively. The two models generated closely comparable results from the simulations. However, the results derived from the Afvalzorg model were higher than the results from the LandGEM model. Figure 4.5 gives the graphical representation of the results derived from the Afvalzorg and LandGEM models.



**Figure 4.5: Comparison of the simulation of CH<sub>4</sub> using the Afvalzorg and LandGEM models for the Thohoyandou landfill site**

Also, Figure 4.6 gives a graphical illustration of the simulation of CH<sub>4</sub> emitted from the Weltervenden landfill site using the Afvalzorg and LandGEM models. The models show that the CH<sub>4</sub> will peak in the year 2023 with the LandGEM reaching a peak of 4061 Mg/year and Afvalzorg model reaching 3128 Mg/year. However, the total potential emission of CH<sub>4</sub> from 1999 - 2040 recorded by the LandGEM and the Afvalzorg models are 85120.92 Mg/year and 65556.86 Mg/year, respectively. The LandGEM simulated the CH<sub>4</sub> emission to be higher than the simulations derived from the Afvalzorg model. The Afvalzorg model underestimated the CH<sub>4</sub> emitted from the landfill.



**Figure 4.6: Comparison of the simulation of CH<sub>4</sub> using the Afvalzorg and LandGEM models for the Weltervenden landfill site**

#### 4.4 Comparison of the results from the two landfill sites

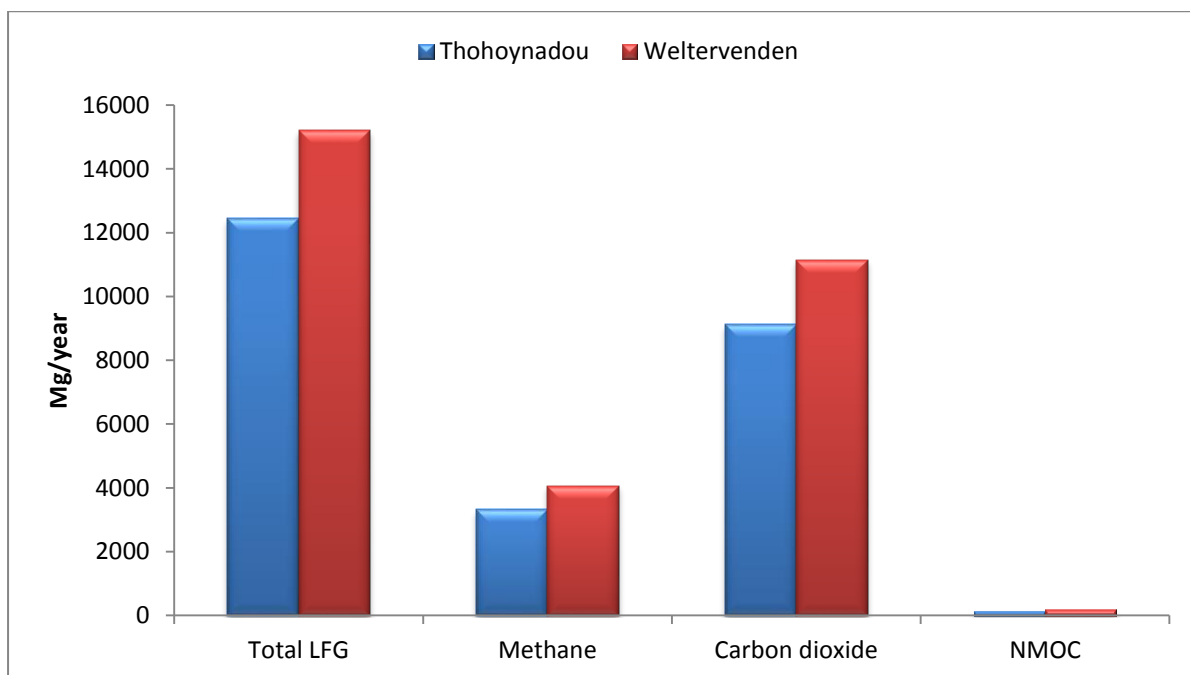
This study shows the Thohoyandou landfill started in 2005 and will close landfill operations in 2019; this is a period of 14 years. Also the total amount of waste that will be deposited in the Thohoyandou landfill during its life time is 1,496,411 tons. However, the Weltervenden landfill in this study was assumed to be operational for 23 years i.e. commenced operations in the year 1999, and will close landfill operations in the year 2022. The total amount of waste deposited during the life time of the Weltervenden landfill is 2,020,331 tons. The most dominant LFGs emitted from the landfill sites are CH<sub>4</sub> and CO<sub>2</sub>. Table 4.1 shows the peak emission of LFG, CH<sub>4</sub>, CO<sub>2</sub> and NMOC emitted from the two landfill sites using the LandGEM and Afvalzorg models.

**Table 4.1 The simulations of LFG, CH<sub>4</sub>, CO<sub>2</sub> and NMOC using the LandGEM and Afvalzorg models for the Thohoyandou and Weltervenden landfill sites**

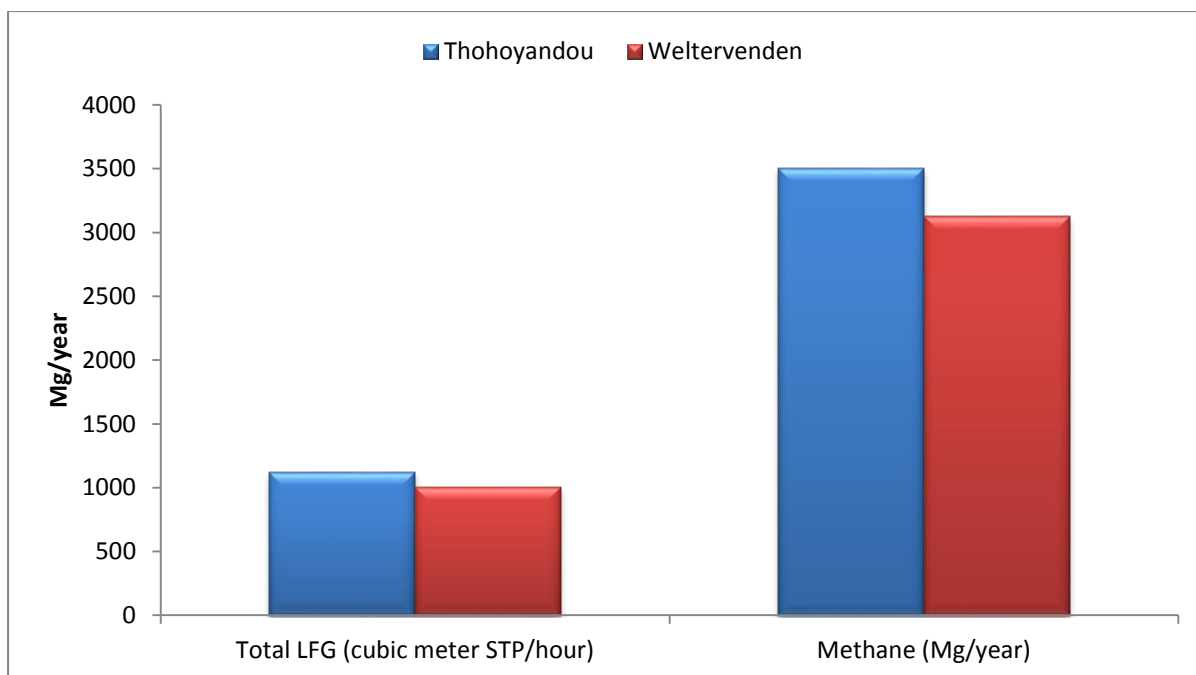
Landfills	LandGEM model				Afvalzorg model	
	LFG (Mg/year)	CH <sub>4</sub> (Mg/year)	CO <sub>2</sub> (Mg/year)	NMOC (Mg/year)	LFG (m <sup>3</sup> STP/h)	CH <sub>4</sub> (Mg/year)
Thohoyandou landfill	12440	3323	9118	142.8	1119	3501
Weltervenden landfill	15200	4061	11140	174.6	1000	3128

From Table 4.1, the LandGEM model simulation shows that the total LFG, CH<sub>4</sub>, CO<sub>2</sub> and NMOC emitted from the Weltervenden landfill is higher than the results derived from the Thohoyandou landfill site. However, the results from the Afvalzorg model's simulations show that the Thohoyandou landfill emitted more LFG and CH<sub>4</sub> than the Weltervenden landfill. The Afvalzorg model gives room to impute the different waste composition of the

landfills. Therefore, the result from the Afvalzorg simulations is as a result of the different waste composition of the two landfills. The waste composition from the Thohoyandou landfill was 81% MSW which has a DOC of 0.2 (High possibility of degrading faster). However, the Weltervenden landfill comprised of 43% MSW and 31% construction and demolition waste (DOC = 0.043, very low possibility of producing LFG quickly). Therefore, the more LFG emissions from the Thohoyandou landfill simulated by the Afvalzorg model was highly influenced by the waste composition of both landfill sites. Figures 4.7 and 4.8, show the graphical comparison between the simulations of LFG from the Thohoyandou and Weltervenden landfill sites using the LandGEM and the Afvalzorg models.



**Figure 4.7: The graphical representation of the LFG, methane, carbon dioxide and NMOC emitted from Thohoyandou and Weltervenden landfill sites using the LandGEM model.**



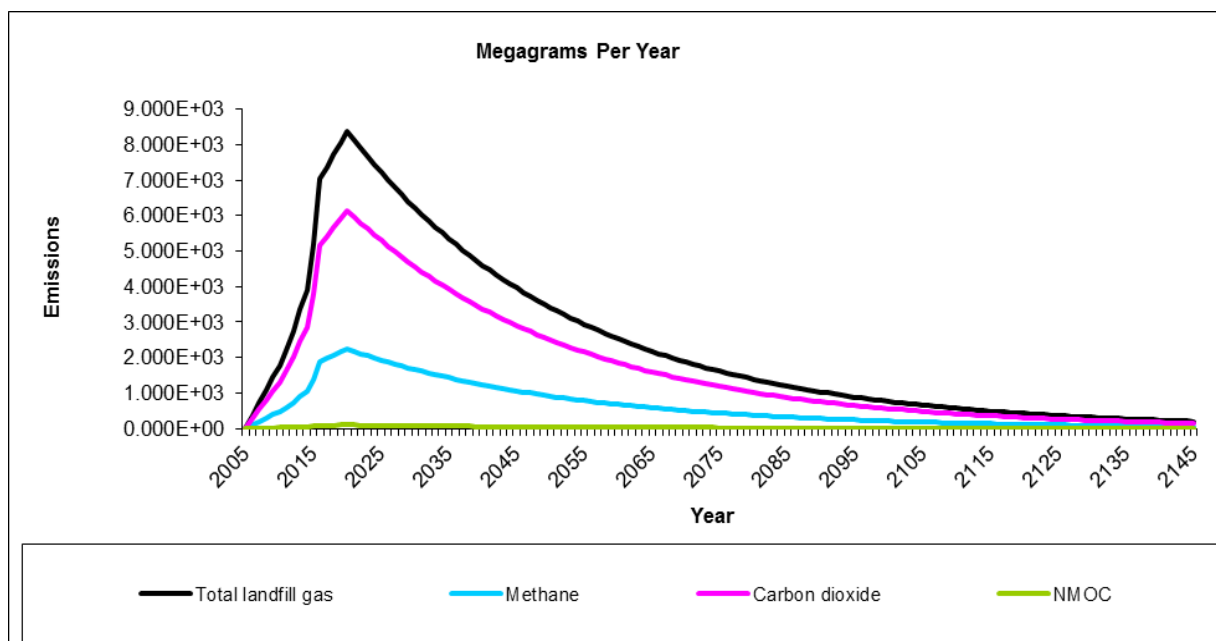
**Figure 4.8: The graphical representation of the LFG emitted from Thohoyandou and Weltervenden landfill sites using the Afvalzorg model.**

According to the hypothesis of the first objective, the results obtained using the LandGEM and Afvalzorg models to estimate the total LFG in Thohoyandou and Weltervenden landfills were considered to have provided estimations when compared to each other and other studies. However, a sub-surface field estimation of the LFG emitted with the aid of air analysers to authentically verify how close the LFG estimation from the two models are from reality is required. Thus, field measurements are essential for validation of the results.

#### 4.5 Sensitivity Analysis

Sensitivity analysis was conducted in order to understand the models reactivity to different parameters imputed. Furthermore, the analysis is also important to acquire the different possible results based on different possible potential parameters. The sensitivity of these models was conducted based on the  $k$  value. The two scenarios for the  $k$  value are  $0.05 \text{ year}^{-1}$  (IPCC default value) and  $0.03 \text{ year}^{-1}$  using the equation  $k = 3.2 \times 10^{-5}(x) + 0.001$  (Daura et al., 2014).

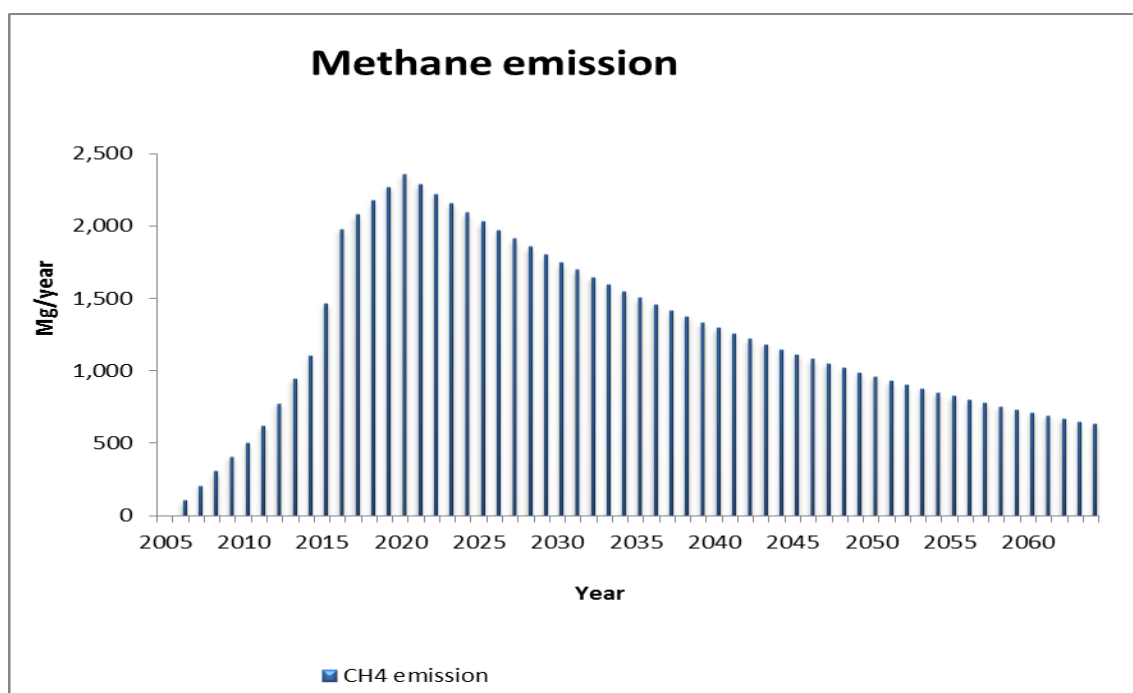
The graphical results of the LandGEM and Afvalzorg models are shown in Figures 4.9 and 4.10, respectively. LandGEM model simulation for  $k$  value =  $0.03 \text{ year}^{-1}$ .



**Figure 4.9: Graphical representation of Total LFG, CH<sub>4</sub>, CO<sub>2</sub> and NMOC emitted from Thohoyandou landfill site using the LandGEM model at  $k = 0.03 \text{ year}^{-1}$ .**

The average annual rainfall and temperature are key determining factor to derive the  $k$  value. Therefore, the lower the  $k$  value, the lower the amount of LFG emitted from the landfill. Figure 4.9 shows the LFG simulation for the landfill using the LandGEM model. The LFG emission will peak in the year 2020 and maximum emission of CH<sub>4</sub> and CO<sub>2</sub> are 2241 Mg/year and 6148 Mg/year, respectively. However, Figure 4.10 which is the results derived from the Afvalzorg model using  $k = 0.03 \text{ year}^{-1}$  shows the LFG will peak in the year 2020 and the maximum emission of CH<sub>4</sub> from the landfill will be 2363 Mg/year. The results derived from the models are lower than the results derived earlier when  $k = 0.05 \text{ year}^{-1}$ . This sensitivity analysis shows that the models are very sensitive to the parameters imputed.

## Afvalzorg model



**Figure 4.10: Graphical representation of CH<sub>4</sub> emitted from Thohoyandou landfill site using the Afvalzorg model at  $k = 0.03$ .**

### 4.6 Limitation of models

The models used in the study had some limitations that were encountered during the study, it is paramount we highlight these limitations.

The LandGEM model simulates about 51 gases out of approximately 300 LFG emitted from a landfill, however, the Afvalzorg model is only able to simulate the Total LFG and CH<sub>4</sub> emitted from the landfill. This was a challenge using the Afvalzorg model as we were not able to simulate the CO<sub>2</sub> and other trace gases in the landfill using the Afvalzorg model. The implication was that, due to the inability of the Afvalzorg model to simulate other LFGs. This study did not use the Afvalzorg model to simulate other LFGs and therefore was not able to compare results derived from the LandGEM. This study used results simulated by the LandGEM model to evaluate other LFGs. Hence other methodologies can be used to simulate other LFGs.

The LandGEM model does not estimate the percentage by volume of the NMOC, it only allows for the estimation by volume of CH<sub>4</sub> and CO<sub>2</sub>. This implied that the NMOC's results derived from the model were all in a fixed percentage volume, this can however not be the

case in all landfills. More research should be conducted in the ability for LFG models to estimate the NMOC derived from a landfill site.

The Afvalzorg model only recognises the CH<sub>4</sub> gas from the total LFG and does not give room for the imputation of percentage by volume. This implies that the CH<sub>4</sub> generated using the Afvalzorg model were all based on a 50% composition of CH<sub>4</sub>, which is not the case for all landfills. The model should look into developing inputs for percentage volume of different components of LFGs.

The Afvalzorg model in its simulation of the LFG only simulates the consecutive 60 years after opening of landfill. However, the LandGEM model can simulate up to 200 years of LFG emission after landfill opening. This was a constraint in this study because the results from the Afvalzorg model was up to 60 years and could not compare results derived from the LandGEM which was up to approximately 200 years after opening of landfill that is there was limited comparison of the results obtained from this study. The comparison of results derived from the models was based on 40 years after opening of landfills.

The LandGEM model does not allow for the imputation of the waste composition of the waste deposited, the oxidation factor, moisture content, DOC and DOC<sub>f</sub> as these are very important factor in LFG simulation. However, the LandGEM considered the degradability constant and methane concentration potential instead, as it seems these latter variables are not enough data for a real life scenario as this could have some effects on the results obtained in this study.

The models did not put into account the seasonal variation of the landfill site, as it is very important in estimation of LFG. In Thohoyandou landfill during summer, the landfill tends to be very hot, however when rainfall occurs the landfill area is wet and this brings about more LFG emission and also increases the smell emitted from the landfill. Therefore, this implies that the results of this study could not be obtained based on seasonal variation.

## **CHAPTER FIVE: IMPLEMENTATION OF LFG UTILISATION TECHNOLOGY**

### **5.1 Cost and benefits analysis**

Over the years, solid waste has been deposited in landfills on regular basis. In South Africa, landfills are the major waste management tools. When waste is deposited in the landfill, the waste decomposes and emits LFG which continues to be emitted even when landfills are closed. These LFG can be emitted up to about 100 years after the closure of the landfill and this can be very harmful to the environment and surrounding community. However, it is also very beneficial to utilize the gases emitted from the landfills. Therefore, proper management of landfill waste has great potential of reducing GHG and air pollution, producing fuel for motor vehicles, generating electricity, providing jobs, etc. Gases generated from landfill contain a lot of impurities than natural gases from pipelines, therefore, organizations use LFG to produce electricity rather than for cooking gas. This chapter gives the cost analysis, benefits, electricity generation, environmental and economic viability of LFG utilization technology in Thohoyandou and Weltervenden landfill sites. The LFGcost web model was used to carefully estimate the cost and economic benefits of a LFG utilization technology. Table 5.1 shows the results derived from the LFGcost model for the Thohoyandou landfills.

**Table 5.1: Economic and financial results for the implementation of a LFG Technology in Thohoyandou landfill site**

LFG Engines	Area of LFG wellfield to supply project	Down payment for project	Net Present Value \$ (NPV) at year of construction	Internal Rate of Return (IRR).	Years to Break even	Gas Collection and Flaring System \$	LFG Energy Project \$	Total Capital Costs \$	Annual O and M costs \$
Standard turbine generator set	20	50%	2,992,404	-17%	None	713,202	3,898,496	4,611,698	335,616
		100%	2,949,911	-8%	None				
	40	50%	3,926,542	-22%	None	1,197,591	3,898,496	5,098,087	400,418
		100%	3,879,586	-13%	None				
Standard reciprocating engine-generator set	20	50%	2,979,265	-22%	None	713,202	3,688,667	4,401,869	479,165
		100%	2,938,706	-11%	None				
	40	50%	3,913,404	-28%	None	1,197,591	3,688,667	4,886,258	543,967
		100%	3,868,381	-17%	None				
Microturbines	20	50%	803,127	2%	None	713,202	2,025,871	2,739,073	206,412
		100%	837,479	4%	None				
	40	50%	1,737,265	-7%	None	1,197,591	2,025,871	3,223,462	271,213
		100%	1,707,564	-2%	None				

LFG Engines	Area of LFG wellfield to supply project	Down payment for project	Net Present Value \$ (NPV) at year of construction	Internal Rate of Return (IRR).	Years to Break even	Gas Collection and Flaring System \$	LFG Energy Project \$	Total Capital Costs \$	Annual O and M costs \$
Combined Heat and Power (CHP) turbine	20	50%	1,818,529	-5%	None	713,202	4,493,989	5,207,192	335,616
		100%	1,961,485	-1%	None				
	40	50%	2,924,000	-16%	None	1,197,591	4,493,989	5,691,580	400,418
		100%	2,927,666	-6%	None				
CHP microturbine	20	50%	275,651	11%	12	713,202	2,161,782	2,874,985	202,629
		100%	182,404	9%	13				
	40	50%	531,366	3%	None	1,197,591	2,161,782	3,359,373	267,431
		100%	640,323	4%	None				

Note: These financial results include the costs associated with a complete new LFG collection and flaring system (costs for expansion of an existing system will be higher).

The results derived from the Thohoyandou's LFG utilisation project assuming the area of wellfield to supply project 20 at 50% down payment rate shows that the conventional engines (Standard turbine generator set, Standard reciprocating engine-generator set and CHP turbine) are negative and none for the Internal Rate of Return (IRR) and years of break-even values, respectively. Meanwhile, the Microturbine and CHP Microturbine are shown to be economically feasible for a LFG utilisation project in Thohoyandou landfill site. The Microturbine has a Net Present Value (NPV) and IRR of \$803127 and 2%, respectively. However, the CHP microturbine has an NPV and IRR of \$275651 and 11%, respectively; and a 12 years payback period for the project. Therefore, these results confirm that if a LFG utilisation project is implemented in the Thohoyandou landfill site, the microturbine and the CHP microturbine engines will be the best engines for the LFG project, i.e. the engines are economically feasible because of the low amount NPV when compared to other engines. The CHP microturbine engine is the best economical feasible engine for the implementation of a LFG utilisation project in Thohoyandou landfill based on the current scenarios.

