Municipal solid waste management in South Africa: evaluation of waste to energy technologies for generating electricity from municipal solid waste, Gauteng Province

BY

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THESIS

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DECLARATION 1 – PLAGIARISM

I, Smangele Qondile Dlamini, declare that this thesis is my own work except as indicated in the references and acknowledgements.

This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then their words have been re-written and the general information attributed to them has been referenced. Where their exact words have been used, then their writings have been placed inside quotation marks, and referenced.

The thesis is being submitted for the award of the degree of Doctor of Philosophy (PhD) to the Faculty of Science at the University of the Witwatersrand, Johannesburg, South Africa. It has not previously been submitted for examination or award of degree to any other institution of learning.

DECLARATION 2 – PUBLICATIONS

I, Smangele Qondile Dlamini, declare that I personally undertook all the data collection, analysis, development and writing of the manuscripts and articles mentioned below. Sections of this work have been published or submitted as manuscripts for publication to the following peer reviewed journals:

1. Smangele Dlamini, Mulala Danny Simatele & Nzalalemba Serge Kubanza (2019). Municipal solid waste management in South Africa: from waste to energy recovery through waste-to-energy technologies in Johannesburg, *Local Environment*, 24:3, 249-257, DOI:10.1080/13549839.2018.1561656 (Published).

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3. Smangele Dlamini, Simphiwe Simelane & Mulala Danny Simatele (2019). Electricity generation and economic viability of waste-to-energy technologies for municipal solid waste management in the Gauteng province, South Africa. *Journal of cleaner Production.* (The second revision has been done and the paper is currently in print)

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Smangele Qondile Dlamini

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- This thesis is dedicated to the ONE "*For I know the plans I have for you, declares the Lord, plans to prosper you and not to harm you, plans to give you hope and a future.*" Jeremiah 29:11.

- My parents (Mr. Elliot Dlamini and Mrs. Judith Masilela), my sister (Miss. Sibongile Dlamini) and my family at large for their constant support, love and encouragement throughout this journey.

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ABSTRACT

"Waste-to-energy" technologies have been presented as one of the avenues to improve the management of solid waste through the recovery of waste whilst promoting a clean urban environment and increasing renewable energy generation. The Gauteng province, however, is still high and solely dependent on landfills for municipal solid waste management. Because of the concern on the depletion of the City of Johannesburg's landfills airspace by the year 2023, increasing waste generation and greenhouse gases emission, the province has an urgent need for a better waste management strategy. This projection becomes a motivation for the identification of suitable waste-to-energy alternative avenues to manage waste in the province. This study evaluated the potential of municipal solid waste for electricity production in nine municipalities in the Gauteng province using landfill gas to energy, incineration and anaerobic digestion technologies as well as the economic viability of the waste-to-energy technologies. The LandGEM equation was used to estimate methane generation from the waste generated in each year in order to evaluate the electricity generation potential of the technologies. The levelised cost of energy, net present value and payback period methods were used to determine the economic viability of the technologies. The study also evaluated the global warming potential, acidification potential and dioxin/furan emission potential of the waste-to-energy technologies using the life cycle assessment methodology. Four scenarios were evaluated, namely scenario 1- landfill, scenario 2 - landfill with energy recovery, scenario 3 - incineration with anaerobic digestion and scenario 4 - incineration with landfill with energy recovery. Key findings revealed that the City of Johannesburg municipality has the highest waste generation potential of 2.18925×10^9 – 3.9103×10^9 kg/yr between the years 2016 to 2035 with methane generation estimates of 181700000 m^3/yr (12210 ft^3/min). The incineration technology is the next best and appropriate technology option for municipal solid waste management in the province in terms of waste recovery and electricity generation potential. However, from an economic point of view, anaerobic digestion technology presented itself as an economically viable waste-to-energy technology with the lowest payback period compared to landfill gas to energy technology and incineration technology. Scenario 3 (incineration with anaerobic digestion) has the highest greenhouse gas emissions in all the municipalities. This was expected as the electricity generation potential for incineration was high in all the municipalities followed by the anaerobic digestion technology with high methane generation during biological degradation of organic waste. Scenario 4 (incineration with landfill gas to energy) has the highest acidification potential compared to the other scenarios. Dioxin emission in scenario 4 (incineration with landfill gas to energy) was higher than that in scenario 2 (landfill gas to energy) and it was not surprising as dioxin are emitted through the combustion of waste. This study is very useful to policy makers, scientists and investors for decision making purposes as it could lead to optimal investment in waste-to-energy technologies.

Keywords: *Municipal Solid Waste, Waste-to-energy technologies, Electricity generation, Life cycle assessment, Global warming potential, Gauteng province, South Africa.*

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LIST OF ABBREVIATIONS

SWM	Solid waste management
MSW	Municipal solid waste
WTE	Waste-to-energy
LFGT	Landfill gas to energy technology
INC	Incineration technology
AD	Anaerobic technology
IPCC	Intergovernmental Panel on Climate Change
LandGEM	Landfill gas generation emission model
US EPA	United States Environmental Protection Agency
APC	Air pollution control
PM	Particulate matter
LCA	Life cycle assessment
LCOE	Levelised cost of energy
NPV	Net present value
PBP	Payback period
GHG	Greenhouse gas
GWP	Global warming potential
AP	Acidification potential

LF	Landfill
NIHSS	National Institute for the Humanities and Social Science
SAHUDA	South African Humanities Deans Association

CHAPTER ONE

FRAMES OF REFERENCE

1.1 OVERVIEW OF THE RESEARCH

As early as the eighteen century, human beings have been exploiting the earth resources in order to survive. During that time, they utilised the natural environment for a living and their activities generated solid waste (Mohee and Simelane, 2015; Wilson and Velis, 2014). The available space for the disposal of solid waste was large and the amount generated was relatively small, thus the generated waste presented no problem. When people began to live together in communities, groups, tribes and villages, solid waste management (SWM) started to become a problem. As the communities grew and expanded, the population increased and their activities generated more solid waste which ended up being a serious health and an environmental problem (Couth and Trois, 2011). Thus, the communities started to dispose solid waste in a manner that was suitable to their way of living. Strategies were developed to minimise the negative impact of waste on the air, water and land environment.

SWM has been one of the challenging, complex and cost-intensive public service, even when well managed. The increase in population, urbanisation and economic development produces increasing quantities of waste that are overburdening existing waste-management systems and infrastructure development. Most countries spent their highest share of municipality budget (20-50%) on SWM and of the budget (80-90%) is used for waste collection, transportation and disposal of municipal solid waste (MSW) (Scarlat et al., 2015; Wilson and Velis, 2014).

The increase in waste generation due to population growth, urbanisation, consumption of products and lack of appropriate infrastructure for waste collection has led to uncollected waste dumps which results in environmental and health problems (Mohee and Simelane, 2015). Integrated SWM strategies and the adoption of a waste hierarchy was seen as an alternative to systematically manage waste at the most resourceful and environmentally friendly manner (Chimuka and Ogola, 2015; Marshall and Farahbakhsh, 2013). Various municipalities viewed the basic management options: waste prevention, recycling, biological treatment, thermal treatment and landfilling as a hierarchical and not as an integrated waste management system (Mngoma et al., 2017). Despite the integrated approaches, theoretical frameworks and environmental efforts to reduce, recycle and re-use waste, there is still volumes of solid waste that needs to be landfilled. Hence, improvements in MSW management are needed to reduce the overall amount of waste generated and to recognise waste as a resource.

Waste-to-energy (WTE) technologies have been considered as one of the optimal methods to solve the waste management problem in a sustainable manner (Lombardi et al., 2015; Scarlat et al., 2015; Yi et al., 2018).WTE technologies are realised as an opportunity for energy recovery from MSW and a potential means of providing a sustainable and environmentally friendly solution to bridge the gap between energy and MSW. The energy content of MSW can be recovered by means of either (i) thermal conversion methods (incineration), (ii) biochemical conversion (anaerobic digestion), (iii) landfill (Tan et al., 2015; Kadir et al., 2013; Lombardi et al., 2015; Tozlu et al., 2016; Tsai, 2007; Onwosi et al., 2017).

Incineration is a direct combustion technology in which the feedstock is directly transformed into energy (Assamoi and Lawryshyn, 2012). Anaerobic Digestion is used to treat organic waste with the ability to recover energy in the form of biogas. In landfills, on the other hand, the organic fraction of MSW decomposes through an anaerobic digestion pathway (Onwosi et al., 2017).

Many developed countries have taken a step forward and implemented WTE technologies successfully as a measure of waste management as well as energy security(Vitorino de Souza Melaré et al., 2017). For instance, in 1990, the USA produced 394 trillion Btu of energy from MSW (Tozlu et al., 2016; Psomopoulos et al., 2009). Japan, at the end of 1991, consumed energy produced from 102 waste incineration plants(Forsyth, 2006). There are also WTE plants in Germany, China, and Canada (Baxter et al., 2016; Xin-gang et al., 2016; Abowei et al., 2009; Assamoi and Lawryshyn, 2012). The world is moving fast in implementing the WTE technologies which do not just help the countries with MSW management, but also with energy security. Therefore, the time is now for South Africa to take a step forward in the direction of sustainable MSW management practice.

Based on the above observations, this study evaluated the potential of MSW for electricity generation in the Gauteng Province, South Africa using landfill gas to energy (LFGT), Incineration (INC) and Anaerobic Digestion (AD) technologies. The technologies were selected in this study because they are the most preferable WTE technologies in existence today.

1.2 PROBLEM STATEMENT

The disposal of MSW is one of the most serious and controversial urban issues facing local government in the Gauteng Province (Simatele, et al., 2017). Urbanisation, population growth, societal lifestyle, development and consumption of products have led to diverse challenges for MSW in municipalities. Urbanisation directly contributes to waste generation and the increase in waste generation has overwhelmed the capacity of city authorities to provide adequate and equitable waste management services. However, landfilling has been treated as the best and preferred waste management disposal method in the province. It is estimated that the City of Johannesburg's landfills airspace will be completely depleted by the year 2023(Baker and Letsoela, 2016; Mbuli, 2015) and alternative waste management practices must be immediately realised. This projection becomes a motivation for the identification of suitable WTE alternative avenues to manage waste in the city.

Currently, recycling and separation at source are viewed as alternative methods of reducing the amount of waste going to landfills. However, with the volume and composition of MSW generated in the urban cities of the Gauteng Province, recycling and separation at source are not compatible methods (Baker and Letsoela, 2016). It is, therefore, high time that WTE technologies are realised to manage the volumes of waste that is generated in the urban cities since landfills are operating at full capacity.

On another note, South Africa is still largely addicted to coal-based electricity, yet the supply of coal is decreasing. The recently released electricity, gas and water supply industry report for 2016 shows that fossil fuel generated 85,7% of the country's power in 2016, followed by nuclear power (5,2%) and natural gas (3,2%). Due to the rapid depletion of fossil fuel reserves, MSW should be treated as an alternative source of energy to mitigate future energy crisis. This potential can be evaluated through the realisation and evaluation of WTE technologies. It is the time to realise the potential of WTE technologies as an option for sustainable SWM and as one of the most significant future renewable energy sources, which is economically viable and environmentally sustainable. Most of the studies concentrated only on landfill gas in determining the energy and gas emissions potential of MSW (Dada and Mbohwa, 2016; Bhailall et al., 2016; Mbav et al., 2012; Fourie and Morris, 2004. However, there is limited information on the potential contribution of the WTE technologies (LFGT, INC and AD) to electricity generation, environmental impact assessment and air emission profile in the Gauteng province.

WTE technologies have been presented as one of the avenues to improve the management of solid waste whilst promoting clean and healthy urban environments through the recovery of waste and generation of energy. This study was, therefore, undertaken to gain an understanding of the technological options of WTE technologies for effective management of MSW in the Gauteng province and to pave a way towards finding a sustainable WTE technology for each municipality. In view of the above observations, this study was guided by the following research questions:

I. How successful are WTE technologies in the Gauteng Province?
II. How much methane and electricity is produced by MSW in each municipality?
III. Are WTE technologies economical and environmentally viable?
IV. What are the environmental impacts of WTE plants?

1.3 RESEARCH AIMS AND OBJECTIVES

The aim of this study was to evaluate WTE technologies in the generation of electricity from MSW in municipalities within the Gauteng Province. It was also to undertake a holistic assessment of WTE technologies to find a suitable technology that can improve the management of solid waste whilst promoting clean and healthy urban environments through the recovery of waste.

The specific objectives are:

I. To present a review of the literature on WTE technologies and the success of the technologies in the Gauteng province.
II. To estimate the methane emission potential and the electricity generation potential of MSW in each municipality.
III. To evaluate the economic viability of the WTE technologies in the context of each municipality.
IV. To estimate the gas to air emission of WTE technologies and the contribution of the gases to global warming.
V. To carry out comparisons of the WTE technologies with the intention of determining the best technology option for each municipality and the Gauteng province.

1.4 JUSTIFICATION AND SIGNIFICANCE OF THE STUDY

The Gauteng province is currently in search of a better strategy to improve the management of solid waste whilst promoting clean and healthy urban environments through the recovery of waste and generation of electricity. Scholarly research on WTE technologies and MSW in the Gauteng Province is limited**.** It is time that WTE technologies requires research attention to shed more light on the issue of MSW management and to pave a way for a solution. Nevertheless, academic research in WTE technologies includes a paper by (Dowling et al., 2012b) which presented an analysis of energy generation potential of landfill sites in Cape Town area in South Africa and economic analysis of landfill gas to energy systems which might be developed using landfills. Apart from this, there are a few studies that dealt with the technical, economic, and environmental assessment of deploying a landfill gas to energy generation system, which includes (Mbav et al., 2012) an article on the feasibility and cost optimization study of landfill gas to energy projects based on a Western Cape landfill site in South Africa; (Bhailall et al., 2016)an article on landfill gas emissions and the associated air quality, energy and climate change implications in South Africa; (Omar and Mncwango, 2005)reviewed the potential uses of sanitary biogas, and the possibility of harnessing biogas from the Bellville South Municipal Landfill (within the City of Cape Town, South Africa); (Dada and Mbohwa, 2016) focused on the type of waste generated from the City of Johannesburg, the potential biomethane that could be produced from the organic wastes, waste collection methods around the city before disposal on landfills within the City of Johannesburg and investigated the energy generation from waste as a better waste management technique; (Fourie and Morris, 2004) measured gas emissions from four landfills in South Africa and some implications for landfill design and methane recovery in semi-arid climates.

Most of the aforementioned scholars have concentrated only on landfill gas in determining the energy potential and gas emissions potential of MSW. However, there is limited information on the potential contribution of the WTE technologies (LFGT, INC and AD) to air emission profile in the Gauteng province, the potential of WTE technologies for electricity generation and its environmental impact assessment. This study evaluated nine municipalities in the Gauteng Province in terms of their methane and electricity generation potential, economic viability, global warming potential, acidification potential and dioxin/furan emission potential. The information in this study could be useful to policy makers, researchers, and industrial energy users. It is expected that the results presented will create awareness on the potential of WTE technologies in MSW management and electricity generation in the Gauteng province and could lead to optimum WTE investment in the country.

1.5 METHODOLOGICAL APPROACH

This section outlines the research methodology that was employed in the study. To determine the electricity generation potential of WTE technologies in each municipality within the Gauteng province, the quantity and composition of waste was estimated. The quantity of waste generated in the municipalities is a function of population and the waste composition. Therefore, the quantity of the MSW generated was calculated using the 2011 census population and interpolated to 2016 based on a 3.1 % growth rate and the per capita generation in each municipality. Figure 1.1 shows the municipalities under study.

Source: Cartography Unit, 2019. School of Geography and Environmental Studies

Figure 1.1: Municipalities under study – Gauteng Province

Landfill gas is produced because of a sequence of physical, chemical, and biological processes occurring within a landfill. The potential of landfill gas to generate electricity depends on its methane generation potential. In this study, US EPA Landfill Gas Emission Model (LandGEM) was used to estimate methane generation for each year from cumulative waste disposed up through a year within the municipalities in each province. According to (Cherubini et al., 2009) LandGEM is a single phase automated user interface tool for estimating total landfill gas, methane and carbon dioxide and non-methane organic compounds from MSW landfills using the total annual disposed wastes during the operation of the site. LandGEM predicts the landfill gas emissions based on a first order decay equation, which assumes that the methane generation rate reaches its peak shortly after the initial waste is placed and decreases exponentially after that (USEPA, 2006). The estimation of GHG emissions from a landfill requires significant input parameters such as landfill opening year, design capacity of landfill or landfill closure year, methane generation rate, methane generation potential and waste acceptance rates(USEPA, 2006). In this study, the LandGEM waste model was chosen as it requires a small amount of data input but provides an estimation of the evolution of cumulative landfill gas emissions over time.

Secondly, the study adopted the Intergovernmental Panel on Climate Change (IPCC) methodology in estimating methane emission, energy recovery, economic and environmental benefits of methane capture from Marie Louse landfill and Robinson Deep landfill in the City of Johannesburg municipality. The IPCC developed a multiphase model in the year 2006 for the estimation of methane generation for specific sites. It formulated guidelines and provided methods for estimating methane emissions from solid waste disposal. It can be used either with default values or site-specific data pertaining to waste generation rates, the composition of waste, degradable organic carbon, the fraction of degradable organic carbon dissimilated, waste decay rate, methane correction factor, landfill gas collection efficiency and oxidation factors(IPCC, 2006). The IPCC model, similar to the LandGEM model, uses a first-order decay equation but instead of methane generation capacity, the IPPC model uses the fraction of degradable organic carbon and default values for methane generation for the different waste categories, for example, food, garden and paper (IPCC, 2006). Therefore, the IPCC model and the LandGEM model were used to predict the methane emissions during the study

Lastly, this study applied the life cycle assessment (LCA) methodology. LCA is one of the most developed and widely used environmental tools for comparing alternative technologies on the basis of their consumptions and potentially harmful emissions(Cherubini et al., 2009). It is a tool for comparing technologies in general, whereas other tools like Environmental Impact Assessment are appropriate for siting decisions (Chandler, 2007). LCA quantifies the number of materials and energy used and the emissions and waste over the complete supply chain (life cycles) of goods and services (McKay, 2002). It is an excellent framework for evaluating MSW management strategies. Many of its application in this study is focused on the use of the LCA methodology as a decision support tool in the selection of the best WTE technology (from an environmental point of view) in the Gauteng province. LCA is widely used in a range of countries including Italy, Spain, Sweden, Germany, USA, Singapore and China (Tsai and Chou, 2006; Chandler, 2007; Tascione, 2011; Psomopoulos et al., 2009; Gómez et al., 2010; Xin-gang et al., 2016; Cherubini et al., 2009).

LCA's are now standardized through the ISO14000 standards (ISO, 2006a; ISO, 2006b). The international standard ISO 14040-43 defines LCA as a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (Zaman, 2010). The structure of a LCA consists of four distinct phases, which contribute to an integrated approach:

I. Goal and scope definition, which serves to define the purpose and extent of the study, to indicate the intended goal and describes the system studied as well as the options that will be compared.
II. Inventory analysis which focuses on the quantification of mass and energy fluxes.
III. Impact assessment aims at understanding and evaluating the magnitude and significance of potential environmental impacts of a system.
IV. Interpretation evaluates the results from the previous phases in relation to the goal and scope to reach conclusions and recommendations.

Four different waste management scenarios were evaluated in this study, namely scenario 1 - landfill (LF), scenario 2 - landfill with energy recovery (LFGT), scenario 3 - incineration with anaerobic digestion (INC with AD) and scenario 4 - incineration with landfill with energy recovery (INC with LFGT). The research framework was divided into 5 processes which are: WTE assessment, electricity generation potential, greenhouse gas emission potential, acidic pollution and organic pollution. A research framework explaining the methodology is illustrated in Figure 1.2 and Figure 1.3.

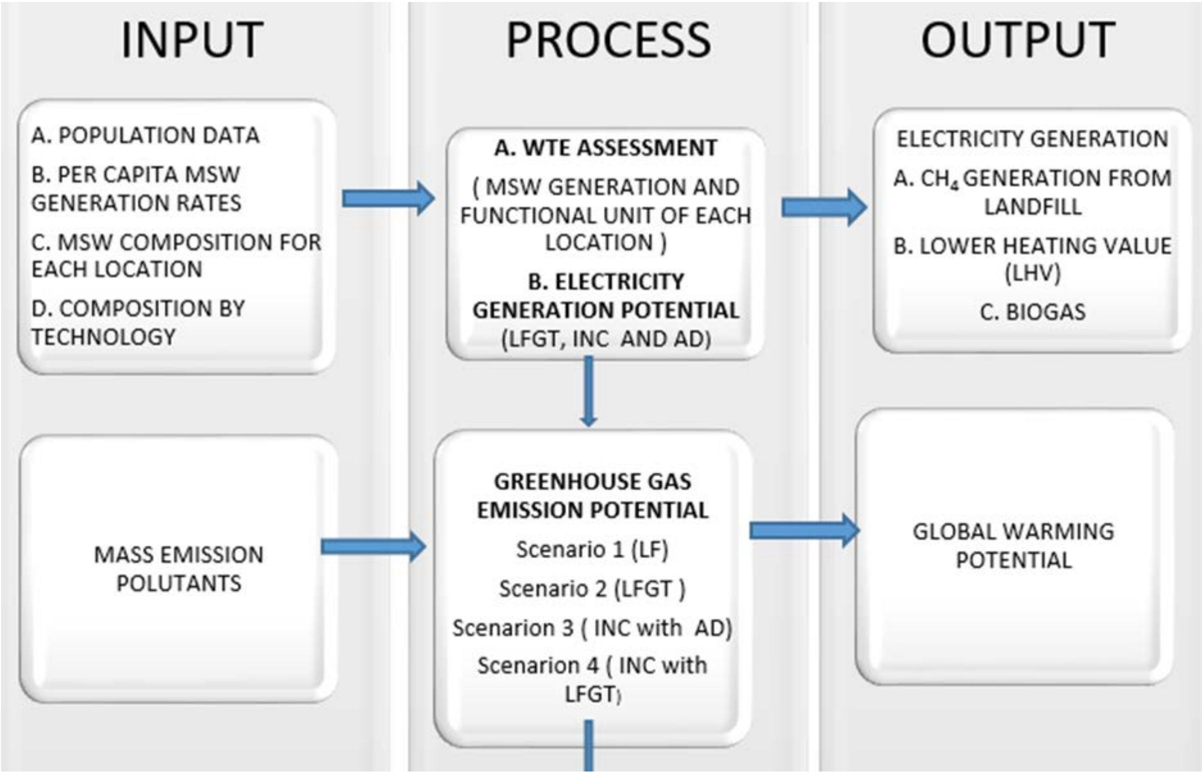

Figure 1.2: Research methodology framework proposed in this study

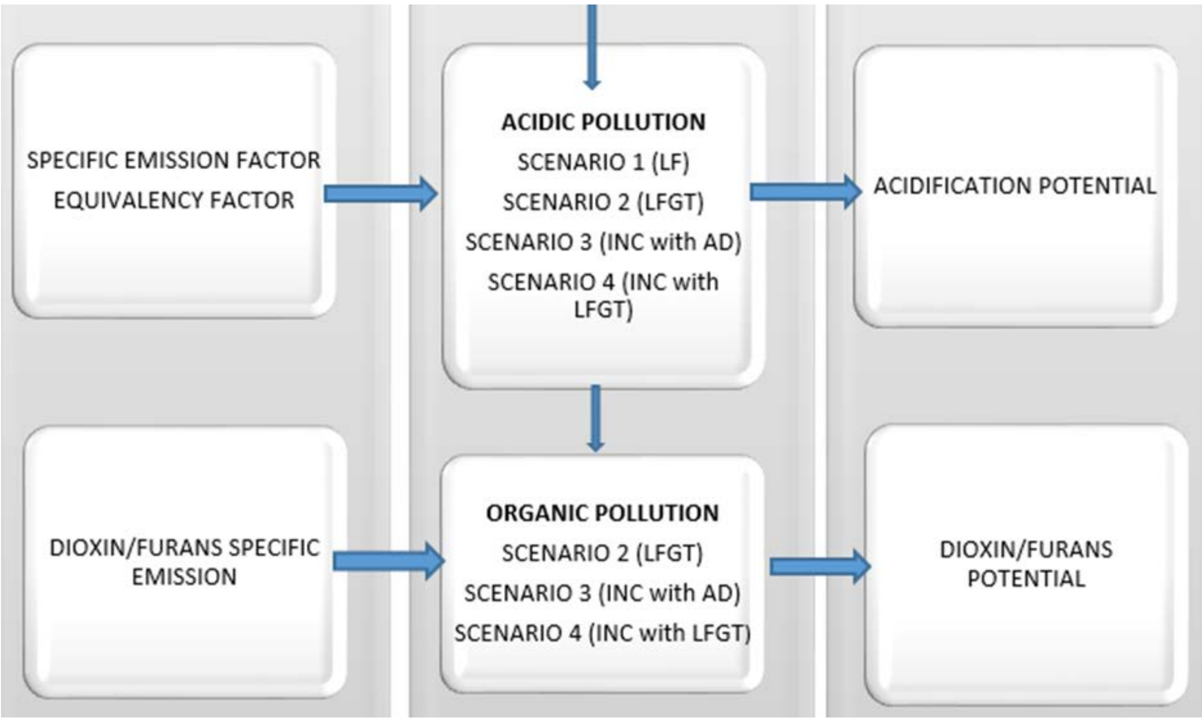

Figure 1.3: Continuity of a research methodology framework proposed in this study

The input data to achieve WTE assessment is the population data in each municipality, per capita MSW generation and MSW composition. Secondly, the input data for greenhouse gas emission potential are the gas emission pollutants and the output is global warming potential. Thirdly, the input data for acidic pollution is the specific emission factor equivalency and the output is the acidification potential of each WTE technology. Lastly, the input data for the organic pollutants are the dioxins specific emission from each scenario, and the output is the potential of each WTE technology to emit dioxin.

1.6 STRUCTURE OF THE STUDY

This thesis is by publication. The first chapter is a frame of reference which starts with the introduction, the problem statement, the research aim and objectives, the justification and significance of the study. It also presents the methodology and structure of the study. The second chapter is a literature review. It presents the paper that was published based on MSW management in South Africa: from waste to energy recovery through waste -to - energy technologies in the Gauteng province. The paper particularly contributes to our understanding of WTE technologies and its potential on MSW in the province. The third chapter estimates the methane emission, energy recovery, economic and environmental benefits of methane capture from Marie Louse landfill and Robinson Deep landfill in the City of Johannesburg municipality using the IPPC methodology. The fourth and the fifth chapter focuses on the application of the US EPA Landfill gas emission model (LandGEM) and the life cycle assessment (LCA) of WTE technologies as methodological imperatives to estimate methane, electricity generation potential, economic viability of WTE technologies for MSW management and the environmental impact assessment of WTE technologies in each municipality within the Gauteng province. The sixth chapter draws synthesis and conclusions of the study followed by recommendations.

CHAPTER TWO

Municipal Solid Waste Management in South Africa: From Waste to Energy Recovery through Waste-to-Energy Technologies in the Gauteng Province.[1]

ABSTRACT

WTE technologies have been presented as one of the avenues to improve the management of solid waste whilst promoting clean and healthy urban environments through the recovery of waste and generation of energy. Research suggests that with the right investment in technologies and institutional changes, waste can potentially become a resource that can contribute to the socio-economic development of cities. It is in this context that this paper presents a review of the literature on WTE technologies and their implications on sustainable waste management in urban areas. The paper particularly contributes to our understanding of WTE technologies and its potential on Municipal Solid Waste Management (MSWM) in the Gauteng province. It is estimated that the City of Johannesburg's landfills airspace will be completely depleted by the year 2023. This projection becomes a motivation for the identification of suitable WTE alternative avenues to manage waste in the city. The paper argues that WTE technologies can contribute significantly to sustainable waste management, economic growth, ecological and environmental well-being.

Keywords*: Solid Waste Management; Waste-to-energy technologies; Johannesburg; South Africa*

[1] This chapter has been published in its current form: Smangele Dlamini, Mulala Danny Simatele & Nzalalemba Serge Kubanza (2019). Municipal solid waste management in South Africa: from waste to energy recovery through waste-to-energy technologies in Johannesburg, *Local Environment*, 24:3, 249-257, DOI:10.1080/13549839.2018.1561656.

2.1. INTRODUCTION

African countries have, over the past years, experienced high rates of population growth as a result of increased rural-urban migration, industrialisation and urbanisation as well as improvements in production processes and standards of living (Kofoworola, 2007; Mohee and Simelane, 2015; Chimuka and Ogola, 2015). These changes have been accompanied by increased environmental challenges among which include amplified solid waste generation. Sub-Saharan African (SSA) countries, like other developing countries, have been affected greatly by rapid urban population growth, migration to urban areas and industrialisation a combination which contributed to urbanisation, particularly during the 19th century, causing unprecedented demands on municipalities to provide waste management services such as waste collection (Mohee and Simelane, 2015; Wilson and Velis, 2014). The lack of financial resources, weak institutional and policy framework have unfortunately made it difficult for local authorities to effectively manage solid waste (Liyala, 2011; Simatele and Etambakonga, 2015; Simatele et al., 2017). This has placed many local authorities under immense pressure to provide efficient and effective municipal waste management services (Mutanga et al., 2013; Muzenda et al., 2012).

The ability of local authorities to provide effective waste management services have been made worse by the deterioration in the solid waste infrastructure and the increase in waste generation (Couth et al., 2011; Karani and Jewasikiewitz, 2007; Friedrich and Trois, 2010). Karani and Jewasikiewitz (2007), supported by Muzenda et al., (2012) for example, observe that in South Africa, particularly in the City of Johannesburg, authorities are struggling to implement effective and sustainable systems for waste management. An increase in the middle class citizens have increased the rate, complexity of the waste flow and the amount of waste generated (Muzenda et al., 2012). In view of the above state of affairs, this paper argues that effective and sustainable waste management strategies must be realised in order to contribute to the advancement of the MSWM system.

WTE technologies have been presented as one of the avenues to advance SWM while promoting clean and healthy urban environments through the recovery of waste and generation of energy. It is estimated that nearly 800 thermal WTE projects are functioning in almost 40 countries globally and that 11% of the MSW that is treated generates up to 429 TWh of power (Tozlu et al., 2016; Johari et al., 2012; Tan et al., 2015). Tan et al., (2015) for example, have pointed out that with the right investment in technology and institutional changes, waste can potentially become a resource that can contribute to the socio-economic development of cities and countries.

WTE technologies extract usable energy stored in the organic portion of MSW to produce heat or electricity through thermal and biological processes (Brunner and Rechberger, 2015). This entails recovery through LFGT, INC and AD of the separated biodegradable fraction of waste (Al-Salem et al., 2014). Based on this observation, this paper recognises LFGT for the generation of electricity on the already operating and existing landfill sites, incineration process for non-recyclable waste and anaerobic digestion for separated biodegradable waste. These approaches can be considered as innovative technologies that could potentially be considered in the Gauteng province in order to enable cities to take advantage of the benefits of electricity contained in waste.

The paper highlights that the success achieved in other countries that have adopted waste to energy technologies may be essential in providing lessons for the province to adopt similar technologies. As noted by Baker and Letsoela (2016), the deployment and use of LFGT, INC and AD technologies has considerable potential to address a number of emerging challenges in waste management in the province, while generating electricity and mitigating greenhouse gas emissions.

Many studies in MSWM in sub-Saharan African cities have focussed on aspects and challenges of SWM, especially in waste collection and recycling (see Simatele et al., 2017, Baker and Letsoela, 2016; Mbuli, 2015). Little or no significant attention has been paid to understanding WTE technologies that can improve MSWM, particularly in the Gauteng province. The province has experienced tremendous increases in urban growth and waste generation(Chimuka and Ogola, 2015). While technologies for transforming WTE have been adopted and implemented for commercial purposes in developed countries such as Japan, China, USA and Germany, South Africa is yet to adopt these technologies and capture the benefits that they offer (Baker and Letsoela, 2016; Mbuli, 2015). Chimuka and Ogola (2015) and supported by Simatele et al., (2017) observe that the lack of funding and the absence of an enabling institutional and policy framework, as well as the none availability of data have combined to negatively impact the adoption and implementation of modern WTE technological solutions. There is therefore, an urgent need for the local authority in the province and its agencies as well as interested stakeholders to identify avenues through which increased adoption of modern waste management technologies can be harnessed in order to realise other economic uses of solid waste. The lack of technical know-how has resulted in compromising the WTE technologies that can achieve a zero-waste concept and sustainable waste management. Ideas on WTE technologies as a potential new innovation in the sustainable management of MSW have been limited to discussions only in policy boardroom conversations (Scarlat et al., 2015).

In view of the above observations, this paper therefore, presents a review of the literature on WTE technologies that can improve MSWM in the Gauteng province, South Africa. It is estimated that the City of Johannesburg's landfills airspace will be completely depleted by year 2023 (Baker and Letsoela, 2016), therefore, it is paramount that new technologies be realised in order to achieve sustainable waste management. The paper firstly presents an introduction that elucidates scenarios in SWM and WTE technologies, followed by a literature review on WTE technologies in developing countries. The remaining sections provide an understanding of SWM and WTE technologies using the City of Johannesburg. The conclusion highlights that the implementation of appropriate technologies in managing MSW can foster changes that will address SWM challenges within the province.

2.2. MUNICIPAL SOLID WASTE MANAGEMENT AND WTE TECHNOLOGIES

The increase in the rate of MSW generation in African countries has been worsened by an increase in urbanisation, rapid population growth, rural-urban migration and industrial growth (Mohee and Simelane, 2015; Karani and Jewasikiewitz, 2007). Effective conversion of MSW is a sustainable innovative way of providing effective management solutions to close the gap between MSW and energy supply. A review of existing literature such as the work of Ogunjuyigbe et al., (2017) and Moya et al., (2017) reveal that depending on the waste composition and moisture content, energy contained in the organic portion of MSW can be extracted through two pathways to produce heat or electricity. According to Ayodele et al., (2017) and Ogunjuyigbe et al., (2017), the first pathways is the bio-chemical conversion method whereby organic components of waste in the presence of oxygen and without oxygen is biologically decomposed to produce compost or energy, for example, AD and LF. The second pathway is the thermo-chemical process that produces heat energy or gas, for example, INC. Much of the available literature on WTE technologies provide that due to the high moisture content and bio-degradable organic matter, the bio-chemical conversion is the most preferred option in MSWM (Moya et al., 2017 and Ayodele et al., 2017). Similarly, Tozlu et al., (2016) agreed that methane in the bio-chemical process can be used through AD. AD is the biological decomposition of organic matter in waste under the influence of microbes in an oxygen deficient environment. They further highlight that the methane is used as fuel during electricity generation to power combustion engines. Likewise, Moya et al., (2017) hold the view that AD controls GHG emissions, less land is needed, is a small-scale project and no power is required during operation. However, this process is not compatible with waste in less organic matter.

Research studies conducted in sub-Saharan African cities estimate that more than 500 million people do not have electricity and depend mostly on firewood, coal and agricultural residue to cater for their energy requirements (Couth et al., 2011; Friedrich and Trois, 2013). Chimuka & Ogola (2015) and Friedrich & Trois, (2010) also reviewed the literature and found out that renewable energy from AD technology carries great potential to solve the energy problem in sub-Saharan African cities and can be regarded as a technology that will ease the energy and environmental problems. However, there is evidence to indicate that countries such as Sudan, Ivory Coast and Tanzania have advanced biogas plants – albeit with only a few being operational due to poor reliability, weak performance and poor technical quality as biogas production plants have a short life-span(Omer and Fadalla, 2003; Walekhwa et al., 2009; Akinbami et al., 2001). The evidence presented by these scholars suggests that marketable development and comprehensive AD advancement is still considered to be in its infancy, but it has immense potential. It has been observed that to improve the development of large-scale anaerobic technology in countries such as Botswana, Burkina Faso, Cameroon, Ethiopia, Malawi, Namibia and Sudan, there is a need to introduce more efficient bioreactors(Gumbo and Simelane, 2015). Considering all of this evidence, AD technology has proven to be a sustainable approach for the treatment of organic solid waste (Cucchiella et al., 2014; Staniskis, 2015; Moya et al., 2017). Sustainable management of solid and organic waste, while allowing the recovery of useful by-products and renewable biofuels offers significant environmental benefits. This paper asserts that this technology will alleviate the problem of energy insecurity and limit greenhouse gas emissions, thereby contributing to the fight against climate change.

In view of the above, Ogunjuyigbe et al., (2017) observe that low moisture content waste and non-biodegradable waste are suitable for thermo-chemical process through INC and LFGT technologies. They elaborate that INC is accepted and a widely used technology in countries around the world and it generates both heat and electricity. Yi et al., (2018) and Ogunjuyigbe et al., (2017) together with Couth et al., (2011) define the INC technology as a process in which MSW is burnt in an excess supply of oxygen in a furnace to produce heat or electricity. A review of the literature indicates that incineration-based technologies produce high amounts of energy as compared to AD (Kadir et al., 2013). A number of studies have pointed out that the main rationale for using INC for MSW management is to reduce the volume going to landfill by at least 95% (Baxter et al., 2016; Tozlu et al., 2016; Eriksson and Finnveden, 2017). However, Omer and Fadalla (2003) argue that since there is still a fair quantity of ash that needs to be taken care of as safely as possible, and which is often disposed of in landfills, as well as some gas emissions that escape into the strata of the atmosphere, this method should not be considered as a disposal option. Tan et al., (2015) and Kadir et al., (2013) are of the view that in terms of waste reduction potential, thermal treatment of waste should be considered more, since around 80% to 90% of the volume of the waste is reduced during this process. In a different vein, Scarlat et al., (2015) and Chimuka & Ogola, (2015), for example, highlight that in sub-Saharan African countries, technical expertise and specific repair and maintenance technology are often scarce and absent. Likewise, Moffet et al., (2008), Ferreira et al., (2000) and Sharholy et al., (2008) hold the view that incinerators have been shut down in many cities around the world, including Mexico City, Sao Paulo and New Delhi owing to their high repair and maintenance costs and related environmental problems. This view is supported by Ayodele et al., (2017) and Ogunjuyigbe et al., (2017) who observe that neither incineration nor any other thermal treatment is practised in Nigeria, with the exception of hospitals, where medical waste is incinerated on a small-scale basis. This paper asserts that fears of emissions are exaggerated because all incinerators have to abide by local environmental regulations and existing literature has shown that an incineration plant is provided with air pollution control equipment such as spray dryer for acid gas control, injection of activated carbon for mercury control , ammonia or urea injection by means of selective catalytic for reduction of nitrous oxide control, and a fabric filter for particular matter control (Ayodele et al., 2017; Ogunjuyigbe et al., 2017).

Scholars also found that LFGT of MSW has been practiced in many developed nations in an effort to promote sustainable development initiatives and it is a less expensive option that requires a minimum number of skilled personnel and the gas that is produced can be used for energy generation (Kadir et al., 2013; Tan et al., 2015; Brunner and Rechberger, 2015). Tan et al., (2015) observe that there are problems associated with landfill gas recovery technology, for example the surface run off causes pollution and the leachate causes soil and ground water pollution. This technology also requires large open tracts of land and it has a high risk of methane explosions and high transportation costs.

Despite the success in the implementation of WTE technologies in many countries of the world, there are challenges associated with WTE technologies. The main challenging areas are operating costs, public perception and acceptance, legislations and institutional frameworks associated with the regulation of the WTE technologies (Kadir et al., 2013; Forsyth, 2006; Chimuka and Ogola, 2015). Literature suggests that the lack of technical skills, absence of financial support, unreliable data, limited waste collection vehicles and inaccessible roads and lack of infrastructure have limited the adoption of WTE technologies in different countries of the world (Guerrero et al., 2013; Tozlu et al., 2016). In Malaysia, for example, incinerators have been put on hold due to the high operational costs arising from fuel costs and maintenance costs (Johari et al., 2012). The implementation of the incineration project, for example, faced many challenges which included unsuitability technology for high moisture content waste incinerators and protests by local residents. The opposition of WTE technologies has been mostly based on the health risks and emissions of toxic organic compounds, metals from stack and complications caused by disposal of inorganic residue (Kadir et al., 2013). This paper, therefore, argue that toxic emissions (dioxin and furan) are significantly lower in concentration compared to other processes which are deemed safe (for example, sewage processes).

2.3. OVERVIEW OF MUNICIPAL SOLID WASTE AND WTE TECHNOLOGY IN THE CONTEXT OF JOHANNESBURG, GAUTENG PROVINCE

In South Africa, there has been an increase in urbanisation, population, industrialisation and modernisation (Simatele et al., 2017; Fourie and Morris, 2004; Mohee and Simelane, 2015). The combination of these processes has increased the waste generation potential and electrical energy demands and has resulted in increased environmental pollution and energy poverty. According to the National Waste Information Baseline (NWIB), South Africa generated approximately 108 million tonnes of waste in 2011, consisting of 59 million tonnes of general waste at a rate of 0.2 – 1.29 kg/capita/day. The City of Johannesburg with an area of approximately 1646 km^2 and a population of over 4.3 million is the leading city as far as waste generation is concerned. It is the commercial and economic hub of South Africa and contributes approximately 47% to the provincial economy and 17% toward national economic growth (Mbuli, 2015 and Dowling et al., 2012). Similar to most developing cities, MSW is commonly landfilled, dumped and burnt in open spaces (Dada and Mbohwa, 2016; du Toit et al., 2017). The waste management practices consists mainly of waste collection, recycling and landfilling (Friedrich and Trois, 2010; Mohee and Simelane, 2015).

According to the literature on WTE technologies in the City of Johannesburg, efforts have been made to embark on WTE projects. The city entered into an agreement with EnerG Systems Joburg (Pty) Ltd to construct and operate landfill gas to electricity projects at no cost to the city for a period of 20 years (Baker and Letsoela, 2016). Through the implementation of the Clean Development Mechanism (CDM) project, the city contributes to the country's realisation of the Kyoto Protocol commitments and generates revenue from the sale electricity and Certified Emission Reductions (CERs). According to (Baker and Letsoela, 2016), the electricity from the project can power approximately 12 500 middle income households.

In 2016, the Robinson Deep landfill gas recovery began generating 3 megawatts (MW) of renewable electricity enough to supply more than 5 500 homes. In Goudkoppies and Marie Louise landfill sites, the gas collected is being flared and installation of gas collection system and a generator is underway, each site will generate 3MW of electricity that will be fed to the City Power electricity grid (Baker and Letsoela, 2016). An average of 1756m^3/h of landfill gas has been recovered and flared at Marie Louise landfill site since May 2011 and May 2012 respectively which would have been emitted to the atmosphere as a harmful greenhouse gas. This is expected to increase as more of the wells are installed for gas collection in preparation for energy generation. During its operation, the project has so far accumulated 243 859 certified emission reductions (carbon credits) and will reduce GHG emissions by 60-70%(Baker and Letsoela, 2016; Mbuli, 2015).

As stated that landfilling is currently the more viable option for the disposal of MSW, and even though recycling and re-use helps to reduce the amount of waste deposited into landfill which has the dominant gas, methane, and has a global warming potential 23 times than that of carbon dioxide, landfill provides the least cost and inefficient option for disposal of waste(Tan et al., 2015). In view of the above observations, this paper establishes that landfill sites should continue to be considered as an alternative source of energy generation, as 90% of the MSW is currently landfilled (Baker and Letsoela, 2016). The alternative LFGT would provide a potential to recover electricity from the waste stream, which complete landfilling would not allow.

Despite the aforementioned development in LFGT is concerned, there is still no large-scale commercial WTE project for electricity generation either by INC or AD technology. In addition to LFGT, this paper suggests that technologies for the incineration of non-recyclable waste and anaerobic digestion of separated biodegradable wastes should be considered to generate electricity and broaden MSW management options within the province. INC technology will help treat non-recyclable waste that will be landfilled if it is not taken into account. In the same way as AD technology, separated biodegradable waste would not need to be landfilled, which would reduce the volume of MSW going to the landfill. Such WTE solutions will not only unlock the value in waste by generating electricity, but also will benefit the economy by generating revenue, create jobs and reduce fuel cost for end users as well as will reduce waste going into landfills and it will also protect the environment. The realisation of the WTE technologies will also increase landfill airspace up to 2030 and also result in 93% waste diversion from the landfill (Baker and Letsoela, 2016).

Despite the progress in terms of landfill gas recovery, utilising MSW for WTE technologies still faces many challenges which include, lack of a regulatory framework, no roadmap on WTE projects, difficulty attracting adequate capital investment for WTE projects, limited demand for WTE conversion technologies and products over alternatives, low investment on infrastructure and WTE technologies, inadequate human capacity and technical know-how, fear of cost recovery, challenges in shifting attitudes of public from landfilling method to resource recovery and towards innovative strategies, poor planning and inadequate data to support decision making on WTE technologies, uncontrolled landfill sites, low convincing academic research on WTE technologies and lack of political will from the government(Baker and Letsoela, 2016; Dowling et al., 2012b; Mbav et al., 2012; Fourie and Morris, 2004; Couth and Trois, 2012).

In the face of the WTE technologies' challenges, there is a question of political will, weakness and commitment of waste authorities in government institutions. Departments in the waste institutions that are tasked for waste management activities in the urban spheres do not have the capacity to coordinate their waste activities and ideas on selected projects (Simatele et al., 2017). Due to a lack of monitoring exercises, many projects fail and this results in wasteful governmental expenditure. Simatele et al., (2017) observe that there is a multiplicity of waste agencies that can deliver and implement waste management services, but there is no coordination between and amongst them. This paper argues that corruption and the lack of effective management systems have contributed to the mismanagement of waste in the province. The high levels of corruption and lack of coordination between departments have pushed the city to drown in piles of uncollected waste dumps along streets.

In order for the above challenges not to occur there is a need for improvements in urban corporative environmental governance systems. Scholars argue that waste management policies and the choice of WTE technologies need to include the participation of local people (Simatele et al., 2017; Muzenda et al., 2012; Scarlat et al., 2015). This concept allows local people to participate in technology and environmental decisions through partnerships with the state (Forsyth, 2006). It also seeks to consult the local people in the selection and implementation of a technology (Dada and Mbohwa, 2016). Cooperative environmental governance will, therefore, result in the increased interaction amongst the government, NGOs and the private sector and networks would be established between cooperatives, associations and small enterprises (Chimuka and Ogola, 2015).

Despite this potential, critics have however urged greater attention to the extent cooperative environmental governance can actually achieve local participation. Forsyth (2006), for example, observed that local participation may be undermined by influential leaders that are members of both state and local groups. Arguing from the above observation, this paper suggests that the participation of local people in decision making is meaningless unless there is attention on how both technology choices and participation are framed, and by whom they are framed.

There is also a need for the government departments to be holistically involved in critical long-term planning and strategic thinking in order to adequately address current, emerging and projected WTE technologies. This paper argues that a project inception and feasibility study aligned with key priorities must be conducted on WTE technology options. A risk management exercise must be carried out for public acceptability, waste characterisation and caloric value, technology, financial risks (affordability and value for money) and environmental requirements. Gaps in the feasibility study must be noted and a treasury must review and recommend the WTE technology project. Before a procurement process, funding from external sources must be secured. A transactional advisor, steering committee and partners and citizens must be consulted. An appointed service provider must carry out an environmental impact assessment process so that the project can be issued with the required waste licence.

2.4. SUMMARY AND CONCLUSION

This paper presented an understanding of WTE technologies that can improve MSWM and provides an overview of MSW and WTE technologies in the context of the Gauteng province. It is estimated that the City of Johannesburg's landfills airspace will be completely depleted by year 2023. This projection becomes a key motivation for the identification of suitable WTE alternative avenues to manage waste in the province. However, efforts have been made by municipal authorities to embark on WTE projects. Currently, the city generates electricity through the LFGT to already existing and operating landfill sites. Therefore, this paper suggests that, besides landfill gas recovery, alternative measures such as the INC technology for non-recyclable waste and AD of separated biodegradable waste should be considered to generate electricity and broaden options for waste management in the province. It is argued in the paper that INC and AD technologies will reduce the amount of waste going to landfill, as biodegradable and non-recyclable waste will be diverted from landfill, which will increase the airspace of the landfill until 2030 with a 93% diversion of waste, potentially to earn carbon credits, create jobs and generate renewable electricity as well as revenue from the sale of by-products.

CHAPTER THREE

The potential of municipal solid waste for energy generation in Johannesburg, South Africa.[2]

ABSTRACT

Solid waste management has become a challenge for urban authorities rather than being a resource for electricity generation in Johannesburg, South Africa. This challenge has been compounded with deficiencies within the institutional and policy frameworks, as well as increased generation of waste owing to the rapid urbanisation process that the city has experienced in recent years. Using secondary data collected through archival record and existing literature, it is argued that the inability for urban authorities to effectively manage MSW has delayed the implementation of sustainable WTE technologies in Johannesburg. As a result, urban authorities have now become overwhelmed by the depletion of the available landfill airspace at the Robinson Deep and Marie Louise landfill sites, estimated to the year 2021 and the magnitude in the generation of waste in the city. The study adopted the Intergovernmental Panel on Climate Change (IPCC) methodology in estimating methane emission, energy recovery, economic and environmental benefits of methane capture from the Robinson Deep and Marie Louise landfill sites. Methane emissions in 2017 was 335 400 tonnes, 321 200 tonnes in 2018 and projected to 435 800 tonnes by 2020, equivalent to 2.37×10^9 kWh, 2.27×10^9 kWh and 3.08×10^9 kWh of electricity with revenues of ZAR2135.36 million, ZAR2045.45 million and ZAR2774.72 million, respectively.

Keywords: *Municipal solid waste, Landfill gas to energy, Methane emission, Economic benefit, Johannesburg and South Africa*

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3.1. INTRODUCTION

Municipal Solid Waste Management (MSWM) presents an ever increasing burden and a challenge for urban residents and authorities in the Gauteng province (Chimuka and Ogola, 2015; Oteng-Ababio et al., 2013). The trajectory of this state of affairs has in part been attributed to the increase in population growth and urbanisation which tends to increase the demand on urban services (Dada and Mbohwa, 2016). As cities continue to grow, there is a decline in MSWM activities, depletion of landfill airspace, drastic deterioration in infrastructure and urban services (Ahmed and Ali, 2004). The decline, for instance in the provision of waste collection services, road maintenance, drainage systems maintenance, electricity and water supply have in a large way affected urban productivity and the overall well-being of urban residents (Simatele et al., 2017). In the urban communities, for example, the collection is inadequate and residents cope with heaps of uncollected waste. The uncollected heaps of waste turn out to be dumping spots and this attracts diseases and serious health and environmental hazards to the local communities (Kubanza and Simatele, 2015; Simatele and Etambakonga, 2015). The combination of the above-mentioned challenges has recently put more pressure on city authorities to search for sustainable municipal waste management interventions (Oteng-Ababio et al., 2013).

Landfill gas to energy technology (LFGT) have been identified as an avenue through which municipal solid waste (MSW) can be used as a resource to generate electricity as well as to reduce the pressure being exerted on landfills in the City of Johannesburg (Chimuka and Ogola, 2015; Friedrich and Trois, 2013), however, LFGT is not an effective and efficient technology to deal with the increasing MSW generation. Most of the current literature on LFGT technology point out that it provides a sustainable investment and it is accepted globally as one of the emerging environmentally sustainable solutions to efficiently generate electricity (Fourie and Morris, 2004; Ayodele et al., 2017; Tozlu et al., 2016). This statement is informed by the recent developments in MSWM which have responded to an evolving trend in the advancement of LFGT particularly in the developed north countries (Noor et al., 2013; Tozlu et al., 2016; Themelis et al., 2002; Friedrich and Trois, 2011). In the City of Johannesburg, efforts on LFGT are under consideration and a contract was signed with EnerG Systems Joburg (Pty) Ltd to construct landfill gas to energy plants and generate electricity under the Clean Development Mechanism (CDM) project (Baker and Letsoela, 2016). They have exclusive rights to operate and generate electricity at five landfill sites namely Robinson Deep, Marie Louise, Linbro Park, Goudkoppies and Ennerdale (Baker and Letsoela, 2016; Mbuli, 2015). A projection of 3 megawatts of electricity is expected to be generated at the gas collection system installed at both the Robinson Deep and Marie Louise landfill sites (Baker and Letsoela, 2016).

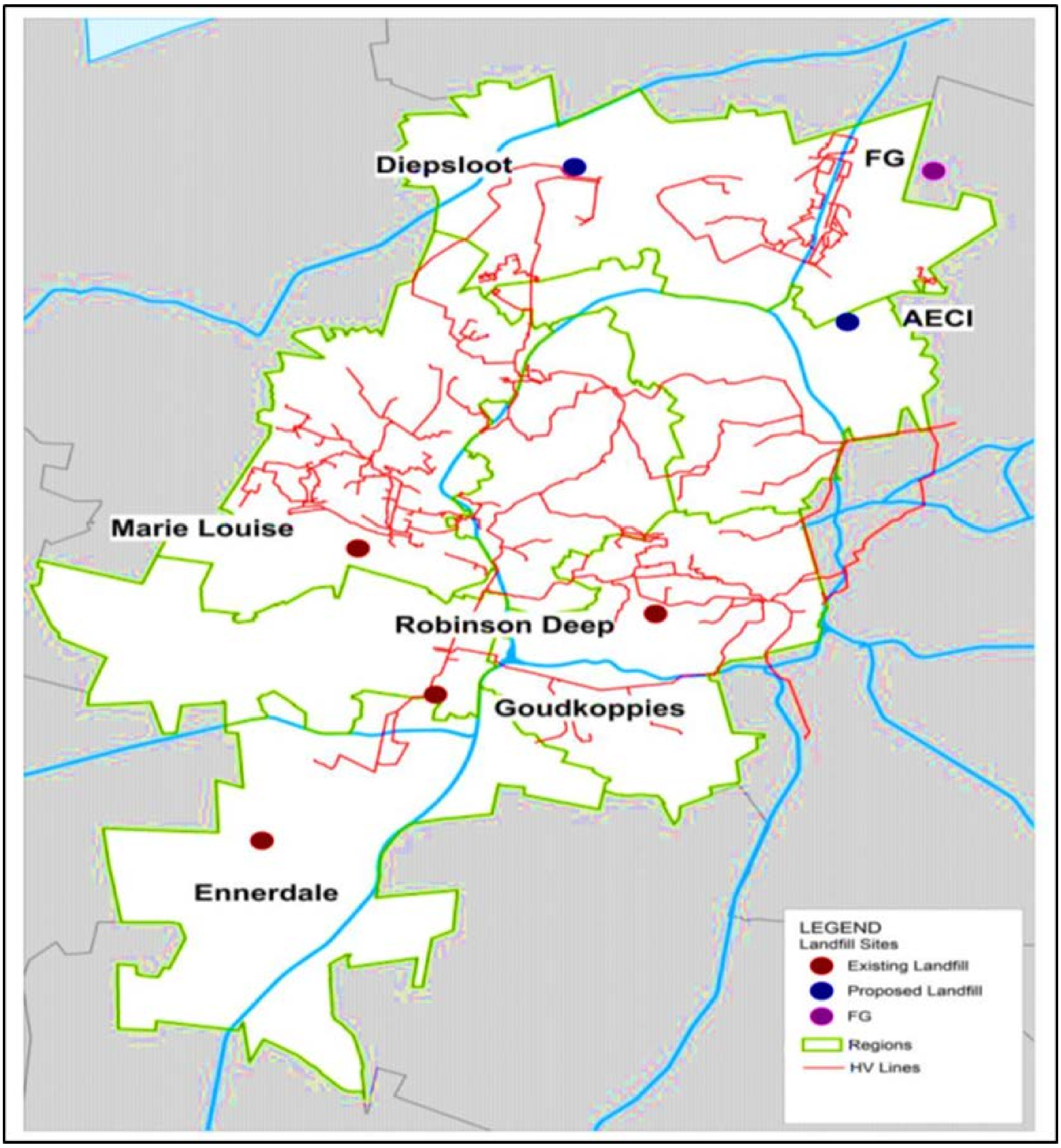
LFGT is now well established from a variety of studies, it is an alternative electricity supply source for urban dwellers, create jobs and bring a solution to the growing challenge of waste management. However, little or no attention has been paid to validate landfill gas to energy investment as a promising technology in the City of Johannesburg (Friedrich and Trois, 2010). Existing literature on LFGT seems not to have come up with methodological innovations that have been successfully researched and implemented to estimate the methane generation potential of specific landfills (Friedrich and Trois, 2011; Dada and Mbohwa, 2016). Instead, existing literature has continued to focus on waste management practices, recycling, separation at source and waste disposal methods as means to improve MSW in the City of Johannesburg (Karani and Jewasikiewitz, 2007).

Previous studies on LFGT have focused on seasonal variations in waste characteristics, polluting potential of landfills and waste composition on landfill gas recovery. Other studies have focused on the seasonal patterns exhibited in landfill gas emission rates through field studies using flux chamber measurements (Couth and Trois, 2011; Mbav et al., 2012; Friedrich and Trois, 2016; Friedrich and Trois, 2010). There is, therefore, an urgent need to estimate methane emissions at Robinson Deep and Marie Louise landfill sites and to calculate the environmental and economic benefits of LFGT. This paper uses the Intergovernmental Panel on Climate Change (IPCC) methodology as an alternative methodological consideration for estimating methane emissions.

3.2. THE MANAGEMENT AND CHARACTERISATION OF MUNICIPAL SOLID WASTE.

Urbanisation, population growth, industrialisation and modernisation has been a challenge in the Gauteng province (Simatele et al., 2017; Fourie and Morris, 2004). The combination of these processes has led to an increase in environmental pollution and waste generation. The increase in waste generation has made authorities to find MSW as a possible alternative to curb energy poverty. According to the National Waste Information Baseline (NWIB), 108 million tonnes of waste was generated in 2011 at a rate of 0.2 – 1.29 kg/capita/day consisting of 59 million tonnes of MSW. Similar to most developing countries, waste management practices are mostly collection and landfilling with limited recycling and separation at source (Mbuli, 2015 and Dowling et al., 2012). The City of Johannesburg is the leading city in MSW generation with a population of over 4.3 million in an area of approximately 1646 km^2 (Dada and Mbohwa, 2016; du Toit et al., 2017). It is also one of the city with the oldest landfills, for example, Robinson Deep landfill site was commissioned in 1930 and it is still operational (Friedrich and Trois, 2010; Mohee and Simelane, 2015).