However, assuming a 100% down payment for construction of a LFG utilisation project, microturbine and CHP micro turbine engines are suitable engines for the LFG utilisation project. The microturbine has a 4% internal rate of return on investment, also the CHP microturbine has a 9% internal rate of return on investment and 13 years period of return on investment (meaning the LFG utilisation project will encounter a profit after 13 years of start of operation of the project). The CHP microturbine engine is the best suitable engine for the LFG utilisation project because of the amount of its NPV for the project. However, the standard reciprocating engine – generator set is the least economically feasible engine for the implementation of the LFG utilisation project taking into consideration the NPV and IRR values.

Assuming the LFG utilisation project has an area of LFG well field to supply a project of 40 wells. The results from Table 5.1 show that at 50% down payment for the LFG utilization technology in Thohoyandou landfill site, the CHP turbine engine, standard turbine generator set, micro turbine and standard reciprocating engine generator set are not suitable engines for the implementation of a LFG utilisation project. However, CHP microturbine engine is a suitable engine for the LFG utilisation project and is economically feasible because of its negative IRR. The CHP microturbine engine has an NPV of \$531,366 and 3% internal rate of returns for the LFG utilisation project.

However, at a 100% down payment LFG utilisation project, the standard turbine generator set, micro turbine, CHP turbine and standard reciprocating engine – generator set are not economically feasible for a LFG utilisation project in Thohoyandou landfill site. Meanwhile, CHP microturbine engine is an economically feasible engine for the project. The CHP microturbine has an NPV of 640,323 and 4% internal rate of return of the LFG utilisation project. The CHP microturbine engine is the best suitable for the LFG utilisation project. The standard turbine generator set is the least suitable engine for the project while the standard turbine generator set is the least economically viable engine for the LFG utilisation project based on the NPV and high negative IRR values.

Table 5.2 shows the results derived from the LFGcost model for the Weltervenden landfill.

Table 5.2: Economic and financial results for the implementation of a LFG Technology for Weltervenden landfill site

LFG Engines	Area of LFG wellfield to supply project	Down payment for project	Net Present Value (NPV) (\$) at year of construction	Internal Rate of Return (IRR)	Years to Breakeven	Gas Collection and Flaring System \$	LFG Energy Project \$	Total Capital Costs \$	Annual O and M costs \$
Standard turbine generator set	20	50%	4,001,393	Negative	None	788,826	5,013,073	5,801,899	430,287
		100%	3,947,933	-32	None				
	40	50%	5,244,897	Negative	None	1,302,862	5,013,073	6,315,936	504,237
		100%	5,186,702	Negative	None				
Standard reciprocating engine-generator set	20	50%	4,099,736	Negative	None	788,826	4,503,689	5,292,514	622,384
		100%	4,050,970	Negative	None				
	40	50%	5,343,241	Negative	None	1,302,862	4,503,689	5,806,551	696,334
		100%	5,289,739	Negative	None				
Microturbines	20	50%	653,163	5%	None	788,826	2,468,373	3,257,198	210,980
		100%	742,872	6%	None				
	40	50%	1,650,236	-3%	None	1,302,862	2,468,373	3,771,235	284,929
		100%	1,617,700	1%	None				

LFG Engines	Area of LFG wellfield to supply project	Down payment for project	Net Present Value (NPV) (\$) at year of construction)	Internal Rate of Return (IRR)	Years to Breakeven	Gas Collection and Flaring System \$	LFG Energy Project \$	Total Capital Costs \$	Annual O and M costs \$
Combined Heat and Power (CHP) turbine	20	50%	3,055,958	-7%	None	788,826	5,798,758	6,587,583	430,287
		100%	2,995,259	-1%	None				
	40	50%	4,085,746	-11%	None	1,302,862	5,798,758	7,101,620	504,237
		100%	4,020,311	-5%	None				
CHP microturbine	20	50%	308,195	16%	8	788,826	2,631,716	3,420,542	207,704
		100%	197,254	12%	9				
	40	50%	397,512	10%	None	1,302,862	2,631,716	3,934,578	281,653
		100%	525,125	8%	None				

Note: These financial results include the costs associated with a complete new LFG collection and flaring system (costs for expansion of an existing system will be higher).

Assuming the area of LFG wellfield to supply project is 20 acres and a 50% down payment for the project, the IRR for the project shows a negative value for most of the LFG utilisation engines. However, the microturbine shows a positive value \$653,163 for the NPV and 5% for the IRR, while the CHP microturbine engine shows a positive NPV (\$308,195), the IRR value of 16% and a payback period of 9 years. This shows that for the CHP microturbine engine for the LFG utilisation project there is a 16% return on investment and 9 years payback period on project's lifetime.

However, this study assumes a down payment of 100% before commencement of the project at 20 acres as the area of well field to supply project. The standard turbine generator set, standard reciprocating engine generator set and CHP turbine showed a negative value for IRR. This signifies that the use of these engines in LFG utilisation project, is not economically reasonable, based on the scenarios of this study. Meanwhile, the microturbine shows a NPV of \$742,872 and an IRR of 6%. Also, the CHP microturbine shows that there will be a 12% return on investment and 9 years payback period for the LFG utilisation project. These CHP microturbine and micro turbine engines are economically feasible since their IRR are positive values.

The study also assumes 40 acres as the area of well field to supply project at 50% down payment for the LFG utilisation project. The standard turbine engine, standard reciprocating engine, microturbine, and CHP turbine engines have values for IRR as negative. However, the CHP microturbine engine shows a 10% return on investment for the LFG utilisation technology. This means that for this current assumption only the CHP microturbine engine is economically feasible for a LFG utilisation project.

This study also assumes 40 acres as the area of well field to supply project at 100% down payment for the project. The standard turbine generator set, standard reciprocating engine, and CHP turbine engines were not economically feasible engines for the project. The IRR for the above engines are negative except for the microturbine and CHP microturbine engines that had IRR of 1% and 8%, respectively. However, CHP microturbine engine is more economically feasible for the implementation of the project i.e. the IRR value is 8%. This indicates a 8% internal rate of return on investment for the LFG utilisation project.

## 5.2 Environmental and Economic benefits

This study calculated the tonnes in CO<sub>2</sub>e destroyed by the implementation of a LFG utilisation technology to determine the environmental benefits and calculate the potential price of the CER sale of the CO<sub>2</sub> emitted from the landfill. According to Couth et al. (2011) the conversion of CH<sub>4</sub> (m<sup>3</sup>) to tonnes CO<sub>2</sub> equivalent is explicitly explained in Figure 5.1. The LandGEM model's simulation is used to estimate the total CH<sub>4</sub> emitted from the landfill. Table 5.3 shows the CH<sub>4</sub> emitted in tonnes of CO<sub>2</sub>e and potential CER price for the Thohoyandou LFG utilisation technology.

### Key steps of the quality assurance method

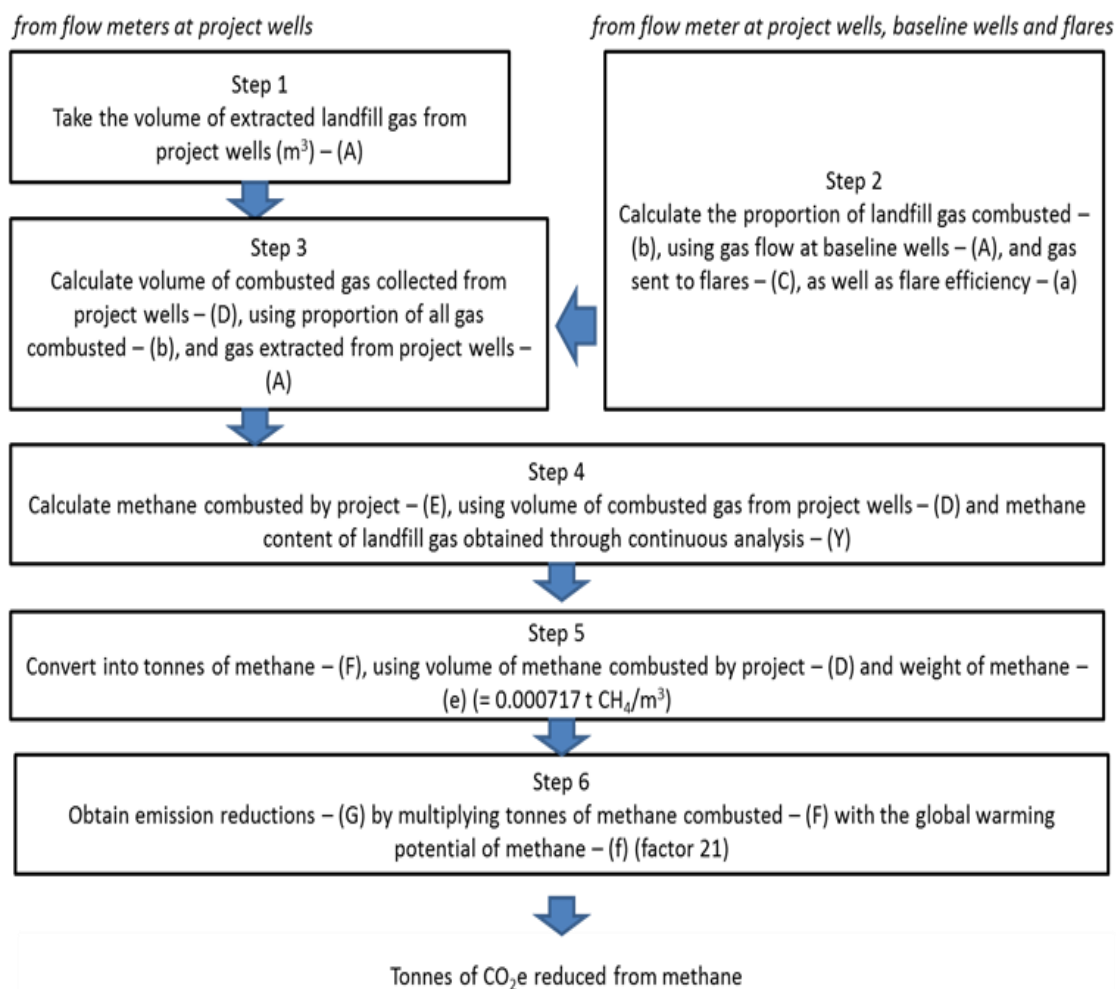


Figure 5.1: Conversion of CH<sub>4</sub> (m<sup>3</sup>) to t CO<sub>2</sub>equivalent (source: Couth et al., 2011)

**Table 5.3: The conversion of methane to tonnes of CO<sub>2</sub>e for Thohoyandou landfill**

Methane (m <sup>3</sup> ) emitted using LandGEM	85% methane (m <sup>3</sup> ) captured and combusted	Covert methane m <sup>3</sup> to tonnes at 0.000717 tCH <sub>4</sub> /m <sup>3</sup>	Convert methane (tonnes) to CO <sub>2</sub> e by multiplying by 25
4.698E+06	3.99E+06	2.86E+03	7.15E+04
4.842E+06	4.12E+06	2.95E+03	7.39E+04
4.981E+06	4.23E+06	3.03E+03	7.58E+04
4.738E+06	4.03E+06	2.89E+03	7.22E+04
4.507E+06	3.83E+06	2.75E+03	6.87E+04
4.287E+06	3.64E+06	2.61E+03	6.52E+04
4.078E+06	3.47E+06	2.49E+03	6.22E+04
3.879E+06	3.30E+06	2.37E+03	5.92E+04
3.690E+06	3.14E+06	2.25E+03	5.63E+04
3.510E+06	2.98E+06	2.14E+03	5.34E+04
3.339E+06	2.84E+06	2.04E+03	5.09E+04
3.176E+06	2.70E+06	1.94E+03	4.84E+04
3.021E+06	2.57E+06	1.84E+03	4.61E+04
2.874E+06	2.44E+06	1.75E+03	4.37E+04
2.734E+06	2.32E+06	1.66E+03	4.16E+04
2.600E+06	2.21E+06	1.58E+03	3.96E+04

Total CO<sub>2</sub> destroyed from the LFG utilisation project is 929,000 t CO<sub>2</sub>e and the price of CER assuming \$16.3 per CER is \$15100000 (Couth et al., 2011). The potential amount that can be obtained through the sale of carbon emission is \$15100000 or 219000000 rand (assuming \$1 to 14.5 rand). From this result comparing with the total capital cost obtained in Table 5.1, all proposed engines in this study, will be economically feasible for the implementation of a LFG utilisation technology. Also, Table 5.4 shows the conversion of methane (m<sup>3</sup>) to CO<sub>2</sub> equivalent and the results of the potential estimation of CO<sub>2</sub> e from a LFG utilisation in Weltervenden landfill.

**Table 5.4: The conversion of methane to t CO<sub>2</sub>e for Weltervenden landfill**

Methane emitted using LandGEM (m <sup>3</sup> )	85% of methane (m <sup>3</sup> ) captured and combusted	Covert methane m <sup>3</sup> to tonnes at 0.000717tCH <sub>4</sub> /m <sup>3</sup>	Convert methane (tonnes) to CO <sub>2</sub> e equivalent by multiplying by 25
6.122E+06	5.20E+06	3.73E+03	9.33E+04
6.521E+06	5.54E+06	3.97E+03	9.94E+04
6.914E+06	5.88E+06	4.21E+03	1.05E+05
6.577E+06	5.59E+06	4.01E+03	1.00E+05
6.256E+06	5.32E+06	3.81E+03	9.53E+04
5.951E+06	5.06E+06	3.63E+03	9.07E+04
5.661E+06	4.81E+06	3.45E+03	8.63E+04
5.385E+06	4.58E+06	3.28E+03	8.20E+04
5.122E+06	4.35E+06	3.12E+03	7.80E+04
4.872E+06	4.14E+06	2.97E+03	7.42E+04
4.635E+06	3.94E+06	2.82E+03	7.06E+04
4.409E+06	3.75E+06	2.69E+03	6.72E+04
4.194E+06	3.56E+06	2.56E+03	6.39E+04
3.989E+06	3.39E+06	2.43E+03	6.08E+04
3.795E+06	3.23E+06	2.31E+03	5.78E+04
3.610E+06	3.07E+06	2.20E+03	5.50E+04

The economic benefits of the implementation of a LFG utilisation technology in Weltervenden landfill could be considered feasible for all the conventional engines, if the t CO<sub>2</sub>e is sold in the carbon credit market. The need of these t CO<sub>2</sub>e is rapidly increasing due to the continuous increase in global warming and climate change.

Total CO<sub>2</sub> destroyed from the LFG utilisation project is 1,280,000 tonnes CO<sub>2</sub>e and the price of CER assuming \$16.3 per CER is \$20,900,000 (Couth et al., 2011). The potential amount that can be obtained through the sale of carbon emission is \$20,900,000 or 303,000,000 rand (assuming \$1 to 14.5 rand). Considering this amount of money derived from the sales of CER in the carbon international market, all the conventional engines used in this study can be considered economically feasible for the implementation of a LFG utilisation technology using the Weltervenden landfill when compared to the total capital cost derived in Table 5.2.

### 5.3 Electricity generated from the Thohoyandou and Weltervenden landfills

A household in South Africa is assumed to use 2267.97 kWh per year (Eskom) based on the use of household electrical appliances such as fridge, freezer, dishwasher, tumble dryer, television, washing machine and household lighting. It is important to explore the potential to

provide household electricity needs from LFGs. Table 5.5 shows the total yearly electricity generated from the Thohoyandou landfill using different LFG engines.

**Table 5.5: Annual electricity generated in kWh for the different LFG engines for Thohoyandou landfill**

Year	Standard turbine generator set	Standard reciprocating engine-generator set	Micro turbines	CHP turbine	CHP microturbine
2018	9,262,542	11311529	8112243	9262542	8112243
2019	9,546,112	11657828	8360596	9546112	8360596
2020	9,820,415	11992810	8600834	9820415	8600834
2021	9,341,468	11407914	8181367	9341468	8181367
2022	8,885,879	10851543	7782357	8885879	7782357
2023	8,452,510	10322307	7402807	8452510	7402807
2024	8,040,276	9818882	7041768	8040276	7041768
2025	7,648,147	9340010	6698336	7648147	6698336
2026	7,275,142	8884492	6371655	7275142	6371655
2027	6,920,330	8451190	6060905	6920330	6060905
2028	6,582,821	8039021	5765312	6582821	5765312
2029	6,261,773	7646953	5484134	6261773	5484134
2030	5,956,383	7274007	5216670	5956383	5216670
2031	5,665,887	6919249	4962250	5665887	4962250
2032	5,389,558	6581794	4720238	5389558	4720238

However, Table 5.5 shows the total amount of electricity (kWh) generated by the engines during the life time of the LFG utilisation project. Standard reciprocating engines produced the highest amount of electricity, although the engine is not economically feasible to implement a LFG utilisation technology in Thohoyandou landfill based on the scenarios used in this study. However, CHP microturbine and microturbine engines generate the same amount of electricity over the 10 years lifespan of the LFG utilisation project. Also these engines are the best fit for the implementation of a LFG utilisation project based on the results derived from the study.

Table 5.6 shows the annual electricity in kWh generated from the Weltervenden landfill during the life time of the LFG utilisation project. Similar to the result derived from the Thohoyandou landfill, standard reciprocating engines produced the highest amount of

electricity from the project. Meanwhile, the engine is not economically feasible to implement a LFG utilisation technology based on the scenarios used in this study. However, with the sales of its CO<sub>2</sub>equivalent in the international market, the use of the engine could be considered economically feasible. The CHP microturbine and microturbine engines generate the same amount of electricity over the 10 year lifespan of the LFG utilisation project. Also the CHP microturbine engine is the best fit for the implementation of a LFG utilisation project based on the results derived from the study without the sale of its t CO<sub>2</sub>equivalent.

**Table 5.6: Annual electricity generated in kWh for the different LFG engines for Weltevenden landfill**

Year	Standard turbine generator set	Standard reciprocating engine-generator set	Microturbines	CHP turbine	CHP microturbine
2023	10861799	13264561	9512891	10861799	9512891
2024	11570525	14130065	10133601	11570525	10133601
2025	12268526	14982472	10744918	12268526	10744918
2026	11670182	14251768	10220882	11670182	10220882
2027	11101021	13556701	9722404	11101021	9722404
2028	10559618	12895533	9248237	10559618	9248237
2029	10044619	12266611	8797195	10044619	8797195
2030	9554737	11668361	8368151	9554737	8368151
2031	9088747	11099288	7960031	9088747	7960031
2032	8645484	10557970	7571816	8645484	7571816
2033	8223839	10043051	7202534	8223839	7202534
2034	7.82E+06	9553246	6851262	7822757	6851262
2035	7.44E+06	9087329	6517122	7441237	6517122
2036	7.08E+06	8644134	6199278	7078323	6199278
2037	6.73E+06	8222555	5896936	6733110	5896936

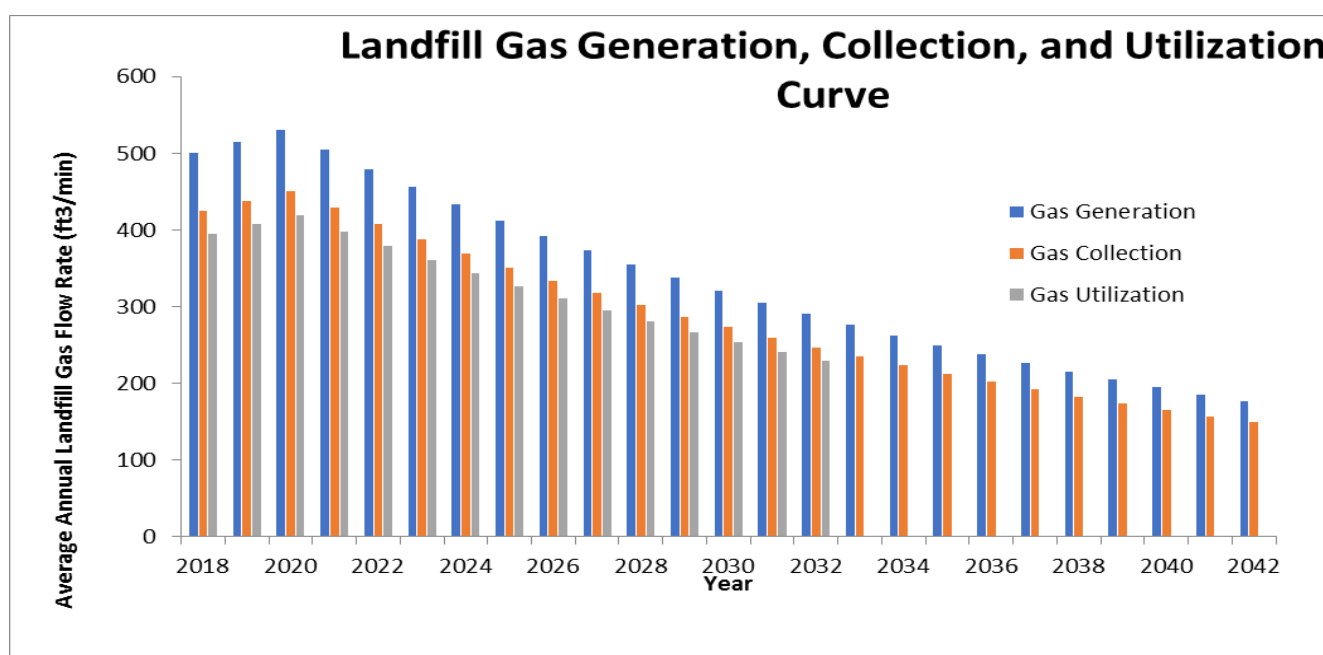
Taking into consideration that a South African household uses 2267.97 kWh of electricity per year as assumed earlier, the households that will directly benefit from the LFG utilisation technology was calculated. Table 5.7 shows the average annual electricity generated from each conventional engine in KWh/year and the average number of households to benefit from the electricity generated in Thohoyandou. As stated earlier, the standard reciprocating engine generated the most electricity and also has the highest number of household usage. The standard reciprocating engine-generator set generates an average electricity of approximately 9366635.263 KWh/year and will supply an average household of approximately 4130 households every year. CHP microturbine engine generates electricity to approximately 2962

households per year and the CHP turbine engine will supply electricity to approximately 3382 households every year.

Figure 5.2 shows the graphical representation of the total LFG generated, LFG collected and LFG utilised during the lifetime of the LFG utilisation project years for Thohoyandou landfill. The graph shows that although the LFG utilisation project will stop in 2032, there is still a continuous emission of LFG from the landfill site until 2042. This is because this study shows a simulation of a maximum of 15 years for the LFG utilisation engines and 10 years period for the microturbine engine. However, Liphoto (2001) has shown that LFG can continue to be emitted from a landfill as long as 100 years after closure of landfill site.