Landfilling, as mentioned above is the most used disposal option for MSW. Other waste management practices include recycling, re-use and separation at source which helps to minimise the volumes of MSW that goes to the landfills. Academic literature on LFGT has revealed that methane is the dominant gas in a landfill, which has a global warming potential 28 times than that of carbon dioxide. This paper therefore, asserts that the methane that is produced in the landfills must be used for electricity production (Tan et al., 2015). Due to the increase in MSW generation within the city and the demand for new interventions, the city authorities approved Marie Louse landfill and Robinson Deep landfill (Figure 3.1 and Figure 3.2) as pilot landfills for the electricity generation projects (Baker and Letsoela, 2016). The Marie Louise landfill is located 20 km Johannesburg west, covers an area of 44 hectares and accepts approximately 30 000 tonnes of municipal waste per month. The Robinson Deep landfill site was commissioned in 1930 and is located approximately 3 km south of Johannesburg.



Source: Cartography Unit, 2019. School of Geography and Environmental Studies

Figure 3.1: Location of landfills used in this study. Robinson Deep and Marie Louise service the greater part of the inner City of Johannesburg.

A B

Source: City of Johannesburg database, 2017.

Figure 3.2: Ariel view and boundary along Robinson Deep (A) and Marie Louise (B) landfill sites.

It is estimated that Robinson Deep and Marie Louise landfills airspace will be completely depleted by the year 2021 (Baker and Letsoela, 2016), therefore, it is necessary that LFGT must be recognised in order to achieve sustainable waste management. Table 3.1 shows the estimated cumulative remaining airspace expected to last up to 2021, assuming no further interventions are implemented. The landfill airspace modelling was undertaken in consultation with Pikitup and indicates that there is an estimated two years lifespan remaining for Robinson Deep and two years for Marie Louise landfill site.

Table 3.1: Airspace remaining for the Robinson Deep and Marie Louse landfill sites

Landfill Name	Designed Capacity	Airspace Utilised (Incl. cover material)		Airspace Available (Incl. cover material)		Growth rate	Landfill site lifespan remaining			
	Pikitup Data	Aurecon Data	Pikitup Data	Aurecon Data	Pikitup Data	Pikitup Data	Pikitup Data		Aurecon Data	
	(m^3)	(m^3)	(m^3)	(m^3)	(m^3)	(m^3)	Y	End Date	Y	End Date
Robinson Deep	22,968,866	17,684,789	17,996,186	4,432,204	4,972,680	2.60%	7	May/ 2021	5	Sep/ 2019
Marie - Louse	6,796,717	4,581,259	5,052,104	2,113,971	1,744,613	1.65%	6	Jan/ 2021	6	Sep/ 2020

Source: Pikitup and Aurecon database, 2014.

It has previously been shown that warm climate and high precipitation rates encourages methane generation in a landfill (Fourie and Morris, 2004; Couth and Trois, 2012). It is stated that methane production and electricity generation depends on the waste composition, landfill design, local climatic conditions and the landfill operation practices (Baker and Letsoela, 2016). The presence of organic waste (paper, food waste, garden waste) in a landfill results in higher levels of methane production, and high levels of moisture accelerate methane generation. Therefore, the generated methane can be estimated on the basis of waste quantities and waste composition disposed as well as the waste management practices imposed in the landfills. With that said, the landfills used in this study to estimate methane generation are managed MSW disposal sites and are administered by guidelines outlined in the DWAF Minimum Requirements for Waste Disposal by Landfills as well as the National Environmental Management: Waste Act, 2008 (Act 59 of 2008) and its accompanying Waste Regulations.

Table 3.2: Annual solid waste generated in the City of Johannesburg

Year	**MSW tonnes/ year**
2010	2 589 000
2011	2 950 000
2012	3 573 000
2013	3 663 000
2014	4 775 000
2015	5 211 000
2016	3 832 000
2017	4 282 000
2018	4 100 000
2020*	5 563 000
Total	**40 538 000**

* Projected value.

Source: Gauteng waste information system database, 2017.

Table 3.2 above shows the annual solid waste generated in Johannesburg, estimated from 2010, 2018 and 2020 to be 2 589 000 tonnes, 4 100 000 tonnes and 5 563 000 tonnes, respectively. However, the nature of waste generated, and the amount deposited in the landfill differ in quantities and in categories.

Table 3. 3: Typical waste characterisation in Robinson Deep and Marie Louse landfill site

Waste Category	Total Mass(kg)	%
Destruction foodstuff	113 320	0.01
Plastic	561 120	0.06
Polyprop	557 175	0.06
Street cleaning	25 969 691	2.70
Household waste	264 974 925	27.53
Paper	684 380	0.07
Boxes	1 123 040	0.12
Bottle plastic	947 320	0.10
Builders rubble	258 704 551	26.9
Compacted refuse	51 209 597	5.32
Container service	27 095 244	2.82
Dallies	10 915 790	1.13
Garden refuse	92 409 336	9.60
Illegal dumping	113 984 756	11.84
Recycling material	40 920	0.004
Scrap metals	520 100	0.05
Glass	429 110	0.04
Sludge	190 960	0.02
Special industrial refuse	18 040	0.002
Un-compacted nonsolid refuse	93 138 235	9.68
Universal materials/ special	286 380	0.03
Cover soil	18 628 947	1.93
Other: HD	424 420	0.04
Total	**962 498 247**	**100**

Source: Robinson Deep and Marie Louse landfill site database, 2017.

Table 3.3 shows the MSW categories or characteristics (Robinson Deep and Marie Louse landfill site) from 2016 to 2017. It indicates that at least 37.37% of MSW is mostly organic waste (destruction foodstuff, household waste, paper and garden waste). Food/organic makes up to 27.53% and paper (boxes, paper, other HD) is 0.23 % and garden refuse is 9.60%. Food/organic waste makes the largest percentage of 27.53%. Household waste, which forms the highest percentage of biodegradable organic matter creates an encouraging environment for landfill gas generation and recovery.

3.3. METHODOLOGY

3.3.1 Anaerobic decomposition of MSW in a landfill

MSW in a landfill undergoes a process of anaerobic decomposition of the organic matter to a by-product called landfill gas. Methane and carbon dioxide is contained in the landfill gas with other air pollutants and volatile acid. The organic matter is oxidized by the atmospheric oxygen to form water vapour and carbon dioxide. There are three phases that are involved in the anaerobic biodegradation reaction of waste in a landfill. Firstly, bacteria hydrolyse complex molecules into soluble products such as fatty acids, amino acids and glucose. Secondly, acid forming bacteria then convert soluble products to organic acids, ethanol, hydrogen, acetic acid and carbon dioxide. Finally, bacteria then break down the acids or reduce carbon dioxide with water to form methane. The reaction is shown as follows:

Acetogenesis

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \quad (3.1)$$

glucose

Methanogenesis

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (3.2)$$

acetic or ethanoic acid

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (3.3)$$

The portion of organic waste is estimated using the chemical formula $C_6H_{10}O_4$. This chemical formula is a representative formula corresponding to that of not less than 10 organic compounds that include adipic acid and ethylene glycol diacetate (Noor et al., 2013; Johari et al., 2012; Themelis et al., 2002). The following reaction estimates generated landfill gas in the anaerobic decomposition process:

$C_6H_{10}O_4 + 1.5H_2O \rightarrow 3.25CH_4 + 2.75CO_2$ (3.4)

adipic acid (waste)

Academic literature indicates that about 45-60% methane and 40-55% carbon dioxide is contained in the landfill gas produced and the principal reagent (water) makes the reaction better (Themelis and Ulloa, 2007). Without taking into consideration organic dirt and moisture, waste is said to contain 69.5% biomass or 60% dry biomass, Eq. (3.4) indicates that 5.4 kg of the waste can react with 1 kg of water (ratio of waste to water is 5.4:1).

3.3.2 Estimation of methane using the IPCC methodology

The waste composition, operating practices in a landfill, presence of organic waste and high moisture content in the waste determines the rate of methane production (Tan et al., 2015). Below is the equation to estimate methane emission from a landfill site:

$$Q = (MSW_T \times MSW_F \times MCF \times DOC \times DOC_F \times F \times 16/12 - R)(1 - OX) \quad (3.5)$$

Where:

Q = total methane emissions (tonnes)

MSW_T = total MSW generated (tonnes)

MSW_F = fraction of solid waste disposed to landfill

DOC = fraction of degradable organic carbon

DOC_F = fraction of total DOC that actually degrades

F = fraction of methane in landfill gas

16/12 = molecular weight ration of methane and carbon

R = recovered methane

OX = oxidation factor (fraction)

For MCF, the default values (0.4 - 1.0) are used and they depend on the landfill disposal method. A value of about 1.0 is used if most of the landfills under consideration are anaerobic managed solid waste disposal sites (IPCC, 2006). A default value for DOC_F is 0.77. This is because biodegradation of DOC occur over a short period of time. DOC is estimated from Eq. (3.6) and ranges from 0.08 to 0.21:

$$DOC = 0.4P + 0.15K + 0.3W \tag{3.6}$$

where:

P= fraction of MSW papers

K= fraction of MSW kitchen garbage

W= fraction of MSW woods/leaves

3.4. RESULTS AND DISCUSSION

3.4.1 Methane estimation from the City of Johannesburg landfills

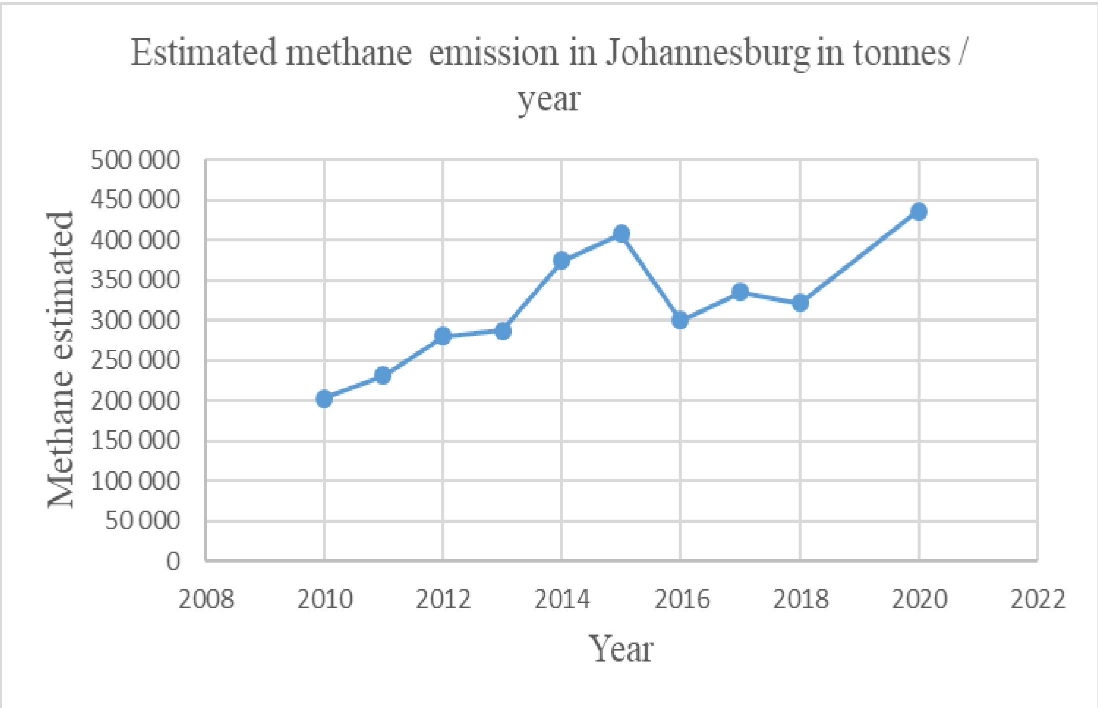
Methane generated in the Robinson Deep and Marie Louse landfill sites from 2010 to 2018 and 2020 is shown in Table 3.4 below. The IPCC methodology was used to estimate methane generated from the landfills (IPCC, 2006).

Table 3.4: Estimated methane in Robinson Deep and Marie Louse landfill site

Year	MSW_T tons/ yr[a]	MSW_F	MCF	DOC[b]	DOC_F	F	16/12	CH_4 tons /yr[c]
2010	2 589 000	0.90	1.0	0.17	0.77	0.50	1.33	202 800
2011	2 950 000	0.90	1.0	0.17	0.77	0.50	1.33	231 100
2012	3 573 000	0.90	1.0	0.17	0.77	0.50	1.33	279 900
2013	3 663 000	0.90	1.0	0.17	0.77	0.50	1.33	287 000
2014	4 775 000	0.90	1.0	0.17	0.77	0.50	1.33	374 000
2015	5 211 000	0.90	1.0	0.17	0.77	0.50	1.33	408 000
2016	3 832 000	0.90	1.0	0.17	0.77	0.50	1.33	300 000
2017	4 282 000	0.90	1.0	0.17	0.77	0.50	1.33	335 400
2018	4 100 000	0.90	1.0	0.17	0.77	0.50	1.33	321 200
2020	5 563 000	0.90	1.0	0.17	0.77	0.50	1.33	435 800
Total	**40 538 000**							**3 175 200**

Source: [a] taken from Table 3.2, [b] calculated from Eq. (3.6) and [c] calculated from Eq. (3.5).

Table 3.4 show values substituted into Eq. (3.5) and Eq. (3.6) for methane generated. For the estimation of total waste generated, MSW_T from 2010 to 2018 and 2020 was used. According to (Mohee and Simelane, 2015) 90% of MSW in Johannesburg is landfilled, therefore, MSW_F was taken as 0.9, the value of waste fraction. Based on the landfill disposal method, MCF ranges from 0.4 and 1.0 (IPCC, 2006). A value of 1.0 was used since the landfills are managed. For DOC, a default value of 0.08 - 0.21 was used based on Eq. (3.6). Substituting default values of MSW composition by percentage (regional defaults - Southern Africa) into Eq. (3.6) gives DOC of 0.17 (IPCC, 2006). The same value (DOC_F = 0.77) is used in this paper because DOC biodegradation does not occur to completion. Based on the IPCC, a default value for F is 0.50. R has a default value of zero and the oxidation factor also has a default value of zero as it is assumed that there is no methane recovery.



Source: Based on information in Table 3.4

Figure 3.3: Estimated methane emission at Marie Louse and Robinson Deep landfills

Figure 3.3 shows an increasing methane emission trend from a value of 202 800 tonnes in 2010 to a value of 435 800 tonnes in 2020. The emission, however decreased from 408 300 tonnes in 2015 to 300 000 tonnes in 2016 due to increased recycling, separation at source activities and the establishment of buyback centres which led to the realisation of the informal waste sector. The projected methane emission level reached 435 800 in 2020 and is expected to increase as population growth, urbanisation and economic growth impacts the rate of waste generation in the city. The methane emission estimates of this paper is related to that of a study conducted in Malaysia (Noor et al., 2013; Johari et al., 2012), which estimated methane emissions of 350 000 tonnes in 2015 and an increase to 370 000 tonnes in 2020.

3.4.2 Energy, economic and environmental benefits of methane recovery

3.4.2.1 Energy benefits of methane recovery

Landfill gas is a reliable and a renewable resource that does not have direct pollution impact to the atmosphere. The gas is a free and clean energy that can be used as a source of electricity other than conventional energy. Table 3.5 below shows the caloric values of methane, estimated from Table 3.4.

Table 3.5: Energy potential of methane recovery

Year	CH_4 emitted in Tonnes	[a]CO_2 equi-valent ($MtCO_2eq$)	[b]Revenue from carbon credit ($\times 10^6$ R)	Volume of CH_4 ($\times 10^6 m^3$)	[c]Calorific value ($\times 10^9$MJ)	[d]Equivalent electricity generation ($\times 10^9$kWh)	[e]Revenue from electricity sale ($\times 10^6$ R)
2010	202 800	5.68	681.6	304.05	5.17	1.43	1291.21
2011	231 100	6.47	776.4	154.14	2.62	0.73	654.34
2012	279 900	7.84	940.8	419.64	7.13	2.00	1780.72
2013	287 000	8.04	964.8	430.28	7.31	2.03	1825.67
2014	374 000	10.47	1256.4	560.72	9.53	2.64	2380.11
2015	408 000	11.42	1370.4	611.69	10.34	2.90	2582.42
2016	300 000	8.40	1.008	449.76	7.65	2.12	1910.59
2017	335 400	9.39	1126.8	502.85	8.55	2.37	2135.36
2018	321 200	8.99	1078.8	481.60	8.19	2.27	2045.45
2020	435 800	12.20	1464	653.37	11.11	3.08	2774.72

Source: [a] methane is 28 times more potent than CO_2, [b] at a cost of ZAR120.00/tonne of CO_2, [c] calorific value of 17 MJ/m^3 of methane, [d] 1 MJ=0.2775 kW h, [e] at 90c/kW h.

The landfill gas calorific value is 17MJ/m^3 with a density of 0.667kg/m^3 at 30 °C, and landfill gas composition is 55% methane (Omar and Mncwango, 2005). Using a Global Warming Potential (GWP) of 28 and R120.00/tonne of CO_2, columns 3 and 4 in Table 3.5 show the equivalent CO_2 reduction and revenue from carbon credit. In 2017, CO_2 emission reduction was 7.04 Mt CO_2eq, therefore, a CO_2 emission reduction is expected to be 6.75 Mt CO_2eq by 2018 and 9.15 Mt CO_2eq in 2020. Carbon credit revenues for 2017 and 2018 was ZAR1126.8 million, ZAR1078.8 million and ZAR1464 million for 2020. Similarly, electricity generated was 2.37×10^9 kW h for 2017 alone, 2.27×10^9 kW h for 2018 and projected 3.08×10^9 kW h for 2020. This paper, therefore, holds the view that LFGT is a promising alternative energy resource that can be used for generating renewable electricity.

3.4.2.2 Economic and environmental benefits of methane recovery

As mentioned above, LFGT is used to generate energy, heat and reduces methane emissions that are harmful to the local communities and the environment (Johari et al., 2012; Abbasi and Abbasi, 2010; Kirkeby, 2005). It is a promising source of income, jobs and can boost the country's energy supply (Dada and Mbohwa, 2016). Based on Table 3.5 above, if methane emitted from landfills was recovered, carbon reduction could have generated ZAR1078.8 million revenue in 2018 from carbon credit based on ZAR120.00/tonne of CO_2. 2.27 billion kW h and 3.08 billion kW h of electricity in 2018 and 2020 would have also been generated based on a gas engine efficiency of 40% and methane calorific value of 55,530 kJ/kg (Omar and Mncwango, 2005). In monetary terms, based on 90c/kW h the electricity could have attracted a revenue of ZAR2135.36 × 10^6 in 2017, ZAR2045.45 × 10^6 in 2018 and ZAR2774.72 × 10^6 for the year 2020.

3.5. CONCLUSION

It is estimated that the landfill airspace for Robinson Deep and Marie Louse landfill sites will be depleted by the year 2021. There is, therefore, a definite need for the adoption and implementation of the LFGT to generate electricity. The electricity must be generated from the already existing and operational landfill sites. LFGT is very effective in reducing GHG emissions from landfills, create jobs and generates revenue from the sale of carbon credits. In Table 3.5 above, methane emissions in 2017 was 335 400 tonnes, 321 200 tonnes in 2018 and projected to 435 800 tonnes by 2020, equivalent to 2.37 × 10^9 kWh, 2.27 × 10^9 kWh and 3.08 × 10^9 kWh of electricity with revenues of ZAR2135.36 million, ZAR2045.45 million and ZAR2774.72 million, respectively. Carbon credit estimates generated ZAR1126.8 million, ZAR1078.8 million and ZAR1464 million, for the year 2017, 2018 and 2020, respectively.

CHAPTER FOUR

Electricity generation and economic viability of Waste-to-Energy technologies for municipal solid waste management in the Gauteng province, South Africa[3]

ABSTRACT

Globally, the usage of municipal solid waste (MSW) for electricity production has been implemented for many years now. The Gauteng province, however, is still high and solely dependent on landfills for MSW management. Because of the concern on the depletion of the City of Johannesburg's landfills airspace by the year 2023, increasing waste generation and greenhouse gases (GHG) emission, the province has an urgent need for a better waste management strategy. This study evaluated the potential of MSW for electricity production in nine municipalities in the Gauteng province using landfill gas to energy (LFGT), Incineration (INC) and Anaerobic Digestion (AD) technologies as well as to determine the economic viability of the WTE technologies. The LandGEM equation was used to estimate the methane generation potential from MSW generated in each year in order to evaluate the electricity generation potential of each technology. The levelised cost of energy (LCOE), net present value (NPV) and payback period (PBP) methods were used to determine the economic viability of the technologies. Key findings revealed that the City of Johannesburg municipality (MU1) has the highest waste generation potential of 2.18925×10^9 – 3.9103×10^9 kg/yr between the year 2016 and 2035, with methane generation estimates of 181700000 m^3/yr (12210 ft^3/min). In terms of electricity generation potential, INC technology is more attractive (3667.35 GWh per annum). However, from an economic point of view, AD technology presented itself as an economically viable WTE technology with the lowest payback period compared to LFGT and INC technologies.

Keywords: *Municipal Solid Waste, Waste-to-energy technologies, Electricity generation, Gauteng*

[3] The second revision has been done and the paper is currently in print: Smangele Dlamini, Simphiwe Simelane & Mulala Simatele (2019). Electricity generation and economic viability of Waste-to-Energy technologies for municipal solid waste management in the Gauteng province, South Africa. *Journal of cleaner Production.*

4.1. INTRODUCTION

Increased level of urbanisation, industrialisation, population increase, changing consumption pattern have contributed to the unprecedented increase in the rate of municipal solid waste (MSW) generation and energy demand in the developing cities(Simatele et al., 2017; Nzeadibe, 2009; Kofoworola, 2007; Cheru, 2002). MSW is generated from residential, commercial and institutional areas at a rate that outstrips the ability of the natural environment to assimilate it and at a rate that exceeds the ability of municipal authorities to manage it (Tan et al., 2015; Sharholy et al., 2008; Oteng-Ababio et al., 2013; Nzeadibe, 2009). MSW in South Africa is disposed of in a bin and collected with minimum recycling and separation at source before sent to the waste disposal landfills.

Landfilling is still recognised as the cheapest method to handle large quantities of solid waste. One major issue in the use of landfills is that they are operating at full capacity and there is a shortage of available land for waste disposal purposes (Mbuli, 2015; Baker and Letsoela, 2016). According to the National Waste Information Baseline (NWIB), South Africa generated approximately 108 million tonnes of waste in 2011, consisting of 59 million tonnes of general waste at a rate of 0.2 – 1.29 kg/capita/day. The average electrical energy and power per capita in South Africa are in the range of 4347kW h per annum and 496 W, respectively when compared to some other developing countries such as Nigeria (107 kW h and 12 W) and Malaysia (3310 kW h and 377 W)(Ayodele and Ogunjuyigbe, 2015). The over dependency on landfilling and inappropriate waste disposal has been continuously pressing the environmental, health and safety issues for the citizens.

The provincial government is seeking practical solutions to improve the current waste situation through the following measures; closure of illegal landfills, upgrading landfills with methane recovery, composting of organic waste, recycling and separation at source and waste minimisation alternatives. Amongst the named and listed practical solutions, waste-to-energy (WTE) technologies are the least mentioned and neglected alternative to overcoming the waste generation problem in the Gauteng province. WTE technologies extract usable energy stored in the organic portion of MSW to produce heat and electricity either through the thermal and biological processes (Tozlu et al., 2016; Maier and Oliveira, 2014; Johari et al., 2012).

The utilisation of MSW as a renewable energy source overcome waste disposal issues, generate power for fossil fuel displacement and mitigate GHG emissions from waste treatment. There are leading examples of WTE technologies around the globe and it was estimated that nearly 800 thermal WTE projects are functioning in almost 40 countries globally and that 11% of the MSW that is treated generates up to 429 TWh of electricity (Tozlu et al., 2016; Johari et al., 2012; Tan et al., 2015). Some large-scale WTE projects have been implemented in developed countries, such as Denmark, Netherlands, Sweden, Germany, Japan and the United Kingdom. For instance, over 80% of the MSW in Japan is incinerated and has 1900 waste incineration plants in the world and 10% are equipped with power generation facilities(Psomopoulos et al., 2009; Tan et al., 2015).

Scholars such as (Tan et al., 2015; Johari et al., 2012) evaluated the energy, economic and environmental impact of WTE technologies for MSW management in Malaysia. It was concluded that incineration and anaerobic digestion are the two potential WTE options for MSW management. The roles which MSW could play in providing energy to African urban areas using incineration and landfill gas technologies have been presented by

(Scarlat et al., 2015). The authors projected that electricity generation from MSW in Africa could reach 122.2 TW h by 2025. They also provided a vision for the spatial distribution of energy from waste based on the population in major cities in Africa. Illustrated on how investments in new WTE technologies may well be ill-fated if the requisite waste stream composition data does not exist to justify such investments. Lastly, they highlighted that authorities in African cities would do well if they can consider integrating proven innovations taking place in developed countries. In Nigeria, attempts have been made by some researchers in evaluating the potentials of MSW in some part of the country (Ogunjuyigbe et al., 2017). They carried out the potential of MSW to generate electricity and heat energy in selected cities in Nigeria and limited their work to a few localities.

Feasibility analyses of WTE technologies from MSW in South Africa have been conducted by scholars over the past years. For example, (Bhailall et al., 2016) estimated landfill gas emissions in South Africa and individual landfills using theoretical models (LandGEM, GasSim, IPCC waste model 2006 and the California landfill methane inventory model. The models estimated the production of landfill gas from the existing landfills and assessed the applicability of the models to South African sites, nevertheless, they did not consider the other different technologies (INC and AD) of extracting useful energy for electricity generation. In another feasibility study in MSW for WTE, (Baker and Letsoela, 2016; Mbuli, 2015) conducted a study on the implementation of landfill methane gas to electricity project in the City of Johannesburg and they did not evaluate the economic viability of the WTE technologies. Other scholars (Dowling et al., 2012a) presented an analysis of energy generation potential of landfill sites in Cape Town area in South Africa and economic analysis of landfill gas to energy systems which might be developed using landfills, but also limited their work to landfill gas recovery and ignored INC and AD as potential WTE technologies.

Despite the previous research, none of the studies determined and compared the suitable technological option, that is, INC, LFGT and AD from the perspective of holistic sustainability, which includes energy generation potential of MSW from each technology and evaluation of the economic viability of the WTE technologies. Only LFGT technology was considered which does not give room for technology comparison.

This study, therefore, assesses the potential of MSW for electricity generation in nine municipalities in the Gauteng province using LFGT, INC and AD technologies. The three WTE technologies are selected because of the complexity in the waste flow and the amount of waste generated in the Gauteng province. This paper recognises LFGT technology for the generation of electricity on the already operating and existing landfill sites, incineration technology for non-recyclable waste and anaerobic digestion technology for separated biodegradable waste. It also evaluates the electricity generation potential of each technology as well as determining the economic viability of WTE technologies in each municipality. It carries out a comparison of the technologies with the intention of determining the best cost-effective technology option for each of the municipalities. This study, therefore, identifies itself as a source of scientific information that could lead to optimal investment in WTE project in the developing economy of the Gauteng province, South Africa. It could also help to increase the share of information on renewable energy in the energy mix of the country.

4.2. OVERVIEW OF WTE TECHNOLOGY AND ENERGY CONVERSION PATHWAYS FROM MUNICIPAL SOLID WASTE

WTE entails the recovery of energy from solid waste materials into useable heat and electricity. In the hierarchy of solid waste management, shown in Figure 4.1, energy recovery is recognised and is ranked before the final disposal of waste. Waste reduction, re-use and recycling are ranked in the top three of the hierarchy, however, they require behaviour of people, societal and cultural change which creates uncertainty whilst energy recovery alternatives are certain and sustainable. WTE technologies are recognised as potential renewable energy sources and promising alternative for MSW management to overcome the waste generation problem.

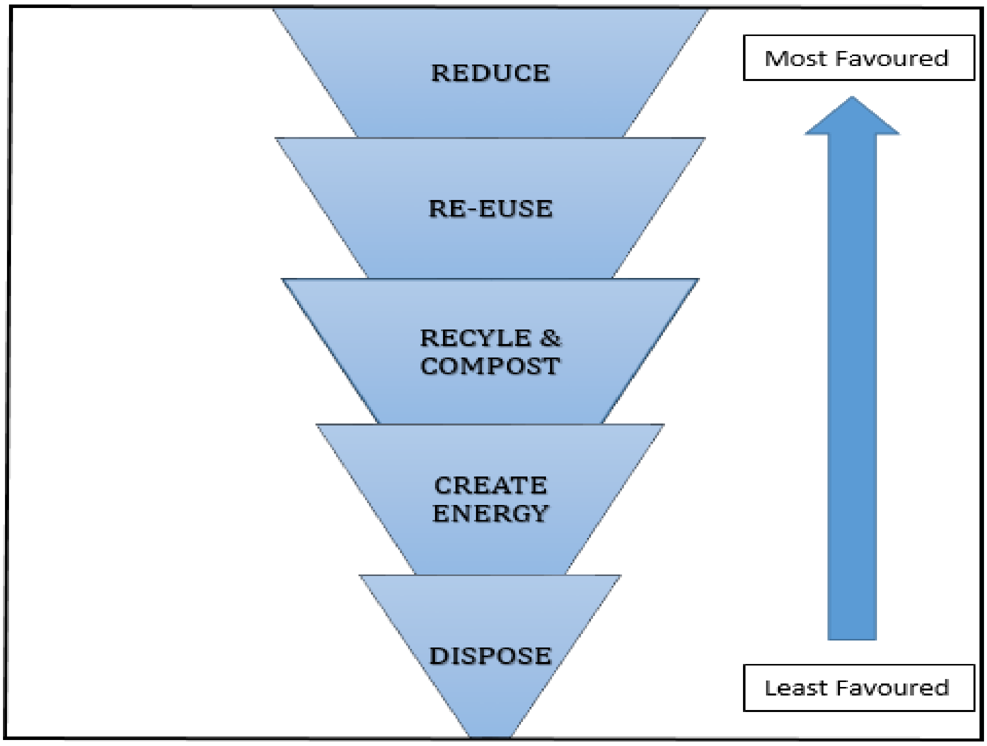


Figure 4.1: Hierarchy of solid waste management

WTE technologies can be categorised into two pathways: biochemical process and thermo-chemical process. Options for biochemical process of WTE to produce electricity and heat includes LFGT and AD. Thermo-chemical process of WTE includes INC with the generation of electricity.