**Table 5.7: The average electricity per year generated and the number of household beneficiaries from the Thohoyandou landfill site project**

Engines	Standard turbine generator set	Standard reciprocating engine-generator set	Micro turbines	CHP turbine	CHP microturbine
electricity generated (KWh/year)	7669949.471	9366635.263	6717431.4	7669949.471	6717431.4
Households to benefit	3382	4130	2962	3382	2962

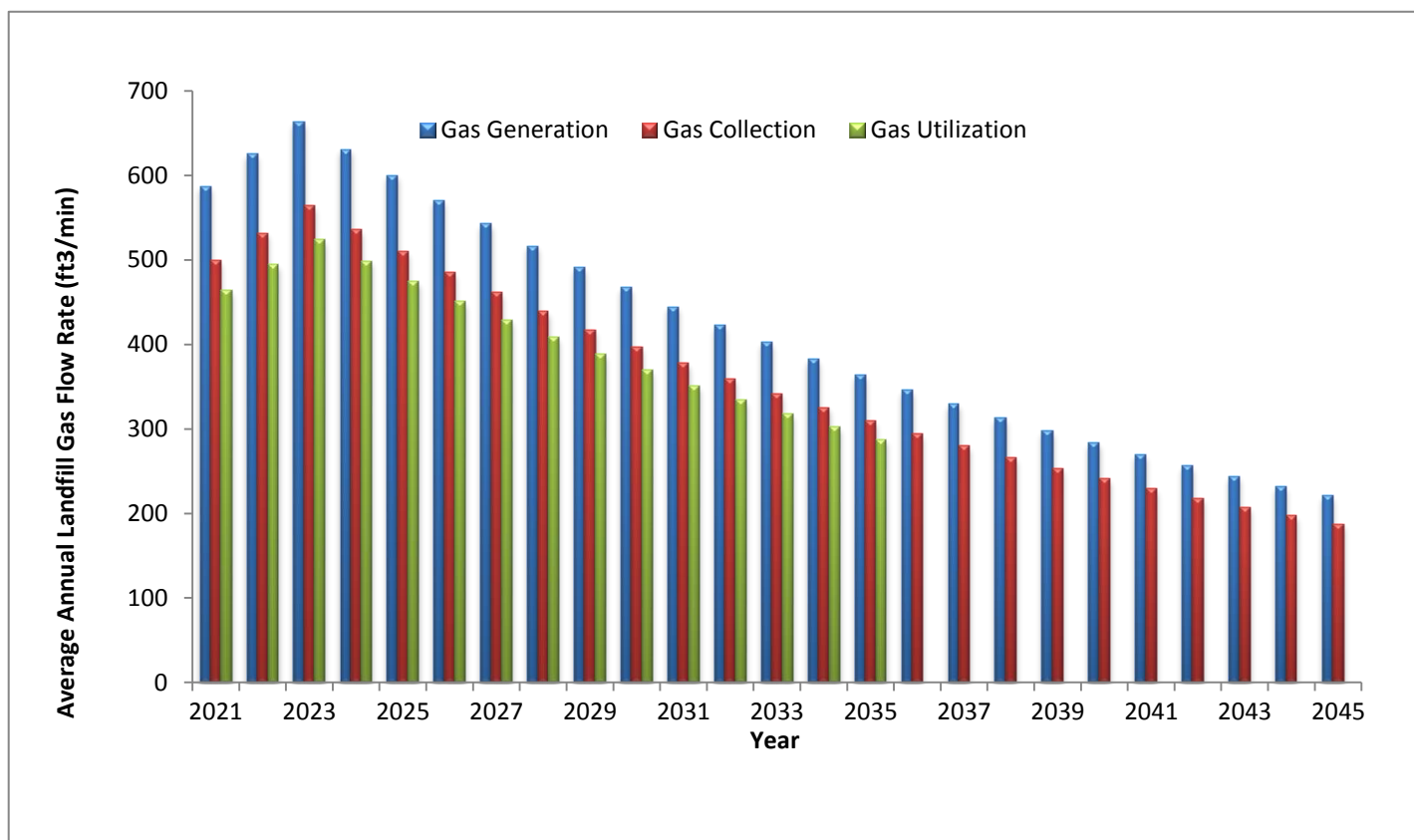


**Figure 5.2: A graphical representation of the LFG generated, collected and utilised from the implementation of a LFG utilisation technology in Thohoyandou landfill site**

Table 5.8 shows the average annual electricity generated from each conventional engine in thousands of KWh/year and the average number of households to benefit from the electricity generated from the implementation of the LFG utilisation technology in Weltervenden landfill. The standard reciprocating engine produced the most electricity and has the highest number of household beneficiaries to the project. The standard reciprocating engine generated an average electricity of 11,614,910 KWh/year and can supply an average of 5121 households. The standard turbine engine generated an average electricity of about 9510968 KWh/year and will supply an average household electricity of approximately 4194 households. Microturbine engine generates electricity to an approximately 3673 households per year and the CHP turbine engine will supply electricity to same number of households like the standard turbine engine. Figure 5.3 shows the graphical representation of the LFG generated, collected and utilised from the implementation of a LFG utilisation technology in Weltervenden landfill site.

**Table 5.8: The average electricity per year generated and the number of household beneficiaries from the Weltervenden landfill site project**

<b>Engines</b>	<b>Standard turbine generator set</b>	<b>Standard reciprocating engine-generator set</b>	<b>Micro turbines</b>	<b>CHP turbine</b>	<b>CHP microturbine</b>
Average electricity generated (KWh/year)	9510968	11614910	8329817	9510968	8329817
Average households to benefit	4194	5121	3673	4194	3673



**Figure 5.3: A graphical representation of the LFG generated, collected and utilised from the implementation of a LFG utilisation technology in Weltervenden landfill site**

Figure 5.3 shows that the LFG utilisation technology project will begin in the year 2021 and end in the year 2035, but there is potential to extend the project to 10 more years.

According to hypotheses two and three of this study, the results from this study and comprehensive literature reviews show that the CH<sub>4</sub> emitted from the landfills are suitable alternative sources of energy. However, this study was able to identify the total amount of LFG, CH<sub>4</sub>, CO<sub>2</sub>, NMOC and other trace gaseous pollutants emitted from both landfills using two different models.

This study was able to identify the best economically feasible engine for the implementation of a LFG utilisation technology for both landfills. Furthermore, this study identified the potential revenue to be obtained for the sale of t CO<sub>2</sub> in the carbon market. Notwithstanding, this study shows that the electricity generation from the two landfill is possible. It identified the total potential electricity that will be derived from the implementation of a LFG utilisation technology. This study further derived the potential number of households to benefit from the LFG utilisation technology when implemented.

## CHAPTER SIX: EVALUATION OF THE PERCEPTIONS OF RESIDENTS LIVING CLOSER TO THOHOYANDOU LANDFILL

### 6.1 Perception on health and environmental impacts due to the presence of a landfill site

The social and demographic characteristics of the respondents were identified to understand the nature of the participants used for this study. Table 6.1, shows the sex, age, employment status, educational attainment and time lived in the communities characteristics with the frequency and percentage.

**Table 6.1: Social and demographic characteristics of respondents**

Living away from landfill (AL)			Living closer to landfill (CL)	
	Number	Percentage %	Number	Percentage %
<b>Sex</b>				
<b>Male</b>	23	46	21	42
<b>Female</b>	27	54	29	58
<b>Total</b>	50	100	50	100.0
<b>Age</b>				
<b>11-21 years</b>	-	-	3	6
<b>21-30 years</b>	29	58	16	32
<b>31-40 years</b>	13	26	16	32
<b>41-50 years</b>	-	-	8	16
<b>51 and above</b>	8	16	6	12
<b>Did not tell</b>	-	-	1	2
<b>Total</b>	50	100.0	50	100
<b>Employment</b>				
<b>Full-time employment</b>	4	8	8	16
<b>Part-time</b>	11	22	11	22
<b>Self employed</b>	13	26	7	14
<b>Unemployed</b>	22	44	20	40
<b>Did not tell</b>	-	-	4	8
<b>Total</b>	50	100.0	50	100.0
<b>Educational attainment</b>				
<b>No formal education</b>	4	8	5	10
<b>Primary</b>	12	24	6	12
<b>High school</b>	15	30	15	30
<b>Tertiary</b>	19	38	20	40

<b>education</b>				
<b>Did not tell</b>	-	-	4	8
<b>Total</b>	50	100.0	50	100.0
<b>Duration of time of living in the community</b>				
<b>Less than 1 year</b>	7	14	7	14
<b>1-5 years</b>	7	14	9	18
<b>5-10 years</b>	8	16	16	32
<b>10-20 years</b>	8	16	15	30
<b>Above 20 years</b>	20	40	2	4
<b>Did not tell</b>	-	-	1	2
<b>Total</b>	50	100.0	50	100.0

Results from Table 6.1 shows that female participants were more than male participants in both communities, this was as a result of the availability and the readiness of the female respondents to participate in this study. The participants aged from 21 – 30 years were the most dominant and the participants were mostly part-time workers. However, most of the participants were in high school and in tertiary institutions and have lived above 5 years in their residents.

## **6.2 Perception of significance of environmental problems faced by the community**

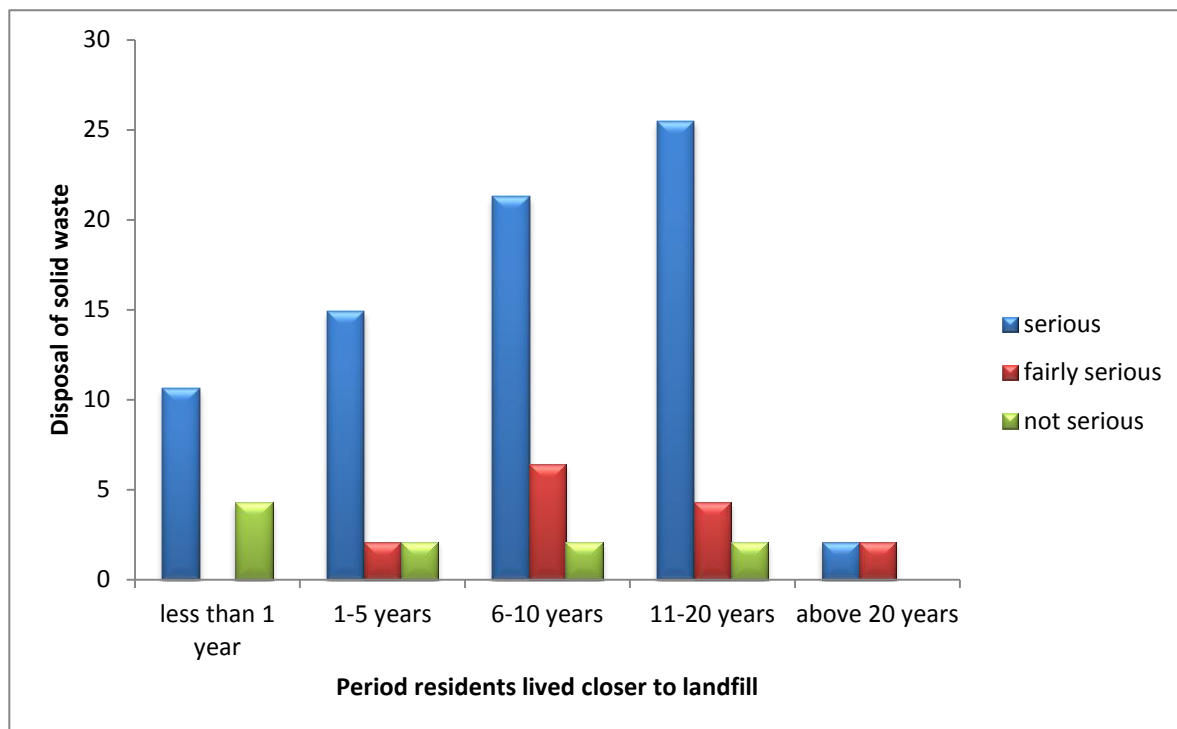
The participants were provided with 7 environmental issues facing the community. The questionnaire was coded as (1) serious, (2) fairly a serious problem and (3) not a serious problem in the community. The environmental problems include disposal of solid waste, garbage and litter in the street, unwelcome location of land fill, air pollution, bad odour, water pollution, noise pollution and dust. Table 6.2 shows the participants rating of the significance of the different environmental problems encountered by the community. An independence sample t-test analysis was conducted to identify the difference in mean, and significance of results obtained from both communities (Appendix H).

**Table 6.2: Respondents' rating of significance of environmental problems in the community**

Living closer to landfill (CL)					Living away from landfill (AL)				Sig
Characteristics	Serious. n(%)	Fairly serious. n(%)	Not serious. n(%)	Did not tell. n(%)	Serious. n(%)	Fairly serious. n(%)	Not serious. n(%)	Did not tell	
Disposal of solid waste (landfill)	35 (70)	8 (16)	5 (10)	2 (4)	6 (12)	12 (24)	31 (62)	1 (2)	0.00
Garbage and litter in the street	15 (30)	9 (18)	25 (50)	1 (2)	13 (26)	28 (56)	6 (12)	3 (6)	0.027
Unwelcome location of landfill	39 (78)	9 (18)	1 (2)	1 (2)	4 (8)	1 (2)	45 (90)	-	0.00
Air pollution, bad odour	39 (78)	3 (6)	7 (14)	1 (2)	8 (16)	12 (24)	28 (56)	2 (4)	0.00
Water pollution	6 (12)	6 (12)	32 (64)	6 (12)	8 (16)	20 (40)	21 (42)	1 (2)	0.034
Noise pollution	11 (22)	7 (14)	29 (58)	3 (6)	11 (22)	26 (52)	11 (22)	2 (4)	0.017
Dust	20 (40)	5 (10)	24 (48)	1 (2)	2 (4)	15 (30)	30 (60)	3 (6)	0.002

### *Disposal of solid waste*

It indicates the rate of disposition of waste in the landfill. However, this landfill characteristic takes into account how serious disposal of MSW activities are influencing the state and wellness of the people. Table 6.2 indicates the comparison of CL and AL communities on the significance of the impact of different landfill characteristics on both communities. As shown in table, 6.2, 70% of participants living closer to landfill site indicated that deposition of solid waste in Thohoyandou landfill is a serious problem, whereas 12% of respondents living far from the landfill indicated the same problem. Furthermore, 10% of the participants living closer to the landfill site indicated that the deposition of solid waste in the Thohoyandou landfill is not a serious problem to them, whereas 62% of participants living far from the landfill said the same. This is as a result of the physical and unpleasant presence of the landfill in the CL community. Studies have shown that there is significant impact of disposition of solid waste in landfills located in close proximity to residential areas which causes negative effects to the people and the environment (Adeola, 2000; Vrijheid, 2000; Sankoh et al., 2013; Brender et al., 2011). This study, however, agrees with the findings derived from the participants concerning the significant impact of disposal of solid waste in the Thohoyandou landfill. Conducting a cross tabulation between the years the participants have lived in the CL community and the significance of deposition of solid waste; shows that all the different years' groupings, indicate the issue to be a serious problem (Figure 6.1).



**Figure 6.1: Cross tabulation between the time the participant lived in the CL community and the seriousness of the disposal of solid waste**

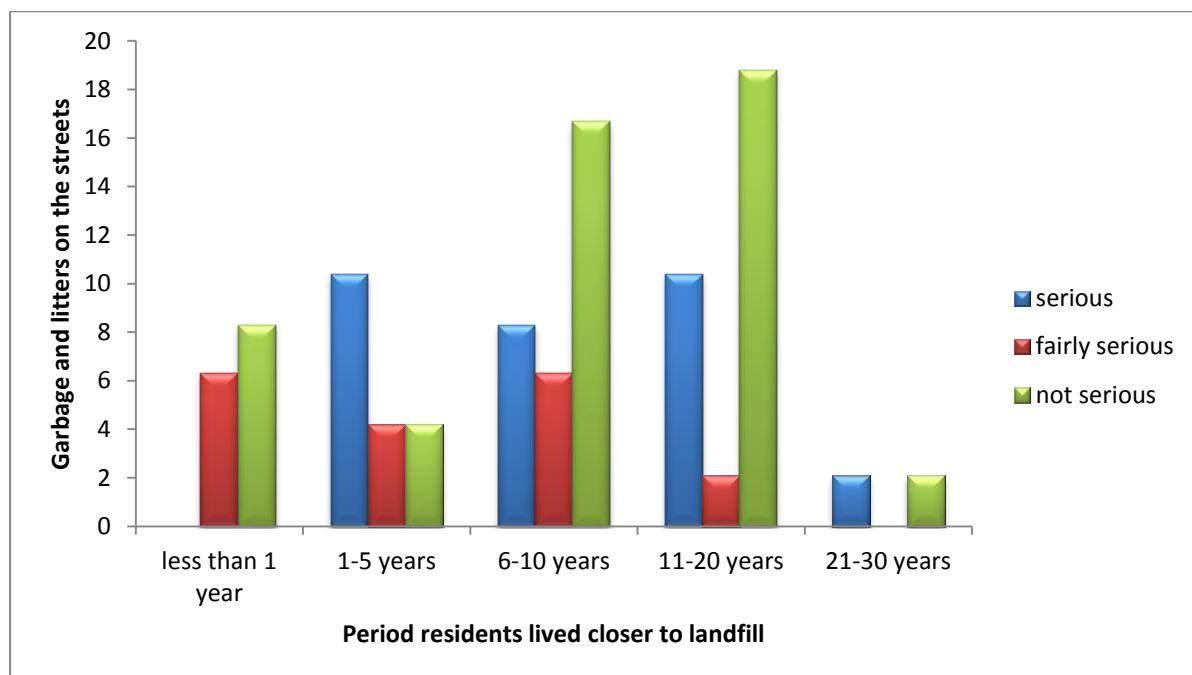
**Note: The no bar section in the figure indicates there was no response by the participants.**

### *Garbage and litters on the street*

This shows the continuous litters and garbage flow from the landfill and other sources into the community. Table 6.2 shows that 30% of the participants living closer to the landfill indicated that garbage and litter in the surrounding CL community is a serious problem, while 26% of participants living far from the landfill indicated the same problem. Meanwhile, 50% of the participants living closer to the landfill indicated that the flow of garbage and litters into the community is not a serious problem to them while, 12% of participants living far from the landfill indicated the same. Fifty-six percent (56%) of participants living far from the Thohoyandou landfill indicated that garbage and litters on the street is a fairly serious problem. Furthermore, for both communities, garbage and litters seemed not to be a serious problem and this could be attributed to the fencing and constant daily covering of the MSW deposited in the landfill. Adeola (2000) indicated that garbage and litters on the streets were major problems encountered by the participants living closer to the landfill, when compared to results derived from the participants living far from the landfill site. Sankoh et al. (2013) conducted a study on the environmental and health impacts of solid waste dumpsite in Freetown Sierra Leone. The study showed that the presence of the dumpsite increased the amount of filth, garbage and litters in the nearby community. Therefore, this shows that a

controlled system of solid waste deposition is very important to achieve a cleaner environment for a community residing next to a landfill.

Figure 6.2, shows a cross tabulation between the length of years the participants lived in the CL community and the seriousness of the problem (garbage and litters). Participants who lived for less than 1 year, 6 - 10 years and 11 - 20 years had high percentages on the significant impact of garbage and litters on the CL community indicating as not a serious problem.



**Figure 6.2 Cross tabulation between the time the participant lived in the CL community and the seriousness of the garbage and litters on the street**

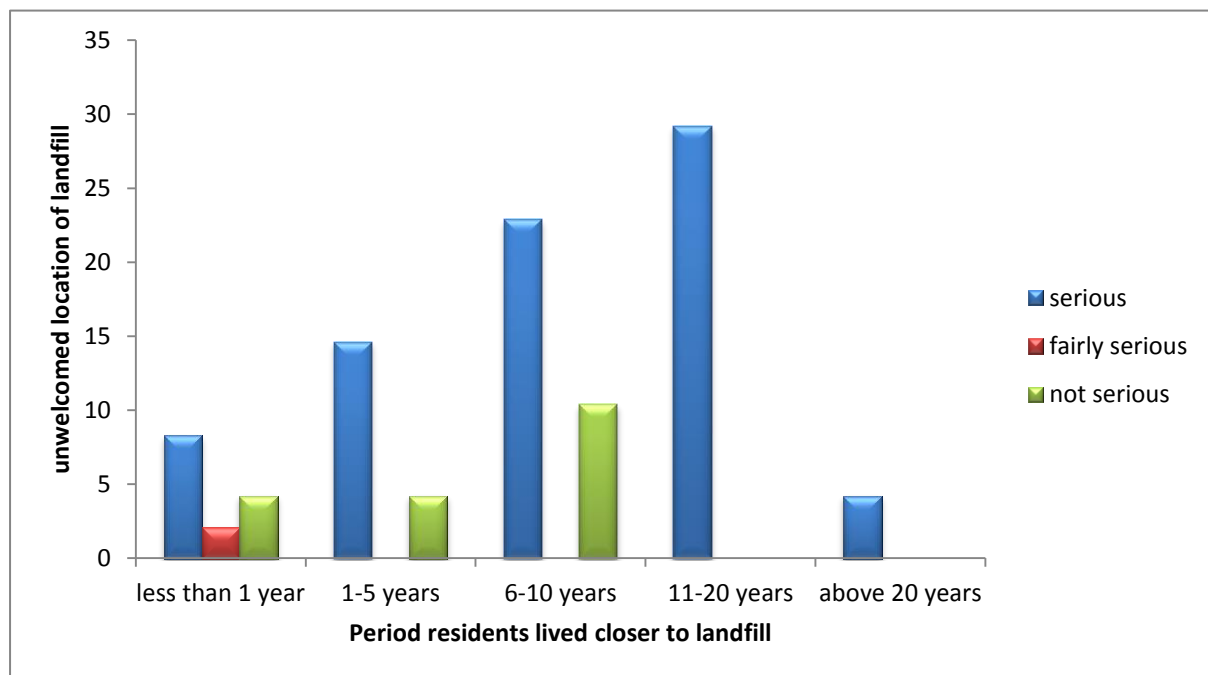
**Note: The no bar section in the figure indicates there was no response by the participant.**

### *Unwelcome location of the landfill*

This indicates the suitability and acceptance of the landfill site by the participants from the community. Meanwhile, table 6.2 shows that 78% of the respondents living closer to the landfill site indicated the unsuitability of the presence of the landfill to them, whereas the community living far from the landfill site felt the site was fine. Studies have shown that residents living closer to the landfill site do not like the idea of landfill's location in close proximity to their homes because of its negative impact on their communities (Garrod and Willis, 1998; Vrijheid, 2000; Brender et al., 2011; Sankoh et al., 2013). Dolk et al. (1998);

Adeola (2000); and Sankoh et al. (2013) further show that the exposure of participants living at least 2 km away from a landfill causes several health and environmental effects when compared to participants living far from a landfill site. However, the findings above from the suitability of location of landfill agree with the results found in the studies mentioned.

Also, considering a cross tabulation in Figure 6.3, it shows that all participants that have lived from 11 years and above indicated that the landfill should not be situated closer to their homes.



**Figure 6.3: Cross tabulation between the time the participant lived in the CL community and the seriousness of unwelcomed location of the landfill to the community**

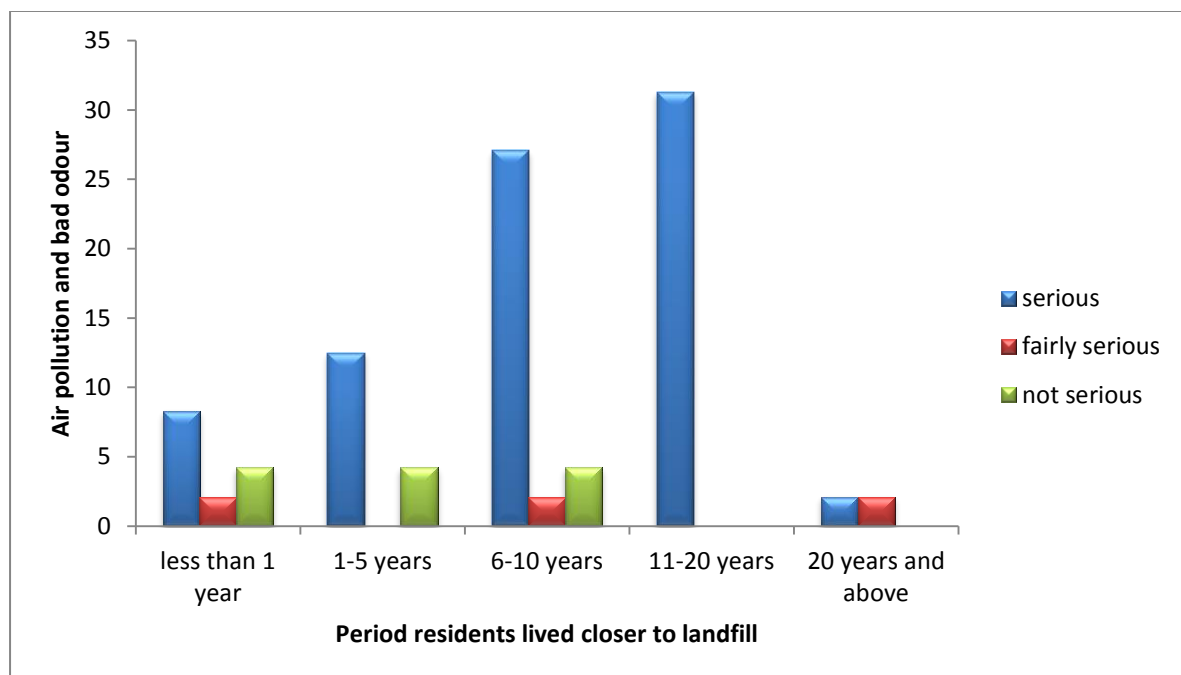
**Note: The no bar section in the figure indicates there was no response by the participants.**

### *Air pollution and bad odour*

Air pollution and bad odour has been found by many scholars to be synonymous to landfill operations. However, this shows the seriousness of air pollution and bad odour emanating from the landfill into the community. Table 6.2 shows 78% of participants living closer to the landfill site indicated a serious contamination of the air quality and often experience bad odour which they believe is from the landfill site. However, 16% of the participants living far from the landfill indicated a serious contamination on air quality and bad odour, thus majority of the participants living far from the landfill indicated a better air quality and that they

experience little or no bad odour. Adeola (2000) showed that residents living closer to landfill experienced higher amount of contamination of air quality with bad odour than residents living far from the landfill site. Liphoto (2001) identified that some components of LFG like hydrogen sulphide are key contributors to odours emanating from a landfill site. These air pollution and bad odour is as a result of poor management by landfill operator like proper compression of waste deposited in the landfill and lack of collection and utilisation of LFG emissions. However, the pungent odour and air pollution can be minimised by proper daily covering of solid waste immediately it is deposited in the landfill; the use of diluting agent which suppresses bad odour from the landfill; and the collection and utilisation of the LFG emitted from the landfill.

Furthermore, cross tabulation between the years of participants living in the CL community and air pollution with bad odour in the community was recorded in Figure 6.4. which shows all participants that lived 11 – 20 years and 50% of participants that lived above 20 years in the CL community indicated a serious contamination in air quality with bad odour from the landfill.



**Figure 6.4: Cross tabulation between the time the participant lived in the CL community and the seriousness of air pollution and bad odour in the community**

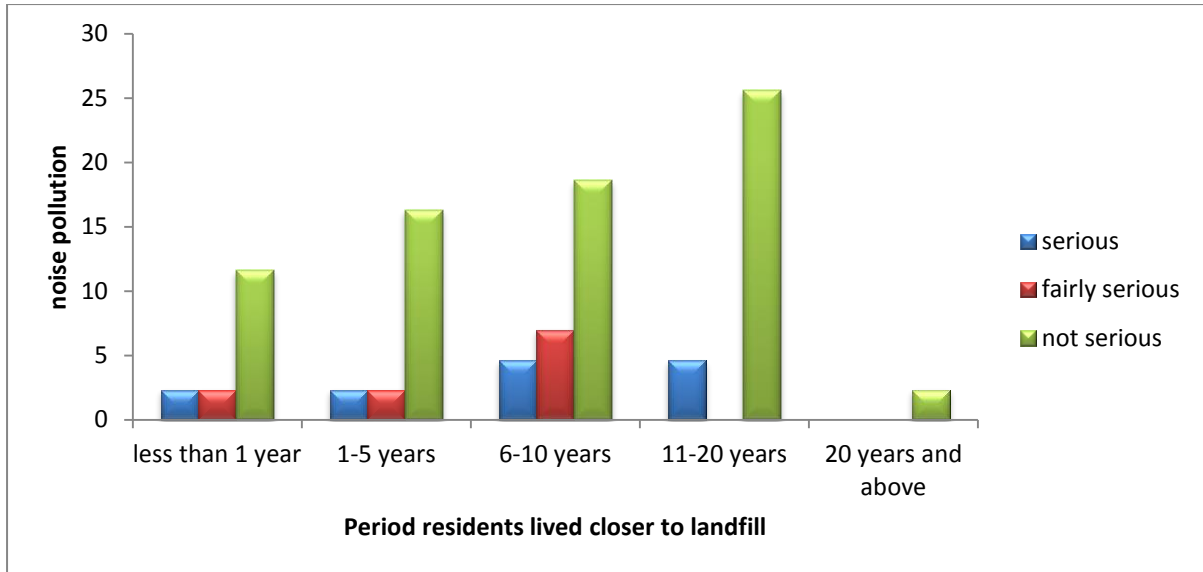
**Note: the no bar section in the figure indicates there was no response by the participant.**

### ***Water pollution and noise pollution***

Water pollution indicates the presence of polluted water in the community. Also noise pollution indicates the level of noise in the community. Table 6.2 shows that 64% of participants living closer to the landfill indicated that the water supply is clean, while 42% of participants living far from the landfill site indicated that the water is clean. Therefore, the tap water supplied to both communities could be from a different source and not from the ground water close to the landfill.

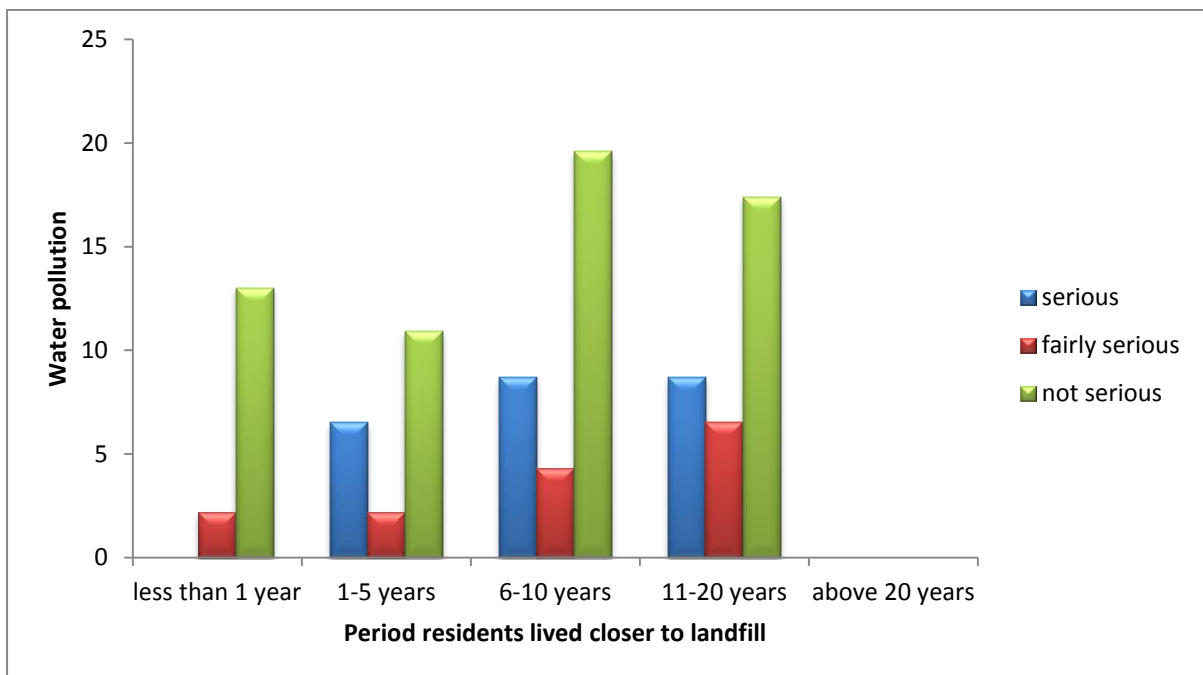
Furthermore, 58% of participants living closer to the landfill indicated that there is no form of noise pollution, while 22% of participants living far from the landfill indicated the same. However, most of the participants living far from the landfill (52%) indicated noise pollution as a fairly serious problem to them. Noise can be generated from different sources and not necessarily from the landfill. Although, it is quite impossible not to notice the heavy trucks and bulldozers in a landfill, the Thohoyandou landfill lack adequate number of bulldozers and heavy trucks due to lack of funds. On a day of our (me and my research assistant) visit to the landfill, there was heavy complains about the bulldozers for daily covering of waste not functioning for several months. However, after some months when we went back to the landfill, some bulldozers were functioning. Also incoming waste trucks contribute some noise pollution in the landfill but not enough to cause pollution to the nearby residents

A cross tabulation of water and noise pollution with the duration of residents living closer to the landfill site were used to analyse the perception of participants who have lived in different years in the CL community and how their perceptions influence the results. Figure 6.5 shows that most participants for all the age groups indicated that noise pollution is not a serious problem to them. Also, the cross tabulation between the years the participants lived closer to the landfill and water pollution shows that most participants for all age groups and all participants that lived above 20 years in the community indicated that water pollution is not a regular problem encountered by them (see Figure 6.6).



**Figure 6.5: Cross tabulation between the time the participant lived in the CL community and the seriousness of noise pollution in the community**

**Note: the no bar section in the figure indicates there was no response by the participant.**



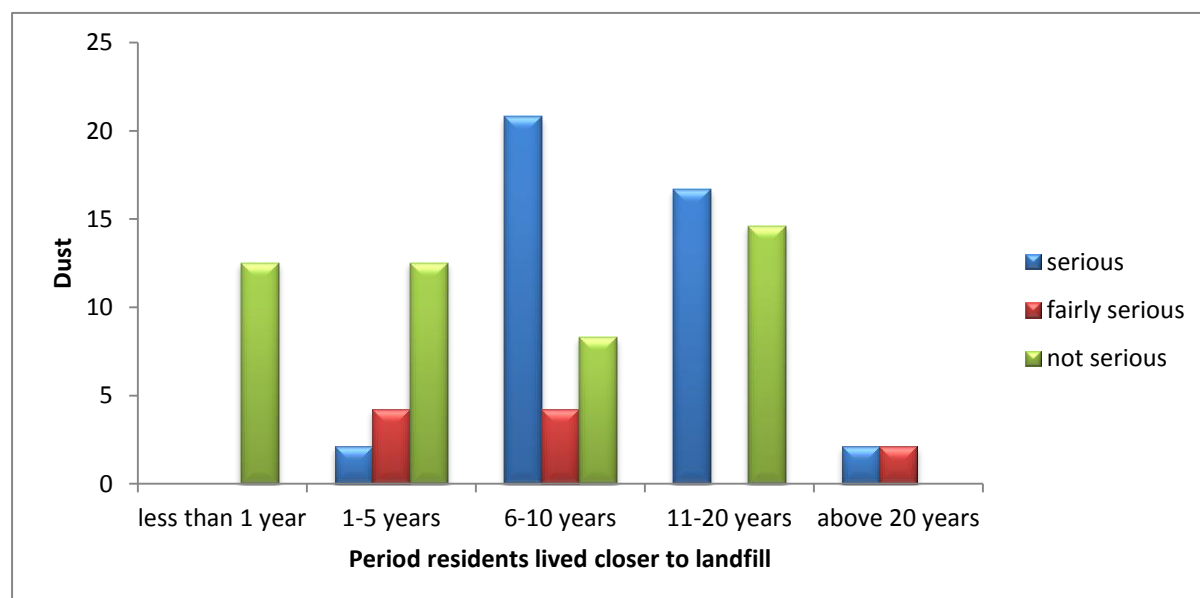
**Figure 6.6: Cross tabulation between the time the participant lived in the CL community and the seriousness of water pollution in the community**

**Note: the no bar section in the figure indicates there was no response by the participant.**

## Dust

This shows the significant level of seriousness of dust particles in the atmosphere. Table 6.2 shows that 40% of the participants living closer to the landfill indicated that dust is a serious problem to them, while 4% of participants living far from the landfill site indicated that the emission of dust particles in the atmosphere is a serious problem. However, most of the participants living far from the landfill site (60%) indicated that the emission of dust particles to the atmosphere is not a serious problem to them. Dust emissions from landfill can be controlled by the continuous spraying of water on the soil to suppress the emissions of the dust particles (Liphoto, 2001). The use of spraying of water on the ground has not been adopted in the Thohoyandou landfill and therefore recommended.

Figure 6.7 shows a cross tabulation between the duration the participants lived in the CL community and dust particles in the atmosphere. All participants that have lived less than one year in the community indicated the emission of dust particles in the atmosphere is not a serious problem to them. However, participants that have lived longer in the community indicated dust percolation is a serious problem in the community. Maybe, it is a matter of time for the participants who have lived less than one year to start experiencing serious impacts of dust emissions in the atmosphere.



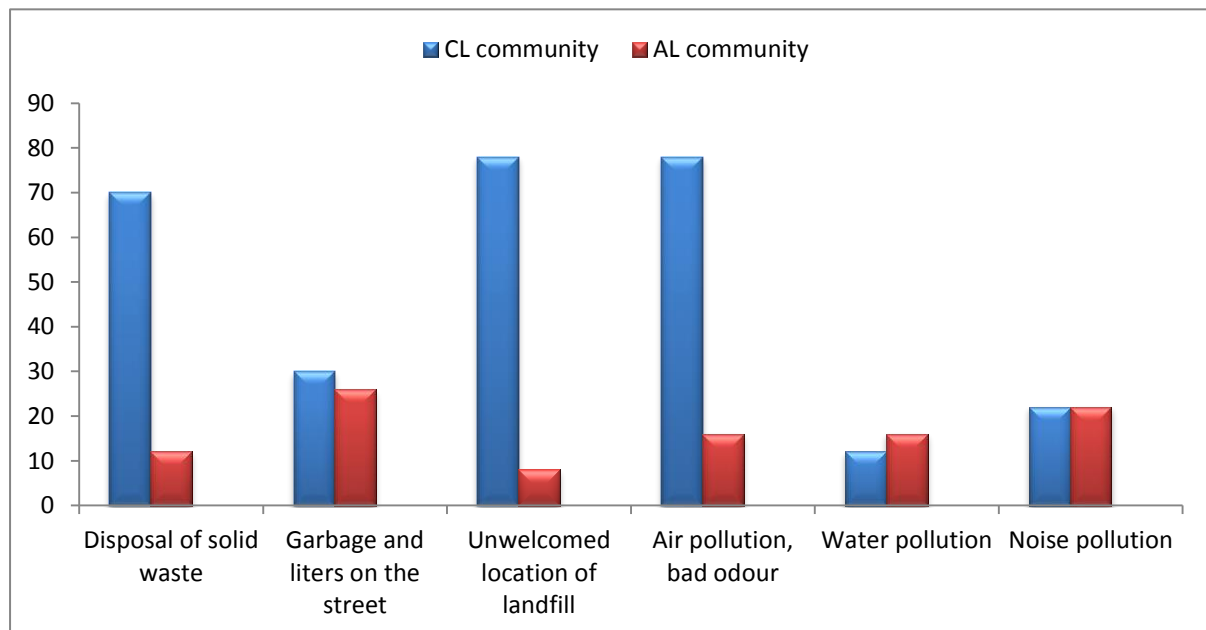
**Figure 6.7: Cross tabulation between the time the participant lived in the CL community and the seriousness of dust pollution in the community**

**Note: the no bar section in the figure indicates there was no response by the participant.**

In conclusion, table 6.2 shows that the participants in CL community experienced serious environmental problems with respect to disposal of solid waste, unwelcome location of landfill and air pollution with odour. Garbage and litters, and water and noise pollution were perceived not to be serious problems by the participants in the CL community. The participants in the AL community, however, showed a lesser serious environmental problem compared to the participants in the CL community. All the environmental problems highlighted were perceived not to be serious problems except noise pollution and garbage and litter on the street which posed fairly some problems to the participants in the AL community.

The results show that more undesirable environmental conditions posed very serious problems to the participants in CL community than the AL community. Specifically, disposal of solid waste; unwelcome location of landfill; and air pollution with bad odour; were considered major threats.

By using t-test, we tested whether the difference noted between the ratings on the significance of environmental problem by the two locations were statistically significant ( $p < 0.05$ ). Table 6.2 shows that the differences were found to be statistically significant for all the 7 variables in both communities. Figure 6.8 shows the summary in graphical representation of the respondent's rating living in both communities in terms of the seriousness of each of the environmental characteristic.



**Figure 6.8: A graphical comparison between the participants response for both communities showing the seriousness of each landfill characteristic**

**Note: the no bar section in the figure indicates there was no response by the participant.**

### **6.3 Perceptions on most reported illnesses encountered by the participants in both communities**

The participants were presented with possible illnesses associated with complaints of people living closer to landfill sites. The participants were asked to indicate whether they or any member of their family experiences these illnesses frequently (1), fairly frequently (2) or not frequently (3) to each of the illnesses listed in table 6.3.

Table 6.3 shows that 24% of participants living closer to the landfill site indicated that breathing disorder was frequently reported by them, while 10% of the participants living far away from the landfill indicated the same problem. However, most of the participants living closer to the landfill (40%) indicated that breathing disorder has not been reported frequently. Similarly, 66% of the participants living far from the landfill indicated that breathing disorder has not been reported frequently by them. Therefore, the participants who have breathing disorder in the CL and AL communities could have contracted it from different sources not necessarily from the landfill, since most of the participants have not experienced the illness before. It is also possible that the participants who have reported breathing difficulties have compromised immune systems that was not tested in this study, and therefore could have been sensitive to mild dust problems reported earlier. It is, however, important to note that more percentage of participants living closer to the landfill experienced breathing disorder than participants living far from the landfill site.

Studies have established that cancer is an illness experienced by people living closer to a landfill or waste dump (Vrijheid, 2000; Adeola, 2000). Table 6.3 indicates that residents living in both communities reported the same frequent level (18%) of cancer illness. Fairly frequent cancer levels were reported at 10% and 12% for CL and AL communities, respectively. Thus cancer was not a highly frequent illness affecting the participants in both communities. Similarly, Health Protection Agency (2011) showed that in several epidemiological studies performed by different scholars showing the relationship of cancer and landfill sites, cancer was a relatively complex illness to identify because of inadequate evidence to back up the claim of increased risk of cancer to communities living closer to landfill sites. Similarly, the review of Jarup et al. (2002) by Small Area Health Statistics Unit (SAHSU) in 2011 showed that there was no excessive risk of cancer in the people living closer to the landfill site (Health Protection Agency, 2011).

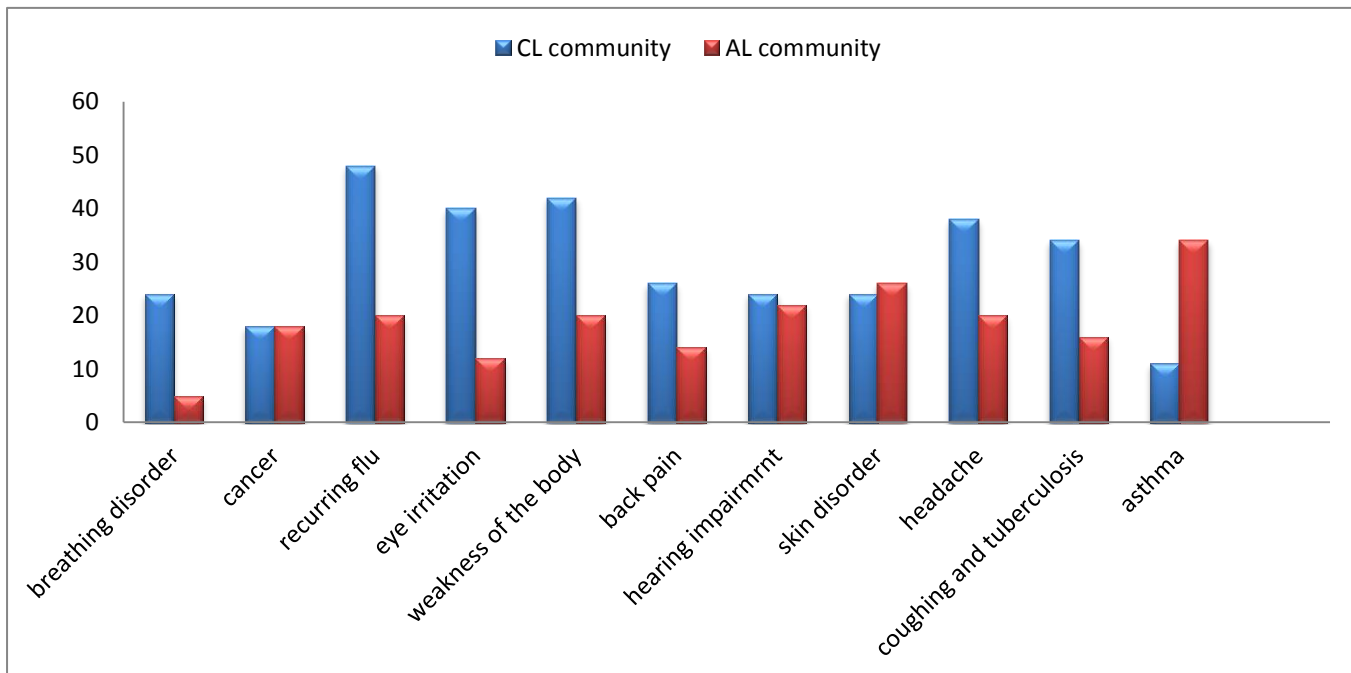
Furthermore, table 6.3 shows that illnesses like flu, eye irritation and weakness of the body were frequently reported by participants living closer to the landfill than participants living far from the landfill. Also from table 6.3, most participants living far from the landfill indicated that they did not experience these illnesses very often and are free from these diseases. Therefore, we can conclude that there is higher possibility of most of these illnesses to be attributed to the landfill but it is also imperative to know that these illnesses could also be contracted from various other sources. Though, headache was more frequent in CL community (38%) than AL community (20%), the latter community showed higher percentage of 54 for fairly frequent which is an indication of significant impact.

Alternatively, some illnesses recorded in this study like back pain, skin disorder, hearing impairment and asthma; were indicated by most participants living closer to the landfill as not often experienced. Likewise, most participants living far from the landfill did not experience these illnesses, often except for asthma to some extent.

In conclusion, table 6.3 showed that the participants living closer to the landfill site reported some illnesses more often than participants living far from the landfill sites. Figure 6.9, shows the graphical representation of comparison of the frequency of reporting the selected illnesses in both communities. T-test analysis was conducted for the most reported illnesses to understand the significance of the difference of results obtained and the result's significance (Appendix I). Seven out of eleven health problems were statistically significant, that is breathing disorder, flu, eye irritation, weakness of the body, back pain, coughing and tuberculosis, and asthma.