4.2.1 Biochemical conversion pathway

This method involves the biological decomposition of the organic components of MSW under microbial action in the presence of oxygen (aerobic digestion) or absence of oxygen (anaerobic digestion) to produce compost or biogas (landfill gas). The main technological options under biochemical conversion include LFGT and AD technologies (Al-Salem et al., 2014; Moya et al., 2017; Tozlu et al., 2016). A typical composition of a biochemical conversion is shown in Figure 4.2. The biochemical conversion processes are preferred for waste with a high percentage of biodegradable organic matter and a high level of moisture/water content, which aids microbial activity.

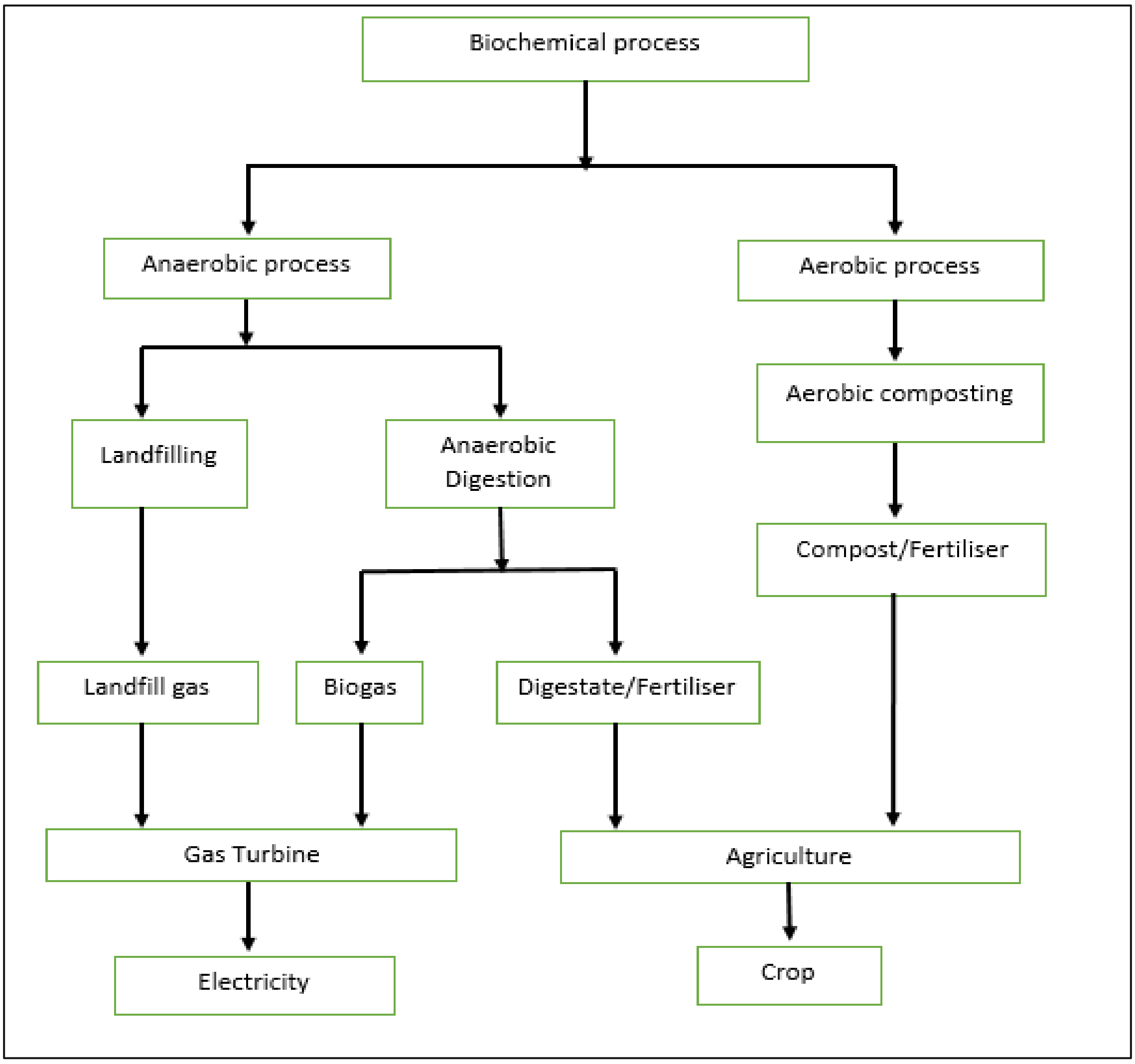


Figure 4.2: LFGT and AD conversion pathways from MSW

4.2.1.1 Landfill gas to energy technology

When waste is deposited in a landfill, the organic matter in the waste decomposes to landfill gas. The complex chemical and biological decomposition processes occur resulting in the production of landfill gas, a mixture of methane (45 -60%), carbon dioxide (40 – 55%) and trace components(Scarlat et al., 2015). The generation of methane from landfill sites has gained increasing attention(Baker and Letsoela, 2016). Landfill gas to energy can be considered as a WTE technology when the generated methane (biogas) is captured and utilised for energy generation (Johari et al., 2012). Unmanaged or poorly managed landfills without landfill gas recovery, leachate collection and treatment pose a serious threat to health and the immediate environment particularly to surface and underground water. It is believed that utilizing methane from landfills for energy (heat or electricity or both) generation will not only reduce the GHGs emission but also serve as a source of renewable electricity.

4.2.1.2 Anaerobic digestion technology

Anaerobic digestion is a natural biodegradable process of organic compounds by microorganisms in the absence of oxygen that decomposes to generate biogas mostly composed of methane and carbon dioxide (Yi et al., 2018; Brunner and Rechberger, 2015; Tozlu et al., 2016). The process of anaerobic digestion has four common steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Noor et al., 2013; Tan et al., 2015).

The first stage, hydrolysis, is when the organic compounds are broken down into soluble units, such as fatty acids, monosaccharides and amino acids. The second stage, acidogenesis change into simpler products such as carbon dioxide, methane and ammonia. The third stage of AD is acetogenesis, during which molecules are further digested by acetogens to produce acetic acid, as well as carbon dioxide and hydrogen. The last stage is methanogenesis, where the bacteria convert the organic acids into carbon dioxide, methane and water (Friedrich and Trois, 2016; Malinauskaite et al., 2017).

4.2.2 Thermo-chemical conversion process

This process involves the thermal decomposition of organic matter to produce heat energy, fuel oil or gas. In the INC technology, waste is directly burned in a furnace by controlling combustion at high temperatures (Tan et al., 2015; Yi et al., 2018; Ogunjuyigbe et al., 2017). This process is useful for less dense waste with a high percentage of organic, non-biodegradable matter and low moisture content. Figure 4.3 shows the process of converting MSW into energy through the thermo-conversion process.

Incineration is one of the common waste technology and the process is carried out in three steps, which are, incineration, energy recovery and air pollution control(Tozlu et al., 2016). Air pollutants such as SO_X, CO_X and NO_X are emitted after the incineration process and they result in air pollution and health hazards (Psomopoulos et al., 2009; Kalyani and Pandey, 2014). A hybrid plant has been developed to reduce the effects of heavy metals (Moya et al., 2017).

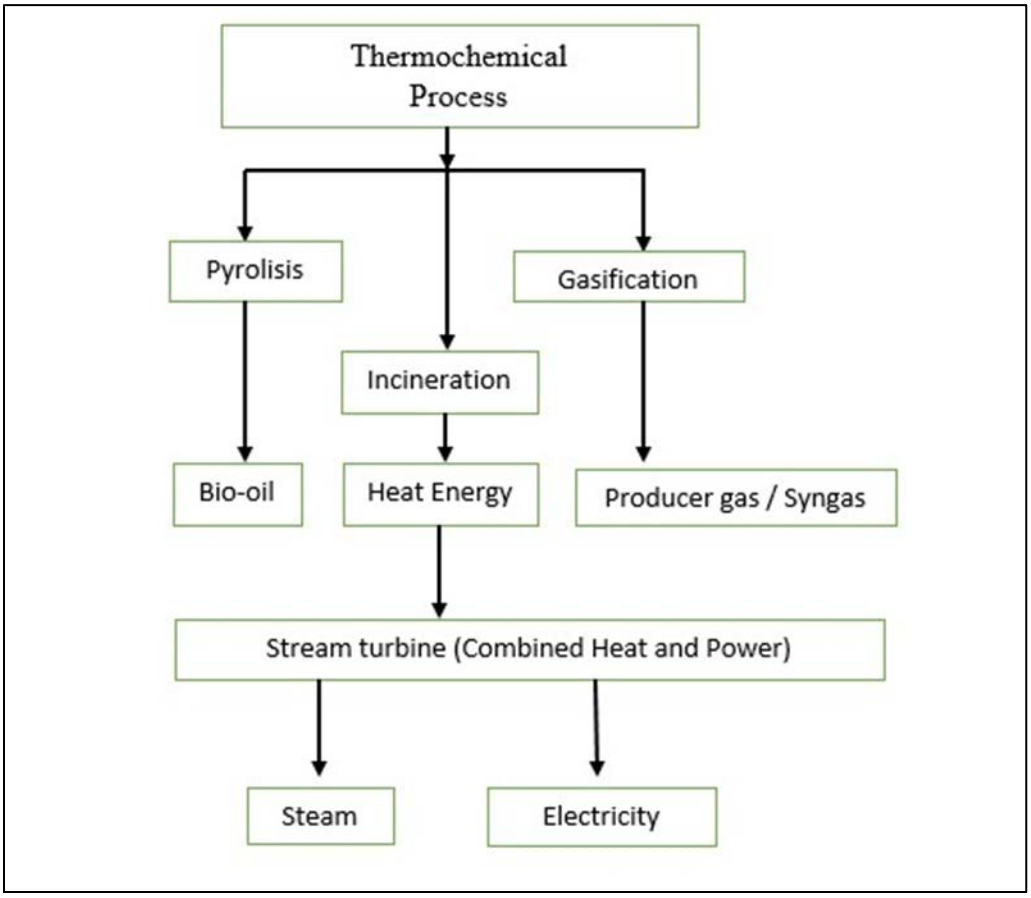
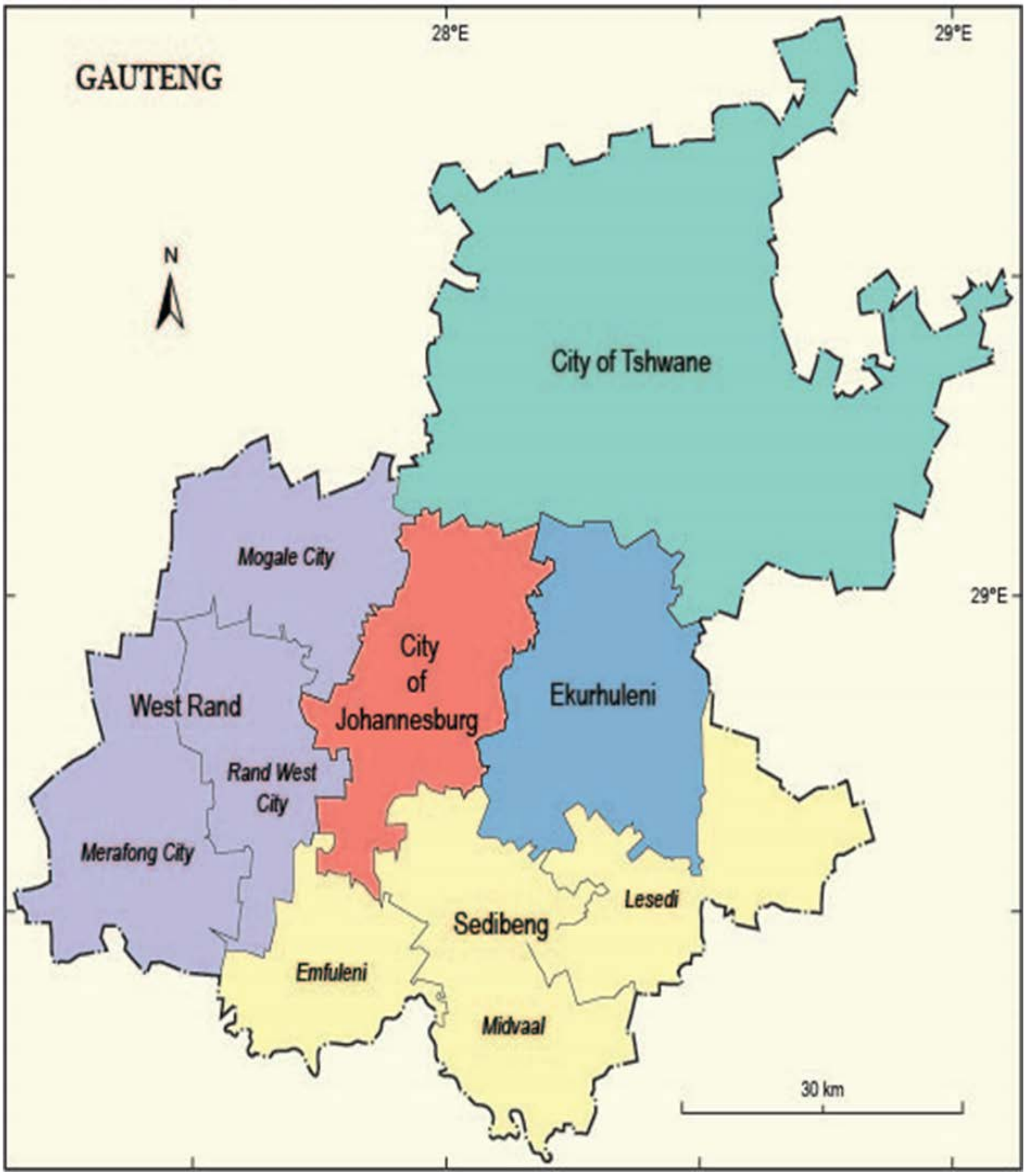


Figure 4.3: Incineration conversion pathway from MSW

4.3. APPROACH AND DATA COLLECTION

The Gauteng province is the smallest province with the largest pollution in South Africa. It is made up of nine municipalities of which 3 are cities (the City of Johannesburg, City of Tshwane and City of Ekurhuleni) and two districts namely the West rand district and the Sedibeng district, as shown in Figure 4.4. The map is most recent and only shows the geographic location of the provinces within the Gauteng province. Table 6 shows the location of the municipalities, the population as obtained from Statistics South Africa and the waste generated in each of the municipalities per capita per day (kg/capita/ day) as obtained from the literature and government databases.

To determine the electricity generation potential of WTE technologies in the municipalities within the Gauteng province, the quantity and waste composition was estimated. The quantity of waste generated in each municipality is a function of the population. The waste composition differs in terms of the consumption pattern, season, income and weather of a location (Tan et al., 2015; Ogunjuyigbe et al., 2017). In this study, the quantity of MSW generated was calculated using the 2011 census population and interpolated to 2016 based on 3.1 % growth rate and the per capita generation in each municipality.



Source: Cartography Unit, 2019. School of Geography and Environmental Studies.

Figure 4.4: Municipalities under study – Gauteng Province

Table 4.1: Population and waste generation rate of municipalities in Gauteng

Municipality	Designate	2011 Census	Waste generated per capita	Lat (N)	Long (E)
City of Johannesburg	MU1	4 434 827	1.29	26.20	28.04
City of Ekurhuleni	MU2	3 178 470	1.1	-26.17	28.34
City of Tshwane	MU3	2 921 488	0.98	25.60	28.39
Emfuleni	MU4	721 663	0.78	26.64	27.78
Merafong	MU5	197 520	0.74	26.37	27.40
Midvaal	MU6	95 301	0.41	26.58	28.06
Mogale	MU7	362 422	0.76	25.98	27.59
Lesedi	MU8	99 520	0.41	26.50	28.43
Rand West	MU9	261 053	0.65	26.19	27.67

Source: Statistics South Africa and Government database, 2019

4.3.1 Estimation of waste generation and composition for each WTE technology

This study assumes that not all waste generated is deposited in a landfill. According to (Mohee and Simelane, 2015; Mngoma et al., 2017), only 90% of the waste generated in the Gauteng province is collected and disposed in landfills. Therefore, the quantity of waste taken to landfill is obtained as:

$$\mathrm{M_F} = 0.90 \times \mathrm{M_T}\ (kg/yr) \tag{4.1}$$

Where $\mathrm{M_T}$ is waste generated per year and calculated as:

$$\mathrm{M_T} = \mathrm{P} \times wc \times 365 \tag{4.2}$$

where P is the extrapolated population in each municipality based on the population rate (r) of 3.1% and wc is the waste generated (kg/capita/day). The population for each municipality can be determined as:

$$P = P_O(1 + r)^t \quad (4.3)$$

where P_O is the base population using 2011 census and t is the time of extrapolation interest. Table 4.2 shows the composition of waste generated in each municipality.

Table 4.2: Waste composition in each municipality within the Gauteng province

Composition (f) in %	**Designate**	**MU 1**	**MU 2**	**MU 3**	**MU 4**	**MU 5**	**MU 6**	**MU 7**	**MU 8**	**MU 9**
Food waste	D1	34	29	27	23	22	21	11.9	20	24
Garden waste	D2	-	-	6	9	4	4	13.4	9	8
Plastics	D3	19	20	26	20	16	15	14.9	17	19
Paper	D4	12	15	18	10	11	14	10.4	13	11
Nylon	D5	-	-	-	-	-	-	-	-	-
Leather	D6	-	-	-	-	-	-	-	-	-
Textiles	D7	3	5	4	6	10	5	7.6	5	5
Metal	D8	5	6	2	7	8	7	5.4	6	3
Glass	D9	9	8	7	8	12	10	4.0	5	11
Wood	D10	-	-	-	-	5	-	-	-	-
Ceramics	D11	-	-	-	-	-	-	-	-	-
E-waste	D12	-	-	-	-	-	-	-	-	-
Other organic	D13	-	10	-	7	4	9	1.7	9	8
Inert	D14	18	3	10	-	-	13	-	9	6
Other inorganic	D15	-	4	-	10	8	2	30.4	7	5
Total		**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Source: Government database and literature review, 2019

Different technologies (LFGT, INC and AD) require different waste composition that could be utilized for electricity generation. The waste composition is estimated from Table 4.2 using:

$$M_{F(i)} = 0.90 \times M_T \times f_{(i)} \; (kg/yr) \quad (4.4)$$

Where, i, is the type of a technology (LFGT, AD and INC), f is the organic fraction for each technology option. It is assumed that rubber, metals and glass, ceramics and plastics are recyclables. Table 4.2 shows the organic fraction (*f*) of each technology. The percentage composition is shown in Table 4.3.

Table 4.3: Percentage composition of waste (*f*) that can be treated in each technology

Municipality	**Extra-ction**	**LFGT**	**Extra-ction**	**INC**	**Extra-ction**	**AD**
MU1	D1+D3+ D4+D7	68	D1+D3+ D4+D7	68	D1	34
MU2	D1+D3+D4+D7 +D13+D15	83	D1+D3+D4+D7 +D13+D15	83	D1+D13	39
MU3	D1+D2+D3 +D4+D7	81	D1+D2+D3 +D4+D7	81	D1	27
MU4	D1+D2+D3+D4 + D7+D13+D15	85	D1+D2+D3+D4 + D7+D13+D15	85	D1+D13	30
MU5	D1+D2+D3+D4 +D7+D10+D13 +D15	80	D1+D2+D3+D4 +D7+D10+D13 +D15	80	D1+D13	26
MU6	D1+D2+D3+D4 +D7+D13+D15	70	D1+D2+D3+D4 +D7+D13+D15	70	D1+D13	30
MU7	D1+D2+D3+D4 +D7+D13+D15	90.3	D1+D2+D3+D4 +D7+D13+D15	90.3	D1+D13	13.6
MU8	D1+D2+D3+D4 +D7+D13+D15	80	D1+D2+D3+D4 +D7+D13+D15	80	D1+D13	29
MU9	D1+D2+D3+D4 +D13+D15	80	D1+D2+D3+D4 +D13+D15	80	D1+D13	32

Source: Based on information in Table 4.2

4.4. WTE TECHNOLOGIES AND ELECTRICITY GENERATION FROM MUNICIPAL SOLID WASTE

4.4.1 Landfill gas recovery technology and electricity generation potential

A landfill generates a number of gases known as landfill gas due to the anaerobic decomposition of biodegradable waste(Kumar et al., 2016). The main gases are methane and carbon dioxide of which methane is the greatest concern. This is because methane is a greenhouse gas with a global warming potential of 28 times than that of carbon dioxide (Kalyani and Pandey, 2014). The potential of a landfill to generate electricity depends on its methane generation potential. In this study, Landfill Gas Emission Model (LandGEM) software was used to estimate methane generation for each year from cumulative waste disposed up through a year for each municipality in the province. The model predicts the landfill gas emissions based on first-order decomposition rate equation, which assumes that the methane generation rate after deposition increases. The first-order decay equation for the annual methane generation flow rate (m^3/year) can be estimated using:

$$Q_{CH_4} = \sum_{k=1}^{n} \sum_{j=0.1}^{1} k\mathrm{Lo}\left(\frac{M_{LFGT}}{10}\right) e^{-t_{kj}} \tag{4.5}$$

where k is the 1-year time increment, n is (year of the calculation) – (initial year of waste acceptance), j is the 0.1-year time increment, k is methane generation rate ($year^{-1}$), Lo is potential methane generation capacity (m^3/Mg), M_{LFGT} is the annual waste landfilled (Mg).

4.4.1.1 The methane generation capacity (Lo)

The methane generation capacity Lo (m^3/Mg), determines the amount of methane gas potentially produced by a metric tonne (Mg) of waste as it decays (Mwesigye et al., 2011). The amount of methane in a landfill is dependent on the temperature and humidity of the landfill, biodegradable waste and level of segregation (Kumar et al., 2016). The methane generation capacity is estimated (Tan et al., 2015) as:

$$L_O = M_F \times MCF \times DOC \times DOC_F \times F \times \frac{16}{12} \tag{4.6}$$

$$DOC = 0.4 \times P + 0.15 \times K + 0.3 \times W + 0.24 \times T \tag{4.7}$$

$$DOC_F = 0.014 \times T_{emp}(°C) + 0.28 \tag{4.8}$$

where M_F indicates the quantity of waste disposed to the landfill as calculated in Eq. (4.4), MCF is 0.1 - the methane correction factor (Tsai, 2007; Tan et al., 2015; IPCC, 2006) for managed landfill, DOC is the fraction of degradable organic carbon, DOC_F is the fraction of total DOC that actually degrades and obtained in Eq. (4.8) (Tsai, 2007), T_{emp} is the temperature of the landfill area taken as 30 °C (IPCC, 2006). F is 0.50 - the methane fraction by volume in the landfill gas, P is the fraction of papers in the waste, K is the fraction of kitchen garbage in the waste and W is the fraction of wood/ leaves in the waste and T is the fraction of textile in the waste (Tsai, 2007).

4.4.1.2 Methane generation rate constant (k)

It describes the rate at which waste decay and produce methane from a waste stream under specific site conditions such as waste composition and moisture content (Noor et al., 2013). The method proposed by (Sil et al., 2014) and (Karagiannidis et al., 2007) was used to determine the methane generation constant (k). Highly decomposable waste (putrescible, food waste and sewage sludge), moderately decomposable waste (garden and park waste) and slowly decomposable waste (paper/textile waste, wood/straw/rubber waste) are the categories of the waste stream. According to (IPCC, 2006), dry and moist climatic zones have mean annual temperature greater than 20 °C and a mean annual rainfall less than 1000 mm. South Africa has annual average temperature and rainfall in the range of 21 - 36°C and 464 - 860 mm. Table 4.4 below shows k values for the dry and moist tropical zone.

Table 4.4: IPPC, 2006 default values for methane generation (k) for dry and moist tropical zone.

% Waste composition	Type of waste	Description	Decay constant value	Default Value	Equation
A	Rapidly degradable	Food waste and sewage sludge	0.07-0.1	0.085	A k_1
B	Moderately degradable	Non-food (organic, garden waste)	0.05-0.08	0.065	B k_2
C	Slowly degrading waste	Paper/textile waste	0.04-0.06	0.045	C k_3
D	Slowly degrading waste	Wood/straw/ rubber	0.02-0.04	0.025	D k_4

Eq. (4.9) estimates the k values applicable to South Africa and can be determined as follows:

$$k = A \times k_1 + B \times k_2 + C \times k_3 + D \times k_4 \quad (4.9)$$

M_{LFGT} with a collection efficiency of 90% (Mohee and Simelane, 2015) is estimated from Eq. (4.4) and 10% oxidation factor (USEPA, 2006) due to landfill cover. The electricity (kWh/year) that could be obtained from the methane is estimated as:

$$\mathrm{Ep}_{(\mathrm{LFGT})} = \frac{\mathrm{LHV}_{\mathrm{methane}} \times 0.9 \times \mathrm{Q_C} \times \mathrm{n}}{3.6} \quad (4.10)$$

where $\mathrm{LHV}_{\mathrm{methane}}$ is 37.2 MJ/m^3 (Lower Heating Value of methane) (Amoo and Fagbenle, 2013), 3.6 is the conversion factor from MJ to kWh, n is 33% (the engine electrical conversion efficiency) (Bove and Lunghi, 2006), and Q_C is the average methane collected per annum (m^3/year) and can be calculated as:

$$\mathrm{Q_C} = \lambda \times \mathrm{Q_g} \quad (4.11)$$

$$Q_g = \frac{\sum_{i=1}^{n} Q_{CH_4(i)}}{n} \tag{4.12}$$

Where λ is 90% (collection efficiency), n is 20 years.

4.4.2 Incineration technology and municipal solid waste for electricity generation

An incineration technology produces heat when an organic portion of the MSW is burnt. The purpose of this technique is the destruction and degradation of organic elements in the waste to decrease the weight and volume with the presence of oxygen to convert into heat and energy (Beyene et al., 2018). Only the combustible MSW fraction is considered in this study. The incineration plant is assumed to be provided with air pollution control (APC) and zero waterborne pollutants. The APC equipment includes a spray dryer for acid gas control; injection of activated carbon for mercury control; ammonia or urea injection for Nitrous oxide control; and a fabric filter for particulate matter (PM) control.

The electricity (kWh/yr) E_{INC}, generated from the heat in a steam turbine is calculated as:

$$E_{p(INC)} = \frac{LHV_{wasteINC} \times M_{FINC} \times n_{inc}}{3.6} \tag{4.13}$$

$$M_{FINC} = \frac{\sum_{t=1}^{n} M_{FINC(t)}}{n} \tag{4.14}$$

where LHV_{waste} (MJ/kg) indicates the lower heating value of waste , n_{inc} is conversion efficiency and 3.6 is the conversion factor from MJ to kWh, $M_{FINC(t)}$ is the amount of waste composition (tons) for INC technology over t time (20 years) obtained from Eq. (4.4). M_{FINC} (tons/yr) is estimated from Eq. (4.14) and indicates the average annual mass of waste incinerated.