**Table 6.3: Respondents' rating of how these illnesses are reported by the participants in both communities**

Characteristics	Living closer to landfill (CL)				Living away from landfill (AL)				Sig.
	Frequent. n(%)	Fairly frequent. n(%)	Not frequent. n(%)	Did not tell. n(%)	Frequent. n(%)	Fairly frequent. n(%)	Not frequent. n(%)	Did not tell	
Breathing disorder	12 (24)	17 (34)	20 (40)	1 (2)	5 (10)	12 (24)	33 (66)	-	0.009
Cancer	9 (18)	5 (10)	34 (68)	2 (4)	9 (18)	6 (12)	33 (66)	2 (4)	0.899
Reoccurring flu	24 (48)	11 (22)	13 (26)	2 (4)	10 (20)	17 (34)	22 (44)	1 (2)	0.005
Eye irritation	20 (40)	17 (34)	12 (24)	1 (2)	6 (12)	10 (20)	33 (66)	1 (2)	0.00
Weakness of the body	21 (42)	7 (14)	19 (38)	3 (6)	10 (20)	8 (16)	32 (64)	-	0.008
Back pain	13 (26)	5 (10)	29 (58)	7 (6)	7 (14)	2 (4)	41 (82)	-	0.040
Hearing impairment	12 (24)	2 (4)	30 (60)	6 (12)	11 (22)	2 (4)	37 (74)	-	0.537
Skin disorder	12 (24)	1 (2)	31 (62)	6 (12)	13 (26)	4 (8)	32 (68)	1 (2)	0.813
Headache	19 (38)	13 (26)	18 (36)	-	10 (20)	27 (54)	13 (26)	-	0.610
Coughing and Tuberculosis	17 (34)	14 (28)	17 (34)	2 (4)	8 (16)	14 (48)	28 (56)	-	0.016
Asthma	11 (22)	3 (6)	29 (58)	7 (14)	17 (34)	15 (30)	17 (34)	1 (2)	0.022



**Figure 6.9: A graphical comparison between the participants living in both communities showing how frequent the illnesses impact on them.**

#### **6.4 Perception of most disturbing landfill site characteristics**

This study highlights 8 disturbing characteristics, which are commonly associated with landfill sites. The participants were asked to rate the landfill characteristics based on a scale of 1 disturbing, 2 fairly disturbing or 3 not disturbing to the participants living in both communities as shown in table 6.4.

Fear of future health indicates the anticipated health issues that will arise in the future based on the current effects. Table 6.4 shows that 56% of participants living closer to the landfill indicated that fear of their health in the future is a disturbing issue, while 24% of participants living far from the landfill indicated the same. However, 56% of the participants living far from the landfill site feel that their health will be fine in the future. This result could be attributed to the physical presence of the landfill, odour and possible fear of accumulated intake of gaseous emissions from the landfill. Similarly, Adeola (2000) made a comparison of participants living closer to a landfill and far from a landfill concerning how they feared their health in the future. Adeola (2000) concluded that more participants living closer to the landfill site feared for their health in the future than participants living far from the landfill site.

**Table 6.4: Respondents' rating of how disturbing are the external characteristics observed by the participants living in both communities**

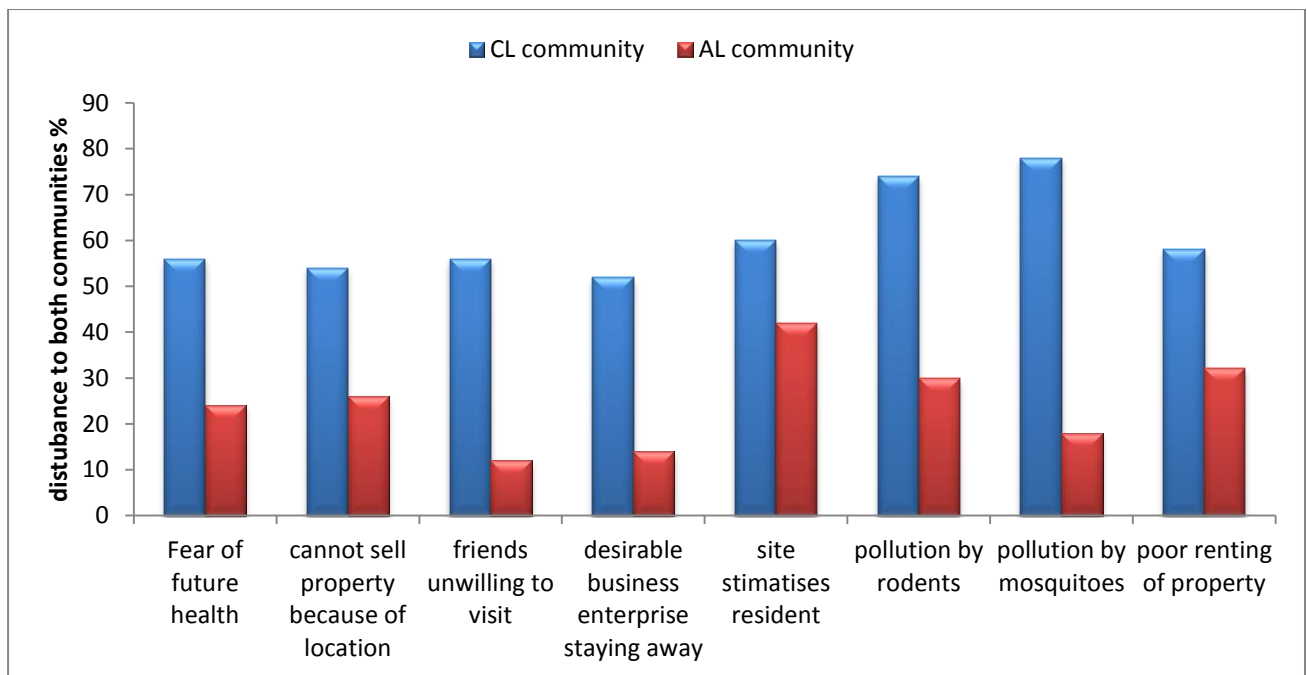
Characteristics	Living closer to landfill (CL)				Living away from landfill (AL)				Sig.
	Disturbing. n(%)	Fairly disturbing. n(%)	Not disturbing. n(%)	Did not tell. n(%)	Disturbing. n(%)	Fairly disturbing. n(%)	Not disturbing. n(%)	Did not tell	
Fear of future health	28 (56)	10 (20)	3 (6)	9 (18)	12 (24)	9 (18)	28 (56)	1 (2)	0.00
Cannot sell property because of location	27 (54)	11 (22)	4 (8)	8 (16)	13 (26)	2 (4)	33 (66)	2 (4)	0.00
Friends unwilling to visit	28 (56)	10 (20)	6 (12)	6 (12)	6 (12)	9 (18)	35 (70)	-	0.00
Desirable business enterprise staying away	26 (52)	8 (16)	6 (12)	10 (20)	7 (14)	6 (12)	33 (66)	4 (8)	0.00
Site stigmatises resident	30 (60)	7 (14)	5 (25)	8 (16)	21 (42)	9 (18)	18 (36)	2 (4)	0.003
Pollution by rodents	37 (74)	7 (14)	2 (4)	4 (8)	15 (30)	-	35 (70)	-	0.00
Pollution by mosquitoes	39 (78)	6 (12)	1 (2)	4 (8)	9 (18)	12 (24)	27 (54)	2 (4)	0.00
Poor renting of property	29 (58)	8 (16)	5 (10)	8 (16)	16 (32)	2 (4)	29 (58)	3 (6)	0.00

Table 6.4 shows that 54% of the participants living closer to the landfill site indicated the difficulties in the sale of property, but 66% of the participants living far from the landfill indicates the property sale as a good business in the community. The respondents targeted to give their views concerning property sales were mainly, house owners, tenants and elderly participants that have lived in both communities for a long time. Adeola (2000) in a study, experienced that participants living closer to the landfill site could not sell property as much as participants living far from the landfill site. Property buyers could be skeptical on purchase because of landfill's close proximity to the property.

Also, other external factors on landfill characteristics like friends unwillingness to visit, desirable business enterprise staying away and landfill stigmatization, show that most participants living closer to the landfill site feel that these external factors are disturbing to them. Participants living far from the landfill feel the external factors are not disturbing to them except for landfill stigmatization. However, these communities are still developing and might still lack some desirable businesses and poor rent for properties. Rodents and mosquitoes were indicated to be more prevalent with participants living closer to the landfill than participants living far from the landfill. Therefore, some participants close doors and windows regularly to avoid mosquitoes and rodents. Figure 6.10 shows the participants' rating on how disturbing the external factors of the landfill characteristics are to them.

In conclusion, the participants living closer to the landfill site rated all the external landfill characteristics mostly as disturbing to them. However, the participants living far from the landfill site ranked most of the external landfill characteristics as not disturbing to them. The overall results show that the CL community is more disturbed by the external landfill characteristic than the AL community.

T-test, tested whether the differences noted between the ratings of the disturbances of the external landfill characteristics is statistically significant ( $p < 0.05$ ) (Appendix J). The CL community rated the landfill characteristics more disturbing than the AL community. Table 6.4 shows the differences were found to be statistically significant for all the external landfill characteristics.



**Figure 6.10: A graphical comparison between the participants living in both communities showing how disturbing the external factors associated with a landfill is to them**

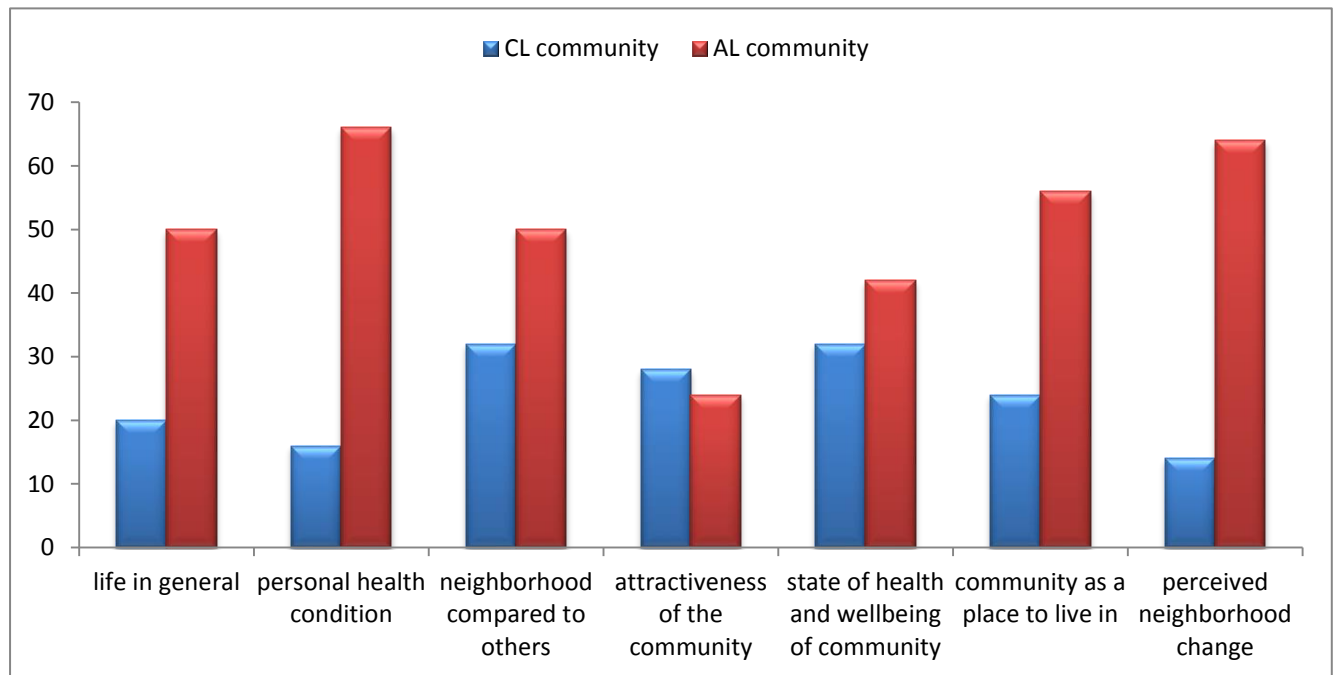
### 6.5 Perception of life satisfaction with living in the community

The participants were asked to rank the life satisfaction characteristics of living closer to a landfill and not living closer to a landfill from scale of 1 satisfied, 2 somewhat satisfied or 3 not satisfied as shown in table 6.5.

**Table 6.5: Respondents' rating of how satisfied the participants are with living in both communities**

Living closer to landfill (CL)					Living away from landfill (AL)				Sig.
Characteristics	Satisfied. n(%)	Somewhat satisfied. n(%)	Unsatisfied. n(%)	Did not tell. n(%)	Satisfied. n(%)	Somewhat satisfied. n(%)	Unsatisfied. n(%)	Did not tell	
Life in general	10 (20)	15 (30)	23 (46)	2 (4)	25 (50)	6 (12)	19 (66)	-	0.029
Personal health condition	8 (16)	20 (40)	20 (40)	2 (4)	33 (66)	1 (2)	15 (30)	1 (2)	0.000
Neighborhood compared to others	16 (32)	15 (30)	15 (30)	4 (8)	25 (50)	20 (40)	5 (10)	-	0.015
Attractiveness of the community	14 (28)	10 (20)	21 (42)	5 (10)	12 (24)	20 (40)	18 (36)	-	0.834
State of health and wellbeing of participants	16 (32)	9 (18)	22 (44)	3 (6)	21 (42)	9 (18)	19 (38)	1 (2)	0.365
Community as a place to live in	13 (24)	17 (4)	18 (60)	2 (12)	28 (56)	12 (24)	10 (20)	-	0.005
Perceived neighbourhood change	7 (14)	11 (22)	30 (60)	2 (4)	32 (64)	13 (26)	5 (10)	-	0.00

Table 6.5 shows that the participants living closer to the landfill site are less satisfied with the variables assessed in this study than the participants living far from the landfill site. Figure 6.11 shows the graphical comparison of the participants' views on how satisfied they are living in both communities.



**Figure 6.11: graphical comparison between the participants living in both communities showing how satisfied the participants are in the community.**

Table 6.5 shows the t-test analysis which was performed to understand the significant differences between both communities and their significance (see appendix K). The results show that the differences between the two communities were found to be statistically significant for five out of seven variables for personal health condition; neighborhood compared to others; community as a place to live in and perceived neighborhood change.

According to hypothesis four of this study, this study shows that the participants living closer to the Thohoyandou landfill site suffer a great deal of environmental pollution, dissatisfaction and illness when compared to the participants living far away from the landfill site based on the different variables assessed in this study.

## CHAPTER SEVEN: CONCLUSION AND RECOMMENDATIONS

### 7.1 CONCLUSIONS

The LandGEM and Afvalzorg models were used to simulate the total LFG and some of its components from the Thohoyandou and Weltervenden landfill sites. The simulations by the models show that both landfills have the potential to emit LFGs up to 100 years after closure of the landfill sites. However, the LFG emissions will continue to decrease with respect to time as years go by. Also, it was observed that the LFG emissions will continue to increase as the waste deposited in the landfills increases. The LFG emissions peak at the closure of the landfill site, which is when the deposition of MSW in the landfill ceases. The LandGEM, apart from the simulations of the total LFG can also simulate up to 60 other components of the LFG. However, this study focused on the simulations of the total LFG, CH<sub>4</sub>, CO<sub>2</sub>, NMOCs and some other trace gases. From the LFG emitted CO<sub>2</sub> constituted the highest amount of LFG emitted, the CO<sub>2</sub> emitted was more than twice the amount of the CH<sub>4</sub> emitted. However, the Afvalzorg model could simulate only the total LFG and CH<sub>4</sub> emissions from both landfills for a period of 60 years after closure of the landfill sites. The results derived from the simulation of CH<sub>4</sub> using both models for the Thohoyandou landfill were very close. The CH<sub>4</sub> emissions from Thohoyandou landfill had a ratio of LandGEM to Afvalzorg model as 1:1.1, respectively. Similarly, the ratio of CH<sub>4</sub> emissions for the LandGEM to Afvalzorg models for the Weltervenden landfills was 1:1, respectively. The total LFG emitted from the Weltervenden landfill was recorded to be more than the LFG emitted from the Thohoyandou landfill using the LandGEM model. However, the simulations using the Afvalzorg model show that the total LFG emitted from the Weltervenden landfill was less than the total LFG emitted from the Thohoyandou landfill. This is as a result of the difference in biodegradability of waste deposited in both landfills. The models were sensitive to the variation of degradability constant  $k$ . It was concluded that as the  $k$  value decreased, the total LFG emitted from both landfills decreased. The  $K$  value is a function of the average precipitation and temperature of the landfill environment.

The cost analysis and benefits for the implementation of a LFG utilisation technology in both landfills was simulated using the LFGcost Web model. This study concludes, assuming an area of 20 acres with a 50% and 100% down payment, the CHP microturbine and microturbine engines are the most economically feasible engines for the implementation of LFG plant in Thohoyandou landfill when compared to other engines. Also at an area of 40

acres with 50% and 100% down payment, the CHP microturbine is more economically feasible in Thohoyandou landfill when compared to other engines. The total potential CO<sub>2</sub> to be destroyed from the implementation of a LFG utilisation project in Thohoyandou is 929,000 t CO<sub>2</sub>e and the price of CER assuming \$16.3 per CER is \$15100000 (Couth et al., 2011). The potential amount that can be obtained through the sale of carbon emission is \$15100000 or 219000000 rand (assuming \$1 to 14.5 rand). Assuming the area of LFG wellfield to supply project is 20 acres and a 50% and 100% down payment, the CHP microturbine and microturbine engines are most economically feasible. The study also assumes 40 acres as the area of well field to supply project at 50% and 100% down payment for the Weltervenden LFG utilisation project, the CHP microturbine is most economically feasible. The Total CO<sub>2</sub> destroyed from the potential Weltervenden LFG utilisation project is 1,280,000 tonnes CO<sub>2</sub>e and the price of CER assuming \$16.3 per CER is \$20,900,000. The potential amount that can be obtained through the sale of carbon emission is \$20,900,000 or 303,000,000 rand (assuming \$1 to 14.5 rand). It was concluded that most of the LFG utilisation engines used in this study was not economically feasible to implement a LFG utilisation technology for both landfills, from the sales of electricity generated from the project alone. However, the sale of Carbon equivalent emitted from both landfills makes all engines in this study for the LFG utilisation project to be economically feasible in both landfills.

Also, this study concludes that the residents living closer to the landfill sites are at higher risk of environmental problems, health risks and dissatisfaction with the neighbourhood than the residents living far away from the landfill sites. However, the landfill associated problems have helped the community living closer to the landfill to be more conscious and educated on environmental pollution and associated impacts.

## **7.2 RECOMMENDATIONS**

This study recommends the following for further studies.

- i. The actual calculation of sub-surface emission of the LFG from the landfill sites to validate the results of this study. This is very important for future studies, since this was beyond the scope of this study.
- ii. The estimation and purification of the leachate from the landfill sites to reduce health and environmental risk in future.

- iii. A detailed health risk assessment on key LFG pollutants on the workers, reclaimers and residents living closer to the landfill site.

The Municipalities are doing a great job but still need to improve in order to get optimum results in their daily landfill operations. Recommendations for the municipality are as follows:

- i. A proper weighing bridge should be installed in the Thohoyandou landfill site. This will help give a better record on the volume of waste received by the landfill on daily basis.
- ii. The provision of spray tankers will help in the reduction of dust particles in the atmosphere.
- iii. The quick implementation of a LFG utilisation technology in the landfill.
- iv. Provision of proper covering of waste daily and the use of diluting agents to reduce the odour emanating from the landfill.
- v. The introduction of carbon tax on landfill management, because of its enormous contribution to anthropogenic GHG emissions in the atmosphere. However, this will steer up the need to implement a LFG capture and utilisation technology.
- vi. Proper sign post should be added to indicate the different sections of the landfill site especially closed cells and currently operating cells.
- vii. Proper training towards health and environmental risks associated with working in a landfill should be given to workers and reclaimers to help the workers understand the health risks involved in working in a landfill and take all precautionary measures seriously.
- viii. Workshops like sorting at source, recycling, and reuse of waste should be introduced to the general public to reduce the amount of waste deposition in the landfill.

## REFERENCES

- Achankeng, E. (2003). Globalization, urbanization and municipal solid waste management in Africa. In Proceedings of the African Studies Association of Australasia and the Pacific 26th Annual Conference.
- Adewumi, I. K., Ogedengbe, M. O., Adepetu, J. A., & Fabiyi, Y. L. (2005). Planning organic fertilizer industries for municipal solid wastes management. *Journal of Applied Sciences Research*, 1(3), 285-291.
- Adeola, F. O. (2000). Endangered community, enduring people: Toxic contamination, health, and adaptive responses in a local context. *Environment and Behavior*, 32(2), 209-249.
- Ahmed, S. I., Johari, A., Hashim, H., Mat, R., Lim, J. S., Ngadi, N., & Ali, A. (2015). Optimal landfill gas utilization for renewable energy production. *Environmental Progress & Sustainable Energy*, 34(1), 289-296.
- Amini, H. R., Reinhart, D. R. & Mackie, K. R. (2012). Determination of first-order landfill gas modeling parameters and uncertainties. *Waste Management*, 32(2), 305-316.
- Agency for Toxic Substances and Disease Registry (ATSDR). (2001). Landfill gas premier: an overview of environmental health professionals. Retrieved October 7, 2016, from <http://www.atsdr.cdc.gov/hac/landfill/html/intro.html>.
- Attenborough, G. M., Hall, D. H., Gregory, R. G., & McGoochan, L. (2002). Development of a landfill gas risk assessment model: GasSim. Proceedings for solid waste association of North America, 25, 25-28.
- Aydi, A. (2012). Energy recovery from a municipal solid waste (MSW) landfill gas: A tunisian case study. *Hydrology Current Research*, 3(4), 1-3 .
- Bella, G., Di Trapani, D., & Viviani, G. (2011). Evaluation of methane emissions from Palermo municipal landfill: Comparison between field measurements and models. *Waste Management*, 31(8), 1820-1826.
- Bhailall, S. (2015). Landfills gas emissions and the associated air quality, energy and climate change implications in South Africa. PhD Thesis. Faculty of Science. University of Witwatersrand Johannesburg.
- Bhailall, S., Piketh, S., Smith, N., & Bogner, J. (2010). Subsurface gas generation at a landfill in Johannesburg. *Clean Air Journal*, 18, 10-13.
- Bialowiec, A. (2011). Hazardous emissions from municipal solid waste. Contemporary Problems of Management and Environmental Protection, Some Aspects of Environmental Impacts of Waste Dumps, 9, 7-28.
- Blignauta, J., Ueckermann, L., & Aronson, J. (2009). Agriculture production's sensitivity to changes in climate in South Africa. *South African Journal of Science*, 105, 61-63.
- Boodhan, G. (2014). An economic analysis of landfill gas to energy projects in the Island State of Trinidad and Tobago. In global interdisciplinary business-economics advancement conference (giba) conference proceedings (p. 652).

- Brender, J. D., Maantay, J. A., & Chakraborty, J. (2011). Residential proximity to environmental hazards and adverse health outcomes. *American Journal of Public Health*, 101(S1), S37-S52.
- Brewer, K. R. W. (1999). Design-based or Prediction-based inference? stratified random vs stratified balanced sampling. *International Statistical Review*, 67(1), 35-47.
- Brindley, T. (2012). *The Management of Landfill Gas*. Landfill gas Industry code of practise.
- Calder, G. V., & Stark, T. D. (2010). Aluminum reactions and problems in municipal solid waste landfills. *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management*, 14(4), 258-265.
- Carey, P., Donlon, B., Nealon, T., & Howley, D. (2000). *Landfill Manual Landfill Design*. Ireland: Ireland: The Environmental Protection Agency.
- City of Polokwane, (2016). 2017/2018 Integrated development plan, Vision 2030 = smart city. Retrieved March 4, 2017, from <https://www.polokwane.gov.za/City-Documents/Shared%20Documents/IDP/2017%20Final%20IDP%20%2029%20May.pdf>.
- Corti, A., Lombardi, L., Pecorini, I., & Frassinetti, L. (2007). Diffused landfill gas emission monitoring in non-hazardous waste landfills: study cases. In *Sardinia 2007 Eleventh International Waste Management and Landfill Symposium*.
- Cooley, D., Murray, B., Ross, M., Lee, M. Y., & Yeh, K. (2013). An Economic Evaluation of North Carolina's Landfill Biogas Development Potential. NIR13-03, Nicholas Institute for Environmental Policy Solutions, Duke University [https://nicholasinstitute.duke.edu/sites/default/files/publications/ni\\_r\\_13-03\\_0.pdf](https://nicholasinstitute.duke.edu/sites/default/files/publications/ni_r_13-03_0.pdf).
- Couth, R., Trois, C., Parkin, J., Strachan, L. J., Gilder, A., & Wright, M. (2011). Delivery and viability of landfill gas CDM projects in Africa—A South African experience. *Renewable and Sustainable Energy Reviews*, 15(1), 392-403.
- Council of Scientist and Industrial Research (CSIR). (2011). *Municipal waste management - good practices*. Edition 1. CSIR, Pretoria. ISBN No: 978-0-7988-5596-9.
- Daura, L. A., Enaburekhan, J., & Rufai, I. A (2014). Estimation of Methane gas Emission from Solid Waste disposal sites in Kano, Nigeria. *International Journal of Scientific & Engineering Research*, 5(10), 590-593.
- Durmusoglu, E., Taspinar, F., & Karademir, A. (2010). Health risk assessment of BTEX emissions in the landfill environment. *Journal of Hazardous Materials*, 176(1), 870-877.
- Department of Environment Agency (DEA). (2012). 2012 South Africa environment outlook Chapter 9: waste management draft 2 version 3. Retrieved December 3<sup>rd</sup>, 2017, from [http://soer.deat.gov.za/dm\\_documents/Chapter\\_9\\_\\_Waste\\_Management\\_wHOt0.pdf](http://soer.deat.gov.za/dm_documents/Chapter_9__Waste_Management_wHOt0.pdf).
- Department of Water Affairs and Forestry (DWAf). (1997). Report on waste generation sub project. Report number 3064/1505/4/S.