Higher heating value (HHV) in MJ/kg is modelled from(Parikh et al., 2005) analysis of the correlation.

$$HHV_{waste} = 0.3491C \times 1.1783H \times 0.1005S - 0.015N - 0.0211A \quad (4.15)$$

where C, H, O, N, S and A represents carbon (45.03%), hydrogen (6.20%), oxygen (41.16%), nitrogen(1.98%), sulphur (0%) and ash (5.56%) contents of the ultimate analysis of the waste stream (Ayeleru et al., 2016). From the HHV_{waste}, the lower heating value $LHV_{wasteINC}$ (MJ/kg) can be calculated as:

$$LHV_{wasteINC} = HHV_{waste} - (9 \times \%H + \%H_2 0) \times 2.44 \quad (4.16)$$

4.4.3 Anaerobic digestion technology and municipal solid waste for electricity generation

Anaerobic digestion is a biological method that decomposes organic matter through microorganisms in the absence of oxygen to produce biogas for combined heat and power (Tozlu et al., 2016; Beyene et al., 2018). The biogas is a mixture of methane (45 - 60%), carbon dioxide (40 – 55%) (Scarlat et al., 2015) with traces of hydrogen sulphide (H_2S), Nitrogen (N_2), Hydrogen (H_2), Carbon monoxide and Oxygen (O_2) (Kalyani and Pandey, 2014; Tozlu et al., 2016). The electricity that can be generated is calculated as follows:

$$Ep_{(AD)} = \frac{(V_{CH_{4actual}} \times \eta \times LHV_{CH_4} \times M_{F(AD)})}{3.6} \quad (4.17)$$

$$M_{F(AD)} = \frac{\sum_{t=1}^{n} M_{FAD(t)}}{n} \quad (4.18)$$

where $M_{FAD(t)}$ is from Eq. (4.4), $V_{CH_{4actual}}$ (m^3/ton) indicates the volume of methane in the biogas, LHV_{CH_4} (MJ/m^3) is the LHV of methane 37.2 MJ/m^3 (Amoo and Fagbenle, 2013; Gómez et al., 2010), $M_{F(AD)}$ (tons/yr) is the average mass of waste into the digester calculated from Eq. (4.18), the conversion factor from MJ to kWh is 3.6 and η is 0.26, the electrical efficiency of biogas generator in Table 4.5 (Gómez et al., 2010). A model proposed by (Salami et al., 2011) was used to calculate $V_{CH_{4actual}}$.

Table 4.5: AD digester values of the volume of methane and energy(Ogunjuyigbe et al., 2017).

Parameters	**Value**
$P_{CH4}(kg/m^3)$	0.717
$P_{CO_2}(kg/m^3)$	1.938
Efficiency (%)	26
C_o	3.6
LHV(MJ/m^3)	37.2
CF	0.85

The size of the AD generator of the estimated biogas can be calculated as:

$$G_{P(AD)} = \frac{E_{PAD}}{8760 \times CF} \tag{4.19}$$

4.5. ECONOMIC ANALYSIS OF THE WTE TECHNOLOGIES

The economic analysis of WTE technologies is necessary. The technology used for the generation of electricity is considered separately for each waste stream and the economic analysis considers the use of LFGT, INC and AD. The Net Present Value (NPV), Levelised Cost of Energy (LCOE) and Pay Back Period (PBP) were used to determine the economic viability of each technology in a municipality.

4.5.1 Net Present Value (NPV)

The costs the system incurred over its lifespan minus the revenue earned is the net present value. It is a method to examine cost outflows and revenue inflows. An economically viable investment must have a positive NPV (Jorgenson et al., 2011)[28,61] and is calculated as follows.

$$NPV = \sum_{n=0}^{N} \frac{F_n}{(1+d_r)^n} = F_0 + \frac{F_1}{(1+d_r)^1} + \frac{F_2}{(1+d_r)^2} + \cdots + \frac{F_N}{(1+d_r)^N} \tag{4.20}$$

where F_n is the net cash flow rate, d_r is annual real discount rate and *N* is the number of years. Both F_n and d_r is calculated using Eq. (4.21) and Eq. (4.22).

$$F_n = R_{ev}(i) - C_{inv}(i) - C_{O\&M}(i) - C_{Tax} \tag{4.21}$$

$$d_r = \left(\frac{1+d_n}{1+e}\right) - 1 \tag{4.22}$$

Where, R_{ev} is revenue earned , C_{inv} is the total investment cost, $C_{O\&M}$ is operation and maintenance cost, C_{Tax} is tax paid on the project, *i* is the type of technology (LFGT, INC or AD), d_n is the nominal discount rate and *e* is the inflation rate as per the statistics of South Africa and provided in Table 4.6.

Table 4.6: Economic parameters and values for the technologies

Parameters	Value
Inflation rate (e)	4.1
Repo rate (d_n)	6.75
Marginal tax rate (t)	28
(F_d) ZAR/kWh	94c
Project life time (N) years	20

Source: Statistics South Africa and Government reports

4.5.2 Investment costs, operation costs and maintenance costs of the technologies

The costs of WTE plants are divided into investment costs (equipment, construction costs, and land use costs), operational costs (raw materials, plant power, salaries, environmental expenses, etc) and maintenance costs. This paper evaluated the net cash flow rate F_n in the investment costs(C_{inv}), operation costs and maintenance costs ($C_{O\&M}$) and the costs are dependent on the type of technology. The revenue (R_{ev}) earned is calculated as follows:

$$\mathrm{R_{ev}(i) = E_p(i) \times F_d} \tag{4.23}$$

Where $\mathrm{E_p}$ is the electricity from each technology in Eqs (4.10), (4.13) and (4.17) for LFGT, INC and AD, respectively, i is the technology type, $\mathrm{F_d}$ is the cost of sale of electricity in ZAR/kWh (94c) as per the National Energy Regulator of South Africa (NERSA)and the parameters are in Table 4.6.

4.5.2.1 Landfill gas to energy technology

The investment cost of the LFGT technology was estimated using information and data from the Department of Energy's Renewable Electricity Independent Power Procurement Program (REIPPP) and from a case study for the city of Ekurhuleni municipality on municipal landfill gas to electricity project conducted by the Sustainable Energy Africa (SEA, 2017) . This paper, therefore, adopted the investment cost estimated for the city of Ekurhuleni municipality with the rest of the municipalities where costs are unknown. The investment costs include the cost of gas extraction wells, cost of installing an internal combustion engine, pipes, wellheads, knockout, blower and flare system, cost of engineering, permitting and surveying. Other costs include costs of operation and maintenance of the landfill site.

4.5.2.2 Anaerobic digestion technology.

According to (Tsilemou and Panagiotakopoulos, 2006), the investment cost , operating cost and maintenance costs of AD technology can be calculated using Eq. (4.24) and Eq.(4.25).

$$C_{inv(AD)} = \left(51827.082 \times M_{F(AD)^{0.55}}\right) \tag{4.24}$$

$$C_{O\&M_{(AD)}} = \left(25340.71553 \times M_{F(AD)^{-0.61}}\right) \tag{4.25}$$

Where $M_{F(AD)}$ indicates the system capacity in tons/yr.

4.5.2.3 Incineration technology

In this study, experimental data in the form of a cost function for European countries was adopted. An appropriate conversion coefficient can be used from in one region or country to another (Tsilemou and Panagiotakopoulos, 2006). The investment costs, operating costs and maintenance costs approved by the authors was adjusted by using the Purchasing Power Parity (PPP), Consumer Price index (CPI) and exchange rate as follows:

$$C_{inv(INC)} = 4900 \times \left(M_{F(INC)}\right)^{0.8} \times Q \times R \times S \tag{4.26}$$

$$C_{O\&M(INC)} = 700 \times \left(M_{F(INC)}\right)^{-0.29} \times Q \times R \times S \tag{4.27}$$

Where, Q, R, S are cost adjustment factors from Euro to ZAR. Q is the exchange rate taken as ZAR 16.28, R is the inflation rate (CPI) taken as 4.1 and S is the Purchasing Power Parity adjustment taken as 7.59.

4.5.3 The levelised cost of energy

Levelised Cost of Energy (LCOE) is a method which measures the economic viability of an investment. It is the minimum cost of energy generated in (ZAR/kWh) at which the investment breaks even(Short et al., 1995). It can be calculated using Eq. (4.28).

$$LCOE(i) = \left(\frac{LCC(i)}{E_P(i)}\right) CRF(i) \tag{4.28}$$

where LCC is the life cycle cost of the investment, CRF is the capital recovery factor, *i* is the technology type. The LCC and CFR can be calculated using Eq. (4.29) and Eq. (4.30), respectively.

$$LCC = C_{inv(i)} + \sum_{n=1}^{N} \frac{C_{O\&M_{(i)}}}{(1 + d_n)^n} \infty \tag{4.29}$$

$$CRF = \frac{d_n(1 + d_n)^N}{(1 + d_n)^N - 1} \tag{4.30}$$

where N indicates the years.

4.5.4 Payback Period

Many scholars found the use of WTE technologies economically viable through the estimation of the payback period (PBP). It is the number of years an investment breaks even or the time where the investment costs equal operating costs. Eq. (4.31) is used to calculate the PBP of each technology (i) with zero rebates:

$$PBP(i) = \frac{C_{inv(i)}(R) - Rebates(R)}{Annual\ EnergySavings(i)(R/year)} \tag{4.31}$$

$$AnnualEnergySavings\ (i) = Rev(i) - C_{O\&M(i)} \tag{4.32}$$

4.6. RESULTS AND DISCUSSION

This section evaluates the electricity generation potential of the WTE technologies (LFGT, AD and INC) based on the MSW disposed in landfill, population and per capita waste generation. It also determines the economic viability NPV, LCOE and PBP of the technologies in each municipality.

4.6.1 Projected municipal solid waste generation potential (2016 – 2035)

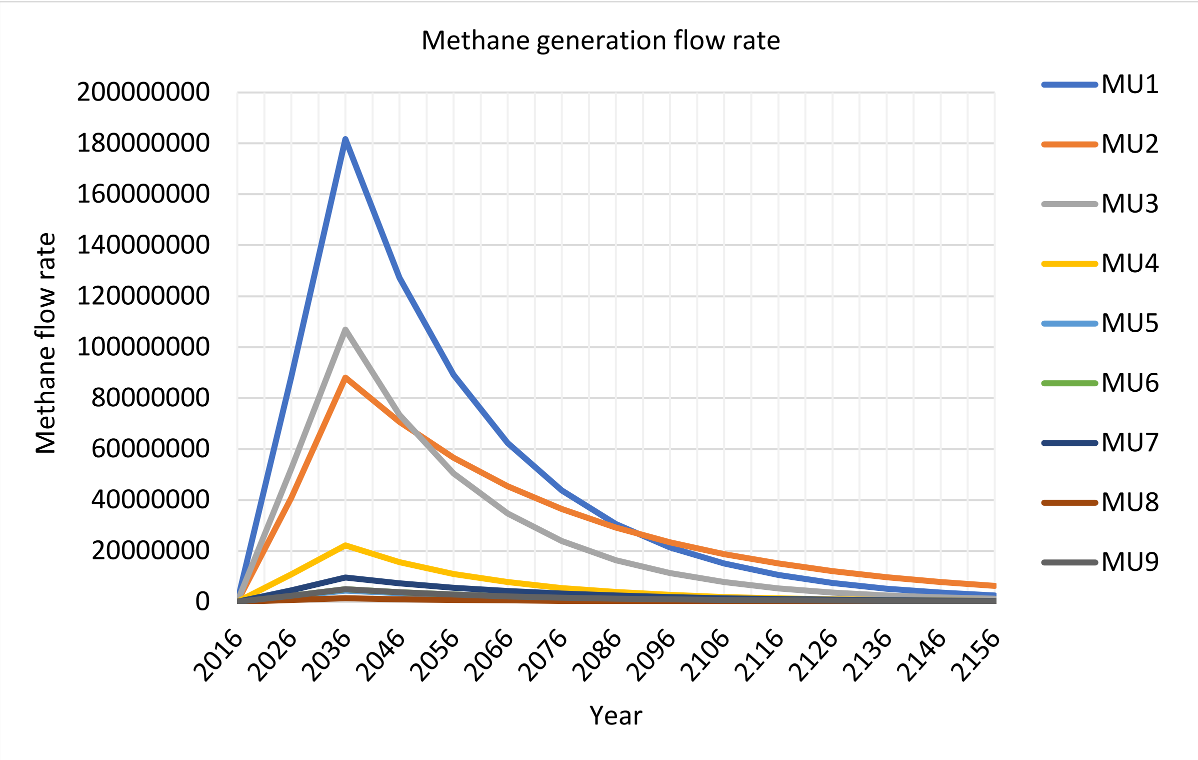
The MSW generated was calculated based on the projected population of each municipality and the waste generated per capita. Table 4.7 shows waste generated from the year 2016 (landfill opens) to the year 2035 (landfill closure).

Table 4.7: Projected MSW generated (kg/yr) for 20 years.

Year	MU1	MU2	MU3	MU4	MU5	MU6	MU7	MU8	MU9
2016	2.18925×10^9	1.33795×10^9	1.09562×10^9	2.15406×10^8	5.59334×10^7	1.49524×10^7	1.05404×10^8	1.56143×10^7	6.49338×10^7
2017	2.25712×10^9	1.37943×10^9	1.12958×10^9	2.22084×10^8	5.76674×10^7	1.54159×10^7	1.08671×10^8	1.60984×10^7	6.69467×10^7
2018	2.32709×10^9	1.42219×10^9	1.1646×10^9	2.28968×10^8	5.94551×10^7	1.58938×10^7	1.1204×10^8	1.65974×10^7	6.90221×10^7
2019	2.39923×10^9	1.46628×10^9	1.2007×10^9	2.36066×10^8	6.12982×10^7	1.63865×10^7	1.15514×10^8	1.71119×10^7	7.11618×10^7
2020	2.4736×10^9	1.51173×10^9	1.23792×10^9	2.43384×10^8	6.31984×10^7	1.68945×10^7	1.19094×10^8	1.76424×10^7	7.33678×10^7
2021	2.62934×10^9	1.60691×10^9	1.31586×10^9	2.58708×10^8	6.71774×10^7	1.79582×10^7	1.26593×10^8	1.87532×10^7	7.79871×10^7
2022	2.71085×10^9	1.65672×10^9	1.35666×10^9	2.66728×10^8	6.92599×10^7	1.85149×10^7	1.30517×10^8	1.93345×10^7	8.04047×10^7
2023	2.79489×10^9	1.70808×10^9	1.39871×10^9	2.74996×10^8	7.1407×10^7	1.90888×10^7	1.34563×10^8	1.99339×10^7	8.28972×10^7
2024	2.88153×10^9	1.76103×10^9	1.44207×10^9	2.83521×10^8	7.36206×10^7	1.96806×10^7	1.38735×10^8	2.05518×10^7	8.54671×10^7
2025	2.97086×10^9	1.81563×10^9	1.48678×10^9	2.9231×10^8	7.59029×10^7	2.02907×10^7	1.43035×10^8	2.1189×10^7	8.81165×10^7
2026	2.55028×10^9	1.55859×10^9	1.2763×10^9	2.50929×10^8	6.51576×10^7	1.74182×10^7	1.22786×10^8	1.81893×10^7	7.56422×10^7
2027	3.06295×10^9	1.87191×10^9	1.53287×10^9	3.01372×10^8	7.82559×10^7	2.09197×10^7	1.47469×10^8	2.18458×10^7	9.08481×10^7
2028	3.15791×10^9	1.92994×10^9	1.58038×10^9	3.10715×10^8	8.06818×10^7	2.15682×10^7	1.52041×10^8	2.2523×10^7	9.36644×10^7
2029	3.2558×10^9	1.98977×10^9	1.62938×10^9	3.20347×10^8	8.31829×10^7	2.22368×10^7	1.56754×10^8	2.32212×10^7	9.6568×10^7
2030	3.35673×10^9	2.05145×10^9	1.67989×10^9	3.30278×10^8	8.57616×10^7	2.29262×10^7	1.61614×10^8	2.39411×10^7	9.95616×10^7
2031	3.46079×10^9	2.11504×10^9	1.73196×10^9	3.40516×10^8	8.84202×10^7	2.36369×10^7	1.66624×10^8	2.46833×10^7	1.02648×10^8
2032	3.56807×10^9	2.18061×10^9	1.78565×10^9	3.51072×10^8	9.11612×10^7	2.43696×10^7	1.71789×10^8	2.54485×10^7	1.0583×10^8
2033	3.67868×10^9	2.24821×10^9	1.84101×10^9	3.61955×10^8	9.39872×10^7	2.51251×10^7	1.77115×10^8	2.62374×10^7	1.09111×10^8
2034	3.79272×10^9	2.3179×10^9	1.89808×10^9	3.73176×10^8	9.69008×10^7	2.59039×10^7	1.82605×10^8	2.70507×10^7	1.12493×10^8
2035	3.9103×10^9	2.38976×10^9	1.95692×10^9	3.84744×10^8	9.99047×10^7	2.6707×10^7	1.88266×10^8	2.78893×10^7	1.15981×10^8

Source: Field-based materials, 2019

MU1 (City of Johannesburg municipality) is projected to have the highest waste generation potential of 2.18925×10^9 – 3.9103×10^9 kg/yr between the year 2016 to 2035, followed by MU2 (City of Ekurhuleni municipality) 1.33795×10^9 – 2.3897×10^9, MU3 (City of Tshwane municipality) 1.09562×10^9 – 1.95692×10^9, MU4 (Emfuleni local municipality) 2.15406×10^8 – 3.84744×10^8 and MU7 (Mogale local municipality) 1.05404×10^8 – 1.88266×10^8, respectively. The high waste generation potential in MU1, MU2 and MU3 is expected as these municipalities are megacities with increasing population and relatively high waste generation per capita. The municipalities with the least waste generation potential are MU6 (Midvaal local municipality) and MU8 (Lesedi local municipality). Figure 4.5 shows the methane generation rate (Q_{CH4}) in each municipality from the year of waste deposition (2016) to closure (2035).



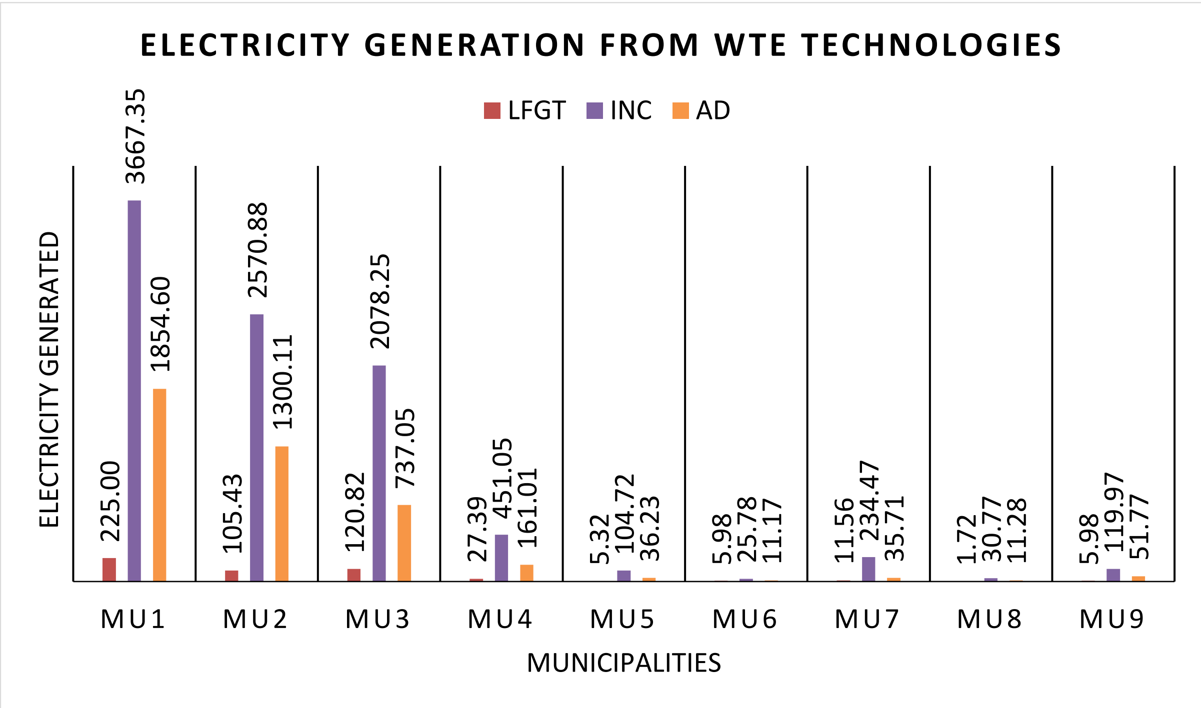
Source: Field-based materials, 2019

Figure 4.5: Methane generation flow rate Q_{CH4} (m^3/yr) from each municipality.

The above figure shows an increase in the methane generation rate from 2016 which is the year of waste deposition till 2036 when deposition stops. The year 2036 is the landfill closure year and the methane generation rate declines rapidly afterwards. The methane generation rate reached its peak in 2036 with estimates ranging from 181700000 m^3/yr (12210 ft^3/min) at MU1 - City of Johannesburg municipality, 106900000 m^3/yr (7182 ft^3/min) at MU3 - City of Tshwane municipality and 88040000 m^3/yr (5916 ft^3/min) at MU2 - City of Ekurhuleni municipality, respectively.

4.6.2 Electricity generation potential for each technology

The electricity generation potential of the WTE technologies in each municipality is shown in Figure 4.6 below.



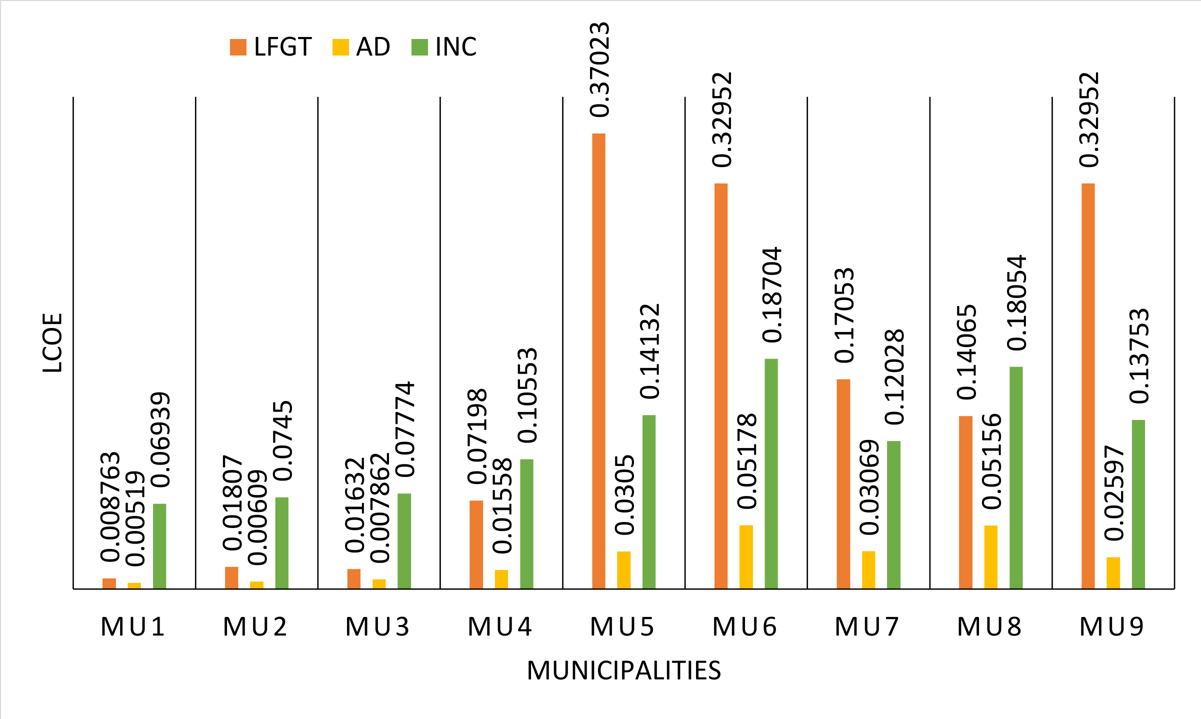
Source: Field-based materials, 2019

Figure 4.6: Electricity generation potential (GWh/ton) in one year for each technology

A look at Figure 4.6 shows that MU1 (City of Johannesburg), MU2 (City of Ekurhuleni) and MU3 (City of Tshwane) have the highest electricity generation potential while the least is at MU6 (Midvaal local municipality) and MU8 (Lesedi local municipality). INC technology is the best waste management technology attractive in terms of electricity generation potential with MU1, MU2, MU3 showing the electricity generation potential of about 3667.35, 2570.88 and 2078.25 GWh per annum, respectively. The potential of the INC technology to generate more electricity than AD and LFGT is explained by the high use of plastics and other combustible waste stream and not to AD and LFGT since plastics are not biodegradable. The results obtained here are consistent with the study conducted by (Gómez et al., 2010; Amoo and Fagbenle, 2013) considering the diversity of approaches and data sources used.

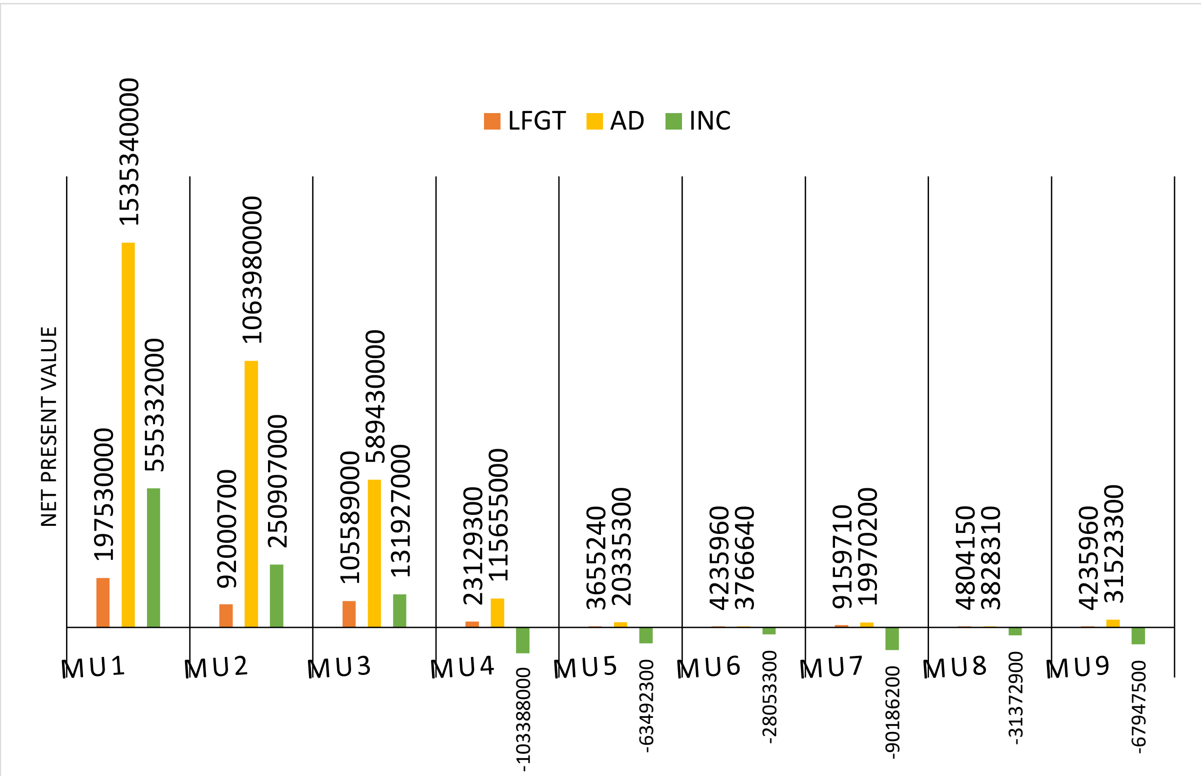
4.6.3 Economic viability of WTE technologies in each municipality

The economic viability of LFGT, AD and INC technologies was evaluated based on LCOE (Figure 4.7) and NPV (Figure 4.8) for each municipality.



Source: Field-based materials, 2019

Figure 4.7: Levelised cost (ZAR/kWh) of energy for each technology



Source: Field-based materials, 2019

Figure 4.8: Net Present Value (ZAR) for each technology

Figure 4.7 shows that LFGT technology has the highest LCOE ranging from R0.37023/kWh at MU5 to R0.32952/kWh at MU9 and the lowest LCOE ranging from R R0.008763/kWh at MU1 to R0.07198/kWh at MU4. In Figure 4.8, LFGT technology presents the lowest NPV in all the municipalities ranging from R3.6 million at MU5 to R197.5 million in MU1. This means that LFGT is the least capital intensive compared to AD and INC. INC technology is shown to have the second highest LCOE in all the municipalities with the highest from R0.10553/kWh at MU4 to R0.13753/kWh at MU9. An interesting finding is noted for the INC technology, a negative NPV is shown from MU4 to MU9. This indicates that the INC technology is more capital intensive compared to LFGT and AD. It can, therefore, be concluded that INC technology is not economically feasible in MU4, MU5, MU6, MU7, MU8 and MU9. However, AD technology has the lowest LCOE in all the municipalities, more especially at MU1, MU2, MU3 and MU4. It can also be observed that the NPV is high and positive at MU1, MU2, MU3 and MU4. This indicates that AD technology is an economically viable WTE technology at MU1, MU2, MU3 and MU4.

4.6.4 Payback period of WTE technologies

Table 4.8 shows the payback period of the WTE technologies in each municipality. The table shows that AD technology has the lowest payback period compared to LFGT and INC. This means that the return on investment is short (only a few months) and economically viable.

Table 4.8: Payback period for LFGT, AD and INC

MUNICIPALITIES	LFGT	AD	INC
MU1	0.1	0.1	0.8
MU2	0.2	0.1	0.9
MU3	0.2	0.1	0.9
MU4	0.8	0.2	1.2
MU5	6.7	0.4	1.6
MU6	5.5	0.6	2.1
MU7	2.2	0.4	1.4
MU8	3.6	0.6	2.1
MU9	5.5	0.3	1.6

Source: Field-based materials, 2019

The return on investment for the LFGT technology at MU1, MU2, MU3 and MU4 are also months. MU5, MU6, MU7, MU8 and MU9 have a payback period of 6.7, 5.5, 2.2, 3.6 and 5.5 years, respectively. INC technology at MU4, MU5, MU6, MU7, MU8 and MU9 have a payback period of 1.2, 1.6, 2.1, 1.4, 2.1, and 1.6 years, respectively.