- Department of Water Affairs and Forestry (DWAF). (1998). Minimum requirement for waste disposal by landfill. Waste Management Series. Project leader: L. Bredenhann, Project Co-ordinator: J.M. Ball, Jarrod Ball & Associates cc, Editor: K. Langmore, Jarrod Ball & Associates cc, Johannesburg, South Africa.
- Department of Water Affairs and Forestry (DWAF). (2004). Permit 16/2/7/A900/D16/ZI/P4P4 issued in terms of section 210 of the environmental conservation Act, 1989 (Act 73 of 1989). Pretoria.
- Dolk, H., Vrijheid, M., Armstrong, B., Abramsky, L., Bianchi, F., Garne, E., Nelen, V., Robert, E., Scott, J.E.S., Stone, D., Tencon, R. (1998). Risk of congenital anomalies near hazardous-waste landfill sites in Europe: the EUROHAZCON study. *Lancet*, 352, 423-427.
- Donovan, S. M., Bateson, T., Gronow, G. R., & Voulvoulis, N. (2009). Modelling the behaviour of mechanical biological treatment outputs in landfills using GasSim model. *Science Of The Total Environment*, 8(408), 1979-1984.
- Dudek, J., Klimek, P., Kolodziejak, G., Niemczewska, J., & Zaleska-Bartosch, J. (2010). Landfill gas energy technologies. *Institut nafty i gazu, Kraków*.
- EGSSAA. (2009). US Aid from the American people. Retrieved September 1, 2016, from <http://www.encapafrika.org/egssaa/solidwaste.pdf>.
- Environment Victoria. (2013). The problem with landfill. Retrieved September 2, 2017, from <https://environmentvictoria.org.au/resource/problem-landfill/>.
- Eskom, [http://www.eskom.co.za/sites/idm/Documents/Appliance\\_Usage\\_rev41.pdf](http://www.eskom.co.za/sites/idm/Documents/Appliance_Usage_rev41.pdf).
- US Environmental Protection Agency (EPA). (2010). Methane and nitrous oxide emissions from natural sources. Washington DC, USA.
- eThekweni Municipality. (2017). Retrieved December 6, 2017, from [http://www.cityenergy.org.za/uploads/resource\\_169.pdf](http://www.cityenergy.org.za/uploads/resource_169.pdf).
- Feldmann, J. (2003). Volatilization of Metals from a Landfill Site. *ACS Symposium Series*, 835, 128-40.
- Finch, A. A., Shaw, P. A., Holmgren, K., & Lee-Thorp, J. (2003). Corroborated rainfall records from aragonitic stalagmites. *Earth and Planetary Science Letters*, 215(1-2), 265-273.
- Gardner N., Manley B.J.W. and Pearson J.M. (1993). Gas Emissions from Landfills and their Contributions to Global Warming, *Applied Energy*, 44, 165-174.
- Garrod, G., & Willis, K. (1998). Estimating lost amenity due to landfill waste disposal. *Resources, Conservation and Recycling*, 22(1), 83-95.
- Guerrero, L. A., Maas, G., & Hogland, W. (2013). Solid waste management challenges for cities in developing countries. *Waste Management*, 33(1), 220-232.

- Global Methane Initiative . (2012). Landfill gas modeling. Retrieved September 2, 2016, from International best practices guidefor LFGE projects: [https://www.globalmethane.org/documents/toolsres\\_lfg\\_IBPGch6.pdf](https://www.globalmethane.org/documents/toolsres_lfg_IBPGch6.pdf).
- Hamer, G. (2003). Solid waste treatment and disposal: effects on public health and environmental safety. *Biotechnology Advances*, 22(1), 71-79.
- Health Protection Agency. (2011). Impact on Health of Emissions from Landfill site, Advice from the Health Protection Agency. Retrieved July 7, 2016, from [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/334356/RCE-18\\_for\\_website\\_with\\_security.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/334356/RCE-18_for_website_with_security.pdf).
- Heyer, K. U., Hupe, K., & Stegmann, R. (2013). Methane emissions from MBT landfills. *Waste Management*, 33(9), 1853-1860.
- Hoornweg, D., & Bhada-tata. (2012). What a waste, A global review of solid waste . *Urban Development Series Knowledge Papers*, 15, 1-98.
- Intergovernmental Panel on Climate Change (IPCC), (2006) IPCC Guidelinesfor National Greenhouse Gas Inventories, Vol.5 Waste, Ch.3 Solid Waste Disposal”,[http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5\\_Volume5/V5\\_3\\_Ch3\\_SWDS.pdf](http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_3_Ch3_SWDS.pdf). Accessed April 6, 2016.
- Jacobs, J., & Scharff, H. (2001). Comparison of methane emission models and methane emission measurements . *NV Avalzorg*.
- Jangikhatoonabad, N. (2015). Feasibility Studies To Support Landfill Gas Recovery In Ghana.
- Jarup, L., Briggs, D., De Hoogh, C., Morris, S., Hurt, C., Lewin, A., & Elliott, P. (2002). Cancer risks in populations living near landfill sites in Great Britain. *British Journal of Cancer*, 86(11), 1732-1736.
- Josimović, B., & Marić, I. (2012). Methodology for the Regional landfill site selection. In *Sustainable Development – Authorithative and leading edge content for environmental management*. Serbia: Intech. Edited by Sime Curkovic.
- Kalantarifard, A., & Yang, G. S. (2012). Estimation of methane production by LANDGEM simulation model from Tanjung Langsat municipal solid waste landfill, Malaysia. *International Journal of Science and Technology*, 1(9), 481-487.
- Kamalan, H., Sabour, M., & Shariatmadari, N. (2011). A review on available landfill gas model. *Journal of Environmental Science and Technology*, 2(4), 79-92.
- Karapidakis, E. S., Tsave, A. A., Soupios, P. M., & Katsigiannis, Y. A. (2010). Energy efficiency and environmental impact of biogas utilization in landfills. *International Journal of Environmental Science & Technology*, 7(3), 599-608.
- Karekezi, S. (2002). Poverty and energy in Africa—a brief review. *Energy Policy*, 30(11), 915-919.

- Lacynski, A. (2015). Paris agreement basics part 1: Global warming. Retrived December 23, 2017, from <http://globe-net.com/paris-agreement-basics-part-1-global-warming/>.
- Landfill Methane Outreach Programe (LMOP). (2015). LFG Energy project development handbook. Retrieved October 10, 2016, from [https://www3.epa.gov/lmop/documents/pdfs/pdf\\_full.pdf](https://www3.epa.gov/lmop/documents/pdfs/pdf_full.pdf).
- Larsson, J. (2014). A case study of landfill gas potential at Kiklas landfill. Assessment of environmental impacts and alternatives for mitigation. Msc Thesis, Department of energy and environment.
- Lays, J. J., Li, Y. Y., Noike, T., Endo, J., & Ishimoto, S. (1997). Analysi of environmental factors affecting methane production from high solid organic waste. *Water Science and Technology*, 6-7(36), 493-500.
- Lanini S, Houi D, Aduilar O, Lefebvre X (2001) The role of aerobic activity on refuse temperature rise: II. Experiment and numerical modeling. *Waste Management Resources*. 19: 58–69.
- Li, L., & Moore, P. K. (2008). Putative biological roles of hydrogen sulfide in health and disease: a breath of not so fresh air?. *Trends in Pharmacological Sciences*, 29(2), 84-90.
- Lide, D. R. (2003). *Handbook on chemistry and physics* (Vol. 83). CRC press.
- Liphoto, L. (2001). The estimation of landfill gas emissions in the Durban Meteropolitan Area (DMA) using the landgem model. MSc Thesis (Environmental Sciences), School of life and environmental Sciences.
- Makgae, M. (2011). Key areas in waste management: A South African perspective. In *Integrated Waste Management-Volume II*. InTech.
- Marilyn, F. V., Carol, H., Leonard, S., Kristen, W., Lorraine, B., Jane, S., Darrah, D., Chiu-Kit J. T. (2000). Effects on the Immune System Associated with Living Near a Pesticide Dump Site. *Environ Health Perspect*. 108: 1113 - 1124
- Mou, Z., Scheutz, C., & kjeldsen, P. (2015). Landfill gas generation and emission at danish waste disposal sites receiving waste with a low organic waste content. In *Proceedings Sardinia 2015: CISA publisher*.
- Nikiema, J., Brzezinski, R., & Heitz, M. (2007). Elimination of methane generated from landfills by biofiltration: a review. *Reviews in Environmental Science and Bio/Technology*, 6(4), 261-284.
- Nsele, S. (2016). news24. Retrieved September 29, 2016, from [www.news24.com: http://www.news24.com/SouthAfrica/News/choking-smoke-shrouds-city-20160809](http://www.news24.com/SouthAfrica/News/choking-smoke-shrouds-city-20160809).
- Ogola, J. S., Chimuka, L., & Tshivhase, S. (2011). Management of municipal solid wastes: A case study in Limpopo Province, South Africa. In *Integrated Waste Management-Volume I*. InTech.
- Oonk, H., 2010. Literature review: methane from landfills. *Methods to Quantify Generation, Oxidation and Emission*. OonKay, Apeldoorn.

- Patterson, T., Esteves, S., Dinsdale, R., & Guwy, A. (2011). An evaluation of the policy and techno-economic factors affecting the potential for biogas upgrading for transport fuel use in the UK. *Energy Policy*, 39(3), 1806-1816.
- Parker, T., Dottridge, J., & Kelly, S. (2002). Investigation of the composition and emissions of trace components in landfill gas. Environment Agency, R&D Technical Report P1-438/TR.
- Phiri, A., & Godfrey, L. (2012). Modeling the generation of domestic waste for supporting the planning of municipal waste services. *International Journal of Water Resources and Environmental Engineering*, 4(6), 171-191.
- Penteado, R., Cavalli, M., Magnano, E., & Chiampo, F. (2012). Application of the IPCC model to a Brazilian landfill: First results. *Energy Policy*, 42, 551-556.
- Polokwane climate, (2017). Retrived on the January 4, 2018, from [http://www.saexplorer.co.za/south-africa/climate/polokwane\\_climate.asp](http://www.saexplorer.co.za/south-africa/climate/polokwane_climate.asp).
- Polokwane Municipality. (2011). Polokwane Integrated development plan 2011/2016. Open file report, Polokwane Municipality, South Africa.
- Porta, D., Milani, S., Lazzarino, I.A., Perucci, A.C., & Forastiere, F. (2009). Systematic review of epidemiological studies on health effects associated with management of solid waste. *Environmental Health*. 8:16.
- Rajaram, R., Siddiqui, F. Z., & Khan, M. E. (2011). From landfill gas to energy. Technologies and challengies. CRC press. United Kingdom.
- Rakib, M. A., Rahman, M. A., Akter, M. S., Ali, M., Huda, M. E., & Bhuiyan, M. A. (2014). An emerging city: solid waste generation and recycling approach. *International Journal of Scientific Research in Environmental Sciences*, 2(3), 74.
- Rasi, S., Lantela, J., & Rintala, J. (2014). Upgrading landfill gas using high pressure water absorption process. *Fuel*, 115, 539-543.
- Renault, M., & Richard, Y. (2003). Intensity and spatial extension of drought in South Africa at different time scale . *Water SA*, 29(4), 489-500.
- Rezaee, R. (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(1).
- Rogerson, C. M. (2016). Climate change, tourism and local economic development in South Africa. *Local Economy*, 1-10.
- Roots, O., Henkelmann, B., & Schramm, K. W. (2004). Concentrations of polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofuransin soil in the vicinity of a landfill. *Chemosphere*, 5(57), 337-342.
- Rushton, L. (2003). Health Harzards and Waste Management. *Brishtish Medical Bulleton*,
- Saexplorer. (2017a). Polokwane Climate. Retrieved November 3, 2017, from [http://www.saexplorer.co.za/south-africa/climate/polokwane\\_climate.asp](http://www.saexplorer.co.za/south-africa/climate/polokwane_climate.asp).

- Saexplorer. (2017b). Thohoyandou Climate. Retrived November 3, 2017 from [http://www.saexplorer.co.za/south-africa/climate/thohoyandou\\_climate.asp](http://www.saexplorer.co.za/south-africa/climate/thohoyandou_climate.asp)
- Sankoh, F. P., Yan, X., & Tran, Q. (2013). Environmental and health impact of solid waste disposal in developing cities: a case study of granville brook dumpsite, Freetown, Sierra Leone. *Journal of Environmental Protection*, 4(07), 665.
- Scarlat, N., Motola, V., Dallemand, J. F., Monforti-Ferrario, F., Mofor, L. (2015). Evaluation of energy potential of municipal solid waste from African urban areas. *Renewable and Sustainable Energy Reviews*, 50, 1269-1286.183-190.
- Scharff, H., & Jacobs, J. (2006). Applying guidance for methane emission estimation for landfills. *Waste Management*, 26(4), 417-429.
- Scheutz, C., Fredenslund, A. M., Nedenskov, J., Samuelsson, J., & Kjeldsen, P. (2011). Gas production, composition and emission at a modern disposal site receiving waste with a low-organic content. *Waste Management*, 31(5), 946-955.
- Sharholy, M., Ahmad, K., Mahmood, G., & Trivedi, R. C. (2008). Municipal solid waste management in Indian cities—A review. *Waste Management*, 28(2), 459-467.
- Shin, H. C., Park, J. W., Kim, H. S., & Shin, E. S. (2005). Environmental and economic assessment of landfill gas electricity generation in Korea using LEAP model. *Energy policy*, 33(10), 1261-1270.
- South African Weather Service, (2018). What is a heat wave? Retrieved January 24, 2018, from <http://www.weathersa.co.za/learning/weather-questions/346-what-is-a-heat-wave>.
- Staub, M., Gourc, J. P., & Simonin, R. (2010). Influence of landfill cap cover characteristics on the mitigation of GHG emissions. In Proc. 9th International Conference on Geosynthetics. France.
- Taherian, S., Adl, M., & Sharghi, E. A. (2016). Estimation of Biogas Generation by the Use of First-order Kinetic Models for a Landfill Site in Karaj, Iran. *International Journal of Innovative Research and Development*. ISSN 2278–0211, 5(10).
- Terraza, H., & Willumsen, H. (2010). Guidance note on landfill gas capture and utilization. Inter-American Development Bank.
- Thada, M. R. (2012). The effects of the legislation of informal waste salvaging and salvagers on official landfill sites: the case stufdy of weltevreden (Polokwane). Masters Thesis, University of Johannesburg, Department of Geography, Johannesburg.
- The Center for a competitive waste industries. (2016). Beyond Landfilling. Retrieved July 1, 2016, from [Beyondlandfilling.org](http://www.beyondlandfilling.org): <http://www.beyondlandfilling.org/what-is-a-landfill.html>.
- Themelis, N. J., & Ulloa, P. A. (2007). Methane generation in landfills. *Renewable Energy*, 32(7), 1243-1257.
- Thohoyandou climate, (2017). Retrieved January 3, 2018, from [http://www.saexplorer.co.za/south-africa/map/thohoyandou\\_map.asp](http://www.saexplorer.co.za/south-africa/map/thohoyandou_map.asp).

- Thompson, S., Sawyer, J., Bonam, R., & E, V. (2009). Building a methane better generation model: validating models with methane recovery rates from 35 Canadian landfills. *Waste Management*, 7(29), 2085-2091.
- Thulamela Local Municipality. (2017). Retrieved March 3, 2017, from <http://www.thulamela.gov.za/index.php?page=background>.
- Thulamela Municipality, (2014). IDP review: 2013/2014. Retrived March 4, 2017, from [http://www.thulamela.gov.za/docs/idp/IDP\\_2013\\_14.pdf](http://www.thulamela.gov.za/docs/idp/IDP_2013_14.pdf).
- Turpie, J., & Visser, M. (2012). The impact of climate change on South Africa's rural area. Technical Report: Submission for the 2013/14 Division of Revenue, Midrand.
- United States Environmental Protection Agency (USEPA), 2005, "Landfill Gas Emissions Model (LandGEM) Version 3.02 User's Guide", Report no. EPA-600/R-05/047, U.S. Environmental Protection Agency, Office of Research and Development, Washington, DCUS.
- United States Environmental Protection Agency (USEPA). (2016). LFGcost Web model, Version 3.1 User's Guide, Landfill Methane Outreach Programme, Washington DC.
- Uruse, T., Okumura, H., Panyosaranya, S., & Inamura, A. (2008). Emission of volatile organic compounds from solid waste disposal sites and importance of heat management . *Waste Management Research*, 6(26), 534-538.
- Vrijheid, M. (2000). Health effects of residence nearhazardous waste landfill sites: A review of epidemiologic literature. *Environmental Health Perspectives*, 108, 101-112.
- Wang, X., Nagpure, A. S., DeCarolis, J. F., & Barlaz, M. A. (2013). Using observed data to improve estimated methane collection from select US landfills. *Environmental Science & Technology*, 47(7), 3251-3257.
- White, P., Dranke, M., & Hindle, P. (2012). *Integrated solid waste management: a lifecycle inventory*. Springer Science & Business Media.
- Wild, S. (2015). Facts sheets and guides. Retrieved December 3, 2015, from Africa check: <http://africa-check.org/factsheets/factsheet-why-do-many-scientists-think-Africa-will-be-the-hardest-hit-by-climate-change/>.
- Willumsen, H. C. (2001). Energy recovery from landfill gas in demark and world wide. *Miedzynarodowegu seminarium-international workshop for the utilisation of landfill gas for energy production*.
- World wide funds for nature (WWF), (2017). The truth about our food waste problem. Retrived December 5, 2017, from [http://www.wwf.org.za/what\\_we\\_do/food\\_energy\\_water\\_nexus/?21962/The-truth-about-our-food-waste-problem](http://www.wwf.org.za/what_we_do/food_energy_water_nexus/?21962/The-truth-about-our-food-waste-problem).
- Woudhuysen, J., & Kaplinsky. (2009). *Energise: A future for energy innovation*. London: Beautiful Books limited.
- Zurbrugg, C. (2002). Urban solid waste management in low-income countries of Asia: How to cope with the garbage crisis. Presented for: Scientific Committee on Problems of

the Environment (SCOPE) Urban Solid Waste Management Review Session, Durban, South Africa, 1-13.

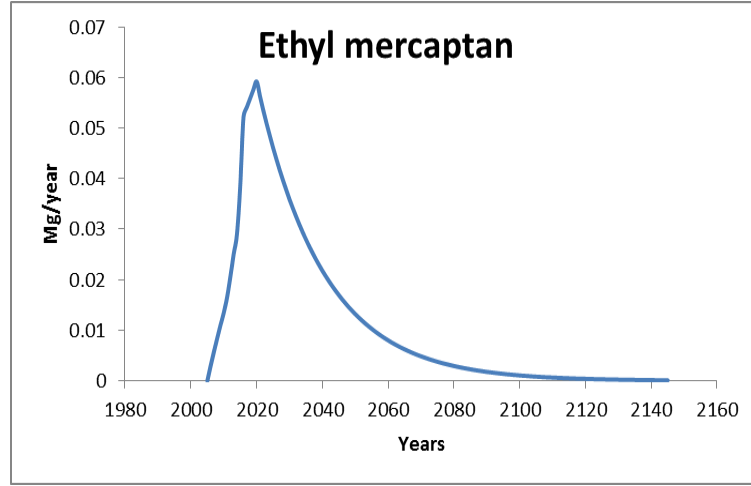
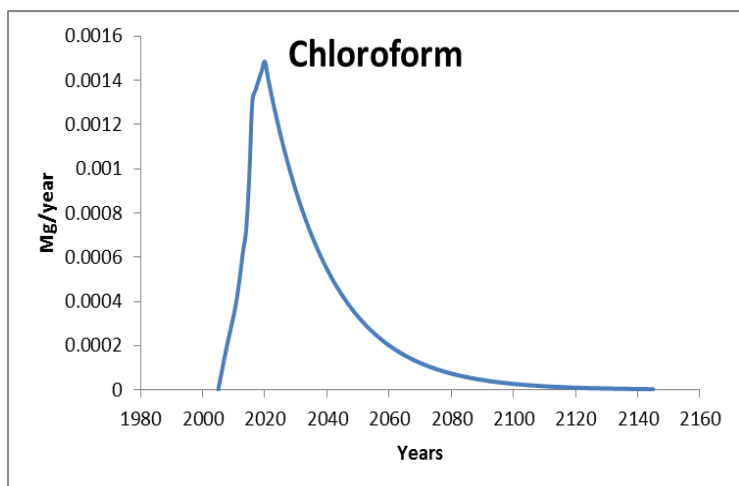
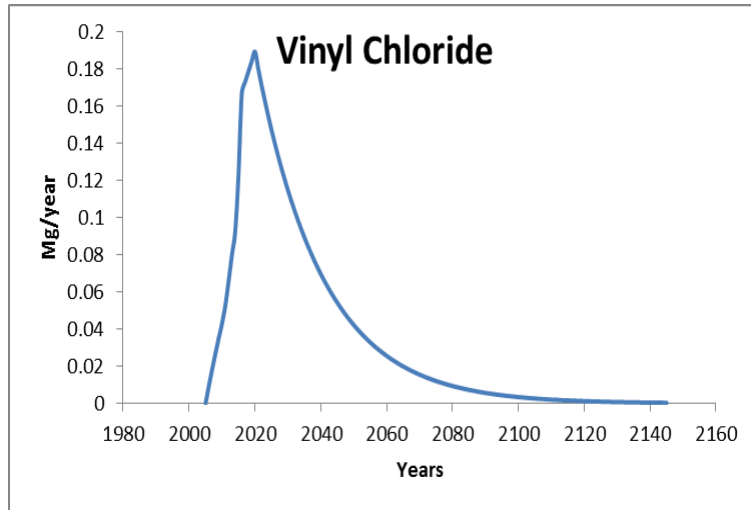
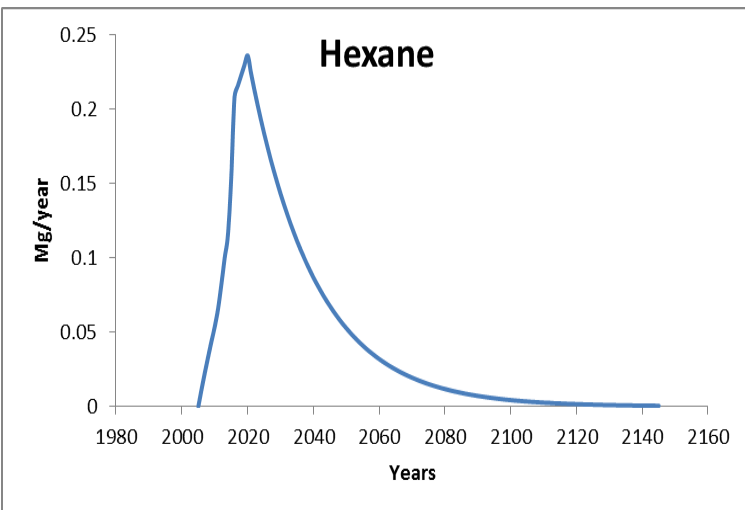
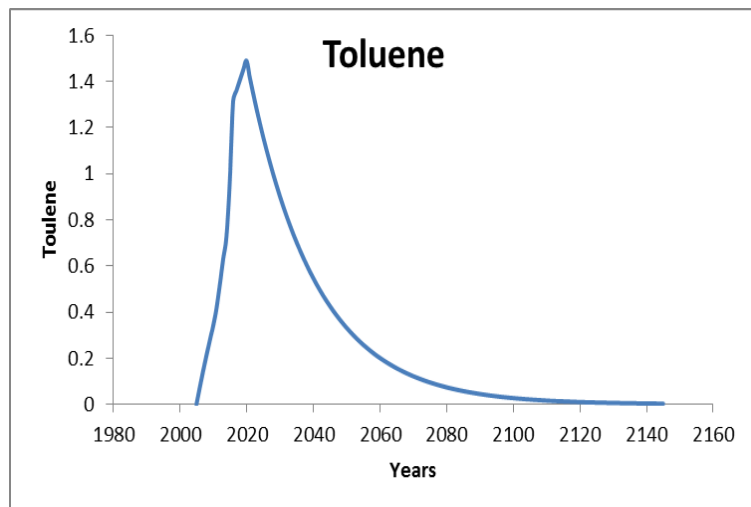
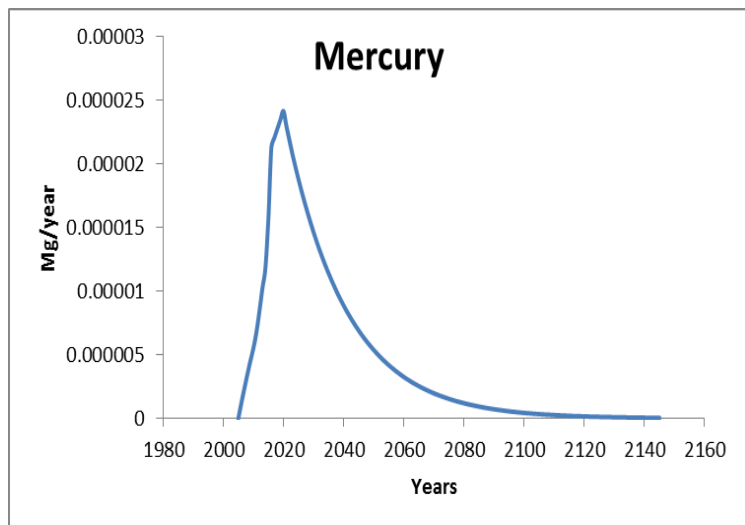
<http://biophysics.sbg.ac.at/waste/landfill.htm>. Retrieved 6<sup>th</sup> December, 2017 from <http://biophysics.sbg.ac.at/waste/landfill.htm>.