4.7. CONCLUSION

In the Gauteng province, WTE technologies can improve the management of solid waste whilst promoting clean and healthy urban environments through the recovery of waste and generation of electricity. In this study, an assessment of the electricity generation potential and the economic analysis of WTE technologies (LFGT, AD, and INC) in each municipality has been presented.

I. MU1 (City of Johannesburg municipality) has the highest waste generation projection with values of 2.1895×10^9 - 3.9103×10^9 m^3/yr between the year 2016 and 2035, followed by MU2 (City of Ekurhuleni municipality) 1.33795×10^9 - 2.38976×10^9 m^3/yr and MU3 (City of Tshwane municipality) 1.09562×10^9 - 1.95692×10^9, respectively.

II. The municipalities with the least generation potential are MU6 (Midvaal local municipality) and MU8 (Lesedi local municipality).

III. It was found that INC technology and AD technology present the best technological option in terms of the electricity generation potential for MU1 (City of Johannesburg municipality), MU2 (City of Ekurhuleni municipality), MU3 (City of Tshwane municipality) and MU4 (Emfuleni local municipality).

IV. In terms of economic viability, AD technology is preferable in all the municipalities because of the low LCOE and positive NPV.

V. INC technology has the highest electricity generation potential in all the municipalities.

VI. In a similar vein, INC is not economically friendly technology because of the high LCOE and a negative NPV.

CHAPTER FIVE

Life cycle assessment of Waste-to- Energy technologies for electricity generation in the Gauteng province, South Africa[4]

ABSTRACT

Waste-to-energy (WTE) technologies have been presented as one of the avenues to improve the management of solid waste whilst promoting clean and healthy urban environments through the recovery of waste while increasing renewable energy generation. However, the landfill gas to energy (LFGT), Incineration (INC) and anaerobic digestion (AD) technologies emit methane gas and polluting chemicals into the atmosphere. Therefore, from a solid waste management perspective, WTE technologies pose challenges to the development of a green and sustainable future. The aim of this study was to evaluate the electricity generation potential, global warming potential (GWP), acidification potential (AP) and dioxin/furan emission potential of the WTE technologies, using the life cycle assessment (LCA) methodology. Four scenarios were evaluated, namely scenario 1 - landfill (LF), scenario 2 - landfill with energy recovery (LFGT), scenario 3 - incineration with anaerobic digestion (INC with AD) and scenario 4 - incineration with landfill with energy recovery (INC with LFGT). Key findings revealed that INC technology has the greatest potential for electricity generation in all municipalities and it has the highest potential in MU1 (City of Johannesburg municipality – 3667.35 GWh/ton). Scenario 3 (INC with AD) has the highest GHG emissions in all the municipalities. This was expected as the electricity generation potential for INC was high in all the municipalities. Scenario 4 (INC with LFGT) has the highest AP compared to the other scenarios. Dioxin emission in scenario 4 (INC with LFGT) was higher than that in scenario 2 (LFGT) and it is not surprising as dioxins are emitted through the combustion of waste.

Keywords: *Life cycle assessment, Waste-to-energy technologies, Global warming potential, Gauteng*

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[4] The second revision has been done and the paper is currently under consideration: Smangele Dlamini, Simphiwe Simelane & Mulala Simatele (2019). Life cycle assessment of Waste-to- Energy technologies for electricity generation in the Gauteng province, South Africa. *Journal of Waste Management.*

5.1. INTRODUCTION

One of the most significant environmental problem of our time is the rapid generation of municipal solid waste (MSW) due to economic development and population growth(du Toit et al., 2017). There has been an increase in urban population, urbanization, industrialization and economic development with changing consumption patterns (Chimuka and Ogola, 2015). The urban population has adopted a lifestyle of the developed countries due to globalisation, resulting in the generation of large quantities of waste that needs to be landfilled and consequently diminishing landfill airspace (Baker and Letsoela, 2016). The increase in the MSW generation rate is mostly due to economic and social prosperity, consumption pattern and living standards of the urban population (Simatele et al., 2017).

The rapid increase in MSW generation requires appropriate waste management strategies which involve landfill gas to energy (LFGT), thermal treatment (INC) and biochemical treatment (AD). The thermal treatment of MSW which in this case is INC technology reduces the volume of waste through combustion (Gómez et al., 2010). On the other hand, biochemical treatment (LFGT and AD) are based on the biological decomposition of organic matter under the influence of microbes to produce methane. LFGT is one of the most used and practical MSW treatment methods. It is a disposal technique that uses engineering principles to keep deposited MSW in one small area possible and reduce it to the lowest allowable volume that creates a major environmental problem due to methane generation, however, the methane produced is the best alternative for energy recovery (Tozlu et al., 2016; Fourie and Morris, 2004).

A promising alternative to overcome waste generation problem and a potential renewable energy source is through WTE technologies. Energy can be recovered through

LFGT, INC and AD from biodegradable and non-biodegradable waste. An advantage of the INC technology is that it avoids the generation of methane gas from the landfill, solves the degradation of valuable land resources for landfill and suitable for non-biodegradable waste with low moisture content (Tan et al., 2014). However, the generation of methane in landfills has gained increasing attention through landfill gas recovery. Landfill gas recovery helps in mitigating GHG emissions from MSW and is suitable for biodegradable waste with high moisture content(Al-Salem et al., 2014; Ayodele et al., 2017).

The growing usage of WTE technologies has necessitated the need for research on associated environmental emissions of WTE plants. Many recent studies, for example,(Tan et al., 2015) assessed the environmental impact of incineration, landfill gas recovery system, gasification and anaerobic digestion in Malaysia and subsequently evaluated the potential of each technology for electricity production and carbon reduction. The authors found that incineration is the best and profitable technology for MSW in terms of electricity generation potential in Malaysia. In another work, (Tan et al., 2014) assessed the WTE technologies in terms of energy conversion and carbon reduction for waste incineration and landfill gas recovery. The study analysed the energy conversion potential based on the biogenic carbon fractions by using IPCC guidelines. They concluded that pre-treatment of MSW is important to boost electricity generation and GHG emission reduction through WTE technologies. Moreover, (Kalantarifard and Yang, 2011) evaluated the composition of MSW by estimating the high heating value and feasibility of an incineration plant in Tanjung langsat landfill in Malaysia. Mathematical models have been used to determine and compare the proximate analysis results and it was found to have a high heating value of approximately 23,000 kJ/kg. Another study by

(Johari et al., 2012) has simulated the heat content of the waste and the effects of moisture content by using mathematical equations and comparing with lab-scale results. The chemical and physical properties of simulated MSW were estimated and successfully overcome the heterogeneous complexity of actual MSW.

Different scholars have proposed models that could be used for the analysis of WTE technologies. A model developed by (Dong et al., 2014), integrated life cycle energy was extended from life cycle 2E assessment model to life cycle 3E assessment model (energy, environment and economy) which was applied for the comparison of WTE technologies. They revealed that incineration performed best among all scenarios that were under study. Similarly, (Yang and Chen, 2014) considered time-varying factors for GHG emissions and energy intensity and proposed a dynamic life cycle assessment approach, which was applied to estimate the life cycle global warming impact of a crop residue gasification in China. Results showed that the project has significant potential in alleviating global warming impact. Moreover, (Ho et al., 2017) presented a method called waste management pinch analysis (WAMPA) for examining the capacity of waste management strategies through graphical representation. It was applied to landfill, WTE technologies and 3R (reduce, re-use and recycle) and showed a 54.6% and 13.5% reduction in GHG emission and in landfill, respectively. The scholars have applied the models in real case scenarios and succeeded in determining the electricity generation potential, environmental suitability and economic viability of WTE technologies in terms of GHG potential and acidification potential. However, the dioxin/furan potential of LFGT, INC and AD technologies is often neglected.

While WTE technologies have been developed and implemented in most develop countries like Germany, Canada, China and Spain (Gómez et al., 2010; Dong et al., 2014;

Xiaoli et al., 2010; Chandler, 2007; Assamoi and Lawryshyn, 2012), South Africa is yet to develop her potential on WTE technologies. A number of local scholars (Dada and Mbohwa, 2016; Mutanga et al., 2013; Muzenda et al., 2012; Baker and Letsoela, 2016; Fourie and Morris, 2004; Dowling et al., 2012b) have attempted to evaluate the potential of WTE technologies for electricity generation in some parts of the country, their environmental impact assessment was rarely carried out. Hence, there is limited information about the potential contribution of WTE technologies and MSW to the emissions profile in the Gauteng province, South Africa.

This paper aims to evaluate WTE technologies in terms of their electricity generation potential, global warming potential, acidification potential and dioxin/furan emission potential by using waste management scenarios. This study will provide valuable information for policy making purposes and decision making that could lead to optimum investment in WTE technologies and a better MSW management strategy in the country.

5.2. LIFE CYCLE ASSESSMENT AND MUNICIPAL SOLID WASTE MANAGEMENT SCENARIOS

Life cycle assessment is a tool used for evaluation and compilation of the inputs, outputs and environmental impacts of a system through its life cycle (Liu et al., 2012; Chandler, 2007). It is a useful tool in waste management systems, waste processing and treatment for recycling and disposal of waste (Tsai and Chou, 2006; Scarlat et al., 2015). It is an adopted methodology used by scholars to evaluate the environmental burden of MSW management (Al-Salem et al., 2014; Tozlu et al., 2016; Vitorino de Souza Melaré et al., 2017). It is also the best option among available MSW strategies applied as an alternative to the waste hierarchy by providing assessments of environmental impacts without assuming a preference for a waste management method over another (Friedrich and Trois, 2010; Couth et al., 2011; Tan et al., 2014).

5.2.1 SCENARIOS DEVELOPMENT

A flow chart (Figure 5.1) was used to develop four different waste management scenarios and expected future treatment systems. To enhance the understanding of the scenarios, this study used different colours.

Scenario 1 (baseline): The landfill (LF)

Currently the old, cheapest and most common method of waste disposal. Most of them are operating at full capacity with some already closed and others will be exhausted in less than 10 years (Mbuli, 2015; Baker and Letsoela, 2016). This is the baseline where all waste streams except for recyclables are sent to the landfill.

Scenario 2: Landfill with energy recovery (LFGT)

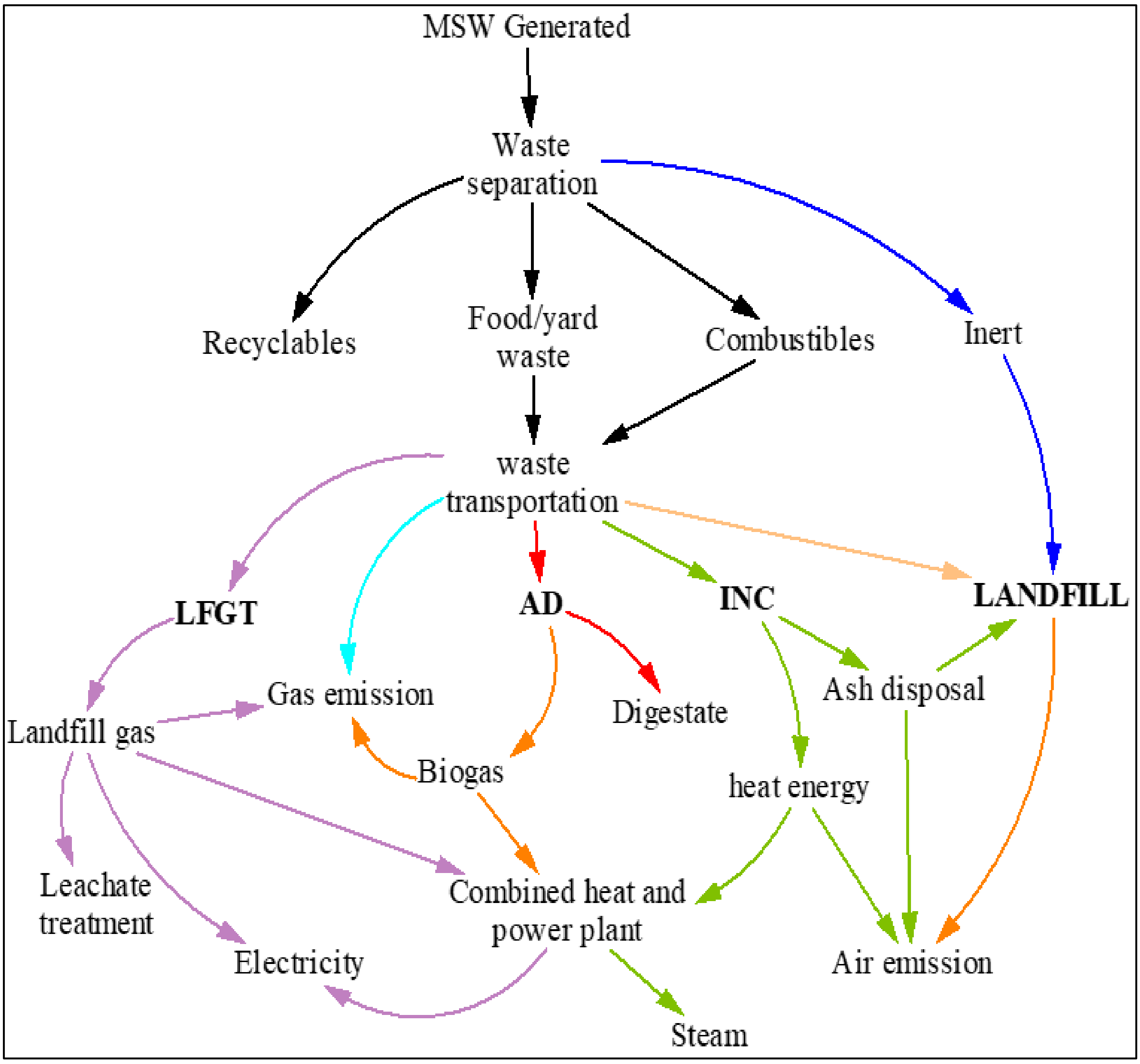
Except for recyclable materials, all other waste streams are sent to the landfill with energy recovery. The methane that is produced in this scenario is captured for electricity generation. Leachate production and treatment is not considered.

Scenario 3: Incineration (INC) with anaerobic digestion (AD)

This scenario involves both (INC) and (AD) technologies. Only biodegradable waste is treated through the AD digester and the methane is used to produce electricity. The residue from the AD can be treated and used as manure. Combustibles and yard waste stream are treated in the incinerator for electricity generation and the fly ash produced is disposed in a landfill.

Scenario 4: Incineration (INC) with landfill gas recovery (LFGT)

This scenario involves both INC and LFGT technologies. Combustible waste is treated in an incinerator for electricity generation and food waste together with yard waste are sent to the landfill where methane will be captured for electricity generation. To allow a fair and consistent comparison, fly ash emissions from incineration are disposed to a landfill and leachate treatment from LFGT are not considered. Inert waste is sent to the landfill and does not degrade.



Source: Field-based materials, 2019.

Figure 5.1: Simplified flow chart and waste management scenarios

Basic assumptions of the study.

The following are the basic assumptions made for the analysis.

- All environmental impacts generated from the production of a product before becoming a waste are ignored.
- This LCA has omitted the waste collection, separation and transfer station operations and it is applied in all waste management scenarios.

- The emission from waste transportation between the landfill plant, incineration plant and anaerobic digestion plant is ignored since the plants are located at equal distance from the transfer station at the outskirts of the city.
- The active life span of the landfill is considered and the closure and post-closure emissions from the selected landfills are ignored.
- Construction of the waste treatment facilities emissions and energy are ignored.
- In all scenarios, the effects of landfill carbon storage (carbon sequestration) were not considered.
- The performance analyses for all scenarios were carried out over a period of 20 years (2016 - 2035).
- Biodegradable waste includes food waste, yard waste, paper, cardboard, textiles, leather and wood.
- Recyclable waste includes glass, ceramics, plastics, rubber and metals.
- Combustible waste includes paper, textiles, rubber, plastics, leather and wood wastes
- Inert are other waste categories such as sand, ceramic, etc.

5.2.2 DATA COLLECTION AND AREA UNDER STUDY

The Gauteng province at 19 179 km^2 is the smallest and the most populous with an estimated 12.9 million people (Stats SA, 2014). It is the economic and industrial hub of South Africa. It is made up of nine municipalities of which 3 are cities (the City of Johannesburg, City of Tshwane and City of Ekurhuleni) and two districts namely the West rand district and the Sedibeng district. Figure 5.2 shows the location of the municipalities within the Gauteng province.

Source: Cartography Unit, 2019. School of Geography and Environmental Studies

Figure 5.2: Map of the Gauteng Province showing municipalities

The Gauteng province generates 45% of MSW and is expected to have the highest per capita waste generation in South Africa (Baker and Letsoela, 2016; Mbuli, 2015). The amount of waste generated is a function of the population and societal lifestyles while the waste composition depends on culture, income, consumption pattern and season(Dowling et al., 2012b; Couth and Trois, 2012). The quantity of the MSW generated within the Gauteng province was estimated using the 2011 population census (most recent population data) obtained from Statistics South Africa and interpolated to 2016 based on 3.1 % growth rate and the per capita waste generation in each municipality.

Table 5.1 below shows the municipalities under study, the population as obtained from Statistics South Africa and the waste generated in each municipality per capita per day (kg/capita/day) as obtained from the government databases and various literature. The waste composition obtained from literature and from Government database is presented in Table 5.2 and is assumed to be the same throughout the period of calculation (2016–2035).

Table 5.1: Municipalities, population and waste generated per capita in the province

Municipality	Designate	2011 Census	Waste generated per capita	Lat (N)	Long (E)
City of Johannesburg	MU1	4 434 827	1.29	26.20	28.04
City of Ekurhuleni	MU2	3 178 470	1.1	-26.17	28.34
City of Tshwane	MU3	2 921 488	0.98	25.60	28.39
Emfuleni	MU4	721 663	0.78	26.64	27.78
Merafong	MU5	197 520	0.74	26.37	27.40
Midvaal	MU6	95 301	0.41	26.58	28.06
Mogale	MU7	362 422	0.76	25.98	27.59
Lesedi	MU8	99 520	0.41	26.50	28.43
Rand West	MU9	261 053	0.65	26.19	27.67

Source: Statistics South Africa and Government database,2019

Table 5.2: Waste composition in each municipality within the Gauteng province

Composition (f) in %	Designate	MU 1	MU 2	MU 3	MU 4	MU 5	MU 6	MU 7	MU 8	MU 9
Food waste	D1	34	29	27	23	22	21	11.9	20	24
Garden waste	D2	-	-	6	9	4	4	13.4	9	8
Plastics	D3	19	20	26	20	16	15	14.9	17	19
Paper	D4	12	15	18	10	11	14	10.4	13	11
Nylon	D5	-	-	-	-	-	-	-	-	-
Leather	D6	-	-	-	-	-	-	-	-	-
Textiles	D7	3	5	4	6	10	5	7.6	5	5
Metal	D8	5	6	2	7	8	7	5.4	6	3
Glass	D9	9	8	7	8	12	10	4.0	5	11
Wood	D10	-	-	-	-	5	-	-	-	-
Ceramics	D11	-	-	-	-	-	-	-	-	-
E-waste	D12	-	-	-	-	-	-	-	-	-
Other organic	D13	-	10	-	7	4	9	1.7	9	8
Inert	D14	18	3	10	-	-	13	-	9	6
Other inorganic	D15	-	4	-	10	8	2	30.4	7	5
Total		**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Source: Government database and literature review,2019

5.3. METHODOLOGY

A research framework explaining the methodology used in this study is illustrated in Figure 5.3 and Figure 5.4. To aid the understanding of the study approach, the framework is divided into 5 processes which are: WTE assessment, electricity generation potential, greenhouse gas emission potential, acidic pollution and organic pollution. For instance, the input data for WTE assessment is the population data for each municipality and per capita MSW generation as given in Table 5.1. MSW composition for each of the municipalities is given in Table 5.2.

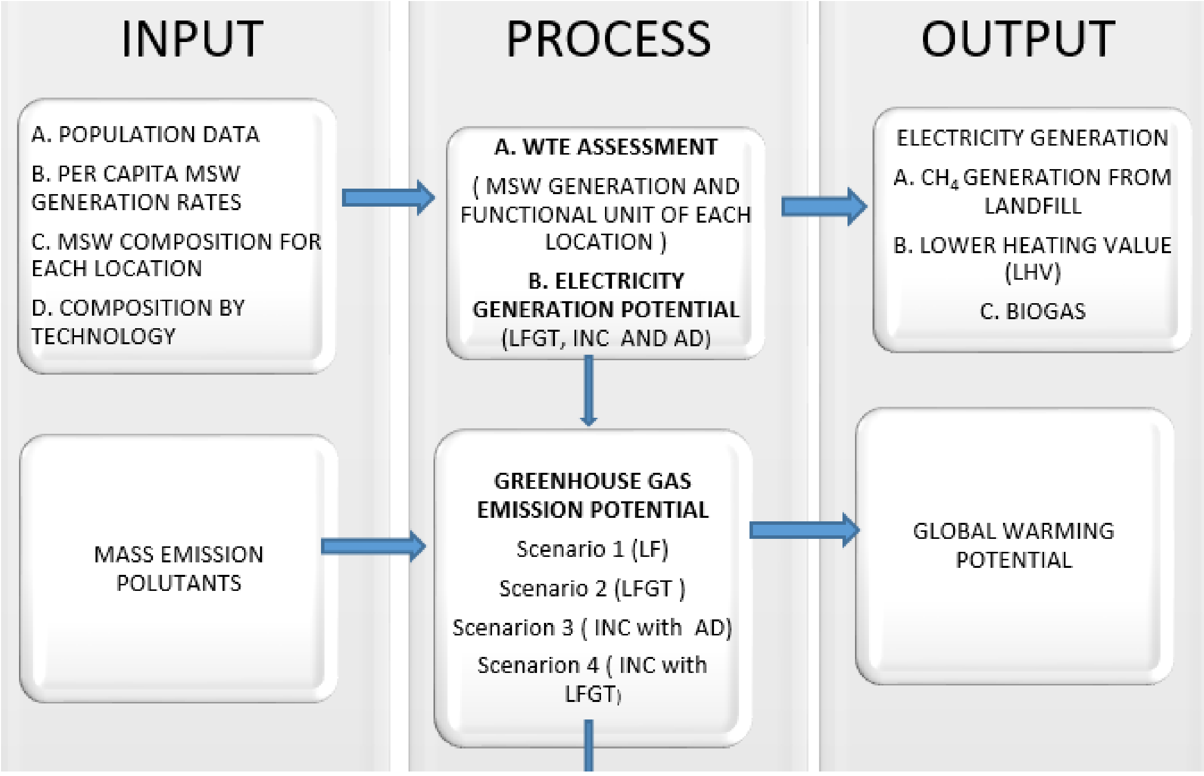


Figure 5.3: Research methodology framework proposed in this study

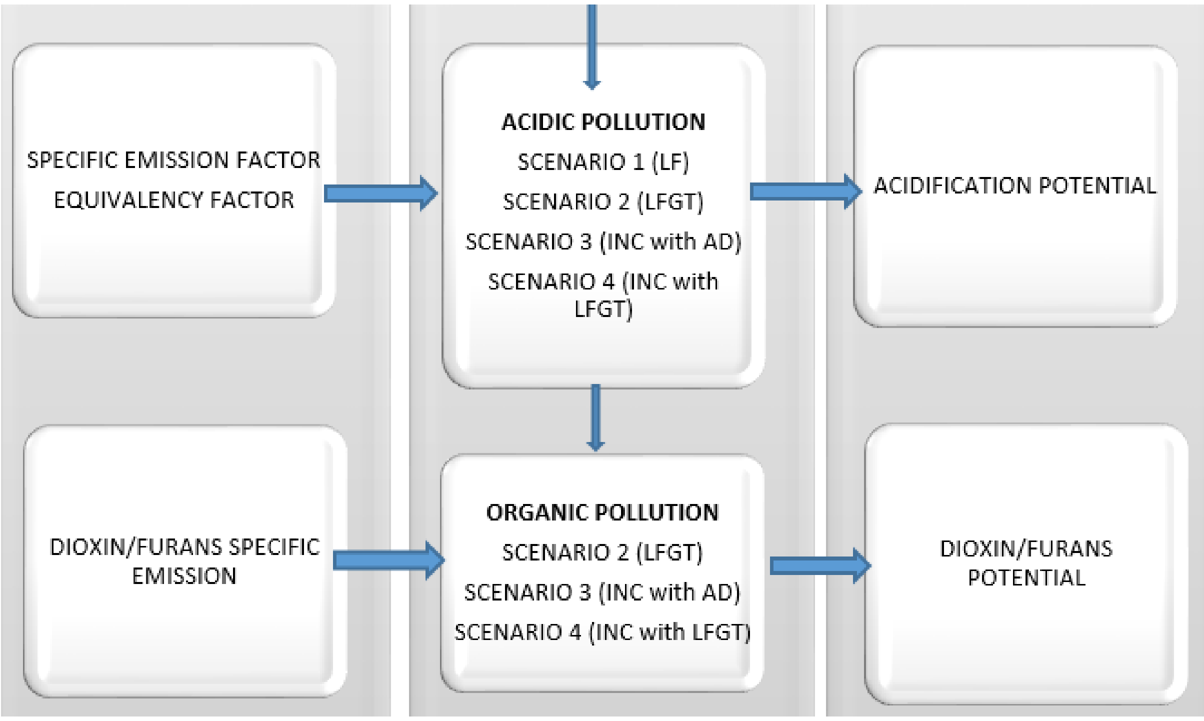


Figure 5.4: Continuity of a research methodology framework proposed in this study

5.3.1 ESTIMATION OF MSW COMPOSITION IN EACH OF THE WTE TECHNOLOGIES

This paper assumes that not all waste generated is deposited in a landfill. According to (Mohee and Simelane, 2015; Mngoma et al., 2017), only 90% of the waste generated in the Gauteng province is collected and disposed in landfills. Therefore, the quantity of waste taken to landfill ($\mathrm{M_F}$) is obtained as:

$$\mathrm{M_F(t)} = 0.90 \times \mathrm{M_T} \quad (5.1)$$

$\mathrm{M_T}$ (tons/yr) is waste generated per year and calculated as:

$$\mathrm{M_T(t)} = \mathrm{P(t)} \times \mathrm{wc} \times 365 \quad (5.2)$$

where P(t) is the projected population of each municipality based on the population growth rate (r) of 3.1% and wc is the waste generation rate (kg/capita/day) in Table 5.1. The population can be determined as:

$$P(t) = P_O(1 + r)^t \quad (5.3)$$

where P_O is the base population of each of the location using 2011 census as depicted in Table 5.1 and t is the time of extrapolation.

An estimation of the amount of waste composition for each technology (LFGT, AD and INC) was calculated from Table 5.2 using the following equation:

$$M_{F(t)i} = 0.90 \times M_T(t) \times f_{(i)}(tons/yr) \quad (5.4)$$

Where, i is the type of technology (LFGT, INC and AD), f is the organic fraction for each technology option.

The percentage composition of waste for each scenario is shown in Table 5.3 below and it is extracted from Table 5.2 where food waste was considered for AD technology, combustible waste stream was considered for INC technology and a combination of combustibles and food waste was considered for LFGT technology.

Table 5.3: Percentage composition of waste (*f*) allocated to each technology that can be treated.

Municipality	**Extra-ction**	**LFGT**	**Extra-ction**	**INC**	**Extra-ction**	**AD**
MU1	D1+D3+ D4+D7	68	D1+D3+ D4+D7	68	D1	34
MU2	D1+D3+D4+D7 +H13+H15	83	D1+D3+D4+D7 +H13+H15	83	D1+D13	39
MU3	D1+D2+D3 +D4+D7	81	D1+D2+D3 +D4+D7	81	D1	27
MU4	D1+D2+D3+D4 + D7+D13+D15	85	D1+D2+D3+D4 + D7+D13+D15	85	D1+D13	30
MU5	D1+D2+D3+D4 +D7+D10+D13 +D15	80	D1+D2+D3+D4 +D7+D10+D13 +D15	80	D1+D13	26
MU6	D1+D2+D3+D4 +D7+D13+D15	70	D1+D2+D3+D4 +D7+D13+D15	70	D1+D13	30
MU7	D1+D2+D3+D4 +D7+D13+D15	90.3	D1+D2+D3+D4 +D7+D13+D15	90.3	D1+D13	13.6
MU8	D1+D2+D3+D4 +D7+D13+D15	80	D1+D2+D3+D4 +D7+D13+D15	80	D1+D13	29
MU9	D1+D2+D3+D4 +D13+D15	80	D1+D2+D3+D4 +D13+D15	80	D1+D13	32

Source: Based on information in Table 5.2.