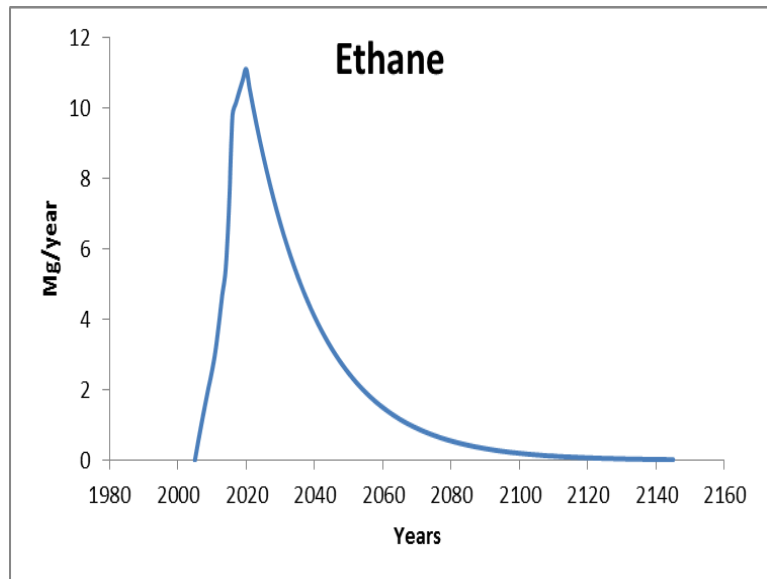
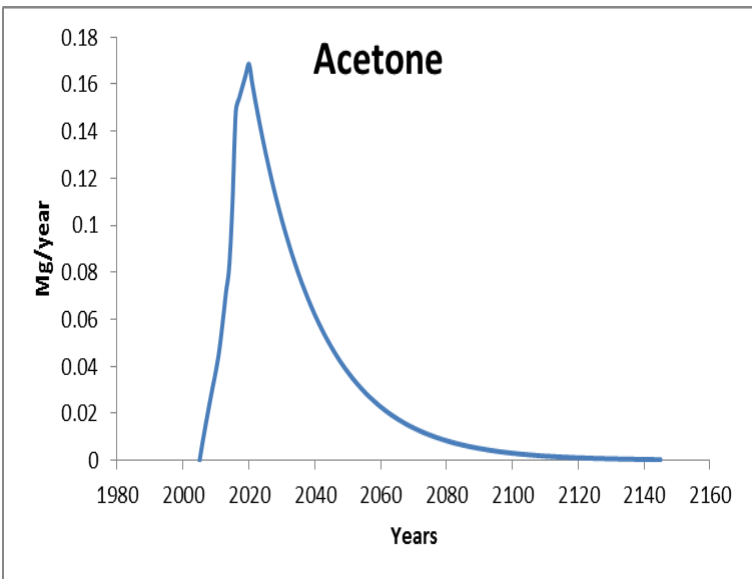
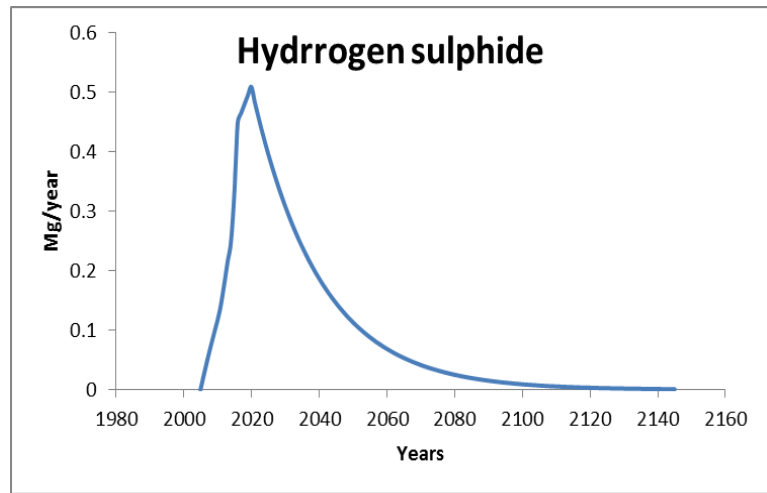
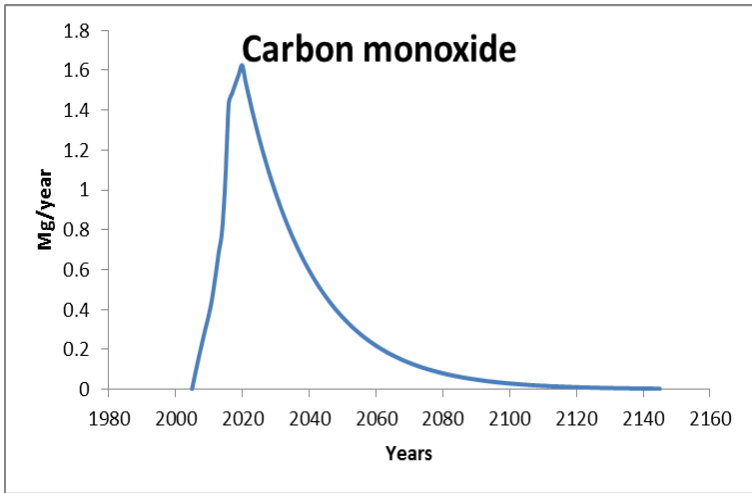
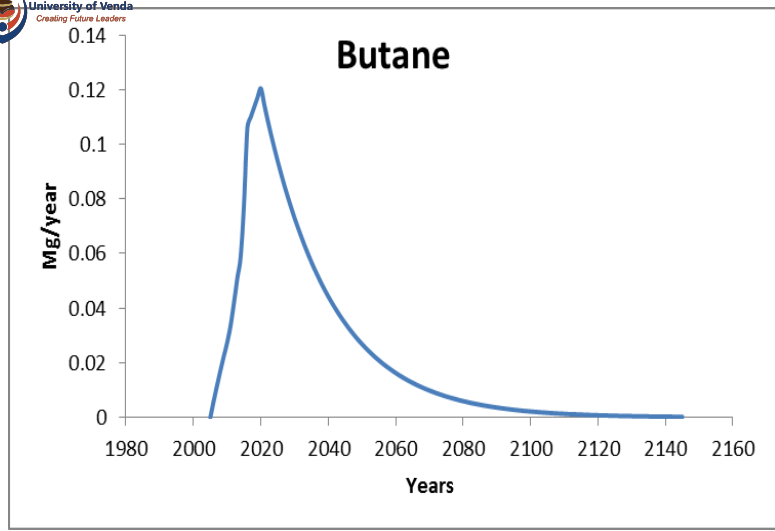
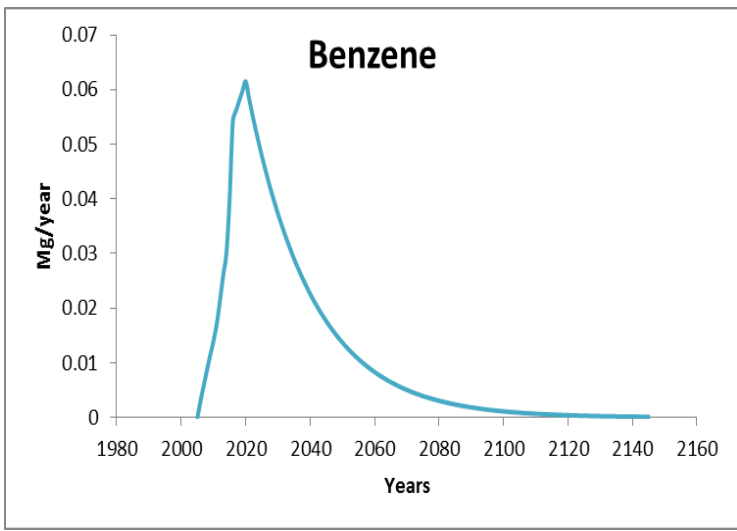


**Appendix A: Results of the LFG generated from the Thohoyandou landfill site using the LandGEM model until 2040**

<b>Year</b>	<b>Total LFG (Mg/year)</b>	<b>Methane (Mg/year)</b>	<b>Carbon dioxide (Mg/year)</b>	<b>NMOC (Mg/year)</b>
2005	0	0	0	0
2006	6.163E+02	1.646E+02	4.516E+02	7.075E+00
2007	1.206E+03	3.222E+02	8.840E+02	1.385E+01
2008	1.771E+03	4.731E+02	1.298E+03	2.034E+01
2009	2.312E+03	6.177E+02	1.695E+03	2.655E+01
2010	2.831E+03	7.563E+02	2.075E+03	3.251E+01
2011	3.470E+03	9.268E+02	2.543E+03	3.984E+01
2012	4.319E+03	1.154E+03	3.165E+03	4.958E+01
2013	5.258E+03	1.404E+03	3.853E+03	6.037E+01
2014	6.078E+03	1.624E+03	4.455E+03	6.978E+01
2015	8.090E+03	2.161E+03	5.929E+03	9.288E+01
2016	1.098E+04	2.932E+03	8.046E+03	1.260E+02
2017	1.136E+04	3.035E+03	8.328E+03	1.305E+02
2018	1.173E+04	3.134E+03	8.600E+03	1.347E+02
2019	1.209E+04	3.230E+03	8.863E+03	1.388E+02
<b>2020</b>	<b>1.244E+04</b>	<b>3.323E+03</b>	<b>9.118E+03</b>	<b>1.428E+02</b>
2021	1.183E+04	3.161E+03	8.673E+03	1.359E+02
2022	1.126E+04	3.007E+03	8.250E+03	1.292E+02
2023	1.071E+04	2.860E+03	7.848E+03	1.229E+02
2024	1.019E+04	2.721E+03	7.465E+03	1.169E+02
2025	9.689E+03	2.588E+03	7.101E+03	1.112E+02
2026	9.217E+03	2.462E+03	6.755E+03	1.058E+02
2027	8.767E+03	2.342E+03	6.425E+03	1.007E+02
2028	8.340E+03	2.228E+03	6.112E+03	9.575E+01
2029	7.933E+03	2.119E+03	5.814E+03	9.108E+01
2030	7.546E+03	2.016E+03	5.530E+03	8.664E+01
2031	7.178E+03	1.917E+03	5.261E+03	8.241E+01
2032	6.828E+03	1.824E+03	5.004E+03	7.839E+01
2033	6.495E+03	1.735E+03	4.760E+03	7.457E+01
2034	6.178E+03	1.650E+03	4.528E+03	7.093E+01
2035	5.877E+03	1.570E+03	4.307E+03	6.747E+01
2036	5.590E+03	1.493E+03	4.097E+03	6.418E+01
2037	5.318E+03	1.420E+03	3.897E+03	6.105E+01
2038	5.058E+03	1.351E+03	3.707E+03	5.807E+01
2039	4.812E+03	1.285E+03	3.526E+03	5.524E+01
2040	4.577E+03	1.223E+03	3.354E+03	5.255E+01

## Appendix B: The total values of different odorous gas pollutants present in Thohoyandou landfill

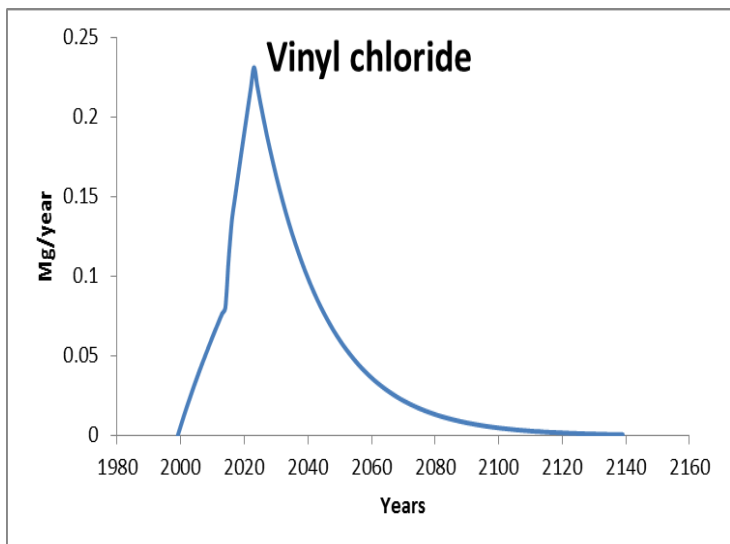
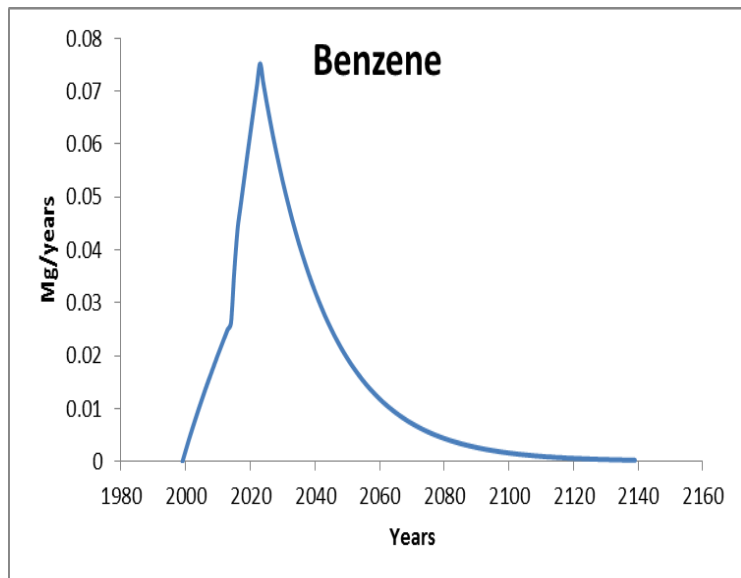
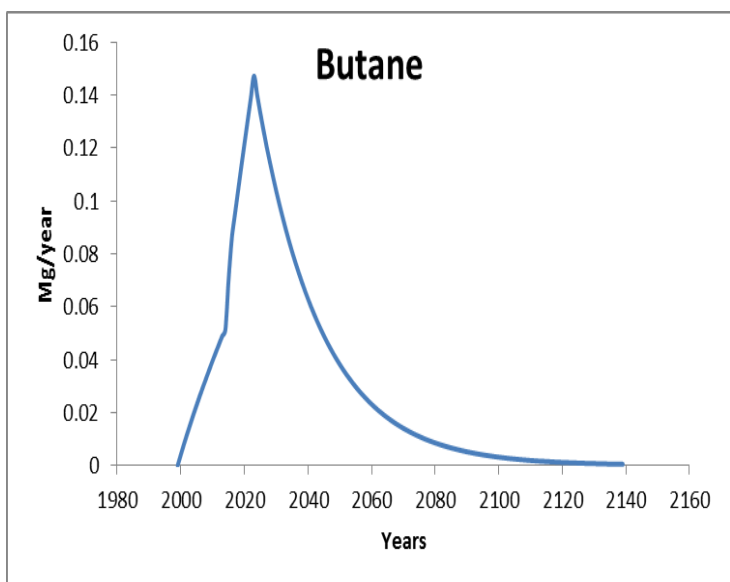
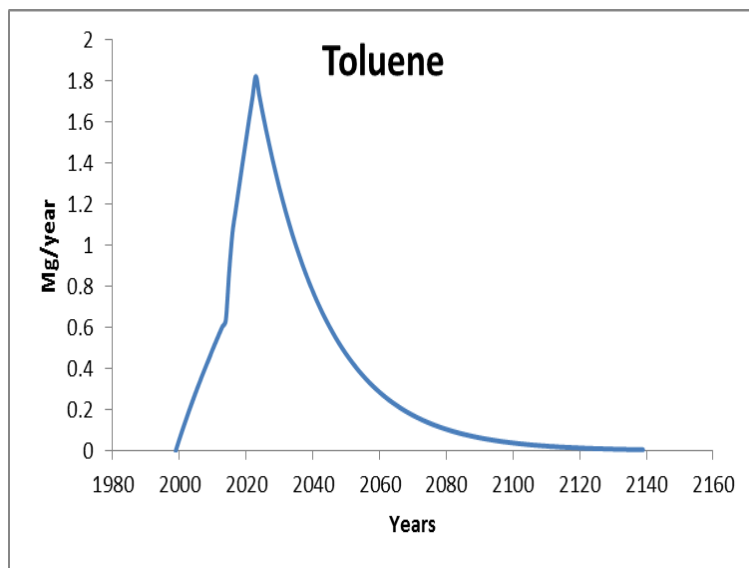
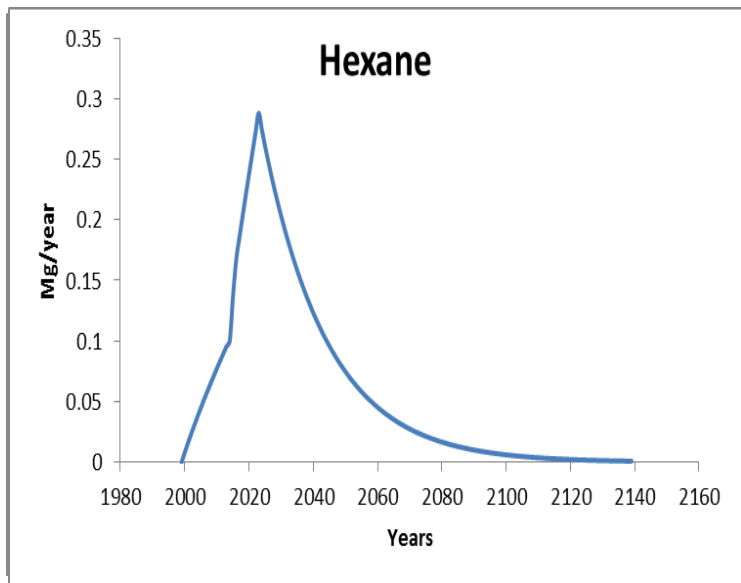