5.4 FUNCTIONAL UNITS

The functional unit is used as a reference unit for the quantified performance of a product or a system(Gentil et al., 2010). The functional unit is a decision-making tool which includes all the managed waste in tonnes with a specific composition in a waste management system over one year period time, for a specific region (Cherubini et al., 2009; Gentil et al., 2010). The functional unit in this case are tonnes of MSW generated in each municipality between the year 2016 and 2035 which is taken as the average annual waste managed within the time period. The estimated average annual waste treated in each municipality over a period of 20 years excluding the recyclables and the inert waste stream was determined using Eq. (5.5) and results are shown in Table 5.4.

$$M_{FU(i)} = \frac{\sum_{t=1}^{n} M_T\,(t) \times f(i)}{n} \tag{5.5}$$

Table 5.4: Waste generated in tonnes in each municipality

Municipality	Designate	Waste generated (tons)
City of Johannesburg	M1	2.9714×10^9
City of Ekurhuleni	M2	1.81596×10^9
City of Tshwane	M3	1.48705×10^9
Emfuleni	M4	2.92364×10^8
Merafong	M5	7.59167×10^7
Midvaal	M6	2.02944×10^7
Mogale	M7	1.43061×10^8
Lesedi	M8	2.11928×10^7
Rand West	M9	8.81326×10^7

Source: Field-based materials, 2019.

5.5 ESTIMATION OF ELECTRICITY GENERATION POTENTIAL OF WTE TECHNOLOGIES

This section evaluates and quantifies the electricity generation potential of the landfill gas to energy (LFGT), incineration (INC) and anaerobic digestion (AD) technologies.

5.5.1 Electricity generation and landfill gas to energy technology

A landfill generates a number of gases known as landfill gas due to the anaerobic decomposition of biodegradable waste(Kumar et al., 2016). The main gases are methane and carbon dioxide of which methane is the greatest concern. This is because methane is a greenhouse gas with a global warming potential of 28 times than that of carbon dioxide (Kalyani and Pandey, 2014). The potential of a landfill to generate electricity depends on its methane generation potential. In this study, Landfill Gas Emission Model (LandGEM) software was used to estimate the methane generation for each year from cumulative waste disposed up through a year in each municipality. The model predicts the landfill gas emissions based on first-order decomposition rate equation, which assumes that the methane generation rate after deposition increases. The first-order decay equation for the annual methane generation flow rate (m^3/year) can be estimated using:

$$Q_{CH_4} = \sum_{k=1}^{n} \sum_{j=0.1}^{1} k\mathrm{Lo} \left(\frac{M_{LFGT}}{10}\right) e^{-t_{kj}} \qquad (5.6)$$

where k is the 1-year time increment, *n* is (year of the calculation) – (initial year of waste acceptance), j is the 0.1-year time increment, *k* is methane generation rate ($year^{-1}$), Lo is the potential methane generation capacity (m^3/Mg), M_{LFGT} is the annual waste landfilled (Mg/yr). Lo determines the amount of methane gas potentially produced by a metric tonne (Mg) of waste as it decays(Mwesigye et al., 2011).

The methane generation potential (Tan et al., 2015) is estimated as:

$$L_O = M_F \times MCF \times DOC \times DOC_F \times F \times \frac{16}{12} \qquad (5.7)$$

$$DOC = 0.4 \times P + 0.15 \times K + 0.3 \times W + 0.24 \times T \qquad (5.8)$$

$$DOC_F = 0.014 \times T_{emp}(°C) + 0.28 \qquad (5.9)$$

where M_F indicates the quantity of waste disposed to the landfill as calculated in Eq. (5.4), MCF is 0.1-the methane correction factor (Tan et al., 2015; Tsai, 2007; IPCC, 2006) for managed landfill, DOC is the fraction of degradable organic carbon, DOC_F is the fraction of total DOC that actually degrades and obtained in Eq. (5.9), T_{emp} is the temperature of the landfill area taken as 30 °C (Dowling et al., 2012b). F is 0.50 - the methane fraction by volume in the landfill gas, P is the fraction of papers in the waste, K is the fraction of kitchen garbage in the waste and W is the fraction of wood/ leaves in the waste and T is the fraction of textile in the waste (Tsai, 2007).

The method proposed by (Sil et al., 2014) and (Karagiannidis et al., 2007) was used to determine the methane generation constant *(k).* M_{LFGT} is the collection efficiency which is 90% (Mohee and Simelane, 2015) estimated from Eq. (5.4) and 10% oxidation factor (USEPA, 2006) due to landfill cover.

The electricity (kWh/year) that could be obtained from the methane is estimated as:

$$Ep_{(LFGT)} = \frac{LHV_{methane} \times 0.9 \times Q_C \times n}{3.6} \tag{5.10}$$

where $LHV_{methane}$ is 37.2 MJ/m^3 (Lower Heating Value) of methane(Amoo and Fagbenle, 2013), 3.6 is the conversion factor from MJ to kWh, *n* is 33% (the engine electrical conversion efficiency) (Bove and Lunghi, 2006), and Q_C is the average methane collected per annum (m^3/year) and can be calculated as:

$$Q_C = \lambda \times Q_g \tag{5.11}$$

$$Q_g = \frac{\sum_{i=1}^{n} Q_{CH_4(i)}}{n} \tag{5.12}$$

where λ is 90% (collection efficiency), n is 20 years.

5.5.2 Electricity generation and incineration technology

The incineration technology produces heat when an organic portion of the MSW is burnt. The purpose of this technique is the destruction and degradation of organic elements in the waste to decrease the weight and volume with the presence of oxygen to convert into heat and energy(Beyene et al., 2018). Only the combustible MSW fraction was considered in this study. The incineration plant is assumed to be provided with air pollution control (APC) and zero waterborne pollutants. The APC equipment includes a spray dryer for acid gas control; injection of activated carbon for mercury control; ammonia or urea injection for Nitrous oxide control and a fabric filter for particulate matter (PM) control. The electricity (kWh/yr) E_{INC}, generated from the heat in a steam turbine is calculated as:

$$E_{p(INC)} = \frac{LHV_{wasteINC} \times M_{FINC} \times n_{inc}}{3.6} \quad (5.13)$$

$$M_{FINC} = \frac{\sum_{t=1}^{n} M_{FINC(t)}}{n} \quad (5.14)$$

where LHV_{waste} (MJ/kg) indicates the waste lower heating value, n_{inc} is conversion efficiency and 3.6 is the conversion factor from MJ to kWh, $M_{FINC(t)}$ is the amount of waste composition (tons) that could be utilized over t time (20 years) obtained from Eq. (5.4). M_{FINC} (tons/yr) is estimated from Eq. (5.14) and indicates the average annual mass of waste incinerated.

The Higher Heating Value (HHV) in MJ/kg of the waste is modelled from(Parikh et al., 2005) analysis of the correlation.

$$HHV_{waste} = 0.3491C \times 1.1783H \times 0.1005S - 0.015N - 0.0211A \quad (5.15)$$

where C, H, O, N, S and A represents carbon (45.03%), hydrogen (6.20%), oxygen (41.16%), nitrogen (1.98%), sulphur (0%) and ash (5.56%) contents of the ultimate analysis of the waste stream (Ayeleru et al., 2016). From the $\mathrm{HHV_{waste}}$, the lower heating value $LHV_{wasteINC}$ (MJ/kg) can be calculated as:

$$\mathrm{LHV_{wasteINC}} = \mathrm{HHV_{waste}} - (9 \times \%\mathrm{H} + \%\mathrm{H_2 0}) \times 2.44 \quad (5.16)$$

5.5.3 Electricity generation and anaerobic digestion technology

Anaerobic digestion is a biological method that decomposes organic matter through micro-organisms in the absence of oxygen to produce biogas for combined heat and power (Beyene et al., 2018; Tozlu et al., 2016). The biogas is a mixture of methane (45 - 60%), carbon dioxide (40 – 55%) (Scarlat et al., 2015) with traces of hydrogen sulphide (H_2S), Nitrogen (N_2), Hydrogen (H_2), Carbon monoxide and Oxygen (O_2)(Kalyani and Pandey, 2014; Tozlu et al., 2016). The electricity that can be generated is calculated as follows:

$$\mathrm{Ep_{(AD)}} = \frac{(\mathrm{V_{CH_{4actual}}} \times \eta \times \mathrm{LHV_{CH_4}} \times \mathrm{M_{F(AD)}})}{3.6} \quad (5.17)$$

$$\mathrm{M_{F(AD)}} = \frac{\sum_{t=1}^{n} \mathrm{M_{FAD(t)}}}{n} \quad (5.18)$$

where $\mathrm{M_{FAD(t)}}$ is from Eq. (5.4), $\mathrm{V_{CH_{4actual}}}$ (m^3/ton) indicates the volume of methane in the biogas, $\mathrm{LHV_{CH_4}}$ (MJ/m^3) is the LHV of methane 37.2 MJ/m^3 (Amoo and Fagbenle, 2013; Gómez et al., 2010), $\mathrm{M_{F(AD)}}$ (tons/yr) is the average mass of waste into the digester from Eq. (5.18), the conversion factor from MJ to kWh is 3.6 and η is 0.26, the electrical efficiency of biogas generator (Gómez et al., 2010). A model proposed by (Salami et al., 2011) was used to calculate $\mathrm{V_{CH_{4actual}}}$.

5.6 LIFE CYCLE INVENTORY

The life cycle inventory in the modelling of environmental impact assessment of WTE plants. It was developed using a combination of publications on LCA technical reports, LCA literature from scholars and international organisations and GHG inventory guidelines (EPA, 2014; Assamoi and Lawryshyn, 2012; Zaman, 2010; Cherubini et al., 2009; Tan et al., 2014; EPA, 2008; Mohareb et al., 2011). Some technical documents reviewed to develop this life cycle inventory includes a model developed by the US Environmental Protection Agency called the Waste Reduction Model (WARM) (EPA, 2006). Key literature used to develop this model include, the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006), the US EPA "Compilation of Air Pollutant Emission Factors" (AP-42) (EPA, 2000) and US EPA Background Information Document for Updating AP-42 Section 2.4 for Estimating Emissions from Municipal Solid Waste Landfills (EPA, 2000; EPA, 2008; EPA, 2014).

5.6.1 Gas emissions

There are generally grouped into five air emission compounds and shown in Table 5.5.

Table 5.5: Gas emissions and pollutants emitted into the environment (Assamoi and Lawryshyn, 2012; Tan et al., 2014)

Gas emissions	**Pollutants**
Criteria air pollutants	di-Nitrogen oxide (N_2O), volatile organic carbon (VOC) and Particulate Matter (PM)
Organic pollutants	dioxins/furans otherwise referred to as PCDDs/PCDFs (polychlorinated dibenzodioxins/dibenzofurans)
Greenhouse gases (GHGs)	Carbon dioxide (CO_2), methane (CH_4), diNitrous oxide (N_2O), Sulphur hexafluoride (SF_6), Perfluorocarbons (PFCs) and Hydrofluorocarbons (HFCs).
Acidic gases (AGs)	Hydrochloric acid gas (HCl) and Sulphur IV oxide gas (SO_2)
Heavy metals (HMs).	Nickel, lead and mercury

In this paper, only CO_2, CH_4 and N_2O emissions are considered as emission factors, and for acidic gas emissions HCI and SO_2 are considered. The GHGs emission factors for PFCs and HFCs are not included in this paper because they are not common (Assamoi and Lawryshyn, 2012).

Landfill gas is mainly CO_2 and CH_4, with traces of compounds such as NMOC, VOCs and HCl (Mendes et al., 2004).

5.7. EVALUATION OF AIR EMISSIONS FROM THE SCENARIOS

5.7.1 Scenario 1 (baseline): The landfill (LF)

This scenario is a landfill without energy recovery, where all waste streams are deposited except for recyclables and the total mass treated is given by Eq. (5.4). The biodegradable waste landfilled anaerobically decompose and release CH_4 and CO_2 into the atmosphere with other traces of H_2S, HCl and HF, however, the plastic component does not contribute to landfill emission since they do not degrade. The presence of the gases poses a threat to the environment because they are GHGs more especially CH_4 which has a high global warming potential. It can significantly contribute to climate change and depletion of the ozone layer as it is being 28 times than that of CO_2 (Mendes et al., 2004; Assamoi and Lawryshyn, 2012).Therefore, CH_4 is the only GHG considered in this study and CO_2 is ignored because CO_2 emitted from biodegradable waste (biomass-based) is assumed equal to that absorbed during its lifetime (carbon neutral). The US EPA LandGEM mathematical model Eq. (5.6) was used to estimate the annual methane emission.

It is assumed that all methane component of the landfill gas is released into the atmosphere. However, only 90% of the CH_4 generated is available for atmospheric emission since 10% is oxidised either directly or by bacteria into CO_2 near the surface of the landfill (IPCC, 2006).

Carbon IV oxide equivalent of methane (CO_{2eq}) emission was estimated by multiplying annual methane emission by 28 as methane has about 28 times global warming potential of CO_2. Therefore, the CO_2 equivalent emission (CH_4) due to this scenario is obtained as:

$$E_{BSL}\,(kgCO_2eq/yr) = GWP_{CH_4} \times 0.9 \times M_{CH_4} \times 1000 \quad (5.19)$$

$$M_{CH_4}(Mg/yr) = 6.67 \times Q_g \times 10^{-4} \quad (5.20)$$

where E_{BSL} (Baseline) is the CO_2 equivalent of methane released without energy conversion, M_{CH_4} is the mass of methane gas, Q_g the average methane generated per annum (m^3/year) obtained from Eq. (5.12) and GWP_{CH_4} ($kgCO_2$/kg GHG) is the global warming potential of methane and 0.000667 is a conversion factor from m^3/yr to Mg/yr as used in the LandGEM model.

Besides CH_4 and CO_2, there are other pollutants which are landfill gases that are generated such as VOC and NMOC (hexane), HCl and SO_2. Only SO_2 and HCl (acid gases) are considered and referred by this paper as other pollutants. This is because the concentration of VOC and NMOC is negligible compared to that of SO_2 and HCl. Hence, the mass emission of other pollutants, *p*, ($DM_{(P)}$ in kg/yr) can be calculated as follows:

$$DM_{(P)} = \frac{Q_{(P)} \times MW_{(P)}}{8.205 \times 10^{-5} \times (273 + T)} \quad (5.21)$$

where $MW_{(P)}$ is molecular weight of the pollutant, *p*, (g/gmol) and T is 30 °C - the temperature of the landfill area (Dada and Mbohwa, 2016), *p* is the pollutant gas which could be SO_2 or HCl.

$Q_{(P)}$ is emission rate of pollutant, p, (m^3/yr) and can be calculated as:

$$Q_{(P)} = \frac{Q_{CH_4} \times C_{(P)}}{C_{CH_4} \times 10^6} \quad (5.22)$$

where Q_{CH_4} is methane generation from landfill obtained from Eq. (5.6) (m^3/yr), $C_{(P)}$ is concentration of pollutant, *p*, in the landfill (ppmv) and C_{CH_4} is 0.55 concentration of methane.

5.7.2 Scenario 2: Landfill with energy recovery (LFGT)

In this scenario, the CH_4 generated in the landfill is used to produce electricity where a collection efficiency of 90% is assumed (Mohee and Simelane, 2015) and a landfill gas oxidation of 10% due to landfill cover. An internal combustion engine is used to combust the recovered CH_4 and the amount of electricity generated is estimated using Eq. (5.6) to Eq. (5.12). After capturing, only 28% of the CH_4 generated is released into the atmosphere which contributes to atmospheric global warming. Hence, the methane gas equivalent of CO_2 (CO_2eq) to be released into the atmosphere is calculated as:

$$E_{LFGT}(kgCO_2eq/yr) = GWP_{CH_4} \times 0.28 \times M_{CH_4} \times 1000 \quad (5.23)$$

where E_{LFGT} is the methane emission equivalent of CO_2.

CO_2 released is not considered as GHG because it is biogenic and does not contribute to global warming, however, when CH_4 is combusted, it is oxidised to $C0_2$ and some air pollutants such as HCl, N_2O, SO_2 and other NMOC which are emitted into the atmosphere. Therefore, since the concentration of N_2O and NMOC is low, only HCl and SO_2 are considered as pollutants.

The mass emission of pollutant, p, when CH_4 is collected and combusted in the ICE, $CM_{(P)}$ can be evaluated as follows:

$$CM_{(P)} = DM_{(P)} \times \eta_{col} \times \eta_{cont} \times M_{(P)} \quad (5.24)$$

where $DM_{(P)}$ is the mass emission of pollutant as obtained in Eq. (5.21), $M_{(P)}$ is the ratio of the molecular weight of pollutant to the molecular weight of active element (i.e. HCl to Cl or SO_2 to S), η_{col} is the landfill gas collection efficiency, η_{cont} is the control (conversion) equipment efficiency, p is the pollutant gas which is SO_2 and HCl. The estimates to evaluate the emission of pollutant with and without energy is shown in Table 5.6.

Table 5.6: Pollutants with and without landfill gas energy recovery (EPA, 2008)

Pollutant	**SO_2**	**HCI**
$MW_{(p)}$ (g/gmol)	64.00	36.46
$C_{(p)}$ (ppmv)	46.9	42.0
$M_{(p)}$	2	1.03
η_{cont}	0.972	0.972
η_{col}	0.90	0.90

5.7.3 Scenario 3: Incineration (INC) with anaerobic digestion (AD)

Two waste streams are considered in this scenario. For INC, combustible and yard waste stream are taken to the incinerator with energy recovery whilst for AD, food waste is taken to a digester with energy recovery. Emissions considered in this scenario are for both technologies, the first is the GHG emissions (global warming potential) through waste combustion in an incinerator and the second is the GHG emissions from biological degradation of organic waste (AD). The total electricity generated is, therefore, energy from INC plus energy from AD.

5.7.3.1 Incineration plant emissions

A mass burn or a water wall design incineration facility is adopted in this paper, where the capacity is in accordance with the annual average waste mass in Eq. (5.14).The air pollution control equipment in the incineration plant includes a spray dryer for acid gas control; activated carbon injection for mercury control; ammonia or urea injection by means of selective catalytic reduction for nitrogen oxide reduction and a fabric filter for particulate matter control (Assamoi and Lawryshyn, 2012; Mendes et al., 2004). The incineration facility is assumed to have zero discharge to the waterborne contaminant.

In an incinerator, fossil carbon in the waste is released as CO_2 with other GHGs such as N_2O and CH_4 (Kumar et al., 2016). The emission of HCl, HF, SO_2, NOx and heavy metals depends on the waste characteristics and the air pollution control devices. Bottom ash and fly ash only account for (20-30%) and (2-6%) of the original weight of the waste.

The IPCC's 2006 guidelines for national greenhouse gas inventories were used to calculate the greenhouse gases for the incineration plant (IPCC, 2006) and the US EPA ‘‘compilation of air pollutant emission factors” (AP-42) was considered for the heavy metals; criteria air pollutants, acid gases and dioxins and furans emissions (EPA, 2008). The anthropogenic or non-biogenic CO_2 was calculated by determining the amount of fossil carbon in each MSW component while the other emissions were determined based on the heating value of the waste. Both the amount of fossil fuel carbon in the MSW components and the heating value of the MSW components dependent on the MSW compositions and would be adjusted as the MSW composition changes.

Therefore, the direct GHG emission from combustion of waste is the sum of anthropogenic CO_2 and N_2O emissions converted into an equivalent amount of CO_2

emission using the 100-yr GWP. Only CO_2 emissions of fossil origin (e.g. plastics, textile, rubber, etc.) were included in the estimates for CO2 emissions. Following the IPCC (2006) methodology, the emission of GHGs from incineration technology E_{INC} can be obtained as follows:

$$E_{INC} = E_{CO2} + \sum_{h=1}^{n} E_h \tag{5.25}$$

Where E_{CO2} and E_h can be evaluated as follows

$$E_{CO2} = FC \times M_{FINC} \times \alpha \times \frac{M_{CO2}}{M_C} \tag{5.26}$$

$$E_h = EF_h \times GWP_h \times LHV_{wasteINC} \times M_{FINC} \times \%F_{nonbiogenic} \tag{5.27}$$

where FC is the fossil carbon component, h is the GHG of interest, M_{FINC} is the waste mass flow obtained from Eq. (5.14), M_{CO2} = 44 kg/mole, M_C = 12 kg/mole, α= oxidation factor ($\propto$= 1) (IPCC, 2006), EF_h is the emission factor of the GHGs (30 kg/TJ and 4 kg/TJ for CH_4 and N_2O,respectively (IPCC, 2006)), GWP is Global Warming Potential, $F_{nonbiogenic}$ is the fraction of anthropogenic component in the waste stream and $LHV_{wasteINC}$ is the lower heating value of the waste obtained in Eq. (5.16). According to IPCC 2006, textiles and rubber are comprised of 50% and 20% fossil carbon respectively. However, a default (20%) was suggested by IPCC (2006) for both textile and rubber and was adopted to calculate the anthropogenic carbon emission (Assamoi and Lawryshyn, 2012; IPCC, 2006). The CO_2 emissions from the combustion of biomass-based materials (paper, food, wood and other biodegradable components) contained in the waste are biogenic emissions and were not included in the CO_2 emission estimates (IPCC, 2006).

5.7.3.2 Anaerobic digestion plant emissions

A digester is used to treat biodegradable waste and the mass flow is calculated from Eq. (5.4) in section 5.3.1. The AD facility is designed based on the widely used Valorga process. There is the batch system which handles a large amount of biodegradable waste and needs a little amount of water with low microbial activity and produces low product yield. The continuous stirred tank reactor (CSTR) is capable of utilizing little quantity of biodegradable waste and needs a large amount of water and high microbial activity and produces high product yield (Abowei et al., 2009). This paper adopted the batch system digester and operates under mesophilic conditions because the mesophilic reactor operate at temperatures (30 - 40°C)(Poulsen, 2003). The typical biogas generation potential for the Valorga plant is in the range of 80 - 160 Nm^3/ Mg MSW with methane fraction of 0.6. The residue (digestate) that remains inside the digester can be treated and used as fertiliser since it is rich in nitrogen and potassium. The CO_2 component of the biogas and that which is produced from the biogas methane are of biogenic origin and are presumably carbon-neutral (Mohareb et al., 2011).

The CH_4 and N_2O emissions released during the composting process are very low, as a result N_2O emissions from the digester are assumed to be negligible (IPCC, 2006). However, leakage of CH_4 is expected from the AD facility which is considered as the main source of GHG emission (IPCC, 2006; Mohareb et al., 2011). The IPCC 2006 methodology suggested using a 5% CH_4 leakage rate for AD facilities. The amount of CH_4 emitted to the atmosphere due to leakage E_{CH_4AD} can, therefore, be estimated as follows:

$$E_{CH_4AD} = 0.05 \times GWP_{CH_{4actual}} \times p_{methane} \times M_{FAD} \tag{5.28}$$

Where $p_{methane}$ is the density of methane, (0.717 kg/m^3) (Supple, 2013), $GWP_{CH_4actual}$ is the actual volume of methane produced by the digester (Salami et al., 2011).

5.7.4 Scenario 4: Incineration (INC) with landfill gas recovery (LFGT)

In this scenario, combustible waste are taken into an incinerator to generate electricity and the remaining waste stream except for recyclables is deposited in a landfill with energy recovery. The GHG emissions come from both waste combustion (incineration plant) and the biological degradation of organic waste in the landfill (LFGT). Similarly, the total energy generated was obtained by adding energy from waste INC to that obtained from LFGT through a combined heat and power plant.

5.8 DETERMINATION OF ACIDIC AND ORGANIC POLLUTANTS FROM THE SCENARIOS

The acidic pollutants (SO_2, NO_x, HCl, H_2S, HF and ammonia gases) are responsible for acid rain and forest decline (Assamoi and Lawryshyn, 2012; Cherubini et al., 2009). The organic pollutants are a threat to public health due to their strong carcinogenicity and high toxicity (mainly consist of dioxin/furan)(Tsai, 2007).

5.8.1 Estimation of acidic pollutants

Acidification potential (AP) is the process whereby air pollution, mainly SO_2, NO_x and ammonia gases are converted into acidic substances which results to lake acidification and forest decline (Assamoi and Lawryshyn, 2012). The acidification potential in this paper is based only on SO_2 and HCl. The acidification potential was expressed as SO_2eq of the other acid gas. This was achieved by multiplying the equivalency factor of each gas by their emission potentials. Table 5.7 below shows the specific emission factor (S_{EP}) and

Table 5.8 shows the equivalency factors used in converting emissions to GWP in kgCO2eq and AP in kgSO_2eq.

Table 5.7: Specific emission factor for estimating emission of acid gases (EPA, 2000; Assamoi and Lawryshyn, 2012)

S/N	Pollutants (P)	Specific emission factor for each technology $SE_{(p)}$	
		AD (kg/kWh)	INC (kg/Mg)
1	SO_2	1.00524×10^{-5}	0.277
2	HCI	N/A	0.106

Table 5.8: Equivalency factors and emissions (Assamoi and Lawryshyn, 2012; Mendes et al., 2004; IPCC, 2019)

GWP - Global Warming Potential		AP – Acidification Potential	
GHG	Equivalency factor (kgCO_2eq)	Pollutants	Equivalency factor $EQ_{(p)}$ (kgSO_2eq)
CO_2	1.00	SO_2	1.0
CH_4	28.0	NO_2	0.70
H_2O	265.00	HCI	0.88

For each scenario, the emission potential of acid gases as expressed in SO_2eq are as follows:

Scenario 1

$$E_{SO_{2eqLFG}} = \sum_{P=1}^{2} DM_{(P)} \times EQ_{(P)} \quad (5.29)$$

Scenario 2

$$E_{SO_{2eqLFGT}} = \sum_{P=1}^{2} CM_{(P)} \times EQ_{(P)} \quad (5.30)$$

Scenario 3

$$E_{SO_{2eq(INC/AD)}} = E_{SO_{2eqAD}} + E_{SO_{2eqINC}} \tag{5.31}$$

Where

$$E_{SO_{2eq}AD} = \sum_{P=1}^{n} SE_{(p)} \times E_{AD} \times EQ_{(P)} \tag{5.32}$$

$$E_{SO_{2eq}INC} = \sum_{P=1}^{2} SE_{(p)} \times M_{FINC} \times EQ_{(p)} \tag{5.33}$$

Scenario 4

$$E_{SO_{2eq(INC/LFGT)}} = E_{SO_{2eqLFGT}} + E_{SO_{2eqINC}} \tag{5.34}$$

where p indicates the pollutants under consideration (p = 1 for SO_2 and p = 2 for HCl), $DM_{(P)}$ and $CM_{(P)}$ are mass emission of pollutants calculated from Eq. (5.21) and Eq. (5.24) respectively, $SE_{(p)}$ is the specific emission factor shown in Table 5.7, $EQ_{(P)}$ is the SO_2 equivalency factor shown in Table 5.8, E_{AD} is the electricity potential from AD technology calculated from Eq. (5.17) and M_{FINC} is mass of waste incinerated calculated from Eq. (5.14).

5.8.2 Estimation of organic pollutants

The organic pollutant known as dioxins/ furans otherwise referred to as PCDDs/PCDFs (polychlorinated dibenzodioxins/dibenzofurans) is emitted in the incineration process(Cherubini et al., 2009). Dioxins from an incinerator are produced either through the formation from precursors or the formation by de novo synthesis where the precursors are produced through incomplete combustion or heterogeneous catalytic reaction on the surface of fly ash (Liu et al., 2017; Cherubini et al., 2009). It is important to note that, dioxins/furans are not applicable to scenario 1. The estimation of organic pollutant can be calculated as follows:

Scenario 2

$$E_{dioxin(LFGT)} = SE_{(P)} \times E_{P(LFGT)} \tag{5.35}$$

Scenario 3

$$E_{dioxin(INC/AD)} = E_{dioxin(INC)} + E_{dioxin(AD)} \tag{5.36}$$

Where

$$E_{dioxin(AD)} = SE_{(dioxin)} \times E_{P(AD)} \tag{5.37}$$

$$E_{dioxin(INC)} = SE_{(dioxin)} \times M_{FINC} \tag{5.38}$$

Scenario 4

$$E_{dioxin(INC/LFGT)} = E_{dioxin(INC)} \times E_{dioxin(LFGT)} \tag{5.39}$$

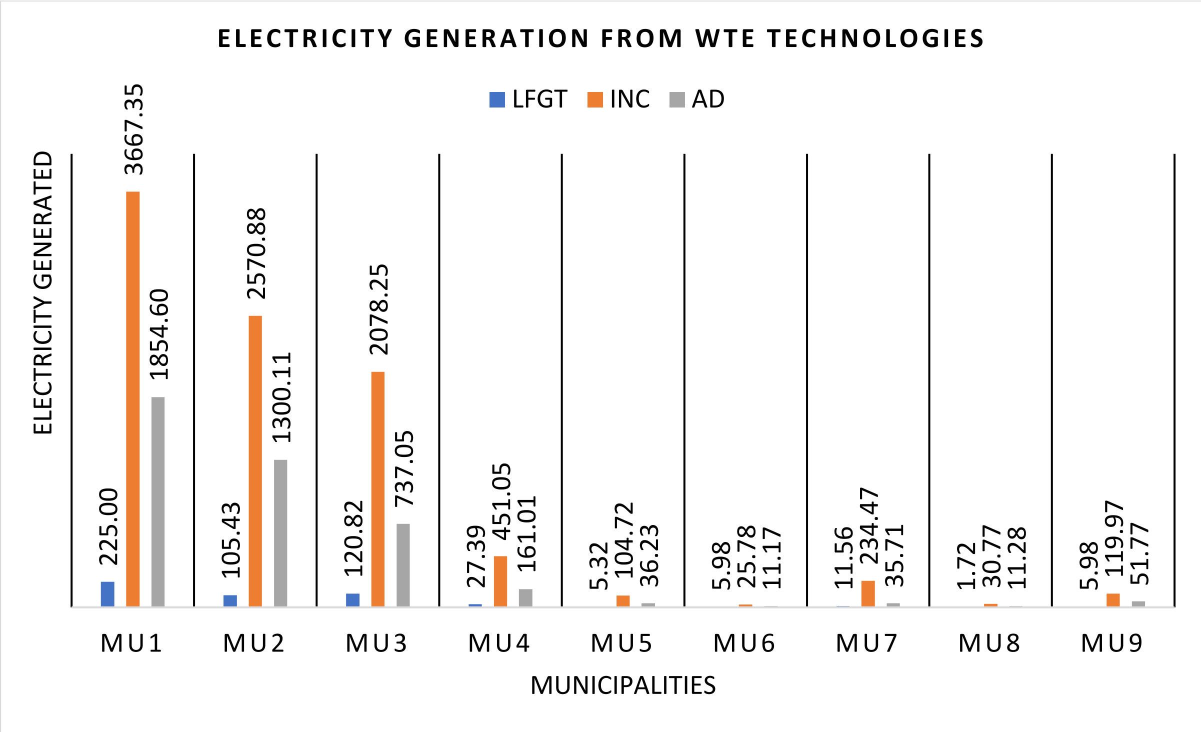
where $SE_{(dioxin)}$ is the specific emission factor for dioxin/furans for each technology; LFGT (kg/MWh) estimated as 1.4946×10^{-9} (EPA, 2008), AD (kg/MWh) estimated as 5.10354×10^{-12} (EPA, 2000) and INC (kg/Mg of waste) estimated as 3.31×10^{-8} (Assamoi and Lawryshyn, 2012). $E_{P(LFGT)}$ and $E_{P(AD)}$ are the electrical energy (MWh) obtained from LFGT and AD technologies respectively while M_{FINC} is the mass of waste incinerated.