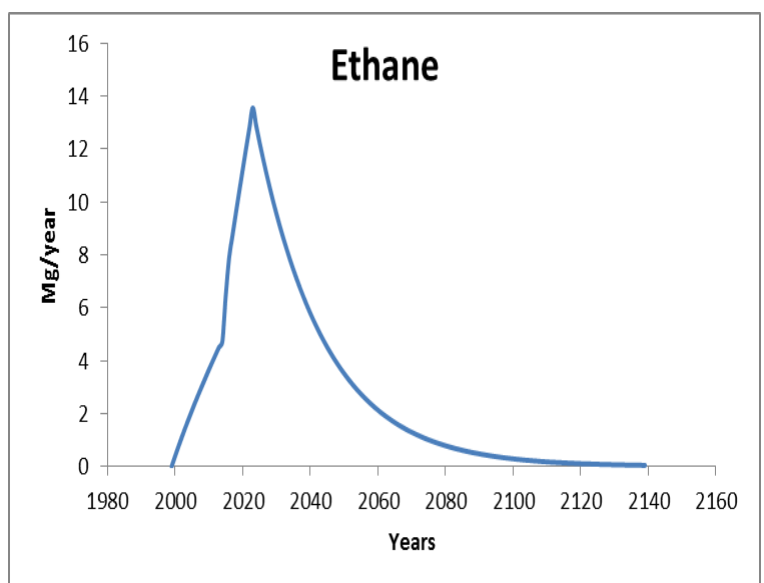
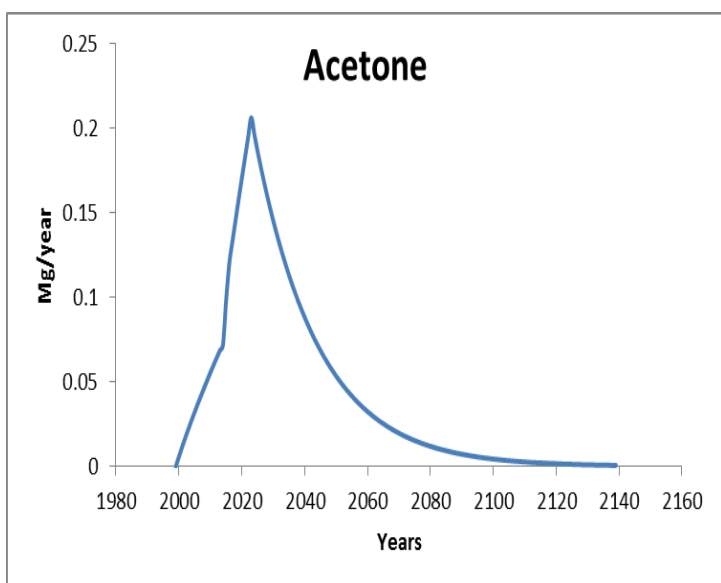
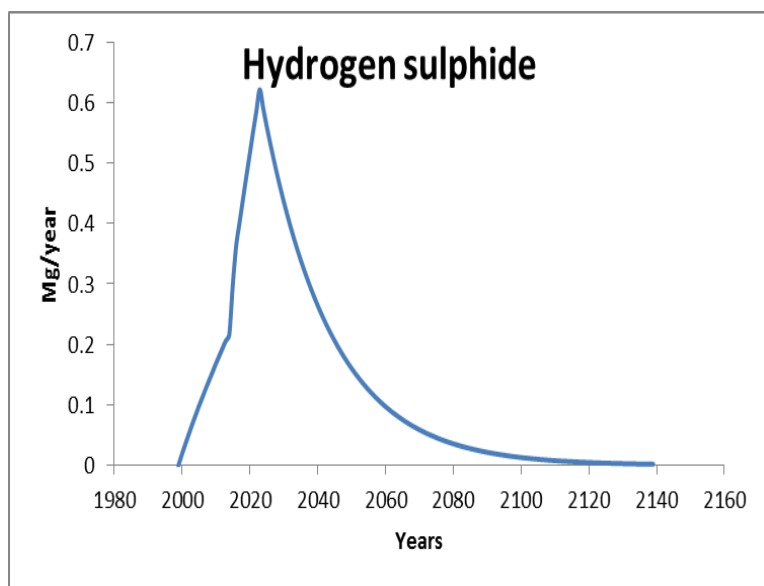
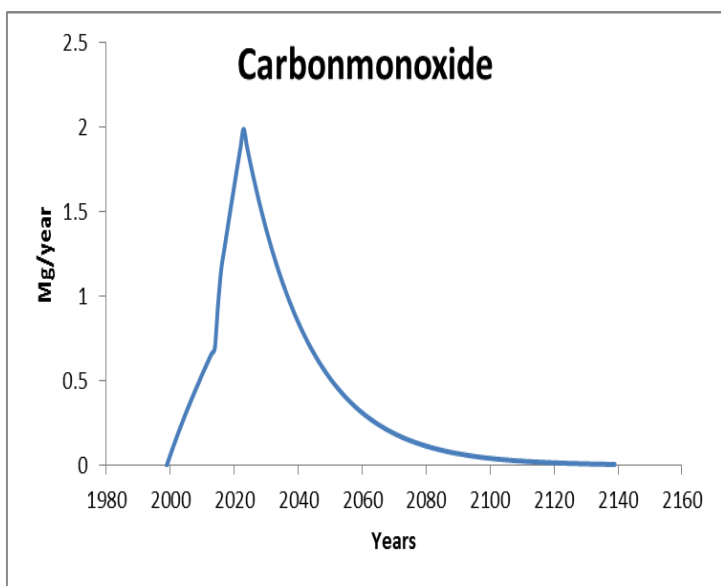
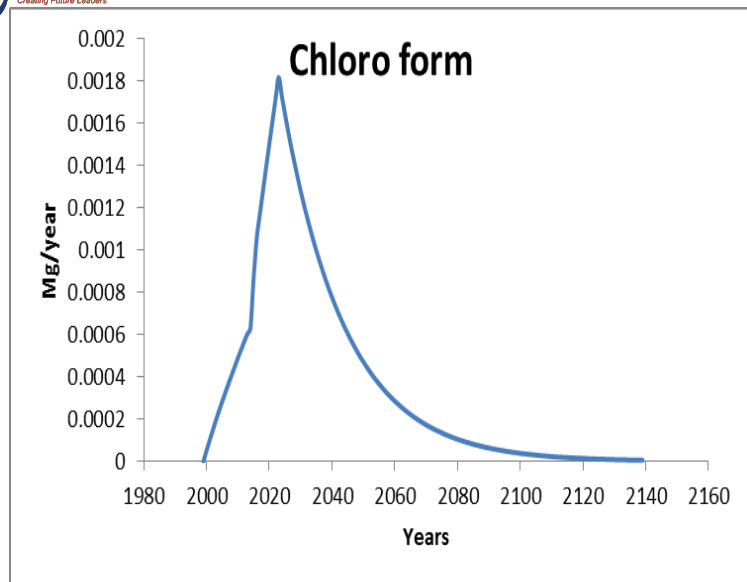
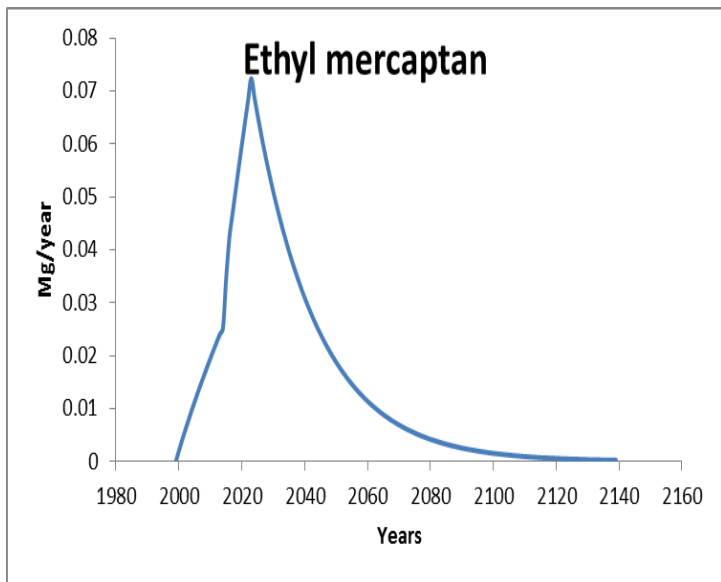


**Appendix C: Results of the LFG generated from the Weltervenden landfill site using the LandGem model until 2040**

<b>Year</b>	<b>Total LFG (Mg/year)</b>	<b>Methane (Mg/year)</b>	<b>Carbon dioxide (Mg/year)</b>	<b>NMOC (Mg/year)</b>
1999	0	0	0	0
2000	4.263E+02	1.139E+02	3.124E+02	4.894E+00
2001	8.390E+02	2.241E+02	6.149E+02	9.633E+00
2002	1.239E+03	3.310E+02	9.081E+02	1.423E+01
2003	1.627E+03	4.347E+02	1.193E+03	1.868E+01
2004	2.005E+03	5.355E+02	1.469E+03	2.302E+01
2005	2.372E+03	6.336E+02	1.738E+03	2.723E+01
2006	2.730E+03	7.292E+02	2.001E+03	3.134E+01
2007	3.080E+03	8.226E+02	2.257E+03	3.536E+01
2008	3.421E+03	9.138E+02	2.507E+03	3.928E+01
2009	3.756E+03	1.003E+03	2.753E+03	4.312E+01
2010	4.097E+03	1.094E+03	3.002E+03	4.703E+01
2011	4.419E+03	1.180E+03	3.239E+03	5.073E+01
2012	4.736E+03	1.265E+03	3.471E+03	5.438E+01
2013	5.050E+03	1.349E+03	3.701E+03	5.798E+01
2014	5.281E+03	1.411E+03	3.871E+03	6.064E+01
2015	7.226E+03	1.930E+03	5.296E+03	8.296E+01
2016	8.837E+03	2.360E+03	6.477E+03	1.015E+02
2017	9.792E+03	2.616E+03	7.177E+03	1.124E+02
2018	1.073E+04	2.866E+03	7.865E+03	1.232E+02
2019	1.165E+04	3.113E+03	8.540E+03	1.338E+02
2020	1.256E+04	3.355E+03	9.205E+03	1.442E+02
2021	1.346E+04	3.596E+03	9.866E+03	1.546E+02
2022	1.434E+04	3.830E+03	1.051E+04	1.646E+02
<b>2023</b>	<b>1.520E+04</b>	<b>4.061E+03</b>	<b>1.114E+04</b>	<b>1.746E+02</b>
2024	1.446E+04	3.863E+03	1.060E+04	1.660E+02
2025	1.376E+04	3.675E+03	1.008E+04	1.579E+02
2026	1.309E+04	3.495E+03	9.591E+03	1.502E+02
2027	1.245E+04	3.325E+03	9.123E+03	1.429E+02
2028	1.184E+04	3.163E+03	8.678E+03	1.359E+02
2029	1.126E+04	3.009E+03	8.255E+03	1.293E+02
2030	1.071E+04	2.862E+03	7.852E+03	1.230E+02
2031	1.019E+04	2.722E+03	7.469E+03	1.170E+02
2032	9.694E+03	2.589E+03	7.105E+03	1.113E+02
2033	9.221E+03	2.463E+03	6.758E+03	1.059E+02
2034	8.772E+03	2.343E+03	6.429E+03	1.007E+02
2035	8.344E+03	2.229E+03	6.115E+03	9.580E+01
2036	7.937E+03	2.120E+03	5.817E+03	9.113E+01
2037	7.550E+03	2.017E+03	5.533E+03	8.668E+01
2038	7.182E+03	1.918E+03	5.263E+03	8.245E+01
2039	6.831E+03	1.825E+03	5.007E+03	7.843E+01
2040	6.498E+03	1.736E+03	4.763E+03	7.461E+01

### Appendix D: The total values of different odorous gas pollutants present in Welteervenden landfill





**Appendix E: Results of the LFG generated from the Thohoyandou landfill site using the Afvalzorg model**

Year	Total LFG (m <sup>3</sup> STP/h)	Methane (Mg/year)
2005	0	0
2006	55	173
2007	109	339
2008	159	498
2009	208	651
2010	255	797
2011	312	976
2012	389	1,215
2013	473	1,480
2014	547	1,710
2015	728	2,276
2016	988	3,089
2017	1,022	3,197
2018	1,056	3,302
2019	1,088	3,403
<b>2020</b>	<b>1,119</b>	<b>3,501</b>
2021	1,065	3,330
2022	1,013	3,168
2023	964	3,013
2024	917	2,866
2025	872	2,726
2026	829	2,594
2027	789	2,467
2028	750	2,347
2029	714	2,232
2030	679	2,123
2031	646	2,020
2032	614	1,921
2033	584	1,828
2034	556	1,738
2035	529	1,654
2036	503	1,573
2037	478	1,496
2038	455	1,423
2039	433	1,354
2040	412	1,288

**Appendix F: Results of the LFG generated from the Weltervenden landfill site using the Afvalzorg model**

<b>Year</b>	<b>Total LFG (m<sup>3</sup> STP/h)</b>	<b>Methane (Mg/year)</b>
1999	0	0
2000	28	88
2001	55	173
2002	82	255
2003	107	335
2004	132	413
2005	156	488
2006	180	562
2007	203	634
2008	225	704
2009	247	773
2010	269	841
2011	290	907
2012	311	973
2013	332	1,037
2014	347	1,085
2015	475	1,485
2016	581	1,817
2017	644	2,014
2018	706	2,207
2019	767	2,397
2020	826	2,584
2021	886	2,770
2022	943	2,950
<b>2023</b>	<b>1,000</b>	<b>3,128</b>
2024	952	2,976
2025	905	2,831
2026	861	2,693
2027	819	2,561
2028	779	2,436
2029	741	2,317
2030	705	2,204
2031	671	2,097
2032	638	1,995
2033	607	1,897
2034	577	1,805
2035	549	1,717
2036	522	1,633
2037	497	1,553
2038	473	1,478
2039	449	1,406
2040	428	1,337

## Appendix G: Questionnaire for the study

Department of Hydrology and Water Resources,

Title: Estimation of the emissions of landfill gases from a landfill site using the LandGEM and Afvalzorg models: A case study of the Weltervenden, Polokwane and Thohoyandou landfill sites.

1. Sex: Male , Female
2. Age (years): 11 – 20 , 21 – 30 , 31 – 40 , 41 – 50 , above 50
3. Educational attainment: No formal education , Primary education , High school , Tertiary education .
4. Are-you: Full-time employed , Part-time employed , Self-employed , Unemployed .
5. How long have you been living close to the landfill? < 1 year , 1-5 years , 5-10 years , 10 - 20 years  >, above 20 years .
6. Specify by ticking how serious is the presence of each characteristics; which is based on seriousness of environmental problems.

Characteristics	Very serious	Fairly a serious problem	Not a serious problem	Dose not exist
Disposal of solid waste (landfill)				
Garbage and litter in the street				
Unwelcome location of landfill				
Air pollution, bad odor				
Water pollution				
Noise pollution				
Dust				

7. Specify by ticking, the most reported illness experienced by the people of the community;

Characteristics	Very frequent	Fairly frequent	Not frequent	Does not exist
Breathing disorder				
Cancer				
Reoccurring flu				
Eye irritation				
Weakness of the body				
Back pain				
Hearing impairment				
Skin disorder				
Depression				
Fear of future health				
Headache				
Coughing, tuberculosis				
Asthma and respiratory disease				
Wounds and cuts				
Others please specify				

8. Specify by ticking appropriately, to what extent is the level of disturbances to the community.

Characteristics	Extremely disturbing	Fairly disturbing	Not disturbing	Does not exist
Appearance of landfill site				
Bad odor and gases				
Perceived health impact in the future				
Cannot sell property because of location				
Friends unwilling to visit				
Desirable business enterprise				

staying away				
Site stigmatizes resident				
Impact of site on drinking water				
Increased pollution of vermin				
Increased pollution of rodents and mosquitoes				
Poor renting of property				

9. Tick as appropriate for respondent's behavior towards adaptive measures for the community

Characteristics	Always	Often	Seldom	Never
Attend environmental meetings				
Join cleanup drive				
Participate in local opposition to locally unwanted land use				
Contributing money for environmental cause				
Door to door environmental campaign				
Closure of windows and doors in-case of any perceived odor, rodents, mosquitoes				

10. Tick as appropriate for life satisfaction (as a place to live in) in the community

Characteristics	Extremely satisfied	Somewhat Satisfied	Unsatisfied	Extremely satisfied
Life in general in the community				
Personal health condition				
Sanitation and environmental protection				
Neighborhood compared to others				
Attractiveness of the community				
State of the health and well being				
Community as a place to live in				
Perceived neighborhood change				



## Appendix H

Independent Samples Test of environmental problems in the community										
		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	T	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Disposal of solid waste	Equal variances assumed	.993	.322	-8.078	95	.000	-1.13520	.14054	-1.41420	-.85621
	Equal variances not assumed			-8.082	94.887	.000	-1.13520	.14045	-1.41405	-.85636
Garbage and litter in the street	Equal variances assumed	19.940	.000	2.242	94	.027	.35302	.15747	.04036	.66568
	Equal variances not assumed			2.258	86.275	.026	.35302	.15635	.04222	.66382
Unwelcome location of land fill	Equal variances assumed	9.785	.002	-10.459	97	.000	-1.43224	.13694	-1.70402	-1.16047
	Equal variances not assumed			-10.425	86.671	.000	-1.43224	.13739	-1.70534	-1.15915
Air pollution, bad odor	Equal variances assumed	2.431	.122	-7.068	95	.000	-1.06973	.15135	-1.37020	-.76925
	Equal variances not assumed			-7.063	94.397	.000	-1.06973	.15145	-1.37041	-.76904
Water pollution	Equal variances assumed	.193	.662	2.154	91	.034	.32560	.15113	.02539	.62581
	Equal variances not assumed			2.155	90.039	.034	.32560	.15109	.02544	.62577
Noise pollution	Equal variances assumed	11.415	.001	2.425	93	.017	.38298	.15796	.06930	.69666
	Equal variances not assumed			2.419	88.225	.018	.38298	.15832	.06837	.69759
Dust	Equal variances assumed	40.267	.000	-3.341	95	.001	-.54337	.16263	-.86623	-.22051
	Equal variances not assumed			-3.356	81.548	.001	-.54337	.16191	-.86549	-.22125

Appendix I

Independent Samples Test on most reported illnesses encountered by the participants in both communities										
		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Breathing disorder	Equal variances assumed	1.889	.172	-2.670	97	.009	-.39673	.14861	-.69168	-.10179
	Equal variances not assumed			-2.665	93.685	.009	-.39673	.14886	-.69232	-.10115
Cancer	Equal variances assumed	.011	.916	.128	94	.899	.02083	.16305	-.30291	.34458
	Equal variances not assumed			.128	94.000	.899	.02083	.16305	-.30291	.34458
Recurring flu	Equal variances assumed	1.587	.211	-2.854	95	.005	-.47406	.16608	-.80378	-.14434
	Equal variances not assumed			-2.852	93.729	.005	-.47406	.16625	-.80417	-.14396
Eye irritation	Equal variances assumed	1.027	.313	-4.679	96	.000	-.71429	.15266	-1.01732	-.41125
	Equal variances not assumed			-4.679	94.640	.000	-.71429	.15266	-1.01738	-.41119
Weakness of the body	Equal variances assumed	3.652	.059	-2.724	95	.008	-.48255	.17716	-.83426	-.13085
	Equal variances not assumed			-2.712	91.410	.008	-.48255	.17792	-.83594	-.12917
Back pain	Equal variances assumed	11.644	.001	-2.078	95	.040	-.33957	.16338	-.66392	-.01523
	Equal variances not assumed			-2.064	88.038	.042	-.33957	.16451	-.66649	-.01266
Hearing impairment	Equal variances assumed	1.279	.261	-.619	92	.537	-.11091	.17916	-.46674	.24492
	Equal variances not assumed			-.616	88.584	.539	-.11091	.17995	-.46848	.24666
Skin disorder	Equal variances assumed	.000	.990	.238	91	.813	.04406	.18529	-.32399	.41212
	Equal variances not assumed			.238	89.608	.813	.04406	.18545	-.32438	.41251
Headache	Equal variances assumed	7.981	.006	-.512	98	.610	-.08000	.15623	-.39004	.23004
	Equal variances not assumed			-.512	92.797	.610	-.08000	.15623	-.39025	.23025
Coughing, tuberculosis	Equal variances assumed	.202	.654	-2.463	96	.016	-.40000	.16239	-.72235	-.07765
	Equal variances not assumed			-2.457	93.653	.016	-.40000	.16279	-.72323	-.07677
Asthma and respiratory disease	Equal variances assumed	1.024	.314	2.331	90	.022	.41860	.17957	.06185	.77535
	Equal variances not assumed			2.324	87.308	.022	.41860	.18009	.06068	.77653

## Appendix J

Independent Samples Test on external characteristics observed by the participants living in both communities										
		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Fear of future health	Equal variances assumed	11.164	.001	-5.838	88	.000	-.93629	.16039	-1.25502	-.61755
	Equal variances not assumed			-5.995	86.712	.000	-.93629	.15618	-1.24673	-.62584
Cannot sell property because of location	Equal variances assumed	8.723	.004	-5.717	88	.000	-.96429	.16866	-1.29946	-.62911
	Equal variances not assumed			-5.827	86.024	.000	-.96429	.16548	-1.29325	-.63532
Friends unwilling to visit	Equal variances assumed	.417	.520	-7.296	92	.000	-1.08000	.14803	-1.37399	-.78601
	Equal variances not assumed			-7.277	89.433	.000	-1.08000	.14841	-1.37487	-.78513
Desirable business enterprise staying away	Equal variances assumed	.099	.754	-6.566	84	.000	-1.06522	.16224	-1.38784	-.74259
	Equal variances not assumed			-6.565	82.314	.000	-1.06522	.16226	-1.38798	-.74246
Site stigmatises residence	Equal variances assumed	9.176	.003	-3.081	88	.003	-.53274	.17291	-.87635	-.18912
	Equal variances not assumed			-3.134	86.684	.002	-.53274	.16996	-.87058	-.19490
Pollution of rodents	Equal variances assumed	38.012	.000	-7.471	94	.000	-1.16087	.15538	-1.46937	-.85237
	Equal variances not assumed			-7.635	78.702	.000	-1.16087	.15205	-1.46353	-.85821
Pollution of mosquitoes and flies	Equal variances assumed	35.559	.000	-9.074	92	.000	-1.20109	.13236	-1.46396	-.93821
	Equal variances not assumed			-9.178	74.032	.000	-1.20109	.13086	-1.46183	-.94035
Poor renting of property	Equal variances assumed	18.344	.000	-4.743	87	.000	-.84802	.17880	-1.20341	-.49264
	Equal variances not assumed			-4.822	84.237	.000	-.84802	.17587	-1.19775	-.49830

## Appendix K

Independent Samples Test on life satisfaction with living in the community										
		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Life in general in the community	Equal variances assumed	7.283	.008	2.222	96	.029	.39083	.17592	.04163	.74003
	Equal variances not assumed			2.229	94.433	.028	.39083	.17531	.04278	.73889
Personal health condition	Equal variances assumed	9.858	.002	3.636	95	.000	.61735	.16977	.28032	.95437
	Equal variances not assumed			3.645	90.740	.000	.61735	.16935	.28095	.95375
Neighbourhood compared to others	Equal variances assumed	1.068	.304	2.466	94	.015	.37826	.15338	.07373	.68279
	Equal variances not assumed			2.444	86.578	.017	.37826	.15474	.07067	.68585
Attractiveness of the community	Equal variances assumed	3.469	.066	.210	93	.834	.03556	.16938	-.30080	.37191
	Equal variances not assumed			.209	88.246	.835	.03556	.17052	-.30331	.37442
State of health and well-being of the community	Equal variances assumed	.005	.942	.911	94	.365	.16848	.18497	-.19878	.53574
	Equal variances not assumed			.911	93.923	.365	.16848	.18492	-.19868	.53564
Community as a place to live in	Equal variances assumed	.324	.570	2.858	96	.005	.46417	.16239	.14182	.78651
	Equal variances not assumed			2.858	95.803	.005	.46417	.16241	.14179	.78655
Perceived neighborhood change	Equal variances assumed	.850	.359	7.103	96	.000	1.01917	.14348	.73436	1.30397
	Equal variances not assumed			7.089	94.275	.000	1.01917	.14376	.73374	1.30459



**RESEARCH AND INNOVATION  
OFFICE OF THE DIRECTOR**

**NAME OF RESEARCHER/INVESTIGATOR:  
Mr PO Njoku**

**Student No:  
16023634**

**PROJECT TITLE: Estimation of the emission of landfill gases form a landfill site using the Landgem and Afvalzorg models: A case study of weltervenden, Polokwane and Thohoyandou landfill sites.**

**PROJECT NO: SES/17/HWR/03/1510**

**SUPERVISORS/ CO-RESEARCHERS/ CO-INVESTIGATORS**

NAME	INSTITUTION & DEPARTMENT	ROLE
Prof JO Odiyo	University of Venda	Supervisor
Dr JN Edokpayi	University of Venda	Co- Supervisor
Mr PO Njoku	University of Venda	Investigator – Student

**ISSUED BY:  
UNIVERSITY OF VENDA, RESEARCH ETHICS COMMITTEE**

Date Considered: October 2017

Decision by Ethical Clearance Committee Granted

Signature of Chairperson of the Committee: .....

Name of the Chairperson of the Committee: Senior Prof. G.E. Ekosse

**UNIVERSITY OF VENDA**  
DIRECTOR  
RESEARCH AND INNOVATION  
**2017 -10- 17**  
Private Bag X5050  
Thohoyandou 0950



University of Venda

PRIVATE BAG X5050, THOHOYANDOU, 0950. LIMPOPO PROVINCE, SOUTH AFRICA  
TELEPHONE (015) 962 8504/8313 FAX (015) 962 9060

*"A quality driven financially sustainable, rural-based Comprehensive University"*

© University of Venda



© University of Venda