5.9. RESULTS AND CONCLUSION

This section concludes the life cycle assessment of four waste management scenarios; scenario 1 - landfill (LF), scenario 2 - landfill with energy recovery (LFGT), scenario 3 - incineration with anaerobic digestion (INC with AD) and scenario 4 - incineration with landfill with energy recovery (INC with LFGT).Global warming potential, acidification potential and dioxin/furan emission potential were assessed as environmental impact categories.

5.9.1 Electricity generation potential of WTE technologies in each municipality

The electrical energy generation potential of WTE technologies (LFGT, AD and INC) is shown in Figure 5.5. It shows that INC technology has the greatest potential for electricity generation in all the municipalities and is the highest (3667.35 GWh per annum) in MU1 (City of Johannesburg municipality). This is due to the presence of plastic and other combustible waste with high calorific values and greater amounts of food waste with high biological degradability in the waste stream. An analysis by (Tan et al., 2014) on the energy benefits of renewable energy from MSW showed that waste incineration had the highest energy potential in Malaysia. AD technology is the second best in terms of electricity generation than LFGT technology. Normally, AD tends to be a preferred technology than LFGT for handling organic content of MSW because of the high decomposition potential and production of biogas which is predominately methane(Amoo and Fagbenle, 2013). LFGT technology contributed the least to energy generation. This may be due to the fact that high proportions of waste in the landfill are plastic. Plastic materials are stable elements which do not degrade and therefore contribute little to methane generation. They only occupy space in the landfill with limited contribution to methane generation which is used for electricity generation.



Source: Field-based materials, 2019.

Figure 5.5: Electricity generated in each municipality - GWh/ton of the total waste treated in one year.

5.9.2 Environmental impact assessment

The environmental impact categories for each scenario was assessed in terms of the Global Warming Potential (GWP), Acidification Potential (AP) and Dioxin emission potential.

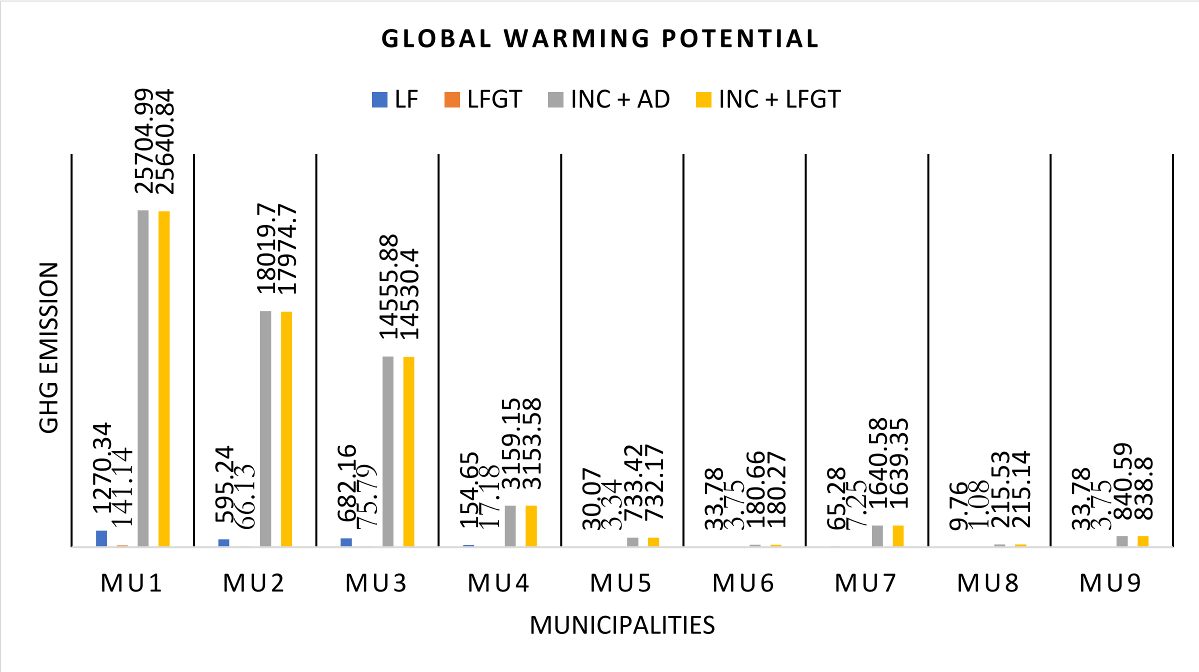
5.9.2.1 Global warming potential (GWP)

Global warming is caused by the emission of GHGs such as CO_2, CH_4, and N_2O which increase the atmospheric temperature. A model developed by the Intergovernmental Panel on Climate Change (IPCC, 2006) was used to determine the characterization factors of the gases and the equivalency factor over 100 years (GWP100) is shown in Table 5.8. The GWP is expressed as CO_2eq of every other GHG and can be calculated by multiplying the equivalency factor of each GHG (Table 5.8) by their emission potentials in section 5. The calculated GWP is shown in Figure 5.6 below.

Figure 5.6 shows that scenario 3 (INC with AD) has the highest GHG emissions in all the municipalities. This was expected as the electricity generation potential for INC was high in all the municipalities followed by the AD technology with high methane generation during the biological degradation of organic waste. The highest GWP in scenario 3 (INC with AD) is largely due to burning plastics, which creates anthropogenic CO_2 emission. This makes sense because the main source of GHG emission in INC technology is fossil carbon (mainly from plastic materials)(Mendes et al., 2004).

MU1 (City of Johannesburg municipality), MU2 (City of Ekurhuleni municipality) and MU3 (City of Tshwane municipality) showed the highest GWP with values of 25 704.99 ktonCO$_2$eq, 18019.7 ktonCO$_2$eq and 14 555.88 ktonCO$_2$eq respectively. MU1 and MU2 are the economic hubs in the Gauteng province with high population density and concentration of industries. These results are mainly influenced by the social prosperity, change in consumption pattern and the increase in the standard of living of the urban population. The lowest GWPs are shown in MU6 (Midvaal municipality) and MU8 (Lesedi municipality) with the values of 180.66 and 215.53 ktonCO$_2$eq, respectively.

GWP in scenario 1 (LF) emissions are higher than that in scenario 2 (LFGT) emissions. This is expected as the landfill gas produced in scenario 1 was emitted into the atmosphere. The GWP of scenario 1 was mainly a result of methane generation during the biological degradation of organic waste.



Source: Field-based materials, 2019.

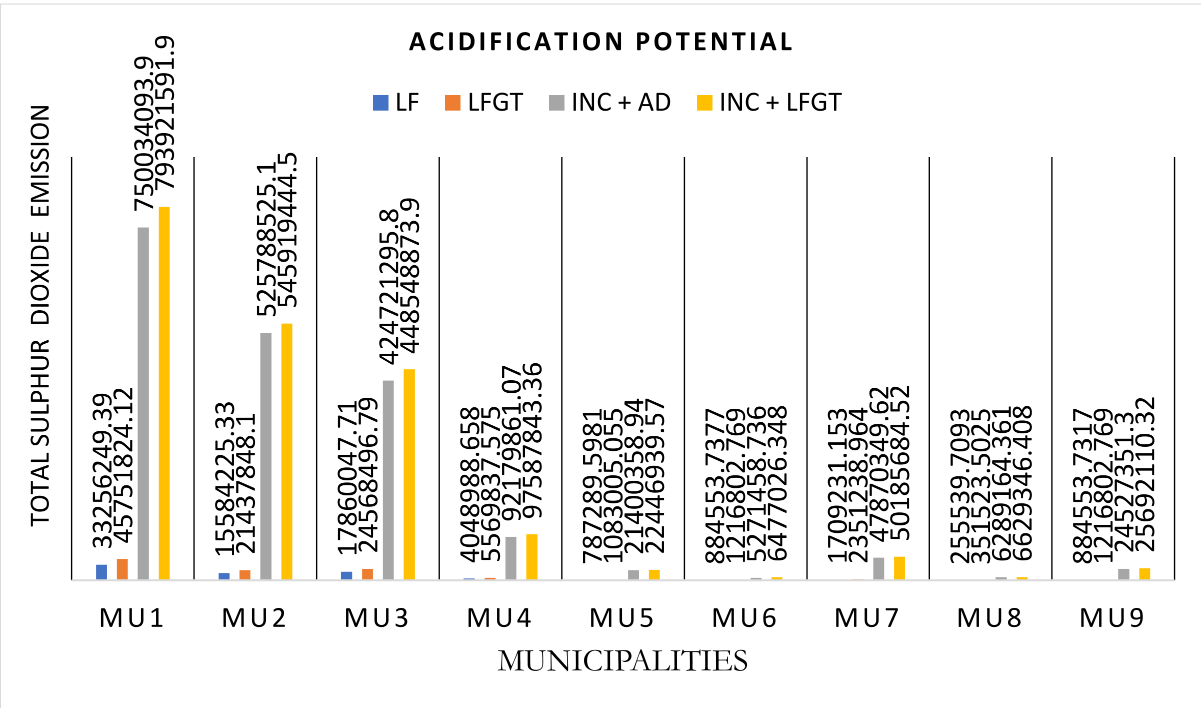
Figure 5.6: Global warming potential per ton of total waste treated in one year.

5.9.2.2. Acidification potential (AP)

Acidification potential is the process whereby air pollution, mainly SO_2, NOx, HCl, H_2S, HF and ammonia gases are converted into acidic substances (Assamoi and Lawryshyn, 2012). The acidification potential is expressed as SO_2eq of every other acid gas. It can be calculated by multiplying the equivalency factor of each gas (Table 5.8) by their emission potentials. Emissions of SO_2 and HCl are considered for the AP and the AP values for scenario 1 (LF) are taken from the procedure developed by the US Environmental Protection Agency (EPA, 2008). However, the AP values for scenario 2 (LFGT), scenario 3 (INC with AD) and scenario 4 (INC with LFGT) were determined by substituting the appropriate emission factors shown in Table 5.7 and the equivalent factors (Table 5.8) in Eqs. (5.29) – (5.34).

The acidification potential of each scenario is shown in Figure 5.7. It shows that scenario 1 (LF) has the least AP which signifies its environmental benefit compared to other scenarios. Scenario 4 (INC with LFGT) has the highest AP compared to the other scenarios. This finding agrees with (Tan et al., 2014) who also discovered that INC and LFGT are the highest contributors of pollutant in Malaysia.

The AP of scenario 1 (LF) ranges from 255539.7093 $kgSO_2eq$ in MU8 to 33259249.39 $kgSO_2eq$ in MU1. The AP of scenario 2 (LFGT) ranges from 351523.5025 $kgSO_2eq$ in MU8 to 45751824.12 $kgSO_2eq$ in MU1. Scenario 3 (INC with AD) and scenario 4 (INC with LFGT) have AP that ranges from 6289164.361 $kgSO_2eq$ to 750034093.9 $kgSO_2eq$ and 6477026.348 $kgSO_2eq$ to 793921591.9 $kgSO_2eq$, respectively.



Source: Field-based materials, 2019.

Figure 5.7: Acidification potential in $kgSO_{2eq}$ per tonne of total waste treated per year.

5.9.2.3 Dioxin emission potential

Dioxin (PCDDs/PCDFs) is one of the most toxic chemicals which form during waste combustion (Cherubini et al., 2009). Dioxins from an incinerator are produced either through the formation from precursors or the formation by de novo synthesis where the precursors are produced through incomplete combustion or heterogeneous catalytic reaction on the surface of fly ash (Liu et al., 2017; Cherubini et al., 2009).

Studies have shown that exposure to dioxins and furans has health implications such as skin cancer, liver, kidney, heart and blood disorder. Since dioxin is formed through the combustion process, then its estimation in scenario 1 (LF) does not apply. Table 5.9 shows that scenario 2 (LFGT) has low emission of dioxin in all the municipalities and this could be attributed to the fact that plastic (PVC) does not degrade to form a landfill gas since it is the major source of chlorinated material in the waste. Dioxin emission in scenario 4 (INC with LFGT) is higher than that in scenario 2 (LFGT) and it is expected as dioxin are emitted through waste combustion.

There are practices that control and prevent the emission of dioxin. Technologies of reducing dioxin include pre-treatment of waste before burning by mixing it with high-sulphur coal before burning, combustion process control, and flue gas control and purification. With the advancement in incinerator design and emission control driven by stringent regulations in the developed countries, incinerators can now operate with the emission of no dioxins (Xin-gang, 2016). It is noted that there is no much difference in the dioxin emission of scenario 3 (INC with AD) and scenario 4 (INC with LFGT). This is because the biological reaction in biogas generation from AD digester is similar to landfill gas in a landfill.

Table 5.9: Dioxins emission potential (kg TCDD) per tonne of total waste treated in one year.

Location	LFGT (scenario 2)	INC/AD (scenario 3)	INC/LFGT (scenario 4)
MU1	0.000336293	0.0668812	0.0672165
MU2	0.000157576	0.046885	0.0470419
MU3	0.000180588	0.0379008	0.038081
MU4	0.0000409404	0.00822574	0.0082666
MU5	0.000007961	0.00190978	0.00191772
MU6	0.000008943	0.000470227	0.000479165
MU7	0.0000172825	0.00427603	0.00429329
MU8	0.000002583	0.000561192	0.00056377
MU9	0.000008943	0.00218792	0.00219684

Source: Field-based materials, 2019.

6. CONCLUSION

The life cycle assessment of WTE technologies for nine different municipalities in the Gauteng Province has been presented with the aim of determining the option that is most environmentally friendly for electricity generation in each of the municipalities. The environmental impact categories for each scenario was assessed in terms of the Global Warming Potential (GWP), Acidification Potential (AP) and Dioxin emission potential. From this study, the following conclusions are made:

I. INC technology has the best electricity generation potential based on the different kind of waste generated in each municipality while LFGT technology presents the least electricity generation potential.

II. Out of the nine municipalities, MU1 (City of Johannesburg municipality) has the highest potential for INC technology with electricity generation potential of 3667.35 GWh/yr, followed by MU2 (City of Ekurhuleni municipality) with 2570.88 GWh/yr and MU3 (City of Tshwane municipality) with 2078.25 GWh/yr.

III. MU1 (City of Johannesburg municipality) presented the highest GWP and this is expected as it has the highest waste generation potential compared with the other municipalities.

IV. Scenario 3 (INC with AD) contributed the highest in the emission of greenhouse gas (highest GWP) compared to scenario 1 (LF), scenario 2 (LFGT) and scenario 4 (INC with LFGT). Therefore, it poses an environmental challenge in terms of climate change.

V. Scenario 2 (LFGT) presented the best option in terms of GWP (ktonCO_2eq) in all the municipalities.

VI. Scenario 1 (LF) presented the best AP in all the municipalities. Scenario 4 (INC with LFGT) has the highest AP and it indicates that it is the highest contributor of pollutants.

VII. Scenario 2 (LFGT) is the best option in term of dioxin/furans emission and scenario 4 (INC with LFGT) has high dioxin emission potential. This is expected as dioxin are emitted through the combustion of waste and LFGT does not incinerate waste.

CHAPTER SIX:

GENERAL CONCLUSION AND RECOMMENDATIONS

6.1. INTRODUCTION

This study presented an understanding of WTE technologies that can improve the inefficient management of MSW in the context of the Gauteng province, South Africa. WTE technologies have been presented as one of the avenues to improve the management of MSW whilst promoting clean and healthy urban environments through the recovery of waste while increasing renewable energy generation. It is estimated that the City of Johannesburg's landfills airspace will be completely depleted by the year 2023. This projection becomes a key motivation for the identification of suitable WTE alternative to manage MSW in the Gauteng province. This study suggested that, besides LFGT technology, alternative measures such as the INC technology for the combustible waste and AD technology of separated biodegradable waste should be considered to generate electricity and to broaden options for MSW management. This study has argued that INC and AD technologies will reduce the amount of waste going to landfill, as biodegradable and combustible waste will be diverted from landfill, which will increase the airspace of the landfill until 2036 with a 93% diversion of waste, potentially to earn carbon credits, create jobs and generate renewable electricity as well as revenue from the sale of by-products.

The Gauteng province is still high and solely dependent on landfills for MSW management. This study evaluated the potential of MSW for electricity production in nine municipalities using LFGT, INC and AD technologies and determined the economic viability of the WTE technologies. To achieve the electricity generation potential of MSW in the municipalities within the Gauteng province, the quantity and composition of the generated waste was calculated using the 2011 census population and interpolated to 2016 based on 3.1 % growth rate and the per capita generation in each municipality. The LandGEM equation was used to estimate methane generation from the waste generated in each year in order to evaluate the electricity generation potential of each technology. The LCOE, NPV and PBP methods were used to determine the economic viability of the technologies.

However, LFGT, INC and AD technologies emit methane gas and polluted chemicals into the atmosphere. Therefore, from a solid waste management perspective, WTE technologies pose challenges to the development of a green and sustainable future. This study evaluated the GWP, AP and dioxin/furan emission potential of the WTE technologies, using the life cycle assessment (LCA) methodology. Four scenarios were evaluated, namely scenario 1 - landfill (LF), scenario 2 - landfill with energy recovery (LFGT), scenario 3 - incineration with anaerobic digestion (INC with AD) and scenario 4 - incineration with landfill with energy recovery (INC with LFGT). The scenarios where evaluated against scenario 1 (LF) to determine the option that best fit each municipality in an environmentally sustainable manner.

6. 2. KEY FINDINGS

It has been shown in this study that:

I. The City of Johannesburg municipality (MU1) has the highest waste generation potential of 2.18925×10^{9} – 3.9103×10^{9} kg/yr between the year 2016 to 2035 with methane generation rate estimates of 181700000 m^3/yr (12210 ft^3/min).The City of Ekurhuleni municipality (MU2) has a waste generation potential of 1.33795×

10^9 – 2.3897×10^9 kg/yr with 88040000 m^3/yr (5916 ft^3/min) and the City of Tshwane municipality (MU3) has a waste generation potential of 1.09562×10^9 – 1.95692×10^9 kg/yr with 106900000 m^3/yr (7182 ft^3/min) methane estimates. The high waste and methane generation potential in MU1, MU2 and MU3 is expected as these municipalities are megacities with increasing population and relatively high waste generated per capita.

II. The second finding was that INC technology has the greatest potential for electricity generation in all the municipalities and the highest in the City of Johannesburg municipality, 3667.35 GWh per annum (MU1). The potential of the INC technology is explained by the high use of plastics and other waste streams which contribute considerably to INC, but not to AD and LFGT since plastics are not biodegradable.

III. The economic viability of WTE technologies indicated that LFGT technology has the highest LCOE ranging from R0.37023/kWh to R0.32952/kWh and a low NPV in all the municipalities ranging from R3.6 million to R197.5 million.

IV. An interesting finding is that the INC technology has a negative NPV. This indicates that the INC technology is more capital intensive compared to LFGT and AD. It can, therefore, be concluded that INC technology is not economically feasible. AD technology has the lowest LCOE and lowest PBP (return on investment is only a few months) in all the municipalities and high NPV which indicates that AD technology is an economically viable technology compared to LFGT and INC technologies.

V. For the GWP, scenario 3 (INC with AD) has the highest GHG emissions in all the municipalities. This was expected as the electricity generation potential for INC was high in all the municipalities followed by the AD technology with high methane generation during the biological degradation of organic waste. The highest GWP in scenario 3 (INC with AD) is due to the complementary contribution of INC. In the case of the INC technology, the GWP is largely due to burning plastics, which creates anthropogenic CO_2 emission. This makes sense because the main source of GHG emission in INC technology is fossil carbon (mainly from plastic materials).

VI. For the AP, scenario 1 (LF) has the least AP which signify its environmental benefit compared to other scenarios. Scenario 4 (INC with LFGT) has the highest AP compared to the other scenarios.

VII. For the dioxin emission potential, scenario 2 (LFGT) has low emission of dioxin in all the municipalities and this could be attributed to the fact that plastic (PVC) does not degrade to form a landfill gas since it is the major source of chlorinated material in the waste. Dioxin emission in scenario 4 (INC with LFGT) is higher than that in scenario 2 (LFGT) and it is expected as dioxin are emitted through combustion of waste.

This study showed that INC technology has high GWP, high AP and high emission potential of dioxin, however, there are practices that control and prevent the pollutants emission, dioxin and acid gases. The advancement in the incinerator design and emission control driven by stringent regulations in the developed countries has made it possible for incinerators to operate with the emission of no dioxins. Technologies to reduce dioxin include pre-treatment of waste before burning by mixing it with high-sulphur coal, combustion process control, flue gas control and purification. A dry method, wet method and semi-dry method are also used to treat acid gases and occurs in the reaction tower.

The most finding to emerge in the study is that INC technology is the next best and appropriate technology option for MSW management in the Gauteng province considering the fact that landfills are currently operating at full capacity due to overuse, however, the implementation of the waste incineration requires higher capital and operating costs.

Compared with a landfill site, firstly, INC technology plants are matured and stable. Secondly, INC technology is capable of reducing land as the plant occupies only limited areas for long time operation, therefore, saving land resources. As the opportunity cost of land is high, saving land resources is equivalent to saving construction costs. Thirdly, INC has the potential to reduce MSW volume and mass (80 - 90%) in converting the MSW into electricity or heat. It is also capable of improving electricity generation mix in the country. Lastly, it achieves complete harmlessness of waste because it has thorough disinfection. It is most effective in decomposing harmful ingredients and can completely kill the pathogen.

6.3. RECOMMENDATIONS

The increasing demand for energy and the abundance of MSW generated have necessitated the need for a provincial INC technology. The study noticed that higher performance of incineration come with higher capital. Therefore, with increasing investment from the government and other capitals, the INC industry can grow more rapidly and expand the market scales. This study recommends that:

I. The Gauteng provincial government should improve the effective management strategies matching the living habits of the citizens. Making effecting recycling and separation at source regulations is necessary to regulate the behaviour of individuals and to improve the system of waste collection and management.

II. An independent third-party rating agency must be established with authority either representing the interest of the Gauteng provincial government or that of enterprises. In the process of project approvals and constructions, the agency must release the main data of WTE plants to strengthen the exchange of information and public participation.

III. The Gauteng provincial government could build some public places or facilities around INC plants which are free of charge for the residents to promote recycling and separation at source.

IV. The waste INC technology and equipment must be developed with independent intellectual property rights. It is important to learn the advanced scientific technologies from abroad and produce waste INC facilities with local characteristics based on the condition of waste composition in the Gauteng province, timely and reasonable improvements or adjustments should be made on the incineration disposal.

V. The Gauteng provincial government and enterprises must have an open-door policy or an open information system to build mutual trust through the full exchange of information. Government, enterprises and residents could discuss together conservative suggestions for improvement.

VI. To reduce emissions of harmful pollutants, exhaust fumes after incineration should be strictly controlled and the government should supervise enterprises to take advantage of high-tech exhaust processing systems. The enterprises failing to meet the requirements of emissions should be strictly banned.

VII. The Gauteng provincial government must develop and implement a regulatory framework to address the environmental challenges and emissions arising from the constructing of an INC plant such as the control of dioxin emissions to the environment.

VIII. Before a procurement process, funding from external sources must be secured. A transactional advisor, steering committee and partners and citizens must be consulted. An appointed service provider must carry out an environmental impact assessment process so that the project can be issued with the required waste licence.

6.4. RECOMMENDATIONS FOR FUTURE RESEARCH

As part of the recommendations for future study, the study suggests that the electricity generation potential of gasification and pyrolysis technologies should be evaluated. INC technology is suitable for waste with low moisture content while AD is appropriate for waste with high moisture content. However, it is intuitive to believe that uncertainty in the waste composition could arise which could be a challenge in the selection of technology. In view of this, a future study should be conducted to incorporate the uncertainty factors in the annual waste generation and waste composition of the MSW into the selection of WTE technology in the Gauteng province.

Managing a WTE plant successfully requires an efficient waste collection system. Unfortunately, there is a lack of adequate facilities that could handle the continuously growing waste generated in the province. There is a need to conduct a study on the collection systems and attitude of citizens towards realising a technology, and the willingness to change existing traditions that are not favourable to the growth of WTE technologies. Such a study will give insights into the level of awareness of citizens with regard to MSW. The study would help in showing the level of awareness of the citizens and in developing strategies that could improve the attitude of the public towards waste sorting for effective waste collection and management. The role of policy and institutional reform in enhancing the managing MSW is also important. As at now, there is no regulatory framework in place which addresses the possible environmental challenges arising from building and utilization of WTE plants such as the control of dioxin emissions to the environment. Hence there should be a study on a comprehensive legal framework on the operation and a roadmap on the maintenance of WTE technologies in South Africa.

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APPENDICE 1- LANDFILLING AND LANDFILL GAS PROJECT

The above pictures show municipal solid waste deposited in a landfill

The above pictures show waste recycling in a landfill site

The above picture shows a landfill gas project in the City of Johannesburg

The above picture shows a landfill gas project in the City of Johannesburg

The above picture shows a landfill gas project in the city of Johannesburg

APPENDICE 2 - CLEARANCE CERTIFICATE

Research Office

HUMAN RESEARCH ETHICS COMMITTEE (NON-MEDICAL)
R14/49 Dlamini

CLEARANCE CERTIFICATE	PROTOCOL NUMBER: H18/03/05
PROJECT TITLE	From landfill to energy resource: Perspectives on the search for alternative solid waste management strategies in Johannesburg, South Africa
INVESTIGATOR(S)	Miss S Dlamini
SCHOOL/DEPARTMENT	GAES/
DATE CONSIDERED	16 March 2018
DECISION OF THE COMMITTEE	Approved
EXPIRY DATE	29 August 2021

DATE 30 August 2018 CHAIRPERSON J. Knight (Professor J Knight)

cc: Supervisor : Professor M Simatele

DECLARATION OF INVESTIGATOR(S)

To be completed in duplicate and **ONE COPY** returned to the Secretary at Room 10004, 10th Floor, Senate House, University. Unreported changes to the application may invalidate the clearance given by the HREC (Non-Medical)

I/We fully understand the conditions under which I am/we are authorized to carry out the abovementioned research and I/we guarantee to ensure compliance with these conditions. Should any departure to be contemplated from the research procedure as approved I/we undertake to resubmit the protocol to the Committee. I agree to completion of a yearly progress report.

Dlamini
Signature

03 / 09 / 2018
Date

PLEASE QUOTE THE PROTOCOL NUMBER ON ALL ENQUIRIES

APPENDICE 3 - PERMISSION LETTER

Joburg
A World Class African City

City of Johannesburg
Environment and Infrastructure Services Department
Office of the Executive Director

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MEMORANDUM

TO	:	**Smangele Dlamini**
FROM	:	**Suleman Shuaib** **Acting Executive Director: EISD**
Cc	:	**Makhosazana Baker** **Unit Head: Waste Management and Regulations**
DATE	:	**28th August 2018**
Re	:	**Permission to undertake research project (Waste to Energy Technologies in Solid Waste Management)**

I acknowledge receipt of your letter of request dated 24 of August 2018.

I Suleman Shuaib, Acting Executive Director: Environment and Infrastructure Services Department, give permission to Smangele Dlamini, a PhD student in the School of Geography, Archaeology and Environment Studies at Wits University in Johannesburg, to undertake a research project on waste to energy technologies in solid waste management within the EISD department.

Attached is request letter from the institution for ease of reference.

Thank you,

Suleman Shuaib
Acting ED: EISD
29/08/2018